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# Various Forms of Phosphorus in Sediments of the Eastern Coast of Thailand

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**ABSTRACT:** The amount of total phosphorus (P) and its chemical forms were investigated in sediments of the Eastern Coast of Thailand in the dry (April 2001) and wet (July 2001) seasons. The amounts of total P ranged from 55.83 to 2,575.83 and from 30.0 to 2,672.50 µg $g^{-1}$ dry weight for the dry and wet seasons, respectively. The P in sediments was mainly in an inorganic rather than organic form. Sediment inorganic P fractions were determined by a sequential extraction technique. In the estuarine sediments, the major form of P was Fe, Al-bound P and the second most abundant form was organic P, whereas the other sediments showed different relative dominant P forms depending on the sediment characteristics of each location. The seasonal change had an influence on the chemical form of P available. In the dry season the available fractions were derived from organic P, those in the wet season were derived largely from Fe, Al-bound P. The available concentrations found for both seasons were very similar in terms of the percentage of total P. It was also found that in most samples, the available forms were very low, comprising less than 10 % of total P.

In this study Fe oxides were found to be the major P sorbent of the sediments, followed by clay contents, while organic matter and $CaCO_3$ were less effective in sorbing P. In addition, the sediment P concentrations decreased with increasing sediment pH and salinity of the overlying water.

**KEYWORDS:** phosphorus, sediment, fractionation, bioavailability, Eastern Coast of Thailand.

## INTRODUCTION

Phosphorus (P) is an essential element for all life forms[1] and is considered to be one of the major nutrients which, when present in large concentrations, could cause eutrophication[2], as well as the key nutrient found to be a limiting factor in natural waters[3]. Phosphorus is found in both inorganic and organic forms in sediments where they serve as sinks and sources of P. It enters the rivers and sea in different chemical forms from various sources, including point sources and non-point sources. It is eventually incorporated into bottom sediments. Dissolved inorganic P is considered bioavailable, whereas organic and particulate P forms generally must undergo a transformation into inorganic forms before being considered bioavailable[3]. Phosphorus adsorbed onto sediments can be released into the overlying water depending on the chemical forms in the sediments[4,5] and the environmental conditions[5,6], such as pH, redox potential, microbes, bioturbation etc. The released P may become available to algae and stimulate blooms of phytoplankton, and excess can lead to eutrophication of the water body.

Knowledge of chemical speciation of sediment-bound P, is necessary to evaluate the bioavailable P which is the amount of P that is biologically usable, because each chemical form has its own ability of release from the sediments[4]. Sediment fractionation helps in identifying the chemical forms of P and can highlight the pathways it takes into the coastal waters[7]. Phosphorus fractionation is commonly achieved by sequential extractions, by which P is supposed to be selectively removed from different forms of attachment in the sediments[8] with a specific reagent preferentially extracting a specific form[7]. The weakly-bound P removed by the first one or two extracting solutions in a sequential extraction method is usually considered bioavailable[3].

The Eastern Coast of Thailand comprises an area of 5 Provinces; Chachoengsao, Chon Buri, Rayong, Chanthaburi and Trat. This area contains various activities including agriculture, fisheries, tourism, industry and urban communities. It is still in a development stage with a high expansion rate of industrialization and urbanization, which will substantially increase the amount of wastewater discharging into the coastal area. In addition, red tide outbreaks occasionally occur in this area, especially in Chon Buri[9].

The present study was undertaken to 1) investigate

**Table 1.** Sediment sampling positions.

| Station | Location | Latitude | Longitude | Main Activity in the Area |
|---|---|---|---|---|
| BK1 | Bangpakong River (n) | 13° 29' 31.8" N | 100° 59' 46.2" E | Aquaculture |
| BK2 | Bangpakong River (o) | 13° 26' 42.8" N | 100° 56' 41.6" E | Aquaculture |
| AS4 | Angsila | 13° 20' 15.2" N | 100° 55' 05.4" E | Aquaculture |
| BS12 | Bangsaen | 13° 17' 12.3" N | 100° 54' 12.7" E | Recreation/Beach |
| SR18 | Koh Loi | 13° 10' 25.7" N | 100° 55' 00.6" E | Urban Community |
| SR22 | Ao Udom | 13° 07' 26.7" N | 100° 53' 28.2" E | Industry |
| PT28 | Pattaya | 12° 55' 49.0" N | 100° 52' 25.3" E | Recreation/Beach |
| MP32 | Nong Fab | 12° 40' 07.7" N | 100° 07' 31.1" E | Industry |
| MP35 | Rayong River (n) | 12° 39' 20.8" N | 100° 16' 48.6" E | Urban Community |
| MP36 | Rayong River (o) | 12° 38' 54.7" N | 100° 17' 04.0" E | Urban Community |
| TP38 | Map Ta Phut (TPI) | 12° 37' 58.6" N | 100° 18' 28.8" E | Industry |
| TP40 | Had Mae Rum Phung | 12° 36' 22.6" N | 100° 22' 49.9" E | Natural Park |
| KG45 | Prasae River (n) | 12° 42' 20.9" N | 100° 42' 22.5" E | Aquaculture |
| KG46 | Prasae River (o) | 12° 29' 27.9" N | 100° 42' 29.7" E | Aquaculture |
| CB47 | Chanthaburi River (n) | 12° 29' 05.8" N | 102° 03' 54.8" E | Aquaculture |
| CB48 | Chanthaburi River (o) | 12° 28' 07.1" N | 102° 03' 56.2" E | Aquaculture |
| VR49 | Weru River (n) | 12° 18' 09.6" N | 102° 16' 47.3" E | Aquaculture |
| VR50 | Weru River (o) | 12° 17' 51.7" N | 102° 15' 45.2" E | Aquaculture |
| TD51 | Trat River (n) | 12° 09' 33.1" N | 102° 34' 58.3" E | Aquaculture |
| TD52 | Trat River (o) | 12° 06' 31.4" N | 102° 36' 17.5" E | Aquaculture |

