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Distributions of diatoms in surface sediments from the Chanthaburi coast, Gulf of Thailand, and correlations with environmental factors

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ABSTRACT

This paper presents an analysis of diatoms collected from surface sediments in the Chanthaburi and Welu estuaries on the northern coast of the Gulf of Thailand. In total, 144 species are identified, representing 41 genera. Diatom abundance ranges from 645 to 24,979 valves/g, with an average of 7,215 valves/g. Diatoms primarily consist of common coastal species, warm water species and a few freshwater species. Additionally, *Surirella tenera* is identified as a unique freshwater species of the Welu River. Using cluster and redundancy analysis, we identified four diatom assemblages representing different environmental conditions. Diatom assemblages I and II are related to freshwater inputs from the Chanthaburi and Welu rivers. Assemblage III is closely related to nutrient concentrations and assemblage IV is representative of offshore waters from the Gulf of Thailand. The environmental factors controlling the distribution of diatoms are temperature, salinity, water depth and turbidity. The interior of the Welu Estuary was characterized by a brackish water environment strongly influenced by freshwater inputs to the south branch of the estuary and invasion of seawater into the north branch of the estuary. The Chanthaburi Estuary is a brackish water environment dominated by a single diatom assemblage. The main causes of differences in the distribution of diatoms between the Chanthaburi and Welu estuaries are runoff, estuary size, river width and nutrient concentrations.

1. Introduction

Diatoms are a common type of single-celled algae found in water bodies ranging from small ponds to the global ocean. Worldwide, diatoms are major contributors to primary productivity in coastal waters and play an important role in estuarine ecosystems. Because of their wide distribution, numerous species, ease of storage and sensitivity to environmental changes, diatoms are effective as environmental indicators. Specifically, the distribution of diatoms in surface sediments can reflect the combined effects of marine environmental factors and indicate the health of marine ecosystems.

The Gulf of Thailand is located on the continental shelf of the South China Sea surrounded by the coastal regions of Thailand, Cambodia, Malaysia and Vietnam. The climate of this region is strongly affected by the tropical monsoon and wind-driven ocean currents, which are strongly affected by the associated seasonal change in wind directions (Zhang et al., 2017). Water depths are shallow, with an average depth of 40 m (Trisirisatayawong et al., 2011) and a maximum depth of 86 m (Radoslaw et al., 2011). Previous studies in this region have examined the various properties of surface sediments (Liu et al., 2016), including the abundance of heavy minerals and authigenic minerals (Wang et al., 2014) as well as clay minerals (Shi et al., 2015). Previous studies of diatoms in the central Gulf of Thailand have reported 86 species (Silathornvisut, 1961) and 133 species (Boonyapiwat, 1999). Diatom assemblages in sandy deposits of the 2004 tsunami at Phra Thong Island, Thailand was discussed (Sawai et al., 2009). However, there are few reports on diatoms in surface sediments from the Gulf of Thailand off the coast of Thailand.

This paper focuses on the abundance, species composition and distribution of diatoms in surface sediments collected from the Chanthaburi coast, which includes the Chanthaburi and Welu estuaries. Such a study helps to identify what diatom assemblages occur within the surface sediments and determine their environmental significance. Comparative study of two adjacent estuaries allows for additional investigation into the effects of environmental characteristics on diatom assemblages.

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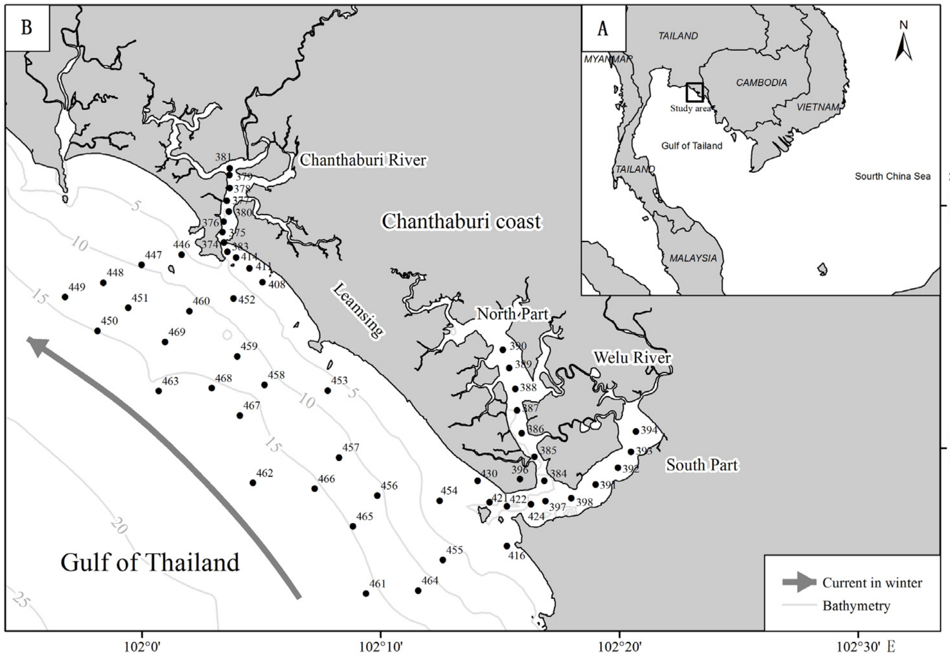

Fig. 1. (A) The study area. (B) The station locations and mean current directions of the Gulf of Thailand in winter (Anukul and Mahunnop, 1998; Liu et al., 2016).

2. Study area and surveys

The study area is located on the northern coast of the Gulf of Thailand (101°50′–102°30′E, 12°10′–12°40′N) and includes the Chanthaburi and Welu estuaries and the adjacent coastal area. Water depths range from 0 to 20 m. Tides in the study area are regular diurnal tides, with an average tidal range of 0.8–1.2 m. No data are available for annual runoff or sediment discharge within the study area.

The majority of the Gulf of Thailand exhibits a tropical monsoon climate. Wind driven currents in the gulf are thus strongly affected by seasonal changes in the prevailing wind directions. When the southwest monsoon prevails, currents primarily flow in a clockwise direction, though a counterclockwise current exists at the entrance of the gulf. When the northeast monsoon prevails, currents in the gulf are still generally clockwise, but are counterclockwise in the eastern part of the gulf (Wu, 2011). Seasonal variations in water circulation patterns are an important characteristic of the Gulf of Thailand (Liu et al., 2016). During the winter, there is a westward current along the coast of the study area (Anukul and Mahunnop, 1998) (Fig. 1). Most of Thailand's major rivers flow into the Gulf of Thailand discharging from the northern coast (Srisuksawad et al., 1997).

