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Research Article

The eutrophication states of Jakarta, Lampung and Semangka Bays: Nutrient and phytoplankton dynamics in Indonesian tropical waters

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ABSTRACT. Eutrophication states of the three different tropical embayments in Indonesian waters were studied. Effects of anthropogenic nutrient inputs on seasonal nutrient gradients and dynamics of phytoplankton biomass were studied over a one year period in three Indonesian embayments, subjected to different levels of anthropogenic pressure. Jakarta Bay receives by far the highest estuarine nutrient load (21260 t DIN y^{-1}, 6741 t P y^{-1}, 52417 t Si y^{-1}), followed by Lampung Bay (5003 t DIN y^{-1}, 1096 t P y^{-1}, 14731 t Si y^{-1}) and Semangka Bay (1378 t DIN y^{-1}, 419 t P y^{-1}, 16449 t Si y^{-1}). As a consequence, mean annual levels of dissolved inorganic nutrients in Jakarta Bay, which accounted for 20 µM N, 5 µM P and 45 µM Si, fairly exceeded those of the two other bays, resulting in high annual means of phytoplankton biomass (13 µg Chl-a l^{-1}) when compared to Lampung Bay (4 µg Chl-a l^{-1}) and Semangka Bay (0.8 µg Chl-a l^{-1}). In all of the bays, the phytoplankton community was dominated by diatoms. The occurrence of Dinoflagellates, Chlorophyceae and Cyanophyceae was mainly restricted to the river mouths and their surrounding waters. In total, spatial variability of parameters was much more pronounced than temporal variability, which is congruent with the moderate meteorological fluctuations typical for tropical regions. Despite high loads into Jakarta Bay, a major part still exhibits an acceptable water quality status with respect to dissolved oxygen saturation, which never falls below 50%.

Keywords: Anthropogenic nutrient enrichment, eutrophication, nutrient dynamics, phytoplankton dynamics, chlorophyll-a.

INTRODUCTION

Anthropogenic eutrophication has been associated with an increase of nutrient concentrations, which in turn may lead to excessive algal growth, resulting in detrimental situations such as hypoxia or anoxia followed by declining fish and shellfish stocks, loss of biodiversity, and an increase of unusual novel and toxic algal blooms (Nixon, 1995). Coastal eutrophication has been a societal and scientific focus only over the last three decades, resulting in a conceptual model developed firstly by limnologists (Cloern, 2001; Nixon, 1995). The early view of coastal eutrophication was highly inspired by a simple causal-relationship involving a one to one ratio of signal and response (Cloern, 2001). In recent times, the comparative evaluation of various coastal-eutrophication studies by Borum

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(1996) and Cloern (2001) has revealed that not all estuaries with high nutrient loads are characterized by a high phytoplankton biomass and that the relation of nutrient inputs with responses in terms of phytoplankton biomass is much more complex. As an example, two nutrient-rich bays, Chesapeake and San Francisco bays, which are quite similar in nutrient loads, exhibit large differences in phytoplankton biomass (Cloern, 2001). In tropical coastal waters, the study on nutrient enrichment and its ecological consequences is not as extensive as in temperate areas (Cloern, 2001; Berdalet *et al.,* 1996; Foy, 1993; Olli *et al.,* 1996; Hessen *et al.,* 1995; Muscatine *et al.*, 1989; Kaswadji *et al.*, 1993). Considering the rapid urbanisation of tropical coastal zones, there is a need for appropriate studies on nutrient enrichment and its relation with phytoplankton development in order to understand eutrophication mechanisms as a basis for future coastal management strategies.

In this paper, the relationship between nutrient loads, gradients and phytoplankton biomass in three main Indonesian coastal embayments (Jakarta, Lampung and Semangka Bays) is presented. Jakarta Bay, subjected to around 15 million inhabitants of Jakarta City, is the most polluted embayment, not only in comparison with Lampung Bay (around 0.9 million inhabitants) and Semangka Bay (around 0.05 million inhabitants), but also among all other coastal waters in Indonesia. This study is expected to further understand the impact level of different nutrient loadings on phytoplankton development and its relation to the variability of monsoonal seasons.

MATERIALS AND METHODS

Measurement campaigns were conducted in all bays over a one-year period, encompassing the dry and rainy monsoonal seasons. Surface water samples (0 to 1.5 m depth) were taken on

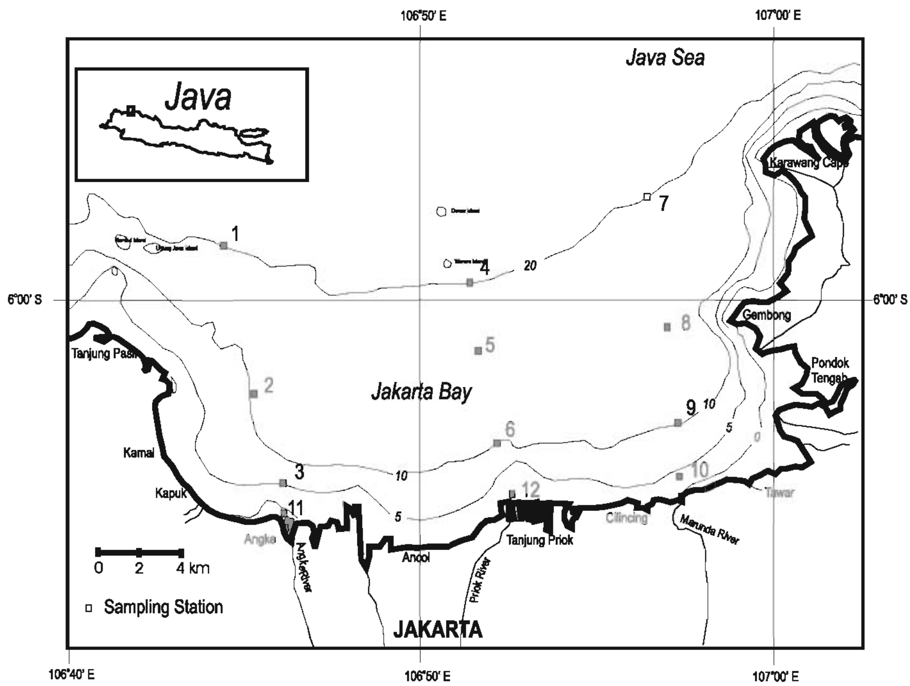


Figure 1. Position of sampling stations in Jakarta Bay, Indonesia.

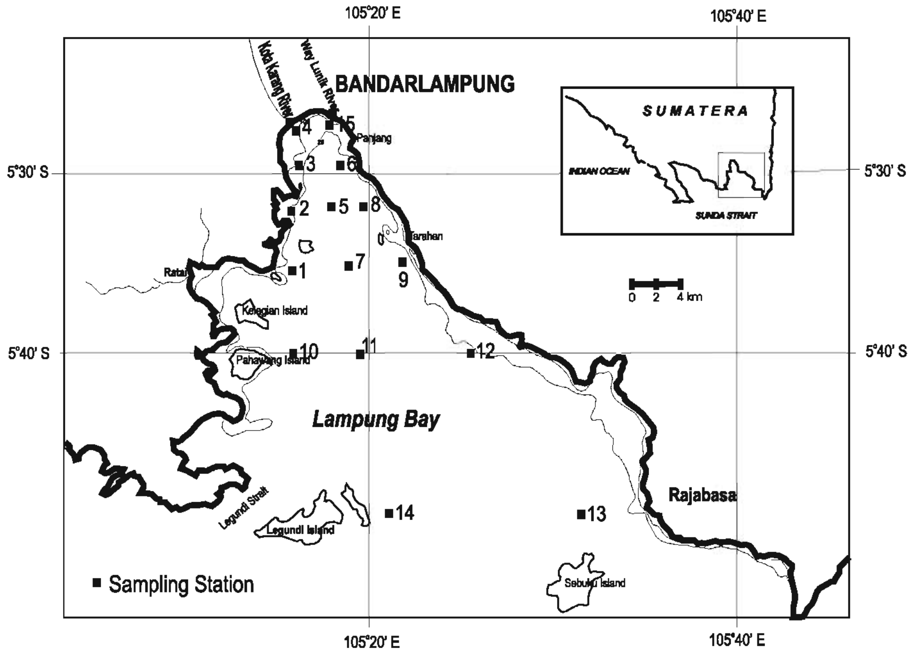


Figure 2. Position of sampling stations in Lampung Bay, Indonesia.