n = inside the river mouth
o = outside the river mouth

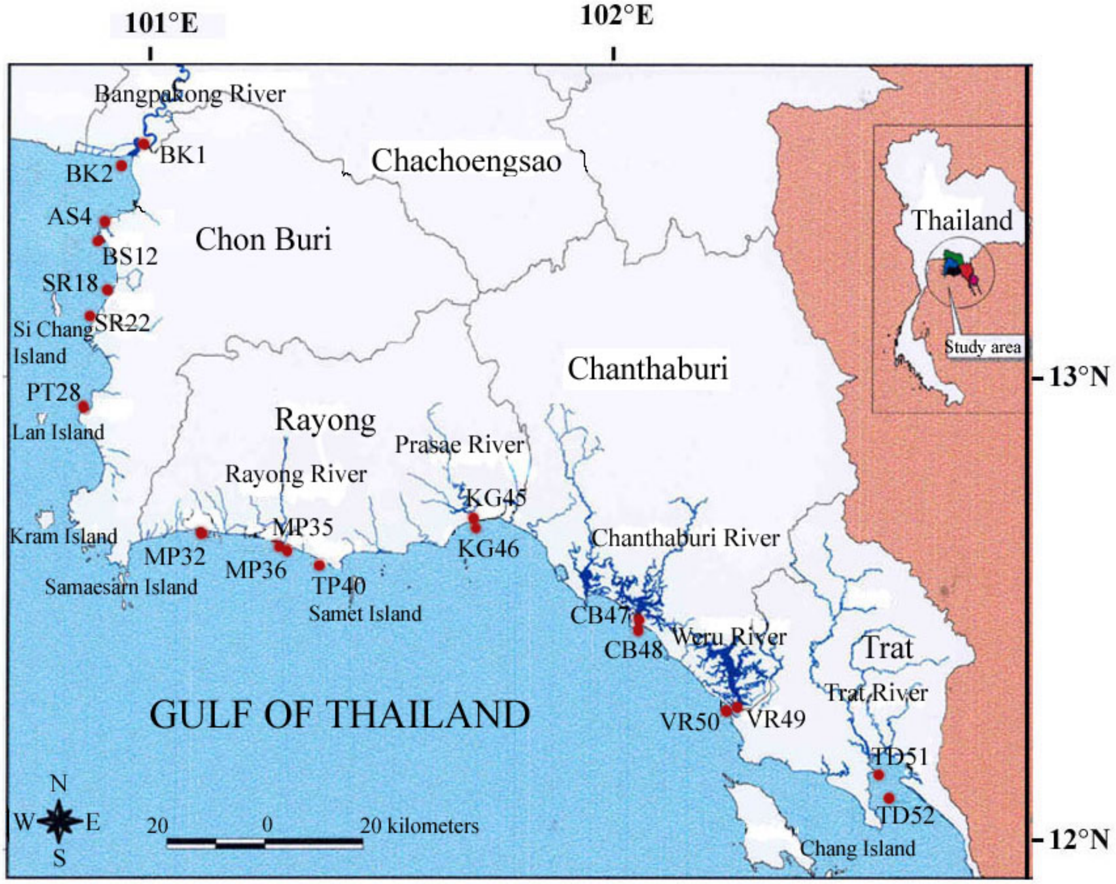

**Fig 1.** Map showing sampling locations.

the concentrations and chemical forms of sediment P distributed along the Eastern Coast of Thailand and their relation with some sediment characteristics, and 2) evaluate the P bioavailability and potential mobility of the sediments. The results obtained will provide the current status of sediment P and a better understanding of P behavior in the sediments, which can be used to assess its impact on water quality and living resources in this area.

## MATERIALS AND METHODS

### Sediment Sampling

Sediment samples were collected from twenty stations along the Eastern Coast of Thailand from the locations indicated in Table 1 and Figure 1. A triplicate set of surface sediment samples was collected at each station in the dry (April) and wet (July) seasons of 2001 using a modified Petersen grab. A Garmin GPS-12 global positioning system was used for accuracy in locating the stations. The samples were freeze-dried, sieved through a 2-mm mesh and then homogenized.

During the sediment sampling, salinity, pH and dissolved oxygen at the bottom of the water (1 m depth above the sediment layer) were also measured using a Multi-Parameter System (YSI 650 MDS). Also included was a bottom water sample collection for P analysis.

**Table 2.** Sequential chemical extraction method used in this study (De Lange[5]).

| Fraction | Extractant | Form of inorganic P |
|---|---|---|
| F1 | 2 N $NH_4Cl$ | Loosely adsorbed P (exchangeable + carbonate) |
| F2 | 0.1 N NaOH | Fe, Al-bound P |
| F3 | 0.5 N HCl | Ca-bound P, apatite |

### Fractionation of Phosphorus

A sequential chemical extraction method described by De Lange[5] (which is similar to the method of Hieltjies and Lijklema[10]) was used to fractionate the inorganic forms of P in the sediments (Table 2). The difference between total P and the sum of the extracted inorganic P, referred to as residual P, was assumed to be organically bound[10].

Each sediment sample was also analyzed for total P by the ignition method at 550 °C followed by extraction for 16 h with 1 N HCl, whereas un-ignited samples were prepared for total inorganic P[11]. The total inorganic P was also compared to the sum of the sequentially extracted inorganic P. The organic P was indirectly obtained by the difference between the total P and inorganic P.

The available P was also extracted from the sediments by direct chemical leaching with a dilute acid-fluoride solution, a combination of HCl and $NH_4F$, according to the method of Olsen and Sommers[12]. Phosphorus in all extracts was analyzed by the ascorbic acid method of Strickland and Parsons[13] and the concentrations were measured with a UV-Vis Spectrophotometer Model UV 300 Unicam.

### Sediment Characterization

Selected sediment characteristics were determined as follows: pH in water at a sediment to solution ratio of 1:2.5, calcium carbonate by the approximate gravimetric method for loss of carbon dioxide[14], organic matter by the acid-dichromate oxidation method[15], particle size distribution by the hydrometer method[16] and sediment texture was classified according to the U.S. Agriculture texture triangle[17]. Extractable iron (Fe) and manganese (Mn) oxides were also examined in the sediments. The total (free) and amorphous oxides were extracted by a dithionite-citrate solution and an acid ammonium oxalate solution respectively, according to the method of Ross and Wang[18]. Total oxides were refered to as "cystralline and amorphous oxides". The concentrations of these Fe and Mn oxides in the extracts were measured with a flame atomic absorption spectrophotometer Model AAnalyst 100 (Perkin Elmer, Connecticut, USA).