3. Methods

3.1. Sample information

Samples were obtained jointly by the Third Ocean Institute of the Ministry of Natural Resources of China and the Department of Mineral Resources of the Ministry of Natural Resources and Environment of Thailand in November 2015. Sediment samples were collected using a cylindrical box sampler off the Chanthaburi coast. Sampling stations are shown in Fig. 1.

3.2. Preparation of diatom samples

Diatom samples were obtained from the uppermost 5 cm of 55 sediment samples collected using a cylindrical box corer. All samples were processed in the diatom analysis laboratory of the Third Institute of Oceanography of the Ministry of Natural Resources, Xiamen, China. Briefly, samples of roughly 5 g were dried in an oven at 60 °C and weighed before processing. Samples were treated with 10% HCl and 30% H_2O_2 to remove carbonates and organic material, respectively, and were then washed in distilled water to remove these chemicals from the solution. Samples were then soaked in distilled water for 24 h and scattered using an ultrasonic dispersion instrument (120 HZ) for 2 min. We chose not to consider microdiatoms in our study. Therefore, samples were filtered through a 15-μm sieve to remove microdiatoms and other material finer than 15 μm. The suspension containing diatoms was then concentrated to a volume of 2 mL for identification under a 400× microscope. When completely homogenized, a subsample of the suspension was transferred to a cover slip and air-dried. Three permanent slides were made for each sample using Canadian balsam as a fixative.

3.3. Diatom identification and counting

Diatom species collected onto slides were observed and identified using an optical microscope (Olympus BX51, objective lens 40×, ocular lens 20×). For each sample, we counted and identified a minimum of 300 diatom valves from at least 3 slides. In cases where the valves were incomplete, we treated pieces that constituted more than half a valve as a whole valve. To identify samples at the genus level and, if possible, the species or even subspecies level, we compared collected samples against illustrations from published studies (Jin et al., 1965, 1982; Round et al., 1990; Jin et al., 1991; Cheng et al., 1996; Guo and Qian, 2003; Qi and Li, 2004; Smol and Stoermer, 2010; Cheng and Gao, 2012).

3.4. Data processing and statistical methods

Statistical analyses of diatom assemblages and correlations with various environmental factors were conducted using the R software environment. In preparation for statistical analyses all species data were first standardized. Seawater species with

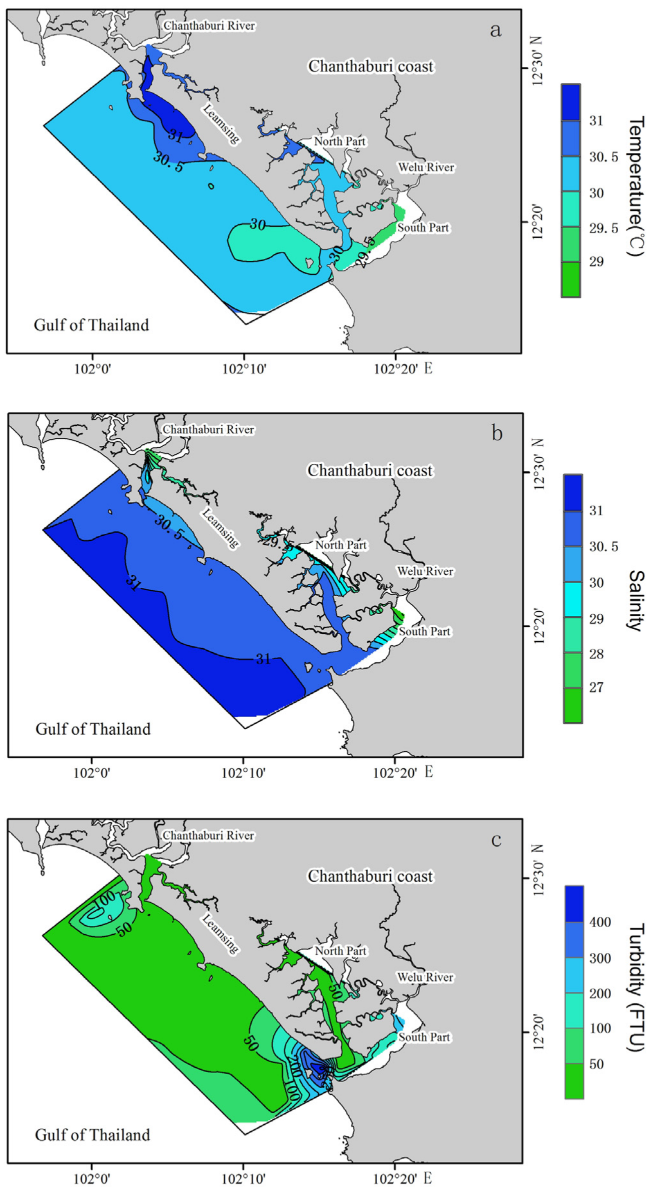

Fig. 2. Distribution of surface water temperature (a), salinity (b) and turbidity (c) in winter 2015.

relative abundances of 2% in at least one sample and all freshwater species were included in the analyses. Species diversity was calculated using the Shannon–Weaver index (Shannon and Weaver, 1949). Diatom assemblages were differentiated using cluster analysis and redundancy analysis (RDA) was used to determine whether differences in the assemblage vectors of each sample were statistically significant.

3.5. Environmental variables

The median grain size (Mz) of all sediment samples was analyzed at the Third Institute of Oceanography of the Ministry of Natural Resources, China. We used the Folk and Ward (1957) formula to calculate Mz as follows (Blott and Pye, 2001):

$$M_Z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \quad (1)$$

where ϕ_{16} ϕ_{50} and ϕ_{84} are the grain sizes of the 16th, 50th, and 84th percentiles, respectively.

The water temperature, salinity and turbidity of the water column were recorded using a conductivity temperature depth probe (RBR XR-620 CTD). The pH, dissolved oxygen (DO) and ammonia nitrogen (NH) were measured using a HQ40d multi-parameter water quality meter. Water depth was measured using a single beam sounder (SonarMite, Ohmex).