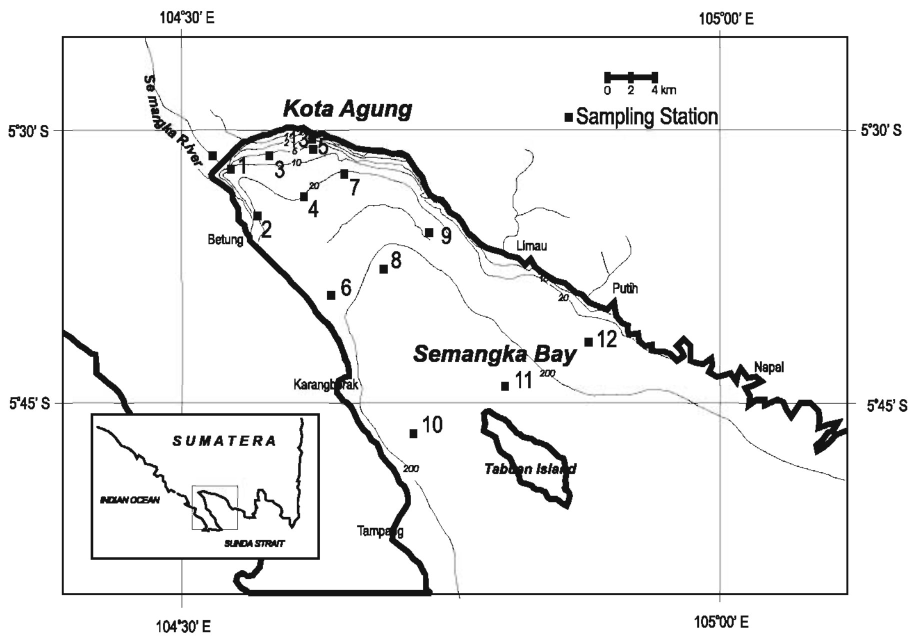


Figure 3. Position of sampling stations in Semangka Bay, Indonesia.

a fixed sampling grid in each bay (Figures 1-3), with a frequency of approximately every two months. Samples from February till July were confined to the dry season whereas all others were taken in the rainy season. Sampling sites were located according to the expected spatial gradients, with narrower spacing in the inner parts of the bays. In Jakarta Bay, a total of 15 stations was sampled, three of which were located in the mouths of the main rivers, the Angke, Priok and Marunda (Figure 1). In Lampung Bay, sampling was conducted at 17 stations, including one station at the mouth of the Kota Karang River and another at the Way Lunik River (Figure 2). In Semangka Bay, the grid consisted of 14 stations, with one station located at the mouth of the Semangka River and another at the main fishery harbour (Station 13, Figure 3).

At each station, a total of 5 litres of water was collected by repetitive sampling with a 2-liter PVC Van Dorn bottle and distributed into several sub-samples for the analyses of dissolved inorganic nutrients (0.25 l), chlorophyll-a (1 to 2 l), and phytoplankton composition (0.25 l). For the purpose of detailed phytoplankton species identification, additional net plankton samples were taken by using a 40-µm plankton net. Phytoplankton samples were preserved with Lugol's solution on board. The other samples were placed temporarily in a cooler box containing dry ice (around 10°C) until further processing. In addition, *in situ* measurements were conducted for under water light attenuation using a 30-cm diameter Secchi disk, while temperature and salinity data were taken using a CTD probe (YSI-30).

Water samples for dissolved inorganic nutrient analysis were filtered on shore through a MFS nucleopore filter (diameter 47 mm, pore size 0.2 µm) approximately 6 hours after sampling. Filtrates were stored in 250-ml PVC flasks. All water samples were transported in dry ice to the main laboratory in Bogor. Transportation took approximately 2 hours from Jakarta Bay and 7 hours from Lampung and Semangka bays.

Dissolved inorganic nutrient analysis was done according to Grasshoff *et al.* (1983). For chlorophyll-a analysis, 1 – 2 litres of water were filtered through a Whatman GF/C filter (47 mm diameter), which was stored in the dark and deep frozen (-20°C) until being analysed using the spectrophotometrical method of Lorenzen (1967). Phytoplankton cell counts were done according to Utermöhl (1958). Prior to being counted, 100 ml of the preserved sub samples were concentrated to 10 ml by settling and siphoning the supernatant.

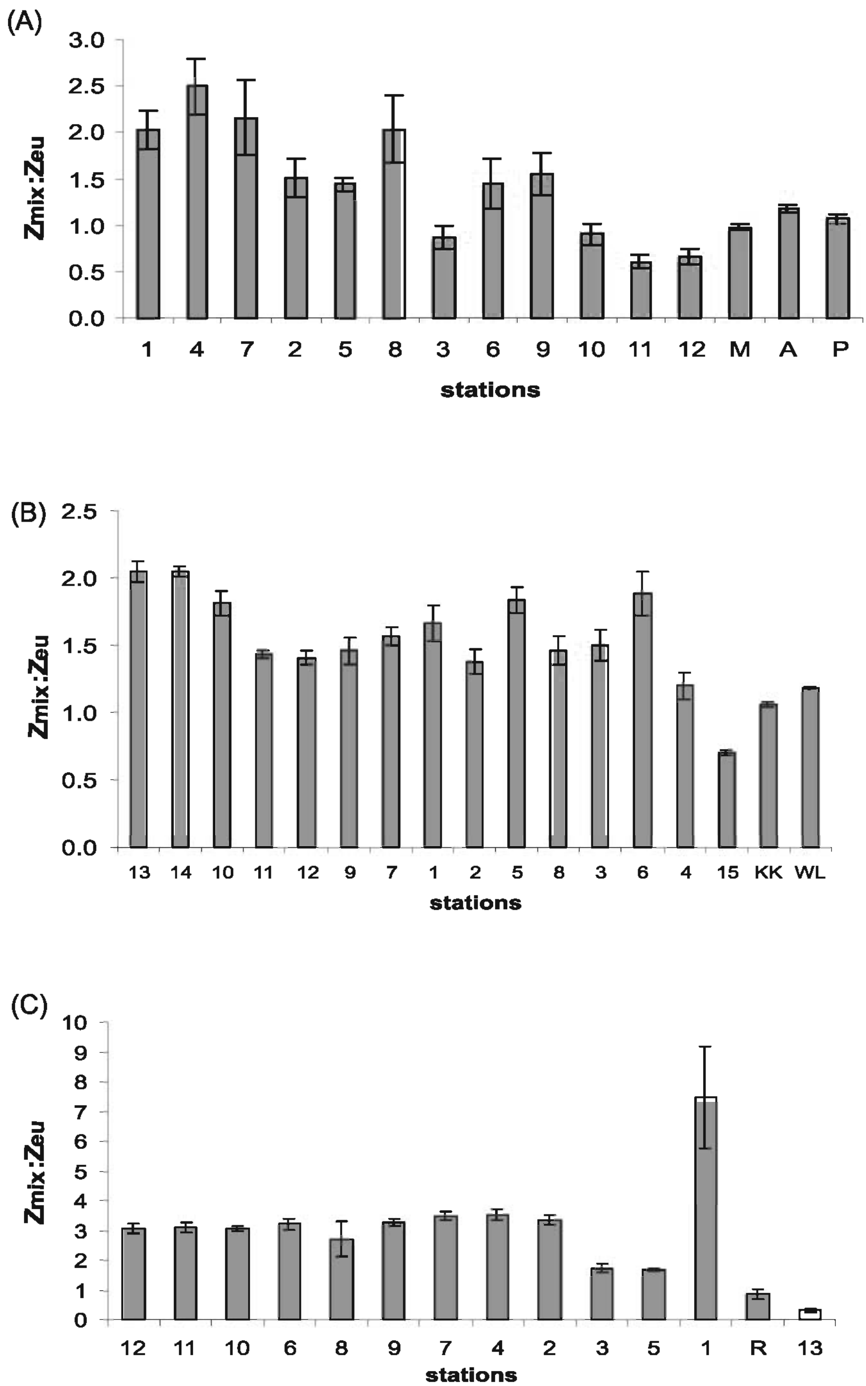
The ratio between mixed depth (Z_{mix}) and euphotic depth (Z_{eu}) was determined in order to evaluate the potential role of underwater light availibility for phytoplankton growth in the three bays. For Semangka Bay, the depth of the mixed layer was taken as 60 m, which was the depth of the thermocline (Hendiarti, pers. comm.; Damar, 2003; Hendiarti *et al.*, 2002). The data collected was statistically analysed by two-ways Analysis of Variance (ANOVA) to test for temporal and spatial differences, and by linear correlation analysis (Pearson) for the detection of coherences.

RESULTS

Light availability for phytoplankton (expressed as Z_{mix}: Z_{eu})

In all bays, the near-shore stations exhibited low Z_{mix}:Z_{eu} ratios of about 1 (Figures 4A - D), while the more offshore stations were characterized by higher values (more than 1.5). An exception was found in the plume of Semangka River (Figure 4C, Station 1), which showed high ratios (around 7.0) due to high turbidity and increased water depth. However, it can be traced that nearshore waters of the bays generally exhibited more favourable underwater light conditions for phytoplankton development than those at middle and outer parts, despite the enhanced transparency at these locations.

