ORIGINAL ARTICLE

Spatio-temporal variation of dissolved inorganic nutrients related to hydrodynamics and land use in the mangrove-fringed Segara Anakan Lagoon, Java, Indonesia

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Abstract Segara Anakan is a mangrove-fringed lagoon in Java, Indonesia, which is affected by human activities in the lagoon and its hinterland. Nutrient and sediment input from the Citanduy River which drains an agriculture-dominated hinterland is thought to be an important factor for ecosystem degradation. From dry and rainy season investigations of dissolved inorganic nutrients between May 2004 and August 2006 we infer that the nutrient inventory of Segara Anakan is controlled by a complex mixture of anthropogenic and natural sources and processes. Maximum inputs into the western lagoon were supplied by the Citanduy during the rainy season while tidal exchange with the Indian Ocean dominated in the eastern lagoon with little freshwater input. During the dry season recycling in mangroves appeared to be an additional source of nutrients to the lagoon. Despite an extremely high population density and intensive agriculture in the hinterland nutrient pollution and eutrophication in the lagoon were low to moderate on a global scale. It is probably due to the short residence time of water in the shallow lagoon which indicates that major part of the land-derived nutrient input is rapidly exported to the sea. Although Segara Anakan is a highly perturbed system for decades, it appears that still natural processes exert major control on the nutrient inventory of the lagoon.

Keywords Nutrients · Eutrophication · River · Mangrove · Land use change · Indonesia · Hydrodynamics · Lagoon

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Introduction

Coastal regions offer living space to humans and habitats for plants and animals and have a high ecological and economic resource potential. Nowadays, human-induced environmental changes often go far beyond natural variations and therefore may lead to irreversible degradation of ecosystems which, in turn, affects their economic resource potential. This is of particular importance in tropical Asia which is among the regions with the highest freshwater, nutrient and sediment inputs into the ocean and maximum human modifications of the coastline (Elvidge et al. 1997). Annually, about one quarter of the water and half of the sediment that is introduced into the ocean by rivers comes from Asia (e.g. Degens et al. 1991; Syvitski et al. 2005). More than half of the world population, i.e. 3.6 billion people live in Asia and to a large extent economically depend on the natural resources of the coastal region. Moreover, agriculture which consumes 81% of Asia's annual water withdrawal (World Resources Institute 2005) is an economic backbone of many countries in tropical Asia.

Overexploitation and degradation of coastal resources and changes in land use and land cover in the hinterland have altered and will continue to alter coastal ecosystems of the tropics. The Indonesian island of Java is a prime example in this respect. More than half of the Indonesian population of 240 million people live on Java resulting in a population density >1,000 inhabitants km^{-2} (Badan Pusat Statistik 2006). It is one of the most densely populated regions in the world. Because of this and its location in a geologically very active zone particularly its coastal ecosystems are extremely vulnerable to any kind of environmental change (e.g. Lavigne and Gunnell 2006).

The Segara Anakan Lagoon in south central Java is an area rich in natural resources and it is fringed by a

mangrove forest which is the last remaining on Java. The lagoon is nourished by the inputs from one of the major Javanese rivers, the Citanduy, and the tidal exchange with the Indian Ocean. It is facing a number of environmental problems for decades, because of resource exploitation. Most important are overfishing, logging of mangrove wood, high sediment input by the Citanduy River because of poor upland agricultural practices, agricultural runoff and potential pesticide and oil pollution (White et al. 1989). In the past decades attempts have been made to overcome these problems by conducting management programmes (Olive 1997; Asian Development Bank 2006). One of the measures taken to compensate for the shrinking yield of fisheries was to intensify rice farming on the newly grown land resulting from the high riverine sediment input. The area used for rice cultivation increased by 62% between 1987 and 2006 to a total of 19,274 ha which makes up 21% of the Segara Anakan region (Ardli and Wolff, this volume). The implementation of this management measure, however, may be critical for lagoon waters with respect to possible eutrophication and deterioration of the water quality. But information on the biogeochemistry and water quality and on cause–effect relationships is scarce.

In this paper we report the results of biogeochemical investigations in the Segara Anakan Lagoon and Citanduy River from rainy and dry season expeditions between 2004 and 2006. The spatio-temporal variation of dissolved inorganic nutrients in the lagoon is presented. The roles of the river inputs, the tidal exchange with the ocean and the recycling in mangroves for the nutrient inventory of the lagoon are examined. Finally, we try to assess the status of the lagoon in terms of nutrient pollution and eutrophication by comparing it to other coastal systems on a global scale.