4. Results

4.1. Hydrological conditions

Based on concurrent measurements at these stations, surface seawater temperatures ranged from 28.97 to 31.47 °C, with an average of 30.33 °C. The Chanthaburi and Welu estuaries contrast significantly with regard to surface seawater temperatures (Fig. 2a). Surface seawater temperatures in the Chanthaburi estuary were above 30.5 °C, while surface seawater temperatures in the Welu Estuary were generally 29–30 °C. The average difference between the two estuaries was 1 °C. The salinity of surface seawater also varied greatly, with a range of 26.31–31.34 psu and an average of 30.48 psu (Fig. 2b). In the Chanthaburi Estuary, a strong salinity gradient existed from land to sea. In contrast, the Welu Estuary could be divided into two parts. In the northern section, surface water salinity was generally high because of the small amount of runoff and no clear salinity gradient was observed. The south branch of the Welu Estuary is the main runoff channel of the Welu River. Thus, a strong salinity gradient is observed from land to sea. The turbidity varied widely within the study area, with a range of 4.61–479.54 FTU and an average of 68.07 FTU (Fig. 2c). High turbidity values at the entrance of the Welu Estuary may be related to flocculation.

4.2. Diatoms distributions

A total of 41 genera and 144 taxa (including species and subspecies) were identified in 55 surface sediment samples. The absolute abundance of diatoms ranged from 645 to 24,979 valves/g, with an average of 7215 valves/g (Fig. 3a). Results indicate that the highest diatom abundances occurred in coastal waters rather than within the estuaries. Abundances in the coastal region were commonly greater than 10,000 valves/g. This value is similar to that of samples taken off the coast of China (20,000–40,000 valves/g) (Chen et al., 2014a,b, 2019). The Shannon–Weaver index reflected high biodiversity in the Chanthaburi Estuary and surrounding areas, with values above 2.5, consistent with samples from the coast of the East China Sea, and lower values in the Welu Estuary (Fig. 3b).

Species with a relative percentage of diatoms >10% were considered to be dominant species. Species with a relative percentage of diatoms between 5% and 10% were considered to be sub-dominant species. The dominant species in the surface sediment samples in the study area were *A. nodulifera, B. reticulata, C. centralis, Coscinodiscus* sp., C. volutus, Cyclotella sp., C. striata, C. stylorum, P. sulcata, T. nizschioides and *T. olivaeformis* (Fig. 4, Table 1). There were 15 sub-dominant species, including *A. ehrenbergii, B. heteroceros, Biddulphia* sp., C. adriaticus, C. asteromphalus, C. lineatus, C. subtilis, C. meneghiniana, Melosira sp., Nitzschia sp., Pleurosigma sp., Rhizosolenia sp., S. tenera, Trachyneis sp., and *T. favus* (Table 1). Diatom assemblages were dominated by warm coastal marine and brackish taxa, which is consistent with the tropical coastal and estuarine locations of the sample sites.

From the perspective of diatom content, *A. nodulifera*, *C. stylorum*, and *P. sulcata* were the most important species with the study area, with an average content of more than 10% (Table 1). *A. nodulifera* is a warm water species. According to previous studies,

Table 1
Species represented in the surface sediment in the study area.

Domin species (Relative abundance >10%)			Sub-dominating species (Relative abundance 5%–10%)		
Name	Abundance range (%)	Average abundance (%)	Name	Abundance range (%)	Average abundance (%)
Azpeitia nodulifera (A. Schmidt) G. Fryxell and P. A. Sims	0–69.23	26.81	*Actinocyclus ehrenbergii* Ralfs	0–5.45	0.67
Biddulphia reticulata Roper	0–46.67	8.04	*Biddulphia heteroceros* Grunow	0–5.45	1.14
Coscinodiscus centralis Ehrenberg	0–34.78	2.41	*Biddulphia* sp.	0–8.16	0.51
Coscinodiscus sp.	0–25.00	5.01	*Campylodiscus adriaticus* Grunow	0–6.52	0.50
Coscinodiscus volutus Baldauf cf.	0–21.21	3.98	*Coscinodiscus asteromphalus* Ehrenberg	0–8.33	0.21
Cyclotella sp.	0–15.91	0.87	*Coscinodiscus lineatus* Ehrenberg	0–7.81	1.29
Cyclotella striata (Kuetz.) Grunow	0–13.04	1.70	*Coscinodiscus subtilis* Ehrenberg	0–9.52	3.5
Cyclotella stylorum Brightwell	0–41.67	10.16	*Cyclotella meneghiniana* Kuetzing	0–5.56	0.32
Paralia sulcata(Ehr.) Cleve	0–34.87	14.29	*Melosira* sp.	0–9.09	0.40
Thalassionema nizschioides Grunow	0–11.35	2.68	*Nitzschia* sp.	0–8.54	0.33
Trachyneis olivaeformis Chin et Cheng	0–13.04	0.55	*Pleurosigma* sp.	0–9.09	0.74
			Rhizosolenia sp.	0–5.56	0.30
			Surirella tenera Gregory	0–6.10	0.19
			Trachyneis sp.	0–8.70	1.00
			Triceratium favus Ehrenberg	0–7.56	1.70

Table 2
Summary of RDA analyses.

Axes	1	2	3	4	5	6	7	8
Eigenvalues	0.04092	0.01997	0.009619	0.004059	0.003047	0.002218	0.001782	0.001074
Proportion explained	0.49483	0.24154	0.116325	0.049089	0.036842	0.026828	0.021555	0.012993
Cumulative proportion	0.49483	0.73637	0.852694	0.901783	0.938625	0.965453	0.987007	1.000000

it is widely distributed with the Gulf of Thailand and is also one of the main diatom species in surface sediments collected from the South China Sea (Lan, 1993; Lan et al., 1995b; Sun et al., 2013). Its dominance in the study area indicates that this diatom species is also abundant in the marginal seas around the South China Sea. *C. stylorum* and *P. sulcata* were widely distributed along the coast. These species likewise appear off the coast of China from the Liaodong Peninsula at 39 °N to Guangxi Province at 21 °N (Sun et al., 2013; Chen et al., 2014a, 2016). *P. sulcata* is widely distributed in offshore and upwelling water columns, especially at mid- to low-latitudes, and in subtropical and temperate offshore sea areas (Blasco et al., 1980; Abrantes, 1988; Karpuz and Schrader, 1990; Lange et al., 1998; Abrantes et al., 2007). This species is also commonly distributed along the coast of China in deeper waters (Shang et al., 2006; Chen et al., 2012, 2014a,b). Within the study area, *P. sulcata* appeared in offshore areas with deeper water depths. The distribution of *C. stylorum* was opposite to that of *P. sulcata* and was mainly distributed in shallower nearshore waters, appearing with greater abundance in the Welu Estuary. *C. striata* and exhibited high abundance at the entrance of the Welu Estuary. *B. reticulata* was primarily distributed in shallow nearshore and estuary waters with water depths of less than 10 m. *C. centralis* was mainly distributed in the Welu Estuary. *T. olivaeformis* was distributed mainly in the northern part of the Welu Estuary and may in fact be a representative species of the Welu Estuary. In contrast to *C. centralis*, *T. nizschioides* was mainly distributed at the entrance of the Chanthaburi Estuary and in nearshore coastal waters.