Comparison between bays showed that ratios in Jakarta and Lampung bays (mean values 1.4 and 1.5, respectively) were lower


(A)
Zmix:Zeu
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 4 7 2 5 8 3 6 9 10 11 12 M A P
stations
(B)
Zmix:Zeu
2.5
2.0
1.5
1.0
0.5
0.0
13 14 10 11 12 9 7 1 2 5 8 3 6 4 15 KK WL
stations
(C)
Zmix:Zeu
10
9
8
7
6
5
4
3
2
1
0
12 11 10 6 8 9 7 4 2 3 5 1 R 13
stations

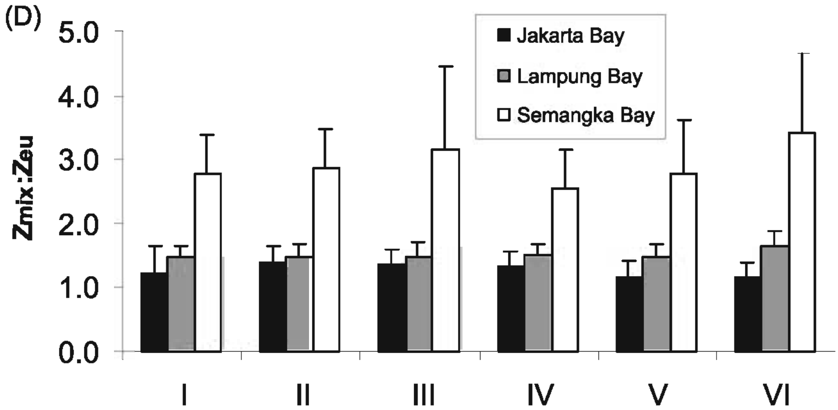


Figure 4. Mean Z_{mix}:Z_{eu} ratios in Jakarta Bay (A), Lampung Bay (B), Semangka Bay (C) and seasonal patterns among the bays (D). M, A, P, KK, WL and R are Marunda, Angke, Priok, Kota Karang, Way Lunik and Semangka river mouths, respectively. I, V and VI surveys = rainy season; II, III and IV surveys = dry season. Bars are standard deviations.

than in Semangka Bay (mean value 2.9) (Figure 4D), showing that light availability for phytoplankton growth in the former two bays is more favourable than in Semangka Bay waters. The relatively shallow water depth in these bays is the main cause for these low ratios. There was no significant temporal difference in the ratios ($p>0.05$), indicating rather stable turbidity levels across the seasons.

Nutrient loads from the inner estuaries into the bays

Comparison between bays showed that Jakarta Bay receives a much higher load of dissolved inorganic nutrients than the two other bays, while Semangka Bay receives the least (Table 1) (ANOVA, $p<0.001$). This holds especially true for nitrogen and phosphorus, which in contrast to silicate, are directly related to anthropogenic emission. Mean molar ratios of the discharged nutrients differed only slightly between bays, with DIN/DIP ratios ranging from 3-4, and DIN/Si ratios of around 0.4. An exception was the Semangka River mouth, which exhibited an extremely low DIN/Si-ratio (0.08) as a consequence of high silicate concentrations in the inner estuary.

Dissolved inorganic nutrient concentrations

Within the three bays studied, nutrient concentrations showed significant spatial differences (ANOVA, $p<0.01$). Spatial nutrient patterns were inversely related to the salinity gradient with high values at river mouths, decreasing steeply offshore (Figures 5 - 8). This pattern was most pronounced in Jakarta

Table 1. Annual nutrient loads and ratios from the inner estuary into the bays.

Nutrient loads	Units	Jakarta Bay	Lampung Bay	Semangka Bay
Phosphate	t y^{-1}	6,741	1,096	419
DIN	t y^{-1}	21,260	5,003	1,378
Silicate	t y^{-1}	52,417	14,731	16,449
DIN/DIP ratio	-	3.15	4.56	3.29
DIN/Si ratio	-	0.41	0.34	0.08

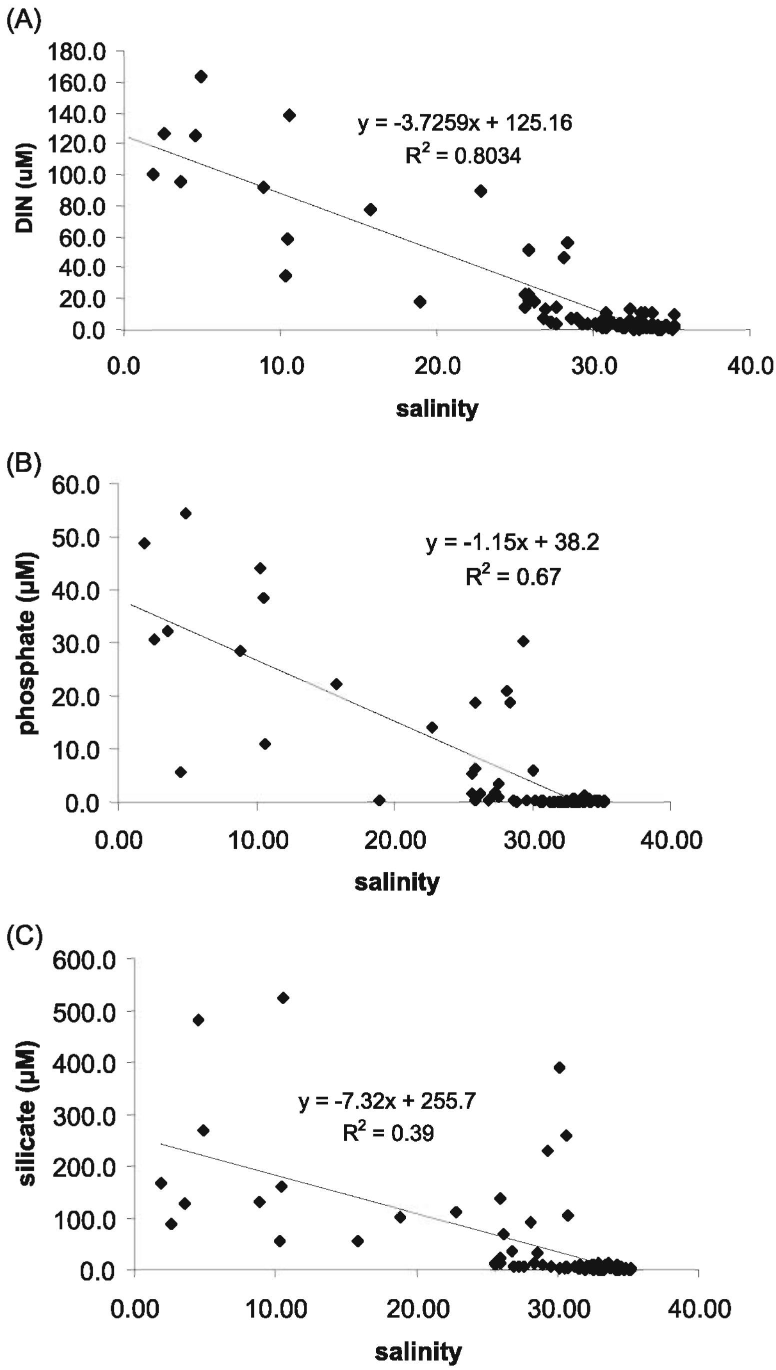


Figure 5. Linear regression between salinity versus DIN (A), phosphate (B) and silicate (C) in Jakarta Bay.