## RESULTS AND DISCUSSION

### Sediment Characteristics

Selected sediment characteristics are shown in Tables 3 and 4. The sediments for the dry and wet seasons were slightly alkaline with pH ranging from 7.0-8.3 and 7.3-8.5, respectively. High organic matter content (>4%) was mainly found in estuarine sediments, especially in the dry season at the Chanthaburi and Weru River estuaries. $CaCO_3$ content was very high at Angsila where there are oyster farms through out the year. The texture of the sediments did not vary much between the two seasons. High clay contents were found in the river estuaries, especially Bangpakong. High total and amorphous Fe and Mn oxides were mainly found in the river estuaries, with the highest at Trat. Normally dithionite-citrate solution is assumed to remove all free (total) Fe and Mn oxides, both cystralline and amorphous, while oxalate removes the amorphous fraction only. Tables 3 and 4 show, however, that in some samples the amount of amorphous oxides was higher than that of total oxides. This was also reported elsewhere in the literature[18,19]. A possible explanation was that some sediments had been subjected to

**Table 3.** East Coast sediment characteristics in the dry season (April 2001). Results reported are the mean of three replicas.

| Station No. | Location | pH | $CaCO_3$ equivalent (%) | Organic matter (%) | Fe ($mg\ g^{-1}$) | | Mn ($mg\ g^{-1}$) | | Particle Size Distribution (%) | | | Texture Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Total Oxides | Amorp. Oxides | Total Oxides | Amorp. Oxides | Sand | Silt | Clay | |
| BK1 | Bangpakong River (n) | 7.6 | 0.70 | 2.22 | 11.86 | 10.92 | 1.84 | 1.92 | 30.9 | 49 | 19.8 | Loam |
| BK2 | Bangpakong River (o) | 7.8 | 1.35 | 2.31 | 14.30 | 12.16 | 1.64 | 1.61 | 42.2 | 32.1 | 25.8 | Clay loam |
| AS4 | Angsila | 8.2 | 41.85 | 1.76 | 2.28 | 2.47 | 0.44 | 0.30 | 73.5 | 16.7 | 9.8 | Sandy loam |
| BS12 | Bangsaen | 8.0 | 5.62 | 0.24 | 0.64 | 2.04 | 0.04 | 0.04 | 92.9 | 2.1 | 5.1 | Sand |
| SR18 | Koh Loi | 8.1 | 12.97 | 0.85 | 1.59 | 2.25 | 0.15 | 0.14 | 58.9 | 33.7 | 7.4 | Sandy loam |
| SR22 | Ao Udom | 8.1 | 11.79 | 1.31 | 1.00 | 1.50 | 0.15 | 0.12 | 54.9 | 36.7 | 8.4 | Sandy loam |
| PT28 | Pattaya | 8.3 | 8.89 | 0.40 | 0.88 | 0.89 | 0.06 | 0.06 | 73.8 | 18.7 | 7.5 | Sandy loam |
| MP32 | Nong Fab | 8.3 | 2.06 | 0.27 | 2.99 | 0.49 | 0.03 | 0.03 | 91.8 | 4.4 | 3.9 | Sand |
| MP35 | Rayong River (n) | 8.1 | 2.28 | 0.44 | 1.59 | 1.33 | 0.07 | 0.01 | 89.6 | 3.5 | 6.8 | Sand |
| MP36 | Rayong River (o) | 7.9 | 4.29 | 2.52 | 8.06 | 6.39 | 0.20 | 0.16 | 44.2 | 43.4 | 12.4 | Loam |
| TP38 | Map Ta Phut (TPI) | 7.7 | 1.94 | 0.42 | 1.60 | 1.11 | 0.03 | 0.04 | 57.5 | 21.1 | 21.4 | Sandy clay loam |
| TP40 | Had Mae Rum Phung | 7.9 | 3.43 | 0.10 | 1.31 | 1.97 | 0.01 | 0.02 | 92.9 | 1.3 | 5.8 | Sand |
| KG45 | Prasae River (n) | 7.9 | 3.08 | 3.09 | 13.63 | 12.55 | 0.15 | 0.18 | 60.6 | 23.3 | 16.1 | Sandy loam |
| KG46 | Prasae River (o) | 8.0 | 8.96 | 3.52 | 9.42 | 11.39 | 0.32 | 0.38 | 74.6 | 16.0 | 9.4 | Sandy loam |
| CB47 | Chanthaburi River (n) | 8.0 | 3.66 | 4.59 | 8.60 | 10.46 | 0.14 | 0.20 | 61.9 | 25.1 | 13.0 | Sandy loam |
| CB48 | Chanthaburi River (o) | 8.0 | 3.99 | 5.94 | 14.28 | 16.05 | 0.44 | 0.50 | 41.2 | 46.0 | 12.8 | Loam |
| VR49 | Weru River (n) | 7.9 | 3.10 | 5.03 | 13.91 | 16.77 | 0.50 | 0.50 | 33.9 | 55.6 | 10.5 | Silt loam |
| VR50 | Weru River (o) | 7.9 | 7.61 | 6.55 | 19.92 | 22.59 | 0.74 | 0.50 | 36.9 | 50.7 | 12.4 | Silt loam |
| TD51 | Trat River (n) | 7.0 | 2.22 | 1.12 | -72.19 | 38.77 | 0.41 | 0.37 | 44.9 | 35.4 | 19.8 | Loam |
| TD52 | Trat River (o) | 7.0 | 2.64 | 2.61 | 49.63 | 28.81 | 0.30 | 0.31 | 41.5 | 44.7 | 13.8 | Loam |

processes causing changes in their structure especially an alteration between aerobic and anaerobic conditions. Upon reoxidation, Fe will precipitate and may form an amorphous, highly hydrated solid phase with the structural Si and Al. Thus, most of Fe extracted by dithionite-citrate in those sediments was also oxalate-extractable[19]. In addition, oxalate itself can extract poorly crystalline oxides as well[18].

## Phosphorus in the Sediments and Its Chemical Forms

Total and various forms of P distributed in the sediments in this study in the dry and wet seasons are given in Tables 5 and 6, respectively. The concentrations of total P showed broad ranges from 55.83 to 2,575.83 and from 30.0 to 2,672.50 µg $g^{-1}$ dry weight for the dry and wet seasons, respectively. Statistical analysis (2-way ANOVA) indicated that the total P content was significantly different depending on both the station and season ($p<0.05$). The difference between each station and season is shown in Figure 2. High concentrations were mainly found in the estuarine sediments, especially in the dry season, and the highest concentrations were found in Trat estuary. At most stations in both seasons, the sediment P generally consisted of more inorganic than organic P. This was in agreement with the reports of Syers et al[21], Fang[22] and Frankowski et al[23] who found that inorganic P constituted the major portion of the total P in their sediment study. From the present study the inorganic P concentrations ranged from 43.33 to 1,358.33 and 11.67 to 1,424.17 µg $g^{-1}$ dry weight for the dry and wet

**Table 4.** East Coast sediment characteristics in the wet season (July 2001). Results reported are the mean of three replicas.