Analysis of data on species exhibiting relative abundances >2% occurring at more than five stations is presented in distribution maps distinguishing between warm water species, freshwater species, brackish water species and saltwater species (Fig. 5). The most prominent warm water species in the study area are *Apz. nodulifer*, *Bid. heteroceros* and *C. adriaticus*. These species are mainly distributed along the coast and occur at lower levels of abundance within the estuaries. Seven primary freshwater species are identified in the study area, including *Cyclotella comta, C. meneghiniana, Cymbella tumida, Diploneis elliptica, Hydrosera whampoensis, Nitzschia sigmoidea*, and *S. tenera*. Among these, *C. comta*, *C. meneghiniana, C. tumida*, *D. elliptica*, *H. whampoensis*, and *N. sigmoidea* are mainly distributed near the Chanthaburi Estuary, while *S. tenera* was primarily distributed in the Welu Estuary. Brackish water species were mainly distributed in the Welu Estuary and nearby coastal waters. Saltwater species were distributed along the coast and in the northern part of the Welu Estuary. These results are consistent with measurements of salinity. Moreover, the distribution of characteristic species in the Welu Estuary reflects the fact that the main freshwater input to the Welu Estuary, namely the Welu River, enters through the south branch of the estuary. Fresh water can also enter the north branch of the estuary through a channel that connects the north and south branches of the estuary.

4.3. Diatom assemblages

Diatom species data used in statistical analyses included data for species with a total abundance >2% and the sum of 7 kinds of fresh water species (*C. comta, C. meneghiniana, C. tumida, D. elliptica, H. whampoensis, N. sigmoidea,* and *S. tenera*). Data on environmental factors included average grain size (Mz), water depth, salinity, temperature, turbidity, pH, ammonia nitrogen (NH) and dissolved oxygen (OC). Results of RDA on environmental variables and samples, and on environmental variables and diatom species are shown in Figs. 5, 6, Tables 2, and 3. Using cluster analysis, the 55 samples can be divided into four groupings based on the composition of the diatom species (Fig. 5, Table 4).

4.3.1. Diatom assemblage I: B. reticulata- T. nizschioides - C. comta - D. elliptica

This group was dominated by saltwater species, including *B. reticulata* and *T. nizschioides*, and contained a certain amount of fresh water species, mostly *C. comta, C. meneghiniana* and *D. elliptica*. It also contained warm water benthic species such as *B. heteroceros*. The most abundant species in diatom assemblage I was *B. reticulata*, with an abundance of 5.04–46.67% and an average of 19.04%. The abundance of *T. nizschioides* ranged from 0.00% to 11.35% with an average of 5.03%, the abundance of *C.*

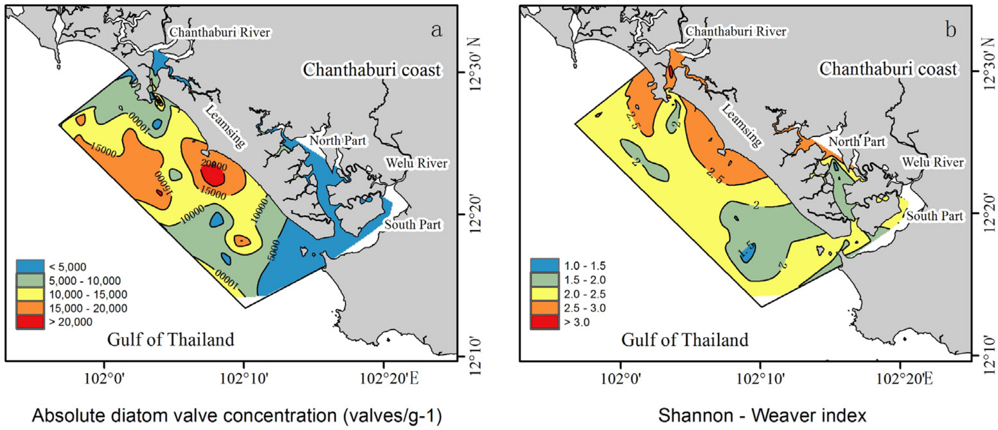

Fig. 3. Abundance and diversity of diatoms in surface sediments collected in 2015.