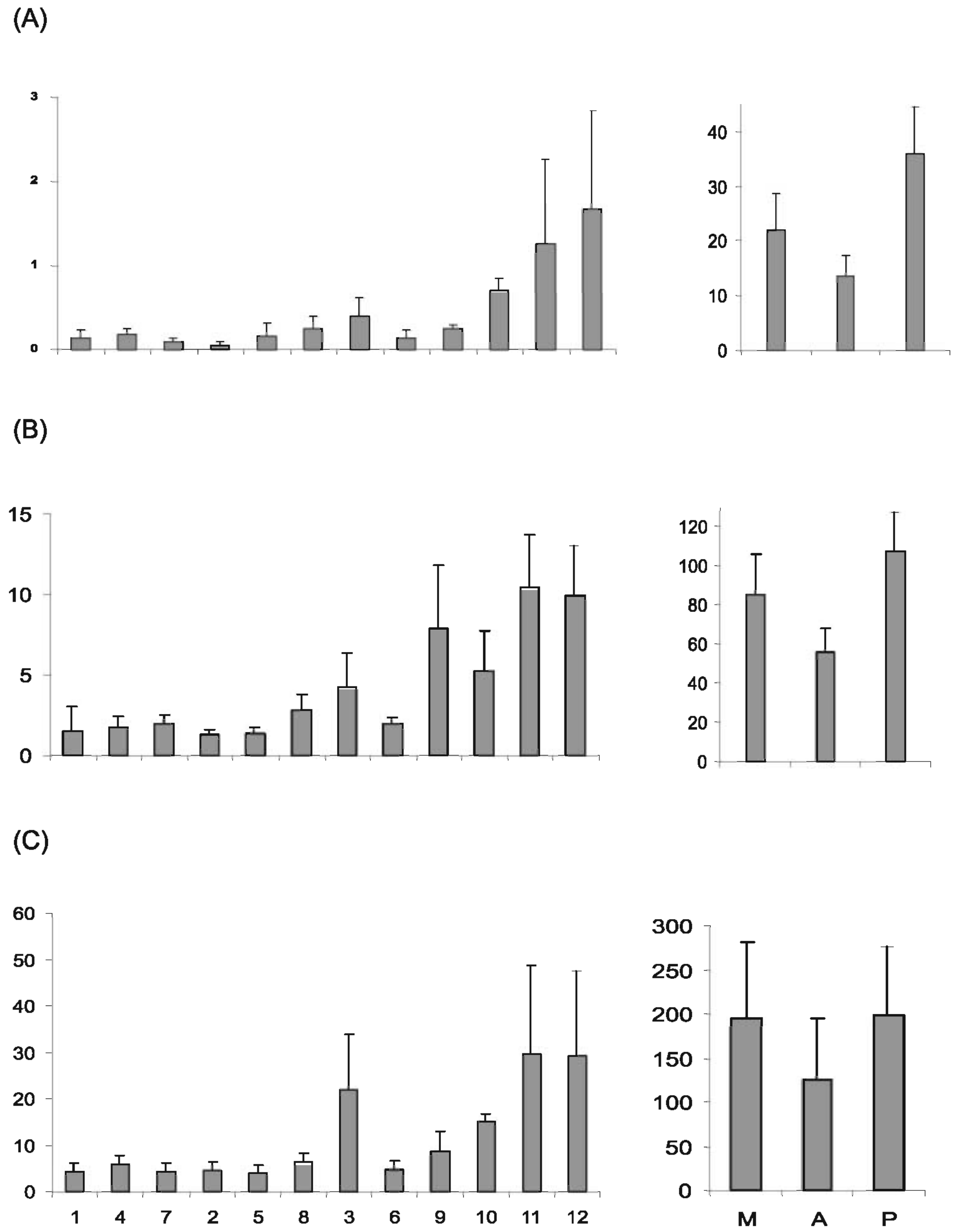


Figure 6. Mean concentrations of dissolved inorganic phosphorus (A), nitrogen (B) and silicate (C) in Jakarta Bay. M, A, and P are Marunda, Angke and Priok rivers, respectively. Bars show standard deviations. Note different scales.

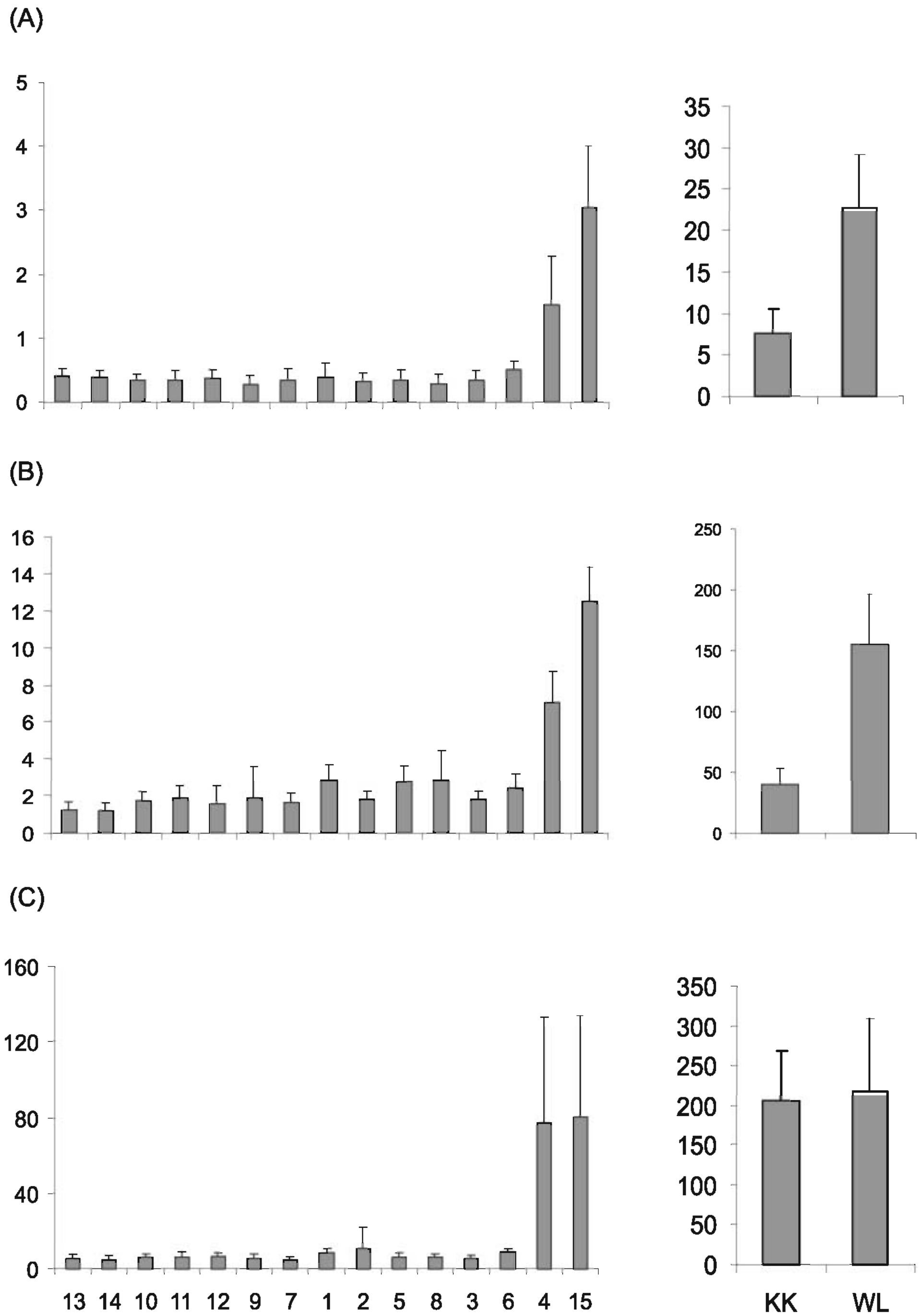


Figure 7. Mean concentrations of dissolved inorganic phosphorus (A), nitrogen (B) and silicate (C) in Lampung Bay. KK and WL are Kota Karang and Way Lunik rivers, respectively. Bars show standard deviations.