| Station No. | Location | pH | $CaCO_3$ equivalent (%) | Organic matter (%) | Fe (mg $g^{-1}$) | | Mn (mg $g^{-1}$) | | Particle Size Distribution (%) | | | Texture Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Total Oxides | Amorp. Oxides | Total Oxides | Amorp. Oxides | Sand | Silt | Clay | |
| BK1 | Bangpakong River (n) | 7.6 | 2.99 | 1.65 | 15.28 | 7.82 | 1.81 | 1.51 | 32.8 | 40.1 | 27.2 | Loam |
| BK2 | Bangpakong River (o) | 7.8 | 2.90 | 2.24 | 15.53 | 8.72 | 1.62 | 1.39 | 44.7 | 35.4 | 19.9 | Loam |
| AS4 | Angsila | 8.1 | 18.42 | 1.74 | 2.76 | 2.06 | 0.47 | 0.32 | 71.2 | 20.4 | 8.4 | Sandy loam |
| BS12 | Bangsaen | 8.1 | 5.71 | 0.10 | 0.50 | 1.34 | 0.04 | 0.05 | 85.5 | 10.0 | 4.5 | Loamy sand |
| SR18 | Koh Loi | 8.2 | 12.25 | 1.01 | 2.27 | 1.74 | 0.17 | 0.12 | 63.0 | 29.7 | 7.3 | Sandy loam |
| SR22 | Ao Udom | 8.3 | 11.83 | 0.88 | 1.53 | 1.19 | 0.16 | 0.10 | 50.1 | 40.6 | 9.3 | Loam |
| PT28 | Pattaya | 8.4 | 9.49 | 0.99 | 1.02 | 0.72 | 0.09 | 0.05 | 69.3 | 26.1 | 4.6 | Sandy loam |
| MP32 | Nong Fab | 8.3 | 3.66 | 0.90 | 0.34 | 0.20 | 0 | 0 | 96.4 | 0.72 | 2.88 | Sand |
| MP35 | Rayong River (n) | 8.5 | 3.48 | 1.58 | 1.25 | 0.84 | 0.04 | 0.03 | 94.2 | 1.4 | 4.3 | Sand |
| MP36 | Rayong River (o) | 7.9 | 3.73 | 0.94 | 6.42 | 3.73 | 0.20 | 0.14 | 41.1 | 44.1 | 14.9 | Loam |
| TP38 | Map Ta Phut (TPI) | 8.2 | 4.80 | 1.01 | 1.66 | 0.80 | 0.04 | 0.03 | 63.4 | 18.7 | 17.9 | Sandy loam |
| TP40 | Had Mae Rum Phung | 8.5 | 5.86 | 0.42 | 0.86 | 0.89 | 0.02 | 0.02 | 96.0 | 0.9 | 3.1 | Sand |
| KG45 | Prasae River (n) | 8.0 | 5.27 | 2.24 | 14.99 | 9.88 | 0.21 | 0.22 | 61.8 | 21.6 | 16.7 | Sandy loam |
| KG46 | Prasae River (o) | 8.0 | 2.09 | 0.97 | 18.13 | 11.99 | 0.28 | 0.27 | 60.8 | 25.7 | 13.5 | Sandy loam |
| CB47 | Chanthaburi River (n) | 8.0 | 5.01 | 3.63 | 11.47 | 9.02 | 0.38 | 0.33 | 63.1 | 28.9 | 8.0 | Sandy loam |
| CB48 | Chanthaburi River (o) | 8.0 | 6.21 | 4.76 | 13.84 | 8.66 | 0.51 | 0.37 | 55.5 | 34.5 | 9.9 | Sandy loam |
| VR49 | Weru River (n) | 7.7 | 9.13 | 3.97 | 24.47 | 11.08 | 0.44 | 0.29 | 46.4 | 31.9 | 21.8 | Loam |
| VR50 | Weru River (o) | 8.0 | 2.58 | 2.75 | 14.92 | 3.07 | 0.71 | 0.49 | 48.0 | 41.8 | 10.2 | Loam |
| TD51 | Trat River (n) | 7.3 | 2.69 | 1.16 | 94.70 | 25.22 | 0.47 | 0.36 | 54.1 | 23.4 | 22.4 | Sandy clay loam |
| TD52 | Trat River (o) | 7.4 | 2.05 | 0.49 | 51.56 | 17.81 | 0.56 | 0.43 | 39.7 | 44.8 | 15.5 | Loam |

seasons, respectively, whereas organic P ranged from 12.50 to 1,217.50 and from 18.33 to 1,247.50 µg $g^{-1}$ dry weight for the dry and wet seasons, respectively.

The inorganic P fractions removable by the sequential extraction are presented in Tables 5 and 6. The results obtained indicated that the sum of the sequential extracted inorganic P of both seasons was in strong agreement with the separately analyzed total inorganic P (r = 0.891, $p<0.01$) and no significant difference between these values was seen ($p>0.05$). Similarly, the residual P agreed well with organic P (r = 0.957, $p<0.01$) and no significant difference between these values was found ($p>0.05$), indicating the residual P was mainly organic, as was reported earlier by Hieltjies and Lijklema[10].

The percentage of each chemical form of sediment P on the basis of total P is presented in Figure 3. In the estuarine sediments, the most abundant fraction of P for both seasons was mainly in the form of Fe, Al-bound P, possibly due to the sediments consisting of higher Fe and Mn oxides than at other locations (Tables 3 and 4), and the second most abundant P in the estuarine sediments was residual P (organic P). For the other locations, Ca-bound P was the major fraction found, e.g. Angsila (AS4), Koh Loi (SR18), Ao Udom (SR22) and Pattaya (PT28), where the sediments consisted of high $CaCO_3$ content. Statistical analysis showed that the difference of each chemical form of P depended on location and season ($p<0.05$), which was similar to that of the total P. This may be due to the difference of sediment characteristics of the study area.

Although chemical forms of P taken from sequential extractions are operationally defined[8], the results can provide more information on the source or origin of sediment P, its transport and possible remobilization and bioavailability. The first two fractions in sequential extraction schemes (loosely adsorbed P and Fe, Al-bound P), which can be easily released from sediments by changes of environmental conditions are considered to be potentially bioavailable forms, while Ca-bound P