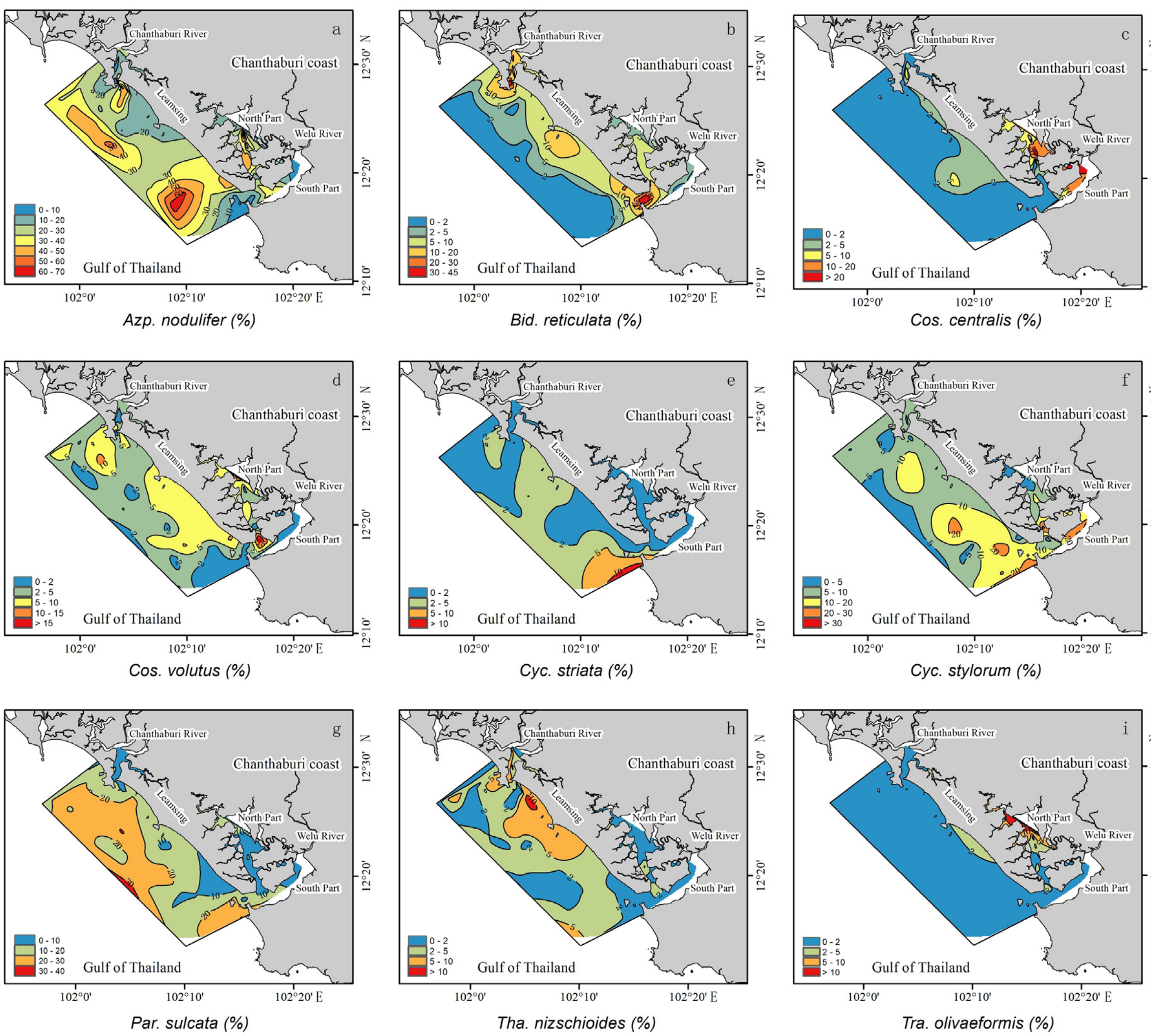

Fig. 4. Distribution of dominant diatom species in surface sediments collected in 2015.

comta ranged from 0.00% to 3.85% with an average of 0.64% and the abundance of *D. elliptica* ranged from 0.00% to 1.52% with an average of 0.21%. Diatom assemblage I represents a brackish water environment subject to both riverine and oceanic inputs, and which is positively correlated with surface water temperatures.

4.3.2. Diatom assemblage II: *C. centralis* - *C. stylorum* - *S. tenera*

Diatom assemblage II is primarily composed of *C. centralis* and *C. stylorum*, which is the most widely distributed species along the coast. The abundance of *C. centralis* ranged from 6.52% to 34.78% with an average of 17.58%. The abundance of *C. stylorum*

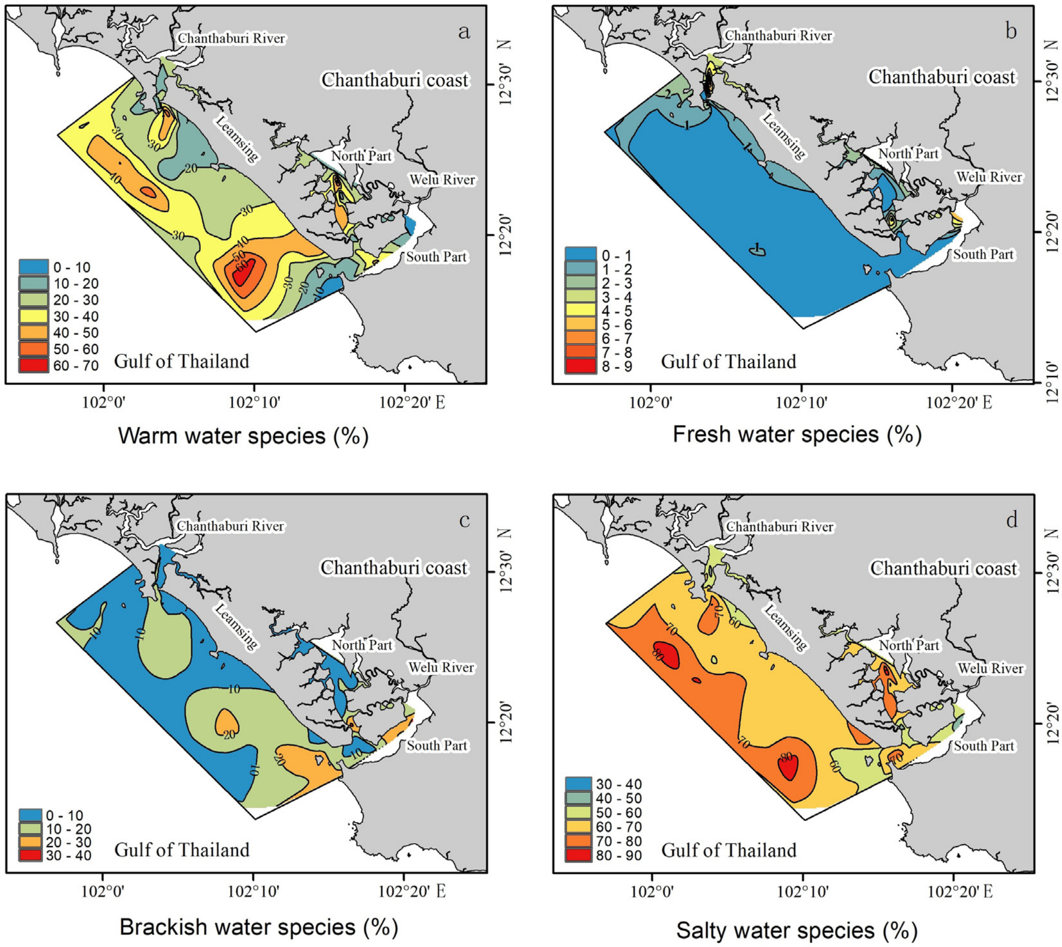

Fig. 5. Distribution of characteristic species.

ranged from 3.41% to 22.22% with an average of 12.60%. The abundance of *S. tenera*, a kind of fresh water species, was 0.00%–6.10% with an average of 2.07%. It only appeared at stations 390 and 394 in the Welu Estuary. This diatom assemblage was positively correlated to turbidity and average grain size. Overall, diatom assemblage II most likely represents a coastal group of diatoms that are affected by fresh water.

4.3.3. Diatom assemblage III: *P. sulcata* -*A. nodulifera* -*C. stylorum*

Diatom assemblage III consists of the most common coastal species including *C. stylorum* and *P. sulcata*. Some samples also contained *A. nodulifera*, which is also a common warm water species in the South China Sea. The abundance of *C. stylorum* ranged from 2.10% to 41.67%, with an average of 19.47%. The abundance of *P. sulcata* ranged from 9.52% to 34.87% with an average of 21.97%. Diatom assemblage III is associated with coastal waters and is positively correlated with concentrations of ammonia nitrogen and dissolved oxygen.