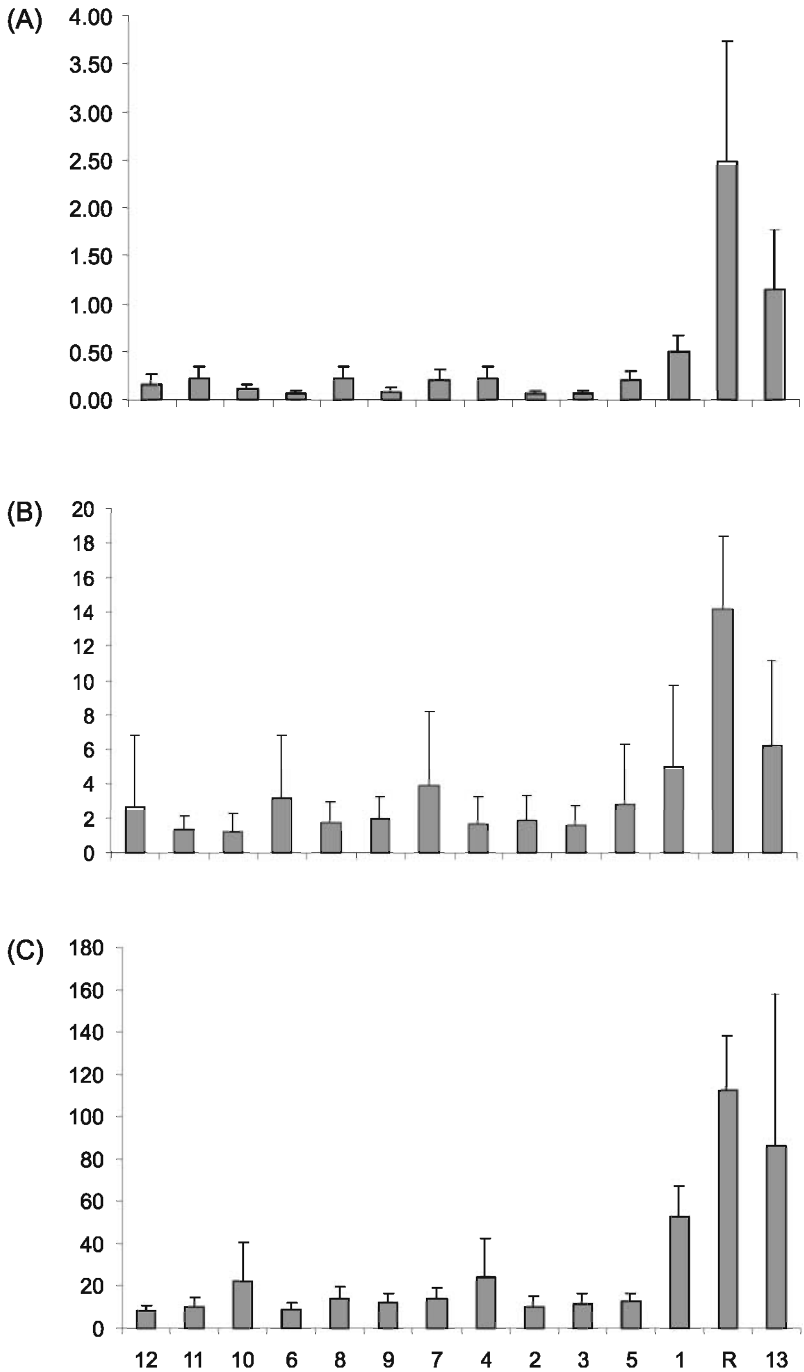


Figure 8. Mean concentrations of dissolved inorganic phosphorus (A), nitrogen (B) and silicate (C) in Semangka Bay. R is Semangka River. Bars show standard deviations.

Bay, where phosphate, DIN and silicate concentrations at the river mouths and near shore stations were 10, 8 and 5 fold higher than at the outer stations (Figure 6). In Semangka Bay, apart from the river mouth, water in the fishery harbour (Station 13 in Figure 8) exhibited high nutrient concentrations. These are assumed to be due to the presence of several municipal sewerage outlets. In addition, waste from fish processing activities may have caused the elevated nutrient levels at this site.

Comparison of annual means of dissolved inorganic nutrient concentrations between bays revealed that in keeping with estuarine nutrient discharges, Jakarta Bay exhibits the strongest nutrient enrichment (mean of 5.1 μM phosphate, 20.1 μM DIN and 44.8 μM silicate) followed by Lampung Bay (mean of 2.3 μM phosphate, 14.3 μM DIN and 39.3 μM silicate). Semangka Bay can be considered as being the most pristine of the three bays (mean of 0.4 μM phosphate, 3.5 μM DIN and 28.4 μM silicate) (ANOVA, $p<0.001$).

Spatial means of seasonal nutrient concentrations did not reveal a clear dependency on the monsoonal periods (Figure 9). In Jakarta Bay, highest phosphate concentrations were observed during the dry season, which is concomitant with higher phosphate loads from the inner estuary during this period. This may be caused by increased agricultural activities and also by an increased remobilisation of phosphorus from anoxic sediments in the river and river mouth beds, and drainage canals of the city. Elevated DIN and silicate levels occurred during times of high precipitation and consequently, of increased river discharge. During periods of heavy rainfall, stormwater removes a high amount of untreated waste water rich in ammonium from urban settlements. Nitrate, however, was most prominent during the dry season. This may be attributed to the intense use of fertiliser in rice fields at the catchment area during this period.

In Jakarta Bay, dissolved inorganic nitrogen concentrations (DIN) at all river mouth stations and in inshore waters (stations 6, 9, 10, 11 and 12) were dominated by ammonium. In the inner estuary, ammonium made up more than 85% of DIN (Figure 10A), which is presumably due to the discharge of large amounts of untreated sewage. At the offshore stations of the bay, nitrate and ammonium contributed almost equally to DIN levels. Here, a substantial share of total nitrogen was also made up by nitrite, indicating the progressive nitrification along with increasing distance from riverine sources. In Lampung Bay, only the Way Lunik river mouth and two stations near islands at the outermost border of the bay showed a strong domination of ammonium, whereas at other stations, nitrate shared comparable contributions to DIN (Figure 10B). Relatively high nitrate and nitrite concentrations in Lampung Bay are supposed to be caused by the more intense agricultural practices in that area (Anonymous, 2002b), and the associated leakage of nitrate fertiliser. By contrast, in the less polluted Semangka Bay, nitrate also dominated at the river mouth, which can be interpreted as a sign of rapid nitrification in the estuary. In this bay, a distinct domination of ammonium only prevailed in the waters of the fishery harbour (Station 13, Figure 10C).

Relationship between nutrient loads and nutrient concentrations

Significant linear correlations between estuarine nutrient loads and the average nutrient concentrations at inshore stations were observed in all bays ($p<0.01$), however, no relation was found between loads and offshore nutrient concentrations ($p>0.5$). Hence, temporal variability of the estuarine nutrient loads does not directly affect the temporal dynamics of the offshore nutrient concentrations. A direct impact of nutrient loads is limited to the inshore area close to the river mouths.

N/P and N/Si ratios

In all bays studied, no statistically significant differences in the N/P ratio both between sites,

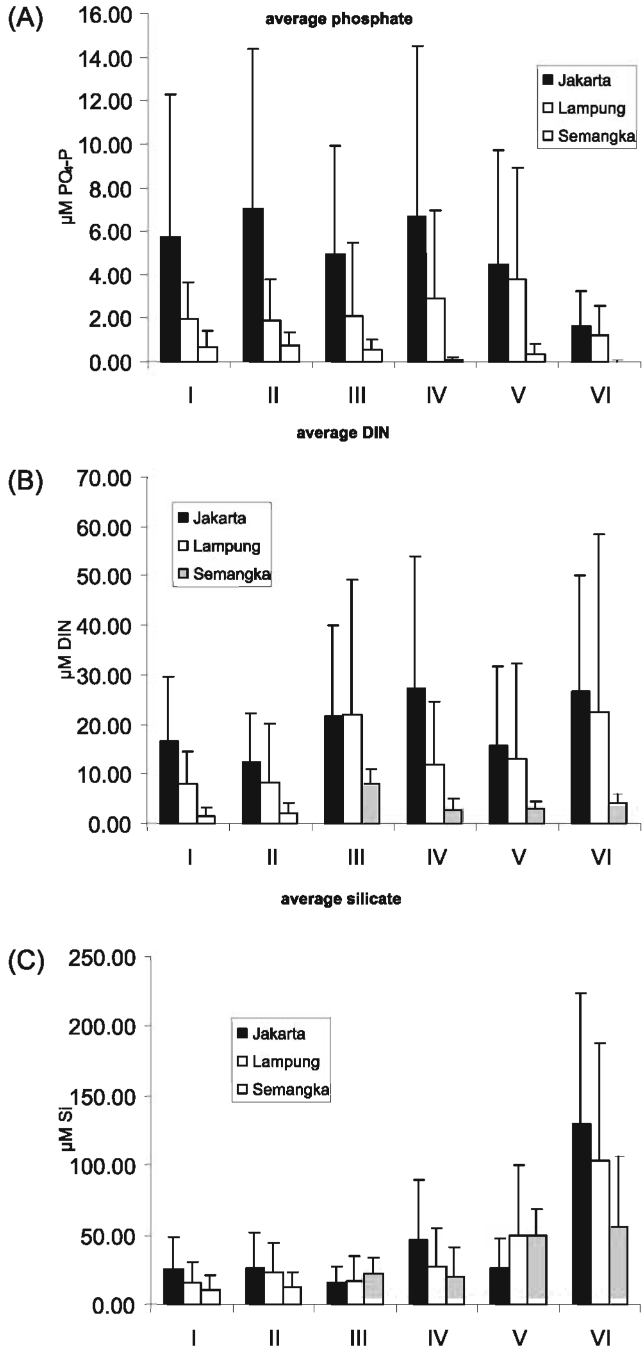


Figure 9. Comparison of seasonal means of phosphate (A), DIN (B) and silicate (C) between Jakarta, Lampung and Semangka bays. I = Dec'00 - Jan'01; II = Feb'01 - Mar'01; III = Apr'01 - May'01; IV = Jul'01; V = Sep'01 - Oct'01 and VI = Nov'01 - Dec'01. Bars show standard deviations calculated from 15 data points (Jakarta Bay), 17 data points (Lampung Bay) and 14 data points (Semangka Bay).