**Table 5.** Various forms of phosphorus in the East Coast sediments in the dry season (April 2001).

| Station No. | Location | Total P (µg g$^{-1}$) | P Fractionation (µg g$^{-1}$) | | | | Inorganic P | | Organic P | | Available P | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Adsorbed P | Fe,Al-P | Ca-P | Residual P | (µg g$^{-1}$) | (%) | (µg g$^{-1}$) | (%) | (µg g$^{-1}$) | (%) |
| BK1 | Bangpakong River (n) | 721.67 | 68.82 | 385.00 | 93.67 | 174.18 | 587.50 | 81.4 | 134.17 | 18.6 | 22.15 | 3.07 |
| BK2 | Bangpakong River (o) | 643.33 | 36.88 | 298.00 | 63.67 | 244.78 | 398.33 | 61.9 | 245.00 | 38.1 | 19.78 | 3.07 |
| AS4 | Angsila | 730.83 | 117.07 | 41.00 | 425.67 | 147.09 | 560.83 | 76.7 | 170.00 | 23.3 | 5.13 | 0.70 |
| BS12 | Bangsaen | 100.83 | 22.12 | 18.00 | 35.33 | 25.38 | 52.50 | 52.1 | 48.33 | 47.9 | 9.95 | 9.87 |
| SR18 | Koh Loi | 528.33 | 94.65 | 39.50 | 315.67 | 78.51 | 410.00 | 77.6 | 118.33 | 22.4 | 8.25 | 1.56 |
| SR22 | Ao Udom | 519.17 | 82.05 | 27.50 | 243.67 | 165.95 | 348.33 | 67.1 | 170.83 | 32.9 | 6.65 | 1.28 |
| PT28 | Pattaya | 310.00 | 76.50 | 20.67 | 155.67 | 57.16 | 187.50 | 60.5 | 122.50 | 39.5 | 9.03 | 2.91 |
| MP32 | Nong Fab River (n) | 136.67 | 22.73 | 21.50 | 14.00 | 78.44 | 51.67 | 37.8 | 85.00 | 62.2 | 10.75 | 7.87 |
| MP35 | Rayong | 172.50 | 25.83 | 25.25 | 14.00 | 107.42 | 60.00 | 34.8 | 112.50 | 65.2 | 17.08 | 9.90 |
| MP36 | Rayong River (o) | 490.83 | 51.93 | 259.67 | 78.33 | 100.90 | 327.50 | 66.7 | 163.33 | 33.3 | 5.55 | 1.13 |
| TP38 | Map Ta Phut (TPI) | 148.33 | 25.82 | 43.17 | 23.00 | 56.34 | 79.17 | 53.4 | 69.17 | 46.6 | 12.73 | 8.58 |
| TP40 | Had Mae Rum Phung | 55.83 | 11.37 | 8.00 | 14.00 | 22.46 | 43.33 | 77.6 | 12.50 | 22.4 | 5.67 | 10.16 |
| KG45 | Prasae River (n) | 400.00 | 22.60 | 188.00 | 89.00 | 100.40 | 284.17 | 71.0 | 115.83 | 29.0 | 2.73 | 0.68 |
| KG46 | Prasae River (o) | 380.83 | 24.88 | 125.00 | 80.67 | 150.28 | 229.17 | 60.2 | 151.67 | 39.8 | 6.22 | 1.63 |
| CB47 | Chanthaburi River (n) | 269.17 | 11.97 | 153.83 | 50.67 | 52.70 | 165.00 | 61.3 | 104.17 | 38.7 | 3.53 | 1.31 |
| CB48 | Chanthaburi River (o) | 452.50 | 51.30 | 196.33 | 111.00 | 93.87 | 315.00 | 69.6 | 137.50 | 30.4 | 3.10 | 0.69 |
| VR49 | Weru River (n) | 497.50 | 62.98 | 172.83 | 108.00 | 153.69 | 319.17 | 64.2 | 178.33 | 35.9 | 2.92 | 0.59 |
| VR50 | Weru River (o) | 560.00 | 42.40 | 233.67 | 162.00 | 121.93 | 386.67 | 69.1 | 173.33 | 31.0 | 4.42 | 0.79 |
| TD51 | Trat River (n) | 2575.83 | 11.68 | 622.00 | 52.33 | 1889.82 | 1358.33 | 52.7 | 1217.50 | 47.3 | 16.85 | 0.65 |
| TD52 | Trat River (o) | 1108.33 | 12.60 | 446.00 | 64.33 | 585.40 | 575.00 | 51.9 | 533.33 | 48.1 | 5.73 | 0.52 |

or apatite, which is the only P mineral[8] in marine sediments, is the least available form or an immobile P form[3,21,24].

## Potential Bioavailability of P in Sediments

The available P extracted from the sediments correlated well with the bottom water phosphate for

**Table 6.** Various forms of phosphorus in the East Coast sediments in the wet season (July 2001).

| Station No. | Location | Total P (µg g$^{-1}$) | P Fractionation (µg g$^{-1}$) | | | | Inorganic P | | Organic P | | Available P | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Adsorbed P | Fe,Al-P | Ca-P | Residual P | (µg g$^{-1}$) | (%) | (µg g$^{-1}$) | (%) | (µg g$^{-1}$) | (%) |
| BK1 | Bangpakong River (n) | 644.17 | 68.33 | 346.33 | 78.00 | 151.51 | 532.50 | 82.7 | 111.67 | 17.3 | 72.53 | 11.3 |
| BK2 | Bangpakong River (o) | 630.83 | 51.67 | 343.67 | 118.00 | 117.49 | 531.67 | 84.3 | 99.17 | 15.7 | 19.48 | 3.09 |
| AS4 | Angsila | 554.17 | 100.83 | 45.00 | 228.67 | 179.67 | 461.67 | 83.3 | 92.50 | 16.7 | 23.65 | 4.27 |
| BS12 | Bangsaen | 74.17 | 19.67 | 13.00 | 19.33 | 22.17 | 48.33 | 65.2 | 25.83 | 34.8 | 6.63 | 8.94 |
| SR18 | Koh Loi | 429.17 | 96.50 | 33.83 | 136.33 | 162.51 | 381.67 | 88.9 | 47.50 | 11.1 | 17.53 | 4.08 |
| SR22 | Ao Udom | 374.17 | 65.67 | 19.50 | 163.67 | 125.33 | 302.50 | 80.9 | 71.67 | 19.2 | 13.10 | 3.50 |
| PT28 | Pattaya | 259.17 | 66.67 | 14.50 | 153.67 | 24.33 | 220.00 | 84.9 | 39.17 | 15.1 | 3.73 | 1.44 |
| MP32 | Nong Fab | 30.00 | 11.50 | 4.50 | 0.33 | 13.67 | 11.67 | 38.9 | 18.33 | 61.1 | 3.42 | 11.4 |
| MP35 | Rayong River (n) | 103.75 | 16.00 | 22.75 | 1.67 | 63.33 | 85.00 | 81.9 | 18.75 | 18.1 | 11.00 | 10.6 |
| MP36 | Rayong River (o) | 477.50 | 37.33 | 225.67 | 35.00 | 179.50 | 263.33 | 55.2 | 214.17 | 44.9 | 13.88 | 2.91 |
| TP38 | Map Ta Phut (TPI) | 129.17 | 30.50 | 35.50 | 13.00 | 50.17 | 70.00 | 54.2 | 50.00 | 38.7 | 13.90 | 10.8 |
| TP40 | Had Mae Rum Phung | 64.17 | 13.00 | 8.50 | 6.00 | 36.67 | 16.67 | 26.0 | 47.50 | 74.0 | 5.93 | 9.24 |
| KG45 | Prasae River (n) | 320.83 | 20.67 | 195.67 | 59.67 | 44.82 | 249.17 | 77.7 | 71.67 | 22.3 | 7.27 | 2.27 |
| KG46 | Prasae River (o) | 385.00 | 7.67 | 274.33 | 66.67 | 36.33 | 335.00 | 87.0 | 50.00 | 13.0 | 7.73 | 2.01 |
| CB47 | Chanthaburi River (n) | 321.67 | 44.83 | 155.50 | 62.50 | 58.84 | 247.50 | 76.9 | 74.17 | 23.1 | 7.70 | 2.39 |
| CB48 | Chanthaburi River (o) | 364.17 | 56.17 | 148.50 | 104.67 | 54.83 | 311.67 | 85.6 | 52.50 | 14.4 | 5.38 | 1.48 |
| VR49 | Weru River (n) | 300.83 | 48.50 | 133.50 | 64.67 | 54.16 | 241.67 | 80.3 | 59.17 | 19.7 | 6.82 | 2.27 |
| VR50 | Weru River (o) | 437.50 | 71.83 | 163.50 | 57.33 | 144.84 | 310.00 | 70.9 | 127.50 | 29.1 | 5.02 | 1.15 |
| TD51 | Trat River (n) | 2672.5 | 10.50 | 1140.33 | 37.00 | 1484.67 | 1424.17 | 53.3 | 1247.50 | 46.7 | 22.62 | 0.85 |
| TD52 | Trat River (o) | 948.33 | 5.50 | 533.00 | 48.33 | 361.50 | 450.00 | 47.5 | 498.33 | 52.6 | 5.22 | 0.55 |