4.3.4. Diatom assemblage IV: *A. nodulifera* - *P. sulcata* -*T. nizschioides* - *C. striata*

Diatom assemblage IV was dominated by warm water coastal species. Among these, *A. nodulifera* and *P. sulcata* were the most abundance, with an average combined abundance >15%. The abundance of *A. nodulifera* ranged from 17.97% to 69.23%, with an average of 43.85%. This species is also common in the South China Sea and Kuroshio regions and constitutes a symbolic warm water species in the Western Pacific (Jousé et al., 1971; Lan et al., 1995a; Hasle, 1997; Onodera et al., 2005; Ren et al., 2014; Shen et al., 2017). The abundance of *P. sulcata* ranged from 0% to 25.39%, with an average of 15.26%. The abundance of *T. nizschioides* ranged from 0.00% to 8.05% with an average of 2.16%. The abundance of *C. striata* ranged from 0.00% to 2.86% with an average of 1.14%. Diatom assemblage IV represents an offshore group consisting of warm water species that is positively correlated with salinity and water depth.

4.4. Environmental factors

By performing a statistical significance test on each environmental factor, results demonstrate that temperature, salinity, water depth and turbidity are the most significant factors controlling the distribution of diatoms within the study area. The results of RDA analyses show that the major species in diatom assemblage IV are positively correlated to water depth and salinity, indicating that the species in this assemblage are primarily distributed in deeper waters far from the coast. Diatom assemblage II was inversely correlated with water depth and salinity, and positively correlated with turbidity and average grain size, indicating that this assemblage is mainly distributed in estuaries and shallow waters with low salinity and high turbidity. Diatom assemblage I was positively correlated with temperature, and distributed in areas of high temperature, medium water depth and medium salinity. Diatom assemblage III was positively correlated with concentrations of ammonia nitrogen and dissolved oxygen, indicating that this assemblage is distributed in areas of high nutrient concentrations (see Fig. 7).

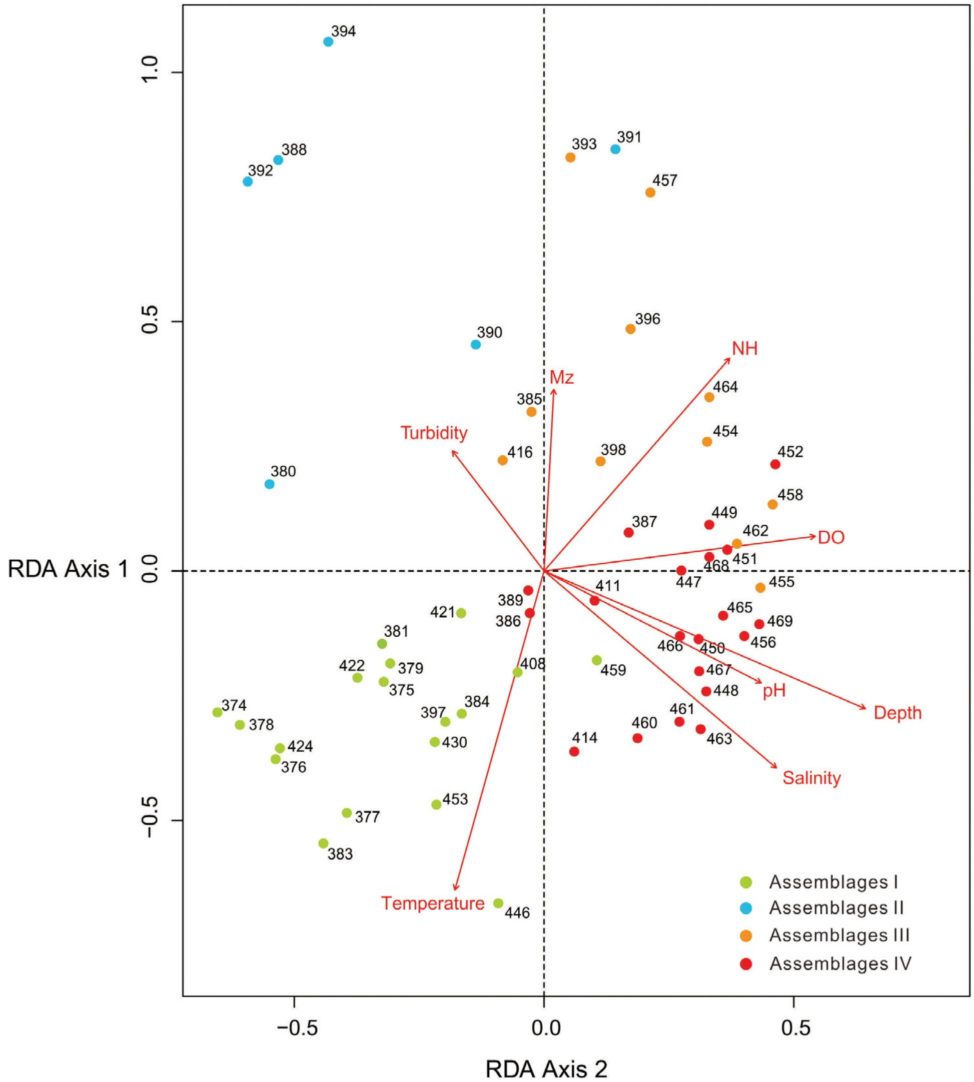

Fig. 6. RDA biplot of environmental variables and samples. The eigenvalues for RDA axis 1 and 2 were 0.041, 0.020, respectively.

Table 3
Correlations between the first and second RDA axes and 8 selected environmental variables.

Variables	Axis 1	Axis 2
Temperature	−0.033	−0.075
Salinity	0.071	−0.064
Turbidity	0.000	0.000
Depth	0.018	−0.005
DO	0.270	0.063
NH	0.001	0.002
pH	−0.626	−0.055
Mz	0.028	0.043

Table 4
Characteristics of the dominant species in different diatom assemblages.