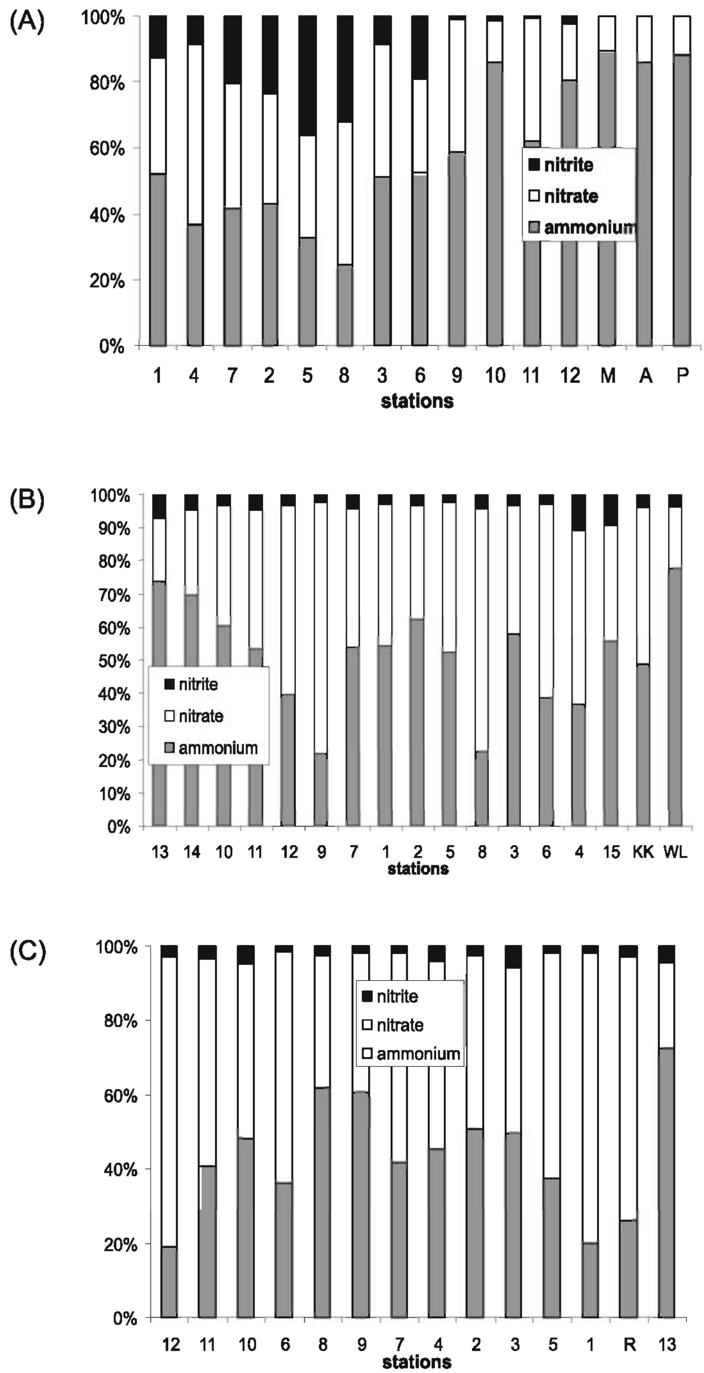


Figure 10. Percentage of dissolved inorganic nitrogen forms on DIN in Jakarta Bay (A), Lampung Bay (B) and Semangka Bay (C). M, A, P, KK, WL and R are Marunda, Angke, Priok, Kota Karang, Way Lunik and Semangka river mouths, respectively.

and temporal surveys, were found. However, generally, N/P ratios were below the Redfield ratio at the river mouths (<16), indicating a potential nitrogen limitation of phytoplankton growth at these sites. This may only partly be due to preferential uptake of nitrogen by the local phytoplankton communities (see 3.6.), because these low ratios were mainly caused by high phosphate levels, instead of nitrogen depletion. Towards the more offshore waters, the N/P ratio increased, exceeding the Redfield ratio of 16, thus suggesting a potential phosphate limitation. Although the nutrient ratios were not very different between the bays, Jakarta Bay exhibited the highest ratios, indicating potential P limitation over a wide area of the bay. In Lampung and Semangka bays, this was the case only in 26% and 50% of the measurements, respectively. In contrast to the situation in Jakarta Bay, the potential limiting nutrient for phytoplankton growth in Lampung and Semangka bays is therefore supposed to be rather N than P.

The highest mean ratio (125) in the offshore water prevailed in Jakarta Bay in September 2001, while the lowest (30) occurred in December 2000. There was a weak positive correlation between N/P ratios and both salinity and turbidity, indicating the influence of river discharge on this ratio (Damar, 2003).

In Lampung and Semangka bays, the N/Si ratios were generally lower (range 0.1 to 0.7) than in Jakarta Bay (range 0.8 to 1.5). This suggests a potential nitrogen limitation of diatom growth in the former two bays and reflects the moderate input of nitrogen relative to that of Si when compared to Jakarta Bay. The excess N loads in Jakarta Bay resulted in N/Si ratios >1 in 21% of the measurements.

Phytoplankton biomass, algae pigments and taxonomic composition

Chlorophyll-a concentrations in the bays are shown in Figure 11. In Jakarta and Lampung bays, there is a distinct spatial pattern, with presistently high levels at the river mouths and surroundings, rapidly declining towards the more offshore sites (ANOVA, $p<0.001$). Seasonal variation was most pronounced in the inshore waters. In Jakarta Bay, seasonal chlorophyll-a levels at the river mouths ranged from 8.2 to 92.6 $\mu g\ l^{-1}$. In the inner bay, concentrations decreased only slightly (stations 10, 11 and 12, range 5.6 to 39.2 $\mu g\ l^{-1}$). By contrast, in the middle and outer parts, a steep decrease in chlorophyll-a down to minimum levels of 0.3 $\mu g\ l^{-1}$ and 0.6 $\mu g\ l^{-1}$, respectively, were observed.

In Lampung Bay, chlorophyll-a levels at the river mouth stations and at the surrounding sites varied from 4.5 to 73.3 $\mu g\ l^{-1}$ (stations 4, 15, KK, WL). Towards the deeper and more saline waters, a sharp decline down to minimum levels of 0.1 $\mu g\ l^{-1}$ was observed.

In Semangka Bay, however, the river mouth and its surroundings did not appear to offer very favourable conditions for phytoplankton development. The low estuarine phytoplankton biomass (0.3 to 1.6 $\mu g\ l^{-1}$) observed at these sites is certainly not due to limited supply of nutrients, but rather due to poor light availability in the turbid river waters. In this bay, higher chlorophyll-a levels (1.2 to 8.3 $\mu g\ l^{-1}$) were restricted to the nutrient-rich water of the fishery harbour (station 13), which exhibited the best growth conditions in terms of light availability, whereas in the middle and outer parts of the bay, phytoplankton biomass was again very low, never exceeding 1 $\mu g\ l^{-1}$.

Comparison of annual means of chlorophyll-a levels between bays (Figure 12) suggests that Jakarta Bay is the most productive area with average concentrations of 13.2 $\mu g\ l^{-1}$, followed by Lampung and Semangka bays (mean chlorophyll-a 4.6 and 0.8 $\mu g\ l^{-1}$, respectively). This is in keeping with differences in nutrient supply to these bays. A distinct seasonal signal in chlorophyll-a concentrations, however, was not observed.

In all areas, the phytoplankton community was dominated by diatoms (Bacillariophyceae). This predominance was