both seasons (r = 0.701, $p<0.01$ for dry season and r = 0.631, $p<0.01$ for wet season) (Tables 7 and 8). The amount of available P fractions found along the East Coast ranged from 2.73 to 22.15 µg $g^{-1}$ and from 3.42 to 72.53 µg $g^{-1}$ dry weight for the dry and wet seasons, respectively (Tables 5 and 6). Variation of available P depended on location and season ($p<0.05$), as indicated in Figure 2; however, in terms of percentage of total P, it ranged from 0.52 to 10.26 % and from 0.55 to 11.4 %, for the dry and wet seasons, respectively (Tables 5 and 6).

In the dry season, available P did not correlate with any P fractions except residual P (r = 0.297, $p<0.05$). However, residual P correlated well with organic P, and the two values obtained did not show any significant difference. This indicated that available P fractions in the dry season were derived from the organic forms of P. López-Piñeiro and Garcia-Navarro[24] also reported that organic P was an important fraction in supplying available P. Although organic P is considered as an

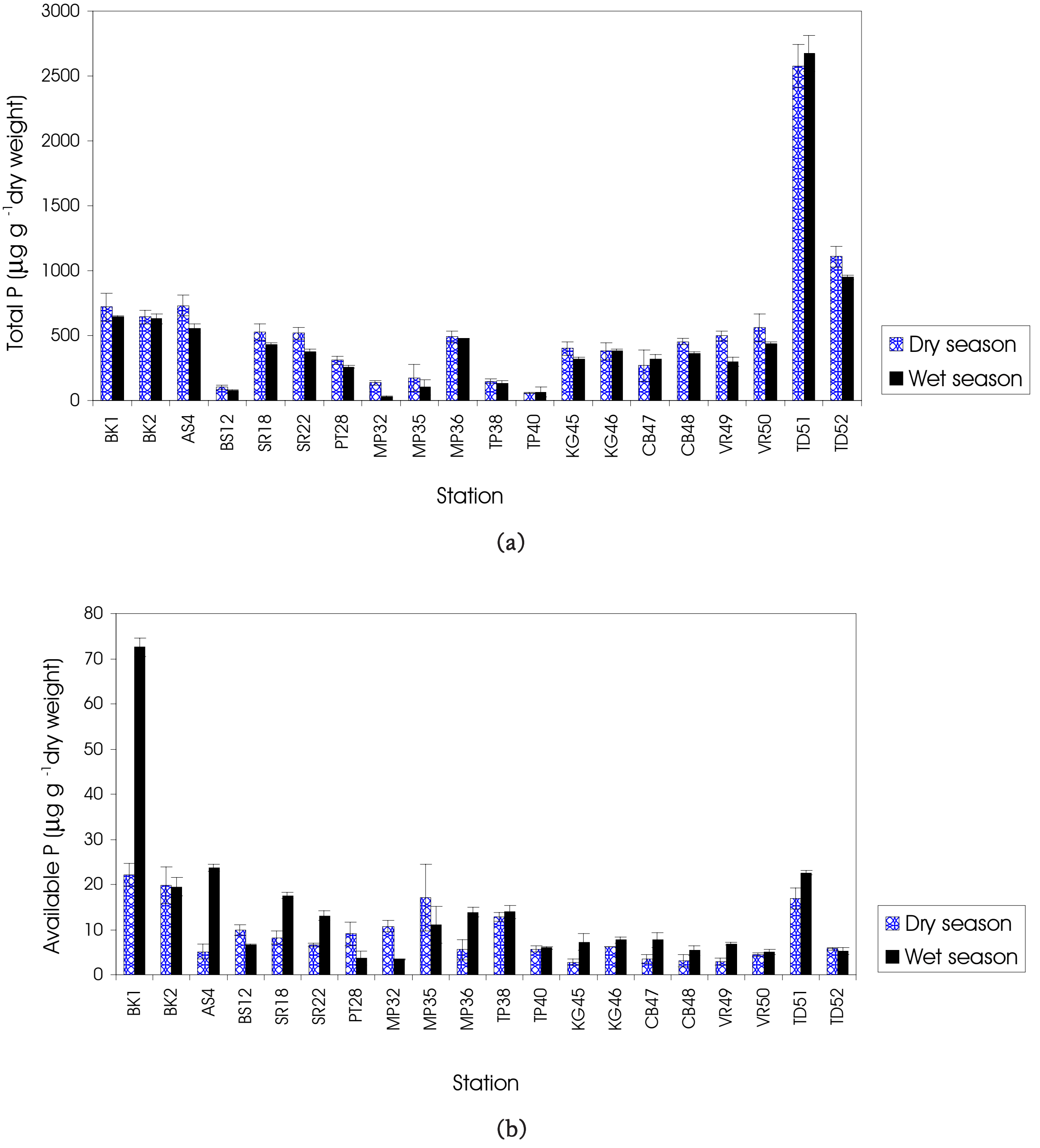

**Fig 2.** Spatial and temporal distribution of (a) total P and (b) available P in the East Coast sediments. Error bars are ± 1 standard error of three replicas. The stations are coded as defined in Table 1.

immobile form in sediments[4], it may become available for algae growth by a mineralization process involving microbial activity[1,4,6]. Moreover, the results obtained here show negative correlation of available P with organic matter (r = -0.431, $p<0.01$) and with dissolved oxygen (r = -0.257, $p<0.05$) (Table 7). This indicates that utilization of oxygen by microbial activity had occurred during organic matter decomposition, resulting in P-release from organic materials in the sediments. Gonsiorczyk et al[25] also reported that the mineralization of organic matter was the driving force of P-release by sediments in eutrophic lakes. Therefore, the role of organic matter was considered a potential source of available P in the dry season of this study. In addition a significant correlation between the available P and clay, as well as Mn oxides, was obtained (Table 7). This was possibly due to organic matter associated with clay content and metal oxides[26].