Diatom assemblage	Dominating species	Average abundance (%)	Abundance range (%)
I	*B. reticulata*	19.04	5.04–46.67
	T. nizschioides	5.03	0–11.35
	C. comta	0.64	0–3.85
	D. elliptica	0.21	0–1.52
II	*C. centralis*	17.58	6.52–34.78
	C. stylorum	12.60	3.41–22.22
	S. tenera	2.07	0–6.10
III	*P. sulcata*	21.91	9.52–34.87
	A. nodulifera	21.97	0–40.82
	C. stylorum	19.47	2.10–41.67
IV	*A. nodulifera*	43.85	17.97–69.23
	P. sulcata	15.26	0–25.39
	T. nizschioides	2.16	0–8.05
	C. striata	1.14	0–2.86

5. Discussion

5.1. Diatom assemblages and their environmental significance

Based on the above analysis, diatoms in surface sediments collected within the study area can be divided into four diatom assemblages. The distribution of these diatom assemblages is shown in Fig. 8. Both diatom assemblage I (green circles) and diatom assemblage II (blue circles) contain fresh water species, related to freshwater inputs. Consequently, these assemblages are primarily distributed in the two estuaries.

Diatom assemblage II was primarily distributed along the landward sides of the north and south branches of the Welu Estuary, associated with freshwater inputs from the Welu River. The occurrence of diatom assemblage II inseparable reflects the effects of freshwater inputs from the Welu River. While the composition of diatom assemblage II is dominated by coastal species

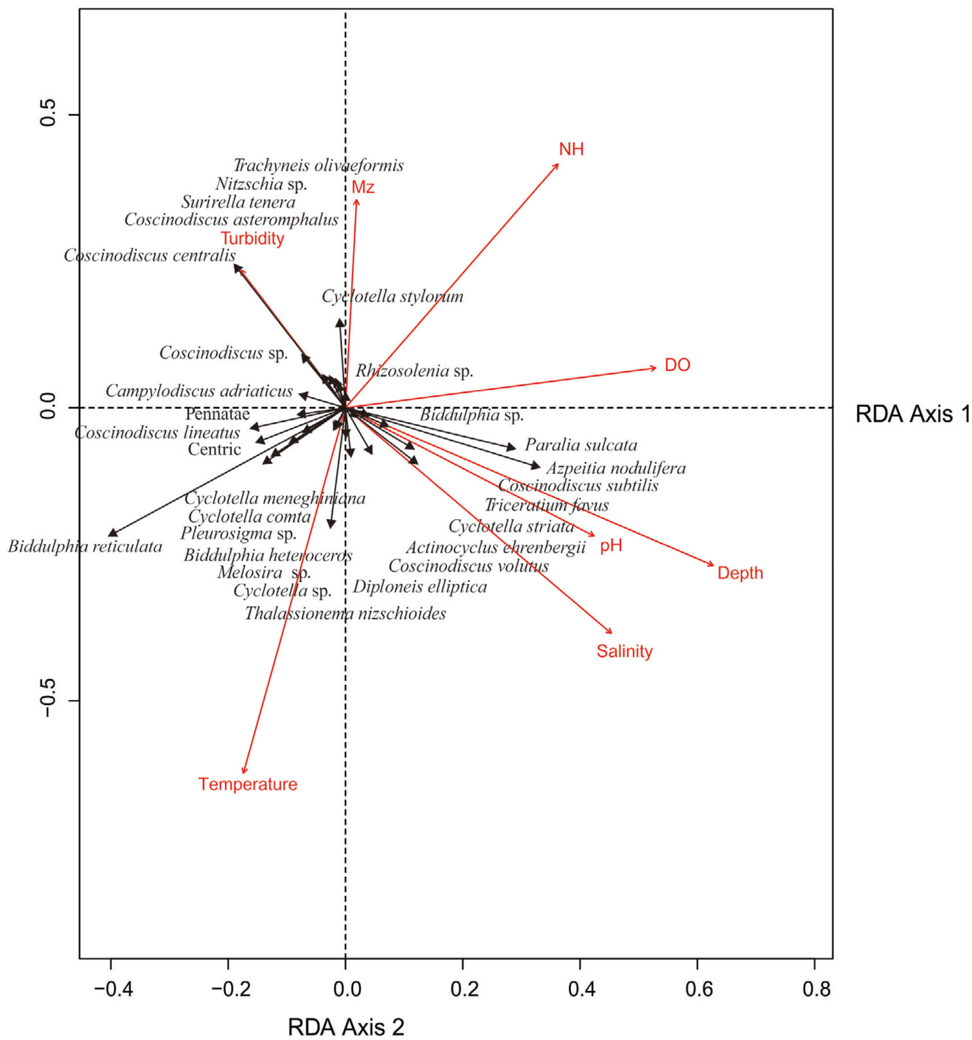

Fig. 7. RDA biplot of diatom taxa and environmental factors. The eigenvalues for RDA axis 1 and 2 were 0.041, 0.020, respectively. (Mz: Everage grain size; NH: ammonia nitrogen; DO: dissolved oxygen; pH: pH value).

(in contrast, the abundance of freshwater species is relatively low), the occurrence of this assemblage corresponds to shallower water depths, lower salinity and higher turbidity. Additionally, the distribution of diatom assemblage II was larger in the south branch of the Welu Estuary compared to the north branch, reflecting freshwater input to the south branch is greater than to the north branch.

Diatom assemblage I is primarily distributed at the entrance of the Welu Estuary, as well as the interior of the Chanthaburi Estuary including the adjacent nearshore area. Compared with diatom assemblage II, diatom assemblage I is mainly composed of saltwater species, and contains several warm water benthic species. Areas characterized by diatom assemblage I are strongly influenced by warm water from the ocean and less affected by freshwater river inputs. Samples from the Chanthaburi Estuary are predominantly characterized by diatom assemblage I, with only station 380 being categorized as diatom assemblage II. These results indicate that the effects of freshwater discharged from the Chanthaburi River are generally less than the effects of seawater entering from the ocean.

Diatom assemblage III (orange circles) is mainly distributed along the central edge and coastal region adjacent to the Welu Estuary, but not in the Chanthaburi Estuary. This diatom assemblage is closely related to high nutrient concentrations, indicating that the nitrifying effect of the Welu River is significantly higher than that of the Chanthaburi River.

Diatom assemblage IV (red circles) is mainly distributed on the offshore side of the study area and contains more warm water species. Diatom assemblage IV represents the water body of the Gulf of Thailand. Three stations in the north branch of the Welu Estuary likewise contain this diatom assemblage, indicating that seawater from the outer ocean likely invaded this area. This may be related to the weaker freshwater runoff here and the intrusion of seawater under the action of strong tides. In general, the distribution of these diatom assemblages is closely related to the environmental characteristics of the study area. Diatom assemblages are thus also good indicators of environmental characteristics within the study area.