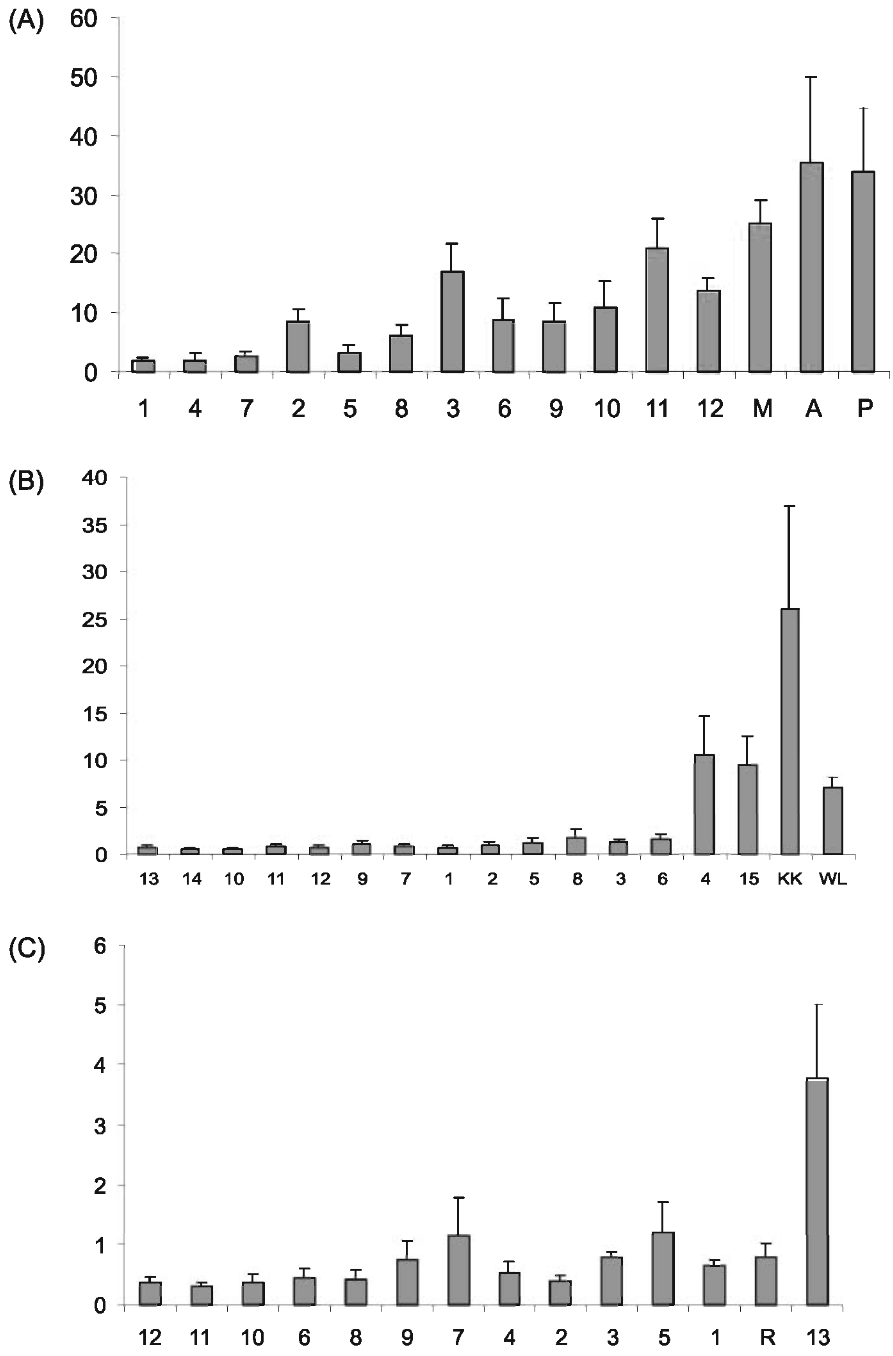


Figure 11. Mean chlorophyll-a concentrations in Jakarta Bay (A), Lampung Bay (B) and Semangka Bay (C). M, A, P, KK, WL and R are Marunda, Angke, Priok, Kota Karang, Way Lunik and Semangka river mouths, respectively. Bars show standard deviations.

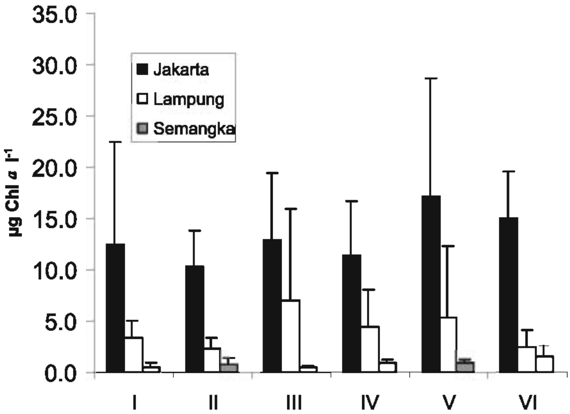


Figure 12. Comparison of seasonal means of chlorophyll-a between Jakarta, Lampung and Semangka bays. I = Dec'00 - Jan'01 ; II = Feb'01 - Mar'01 ; III = Apr'01 - May'01 ; IV = Jul'01; V = Sep'01 - Oct'01 and VI = Nov'01 - Dec'01. Bars show standard deviations calculated from 15 data points (Jakarta Bay), 17 data points (Lampung Bay) and 14 data points (Semangka Bay).

most pronounced at the more offshore stations, while at the nearshore waters, the abundance of dinoflagellates, Cyanophyceae and Chlorophyceae increased along with the decrease in N/P-ratios. A strong dominance of diatoms was generally reflected by low N/Si-ratios. Predominant species in Jakarta Bay were *Skeletonema costatum*, *Chaetoceros debilis* and *Pseudonitzschia* spp.. In Lampung Bay, *Chaetoceros danicus* and *C. debilis* dominated the phytoplankton assemblages whereas in Semangka Bay *Chaetoceros* spp., *Guinardia flaccida* and *Rhizosolenia indica prevailed*. Among the Cyanophyceae and Chlorophyceae, *Trichodesmium* spp. and *Scenedesmus* spp. were the dominant genera in all bays. These genera were mostly found in the less saline river mouths. Algae pigment analysis supported the microscopic observations (data not shown, cf. Damar, 2003). The river mouths and surrounding sites were dominated by chlorophyll-b and lutein, indicating that Chlorophyceae shared an important part at these stations. At all other sites, fucoxanthin dominated, showing the strong abundance of diatoms. The occurrence of zeaxanthin as an indicator for Cyanophyceae was restricted to the inshore waters in all bays (Damar, 2003).

DISCUSSION

Differences in estuarine nutrient loads and mean annual concentrations in the three bays reflect strong differences in anthropogenic pressure among the bays. With the highest population among the three study sites, Jakarta Bay exhibited the highest annual levels of dissolved inorganic nitrogen and phosphorus, followed by Lampung and Semangka bays.

Studies done in Jakarta Bay about 25 years ago resulted in only slightly lower mean annual nutrient levels compared to the present investigation (Praseno & Kastoro, 1980), despite the fact that population density of Jakarta city has almost doubled since that time. The authors found mean annual levels of DIN and phosphate of 15.3 µM DIN and 4.6 µM PO_4-P, respectively. Compared to other Indonesian coastal areas subjected to intense human activities such as the Singapore and the Johor straits, nutrient levels in Jakarta Bay are distinctly higher. They exceed about 5-fold (DIN) and 16-fold (phosphate) the mean concentrations of the Singapore Strait (3.6 µM N and 0.3 µM PO_4-P, Gin *et al.*, 2000) and 1.2-fold (DIN) and 3.5-fold (phosphate) those of Johor Strait (17.4 µM N and 1.4 µM PO_4-P, Gin *et al.*, 2000). The relatively low nutrient concentrations in Singapore Strait are a result of the intense flushing rates of the system (Gin *et al.*, 2000). By contrast, despite a comparable population density, the situation in Jakarta Bay is less severe than that in the tropical Guanabara Bay (Brazil), which is affected by domestic waste water from around 11 million inhabitants in the city of Rio de Janeiro. Annual means of DIN and phosphate in the Guanabara Bay (56.9 µM N and 6.23 µM P) are repectively 3 and 1.5 times higher than those of Jakarta Bay (Ribeiro & Kjerfve, 2002). This is certainly not due to a more adequate sewage treatment in the Jakarta region where about 80% of wastewater runs through an open ditch system into rivers, but due to the higher residence time of the water in the semi-enclosed Guanabara Bay lagoon.

A comparison of the Jakarta Bay nutrient status with that of temperate estuaries shows that dissolved inorganic nutrient concentrations in the latter are usually much higher, despite distinctly lower riverine nutrient loads. In the Chesapeake and San Francisco bays, mean DIN concentrations are 32.3 µM and 32.4 µM, respectively (Cloern, 2001). However, seasonal variability is much less pronounced in tropical regions, resulting in more stable underwater light availability and thus a continuous nutrient uptake by phytoplankton throughout the year (Damar, 2003; Gin *et al.*, 2000).

Distinct differences in the nutritional state of the three bays studied are in accordance with significant differences in chlorophyll-a concentrations. It can therefore be assumed that Jakarta Bay is the most productive bay, followed by Lampung and Semangka bays. The signal/response relationship between nutrient concentrations and phytoplankton biomass in coastal waters has been a focus of interest for many eutrophication scientists (Cloern, 1999).