In the wet season, available P significantly correlated with loosely adsorbed P (r = 0.322, $p<0.05$) and Fe, Al-bound P (r = 0.267, $p<0.05$) (Table 8), indicating the bioavailability of P in the wet season was derived largely from the two fractions. Phosphorus can be released from the two fractions into the overlying water by changes of pH and redox potential (Eh)[4]. Sediment pH is associated with Eh[27]. The redox potential has an influence on the precipitation of Fe and Mn oxides in oxic sediments (high Eh). When sediments become anoxic (low Eh), Fe and Mn can occur as soluble manganous ($Mn^{+2}$) and ferrous ($Fe^{+2}$) ions[28], and allow

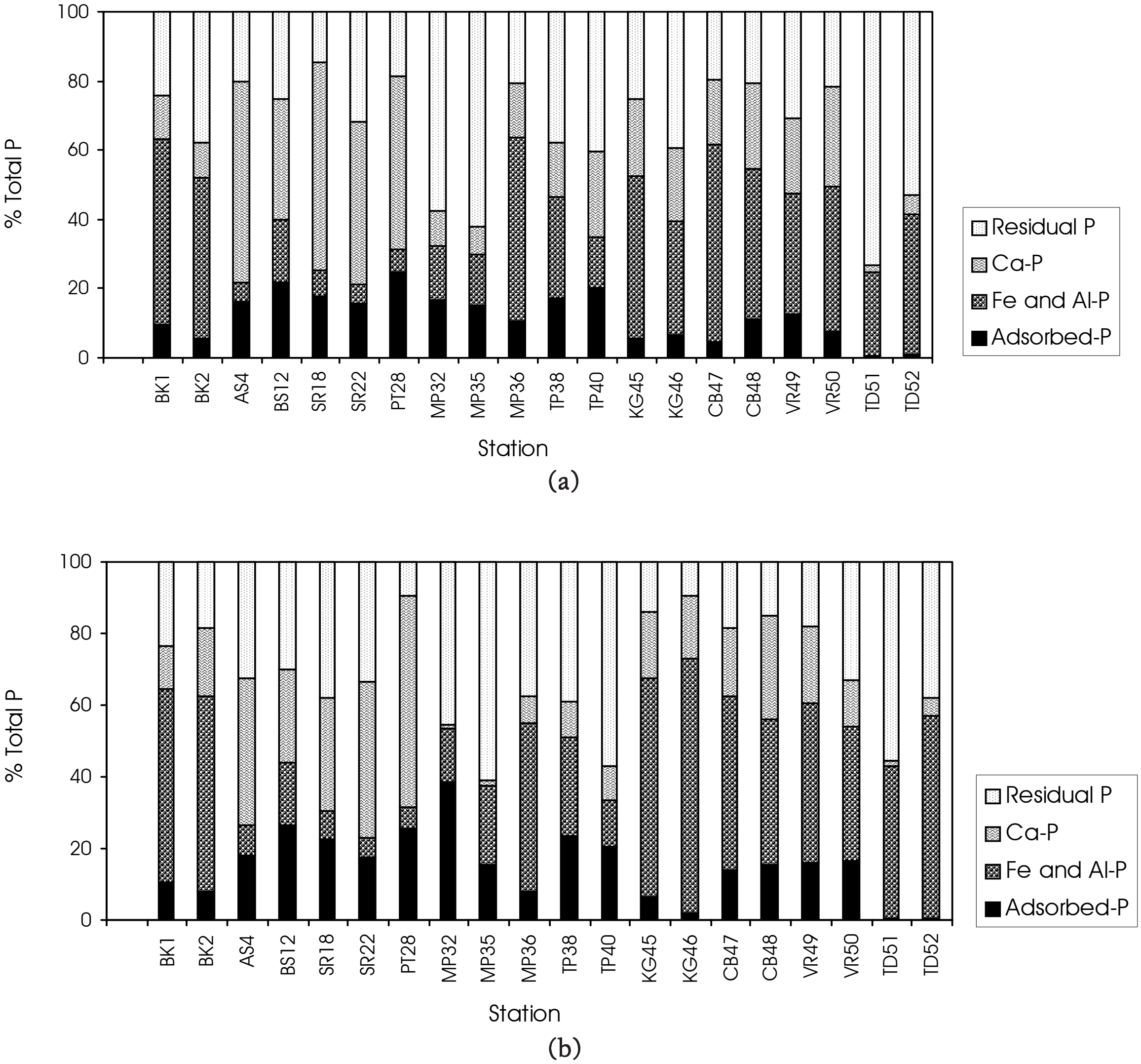

**Fig 3.** Different chemical forms of phosphorus distributed in the East Coast sediments in (a) dry season (April 2001) and (b) wet season (July 2001). The stations are coded as defined in Table 1.

**Table 7.** Correlation coefficients of various forms of phosphorus, selected sediment characteristics, and some water qualities in the dry season (April 2001) (N = 51- 60).

| Parameter | Total P | Adsorbed P | Fe, Al-P | Ca-P | Residual P | Inorganic P | Organic P | Available P |
|---|---|---|---|---|---|---|---|---|
| Sediment pH | -0.705** | 0.418** | -0.794** | 0.293* | -0.706** | -0.650** | -0.709** | NS |
| Organic matter | NS | NS | NS | NS | NS | NS | NS | -0.431** |
| $CaCO_3$ | NS | 0.285* | NS | NS | NS | NS | NS | 0.348** |
| Clay | 0.363** | NS | 0.606** | NS | 0.333* | 0.412** | 0.288* | 0.275* |
| Total Fe oxides | 0.887** | -0.355** | 0.858** | NS | 0.881** | 0.815** | 0.896** | NS |
| Amorphous Fe | 0.793** | -0.320* | 0.866** | NS | 0.757** | 0.751** | 0.776** | NS |
| Total Mn oxides | NS | NS | NS | NS | NS | NS | NS | 0.401** |
| Amorphous Mn | NS | NS | 0.521** | NS | NS | 0.340** | NS | 0.396** |
| Salinity | -0.792** | NS | -0.731** | NS | -0.834** | -0.772** | -0.752** | -0.430** |
| Bottom Water P | NS | NS | NS | NS | NS | NS | NS | 0.701** |
| DO | -0.292* | NS | -0.304* | NS | -0.284* | -0.262* | -0.302* | -0.257* |
| Water pH | -0.611** | NS | -0.718** | NS | -0.603** | -0.665** | -0.503** | -0.489** |
| Available P | NS | NS | NS | -0.261* | 0.297* | NS | NS | |