5.2. Causes of differences in diatoms distributions between the Chanthaburi and Welu estuaries

Our sampling and observations indicate that there are significant differences between the diatom distributions of the Chanthaburi and Welu estuaries. Specifically, diatom assemblages in the Chanthaburi Estuary are relatively simple, while those in the Welu Estuary are more complex. These differences are attributable to several factors including differences in runoff, estuary size and channel width, and nutrient content.

With respect to runoff, the runoff of the Chanthaburi River is significantly smaller than that of the Welu River. Within the Welu

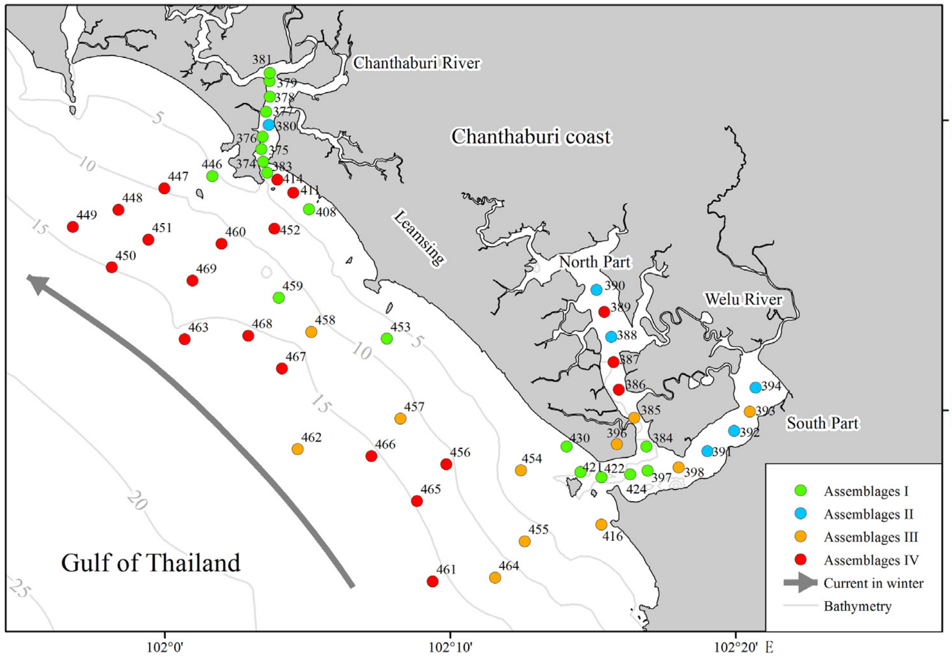

Fig. 8. Distribution of diatom assemblages in the study area. (Green circles: Diatom assemblage I; Blue circles: Diatom assemblage II; Yellow circles: Diatom assemblage III; Red circles: Diatom assemblage IV) . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Estuary, the larger runoff of the Welu River leads to a land-to-sea salinity gradient that likewise corresponds to variations in the distribution of diatom assemblages. The closer to the mouth of the river, the higher the relative content of freshwater species. We also found that the Welu River hosts a unique freshwater species (*S. tenera*).

With regard to estuary size and channel width, the Chanthaburi River has a smaller runoff. The river channel is accordingly narrow and the estuary relatively small, which making it difficult for outer seawater to impact the estuary. A relatively stable brackish water environment results in a relatively simple diatom distribution. The Welu River has a large freshwater input, the estuary is relatively large and the river channel is wide resulting in seawater intrusions to the interior of the estuary at high tide. In the north branch of the estuary where freshwater runoff is low, diatom assemblages closely resemble those of the outer ocean.

With regard to nutrient content, the Welu River had a large runoff and carries more nutrients into the ocean. As a result, a diatom assemblage III is able to exist as a distinct diatom assemblage closely related to the high nutrient contents of the Welu Estuary and adjacent coastal areas. Diatom assemblage III also appears in the northern and western regions of the study area far removed from the Welu Estuary. This may reflect additional inputs of terrigenous nutrients to the sea, at least, from the perspective of diatoms.

6. Conclusions

In this study, we examined the distributions of diatom assemblages in surface sediment samples collected along the northern coast of the Gulf of Thailand, and analyzed how these assemblages related to various environmental factors. Based on this study, the following conclusions can be reached:

(1) In samples collected from 55 stations in November 2015, we identified a total of 144 diatom species and subspecies representing 41 genera. The absolute abundance of diatoms across all 55 stations covered a range of 645–24,979 valves/g with an average of 7215 valves/g. Diatom abundance was thus similar to those of samples collected off the coast of China. The highest diatom abundance occurred in coastal regions rather than within the estuaries. The most abundant species within the study area were *A. nodulifera, C. stylorum,* and *P. sulcata*. The study area also contained some freshwater species, which were mainly distributed within the estuaries. Additionally, *S. tenera* was identified as being unique to the Welu River.

(2) Using cluster analysis and RDA, we identified four diatom assemblages representing different environmental conditions within the study area. Diatom assemblage I represents an environment strongly affected by warm seawater, less affected by fresh water, and positively correlated to temperature. Diatom assemblage II represents a coastal group affected by fresh water that is primarily distributed within the Welu Estuary. Diatom assemblage III represents an additional coastal group closely related to high nutrient contents. Diatom assemblage IV represents an offshore group consisting of warm water species characteristic of the Gulf of Thailand.

(3) The main environmental factors controlling the distribution of diatoms in the study area are temperature, salinity, water depth and turbidity. Based on the distribution of diatoms, the interior of the Welu Estuary is mainly a brackish water environment strongly influenced by freshwater input, and that freshwater input to the south branch of the estuary is greater than the north branch. Due to the invasion of seawater from outside the estuary, diatom assemblage IV, which is associated with outer seawater, was likewise present in the north branch of the estuary, where runoff is small. The Chanthaburi River contributes less fresh water input to its estuary and seawater intrusion is more significant. Accordingly, the Chanthaburi Estuary consists of a relatively simple brackish water environment characterized by a single diatom assemblage.

(4) The main causes of differences in the distribution of diatoms between the Chanthaburi and Welu estuaries are runoff, estuary size, river width and nutrient content. The larger runoff of the Welu River leads to a land-to-sea gradient in salinity and associated diatom assemblages within the Welu Estuary. The Welu River have a high nutrient contents, which promotes a diatom assemblage (diatom assemblage III) closely related to high nutrient contents in its estuary and adjacent coastal waters.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Min Chen: Methodology, Software, Formal analysis, Data curation, Writing - original draft. **Hongshuai Qi:** Conceptualization, Writing - review & editing, Supervision. **Wichen Intasen:** Resources, Supervision. **Apichai Kanchanapant:** Resources. **Chengtao Wang:** Investigation, Data curation. **Aimei Zhang:** Validation.

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