The comparison of the three different Indonesian bays in the present study suggests a rather linear relationship between annual means of nutrient levels and average chlorophyll-a concentrations, at least for the case of phosphate: The relative ratio of annual phosphate levels between Jakarta, Lampung and Semangka bays is 12.75 : 5.75 : 1, while that of chlorophyll-a is almost similar (16.50 : 5.75 : 1). The relationship between nutrient concentration and phytoplankton biomass has been revealed by many authors. In this paper, the authors try to explore the relationship between DIN and chlorophyll-a in several tropical and temperate coastal waters. It can be traced as a rule of thumb that the higher the annual mean nutrient concentration, the higher the annual mean phytoplankton biomass. However, an exception is the case of San Francisco Bay, which shows a relatively low phytoplankton biomass in spite of high nutrient concentrations. In this bay, the effect of hypernutrification in terms of phytoplankton development is counter-acted by high turbidity causing light limitation (Cloern, 2001). In the present study, this is presumably the case in the high nutrient area of the Semangka river mouth, where Z_{mix}:Z_{eu} ratios of 7 prevailed. In spite of higher nutrient concentrations, mean phytoplankton biomass in Jakarta Bay is lower than that of the tropical Johor Strait waters (21.5 µg l^{-1}). The high chlorophyll-*a* concentration in Johor Strait is suggested to be due to the relatively poor water exchange, which supports phytoplankton biomass accumulation (Gin *et al.*, 2000). By contrast, the low chlorophyll-a levels in the well-flushed Singapore Strait (1.7 µg l^{-1}) are consistent with the lower nutrient availability in this area. A clear signal/response relationship is also the case for the hypertrophic Guanabara Bay in Brazil, which, in keeping with its high nutrient levels, exhibits three times higher mean chlorophyll-a values than Jakarta Bay (Ribeiro & Kjerfve, 2002).

Average chlorophyll-a concentrations in the inner waters of Jakarta Bay are similar to those of eutrophied temperate coastal regions. In the Marsdiep (the Netherlands), annual average chlorophyll-a is around 12 µg l^{-1} (Cadée and Hegeman, 2002) and in the German Wadden Sea, around 15 µg l^{-1} (Tillmann *et al.*, 2000). However, it is of note that the most serious manifestations of eutrophication is due to extreme events such as short term outbreaks of high biomass blooms and that, in contrast to the more stable biomass levels in tropical seas, the seasonal variation of chlorophyll-a concentrations in these temperate waters is high, ranging from below 0.1 $\mu g\ l^{-1}$ in winter to 70 $\mu g\ l^{-1}$ in spring (Tillmann *et al.*, 2000).

On a seasonal basis, slightly elevated (but not significantly different) mean chlorophyll-a levels were observed during the rainy season. This is concomitant with the significant increase of N loads from river discharge. An exceptional situation is the increase in chlorophyll-a in the outer part of Lampung Bay during the dry season. This evidences the strong influence of water entering the bay from the Sunda Strait, which is substantially higher in chlorophyll-a during the dry season. This again is a consequence of the regional monsoonal current pattern, which causes a transport of chlorophyll-a - rich water masses from the Java Sea into the Sunda Strait. By contrast, during the rainy season the Sunda Strait is influenced by water of the Indian Ocean that is poor in chlorophyll-a. A study on seasonal chlorophyll-a concentrations in the Sunda Strait by Hendiarti *et al.* (2002) showed a monsoonal pattern similar to that found in the present investigation, with three times higher concentrations (about 1 $\mu g\ l^{-1}$) during the dry season when compared to that of the rainy season.

In order to study the non-linearity between nutrient inputs, concentrations and phytoplankton response, Boynton *et al.* (1982) and Cloern (2001) collected a large amount of data on nutrients, phytoplankton biomass, and primary production from various estuaries all over the world. They concluded that only few of the commonly measured variables (such as nutrients) acted as significant predictors for phytoplankton biomass and production. In their review, Boynton *et al.* (1982) stated that 73% of the observed estuaries missed a significant correlation between nutrients and phytoplankton biomass, whereas only 18% were significantly correlated. Cloern (2001), after an evaluation of data from estuaries in North America and northern Europe, came to a similar conclusion. Some of the estuaries appear to be particularily sensitive regarding the response of phytoplankton to changes in nutrient inputs (e.g. Chesapeake Bay, Adriatic Sea, Baltic Sea, Black Sea, northern Gulf of Mexico), while others have system attributes that impairs the biological response (e.g. San Francisco Bay, Bay of Brest) (Cloern, 2001). The most important among them are: (1) tidal characteristics, (2) horizontal transport, (3) optical (light) properties, and (4) grazing.

The first and second factors are related to water residence time. Also, tidal differences implicate differences in vertical mixing intensity and thus in Z_{mix}:Z_{eu} ratios as an indicator for average light availability in the water column. Cloern (2001) showed that chlorophyll-a concentrations in micro-tidal estuaries are about 10 times higher than in macro-tidal estuaries. Although Jakarta Bay is a micro-tidal estuary (tidal range is around 0.90 m) with a range much smaller than that of Lampung (1.46 m) and Semangka bays (1.60 m), its residence time is distinctly shorter (5 days compared to 15 days and 100 days, respectively; Damar, 2003). However, in spite of its shorter residence time, Jakarta Bay waters seem able to allow for the accumulation of phytoplankton biomass. Ortner & Dagg (1995) stated that phytoplankton accumulation will be limited, if the water residence time is shorter than the community growth rate. Nutrient addition experiments with phytoplankton from Jakarta Bay (Damar, 2003) showed that the community growth rate ranged from 0.12 to 0.48 per day. Thus, 5 days of residence time seem adequate to support phytoplankton biomass accumulation. The role of residence time for the phytoplankton response to nutrient inputs is also obvious in Lampung Bay. There, although estuarine nutrient loads are relatively low, a longer residence time obviously favours phytoplankton biomass accumulation. By contrast, in Semangka Bay, very low nutrient loads and unfavourable light conditions (high Z_{mix}:Z_{eu} ratios) do not support the formation of a substantial phytoplankton biomass in spite of a high residence time. These observations show that the accumulation of phytoplankton biomass is not only governed by the resources of energy and matter (e.g. nutrient and light supply), but also regulated by the temporal scale of hydrodynamic versus biological processes (Ortner & Dagg, 1995; Cloern, 1996; Cloern, 2001).

The third factor is a set of optical properties, controlling light exposure of phytoplankton, expressed in this study as the ratio between mixing depth and euphotic depth (Z_{mix}:Z_{eu} ratio). This ratio is often used to test the possibility of bloom initiation and net primary production (e.g. Kocum *et al.*, 2002, Tillmann *et al.*, 2000). It is often linked to vertical mixing intensity, however, in estuaries, the suspension load of the river water may be the predominant factor.

The low Z_{mix}:Z_{eu} ratios in Jakarta and Lampung bays, however, are mostly due to their shallower water depth. This factor seems to play an important role in supporting high phytoplankton production according to volume, but may be of less relevance with respect to total water column production. In Jakarta Bay, a shallow water depth subjected to high nutrient inputs and the associated low Z_{mix}:Z_{eu} ratios combine to produce a high phytoplankton biomass concentration. In Lampung Bay, although nutrient input is much lower, a low Z_{mix}:Z_{eu} ratio allows for sustaining a moderate phytoplankton biomass in the shallow water column.

The last attribute of susceptibility to nutrient inputs is grazing. Zooplankton and benthic filter feeders may effectively control phytoplankton biomass formation (Jassby *et al.*, 2002). Despite the drawback in this study that quantification of grazing rates could not be performed, the impact of zooplankton grazing is assumed to be comparable in these three bays, because the prevalence of marine copepods (*Pseudocalanus* spp. and *Acartia* spp.) was relatively similar in the different areas (Damar, 2003). However, with respect to benthic filter feeders, the presence of green mussels (*Perna viridis*) in Jakarta Bay, which are widely cultured by local fishermen, may play an important role in controlling phytoplankton biomass. The biomass of phytoplankton decreased rapidly in the outer part of the bay just adjacent to the mussel culture areas, which might be caused by the increased benthic grazing intensity. Suryono *et al.* (1999) conducted a laboratory scale experiment on phytoplankton grazed by *P. viridis*, and concluded that on a daily basis, about 60% of the phytoplankton biomass is effectively removed by this mollusc. A mass culture of *P. viridis* seems thus to be an effective way to control the biomass of phytoplankton as a top-down management measure to mitigate negative effects of nutrient enrichment in Jakarta Bay, thereby invoking more commercial positive effects as well.

The present study is among the few dealing with eutrophication aspects in the tropical ecosystem of Indonesia and constitutes the first comprehensive investigation of this topic in the area. The results confirm the assumption that Jakarta Bay, which is subjected to one of the highest anthropogenic pressures in the Asian region, has the most pronounced eutrophication symptoms among the three bays studied. However, it also revealed that apart from the magnitude of anthropogenic pressure in terms of nutrient input, the natural physical characteristics of the receiving waters are decisive factors modulating the response of phytoplankton to nutrient enrichment. Because the seasonal amplitude of temperature and solar radiation is small in tropical regions, temporal dynamics of these physical factors are of minor importance for future critical load determinations.

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