*, ** : Significant at $p = 0.05$ and 0.01 respectively
NS : Not significant ($p>0.05$)

phosphate to diffuse more freely into the overlying water. Possibly, the release of P in the river estuaries was largely from Fe, Al-bound P, rather than from loosely adsorbed P, because there was a larger portion of the former fraction, which agrees with the reports of Upchurch et al[29] and Gonsiorczyk et al[25]. The available P in the wet season also established a significant and high correlation with total and amorphous Mn oxides (r = 0.620 and r = 0.702, respectively) (Table 8). Such a correlation could not be obtained with any Fe oxides, since Fe oxides are more difficult to reduce than Mn oxides[26] resulting in P being strongly held with Fe rather than with Mn. This being the case, the release of P from Fe, Al-inorganic complexes in the wet season was mainly from Mn oxides, especially the amorphous form, rather than from Fe oxides.

## Relationship between Sediment P and Selected Sediment Characteristics

For both seasons, sediment P (both inorganic and organic forms) was most strongly correlated with total and amorphous Fe oxides, followed by clay content (Tables 7 and 8). No significant correlation between total P and organic matter or $CaCO_3$ could be obtained. This correlation indicated that both cystralline and amorphous Fe oxides were the major P sorbent of the sediments, followed by clay, respectively, while organic matter and $CaCO_3$ were less effective or may not be responsible for P sorbed in the study area. Fe oxides are quite common in sediments as suspended particles and as coatings on clay mineral surfaces and humic substances in organic matter[26]. They have high specific surface areas and great reactivity[26], making them a

**Table 8.** Correlation coefficients of various forms of phosphorus, selected sediment characteristics and some water qualities in the wet season (July 2001) (N = 54-60).

| Parameter | Total P | Adsorbed P | Fe, Al-P | Ca-P | Residual P | Inorganic P | Organic P | Available P |
|---|---|---|---|---|---|---|---|---|
| Sediment pH | -0.705** | NS | -0.824** | NS | -0.611** | -0.651** | -0.661** | -0.305* |
| Organic matter | NS | 0.280* | NS | NS | NS | NS | NS | NS |
| $CaCO_3$ | NS | 0.627** | -0.426** | 0705** | NS | NS | NS | NS |
| Clay | 0.423** | NS | 0.583** | NS | 0.282* | 0.518** | 0.325* | 0.514** |
| Total Fe oxides | 0.903** | -0.337** | 0.963** | NS | 0.858** | 0.848** | 0.892** | NS |
| Amorphous Fe | 0.744** | -0.356** | 0.908** | NS | 0.642** | 0.757** | 0.702** | NS |
| Total Mn oxides | 0.334* | 0.295* | 0.381** | NS | NS | 0.426** | NS | 0.620** |
| Amorphous Mn | 0.314* | NS | 0.357** | NS | NS | 0.391** | NS | 0.702** |
| Salinity | -0.635** | NS | -0.722** | NS | -0.466** | -0.693** | -0.499** | -0.494** |
| Bottom Water P | NS | NS | NS | NS | NS | NS | NS | 0.631** |
| DO | NS | NS | NS | NS | NS | NS | 0.271* | NS |
| Water pH | -0.502** | NS | -0.549** | NS | -0.434** | -0.540** | -0.432** | -0.633** |
| Available P | 0.275* | 0.322* | 0.267* | NS | NS | 0.391** | NS | |

*, ** : Significant at $p = 0.05$ and 0.01 respectively
NS : Not significant ($p>0.05$)

powerful sorbent.

For inorganic P fractions, a positive and strong correlation of the two Fe oxides was obtained with the Fe, Al-bound P fraction only. The correlation between organic P and Fe oxides obtained seemed to be indirect, possibly due to Fe oxides associated with organic matter forming Fe-organic P complex. In most sediment samples, Fe oxides were in amorphous rather than crystalline form (Tables 3 and 4). Therefore, amorphous Fe oxides would be expected to be the most effective sorbent for P in the study area, which agrees with the findings of Shukla et al[20] and Börling et al[30]. In addition, Shukla et al[20] reported that $CaCO_3$ is less effective than amorphous Fe in sorbing added inorganic P in the laboratory and in the lake environment. $CaCO_3$ also acts to dilute the Fe and Al sites as reported by McCallister and Logan[19], which agreed with the negative correlation coefficient obtained between Fe, Al-bound P and $CaCO_3$ content, especially in the wet season ($r = -0.426$, $p<0.01$). Also McDowell et al[31] found that the surface areas of $CaCO_3$ and organic matter are low-energy adsorption sites for P sorbing in soils. These reports are all in agreement with the data presented in the study.

In addition, sediment P in this study showed a strong negative relationship with pH (Tables 7 and 8) indicating that the increase of pH may cause the release of P from the sediments to water, which agreed with the findings of McCallister and Logan[19] and Carpenter and Smith[32]. This was possibly due to the $OH^-$ ions competing with $PO_4^{3-}$ ions associated in the sediments[23]. A similar relationship was also obtained between sediment P and salinity of the overlying water, indicating that P content of sediments decreased with increasing salinity or P desorption occurred as salinity increased, which agreed with the findings of Upchurch et al[29] and Carpenter and Smith[32]. A possible explanation for this is that the adsorbed P is released or displaced by competing anions which predominate in seawater, such as chloride or sulfate[29]. In addition, dissolution of Fe and Mn from the sediments through their complexation with chloride may contribute, in part, to the release of inorganic P complex from the sediments.

In conclusion, the total P in sediments of the study area showed broad ranges, possibly due to the difference of sediment characteristics of the study area, especially the amount of Fe oxides, which is considered to be the major P sorbent of the sediments. Fractionation of P can show the nature of P in the sediments of the area. Fe, Al-bound P was the major fraction of P in the estuarine sediments. Reducing conditions in the sediments may increase the solubility of Fe, Al-bound P. Therefore, P may be released from the sediments and at high concentrations can stimulate phytoplankton blooms. The season had an influence on the fractions of P available, which included exchangeable or loosely adsorbed P and Fe, Al-bound P found in the wet season and organic P found in the dry season. The bioavailable P fractions can be used to assess eutrophication in estuaries and coastal waters.

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