Materials and methods

Study area

The mangrove-fringed Segara Anakan lagoon is located in south central Java (108°46′E–109°03′E, 7°35′S–7°48′S; Fig. 1) and separated from the Indian Ocean by the rocky mountainous island of Nusakambangan. Its climate is dominated by the monsoons. The wet NW monsoon brings heavy precipitation during austral summer (November–March) while the SE monsoon brings drier and cooler air masses during austral winter with the driest months being July–September. Superimposed on these seasonal variations are interannual variations caused by the El Niño/Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). During the time of this investigation (2004–2006) precipitation varied largely in Cilacap, a city of approximately 250,000 inhabitants which is bordering the lagoon in the east. Compared to the 38-year average of 3,340 mm year^{-1} (Weatherbase 2008), precipitation was almost normal in 2005 with 3,200 mm year^{-1}, but was significantly lower during 2004 (1,360 mm year^{-1}) and 2006 (1,210 mm year^{-1}; Fig. 2). Positive sea surface temperature anomalies in the Pacific Ocean during the second half of these years indicate El Niño conditions (National Oceanic and Atmospheric Administration 2008) which usually result in low precipitation over Indonesia.

The hydrology of the lagoon is governed by the tides and freshwater input by perennial and intermittent rivers. Major freshwater and sediment input to the lagoon occurs through the Citanduy River and to a lesser extent by the Cibereum and Cikolang rivers in the western part. The eastern part receives considerable freshwater input only during the wet season. Tidal exchange with the Indian

Fig. 1 Map of the Segara Anakan Lagoon with major types of land use/cover and sample stations (*circles*). *Boxes* denote the western, central and eastern parts of the lagoon. C24, C26 and E16 are mangrove stations where sediment cores were retrieved. Basic maps were provided by Erwin Riyanto Ardli
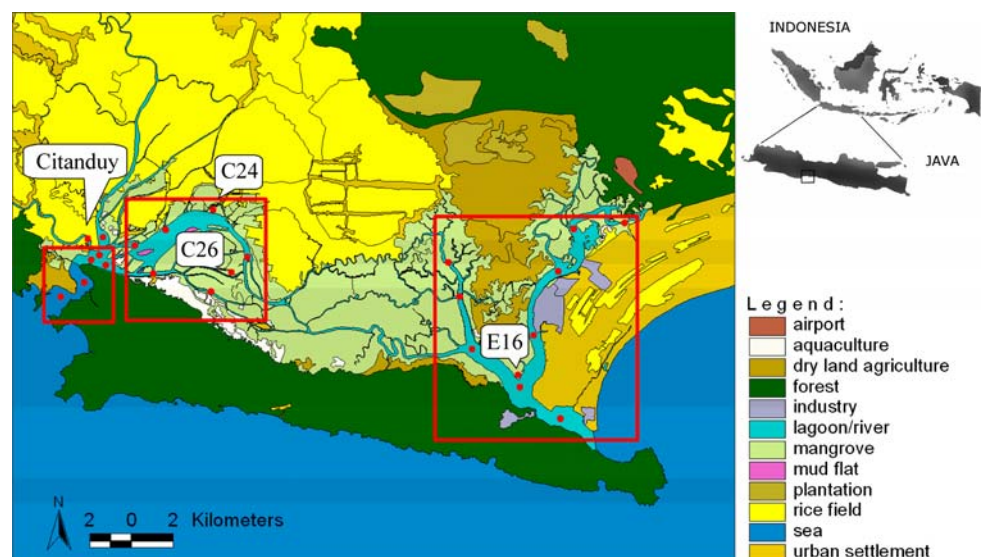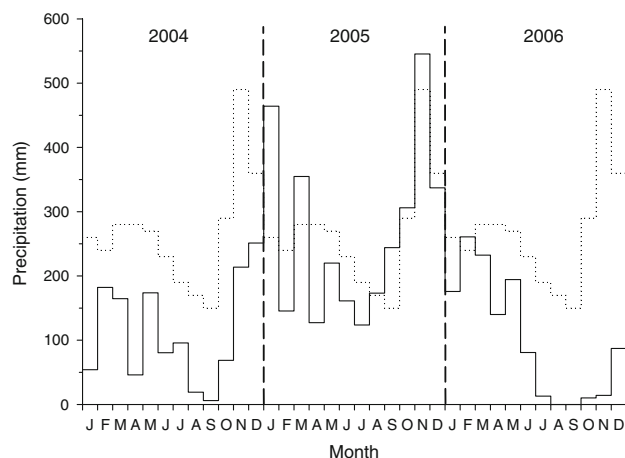
Fig. 2 Precipitation in Cilacap during the investigated period 2004–2006 (*solid line*). The *dashed line* denotes the 38-year average precipitation

Ocean occurs through two channels in the western and eastern parts of the lagoon. The mixed and predominantly semidiurnal tide ranges between 0.4 m during neap tide and 1.9 m during spring tide (White et al. 1989; Holtermann et al., this volume). The Citanduy is the fifth largest river of Java in terms of discharge which is estimated to an annual average of 227 $m^3 s^{-1}$ (dry season 171 $m^3 s^{-1}$, rainy season 283 $m^3 s^{-1}$) resulting in an annual total of 7.2 km^3 (Whitten et al. 1996). The discharge of the Cibereum makes up about one-fifth while that of the other rivers emptying into the lagoon is lower by at least one order of magnitude (Holtermann et al., this volume). Major land use in the area is agriculture, mainly cultivation of irrigated rice which increased by 18% since 1982. Upland crops increased by 25% while the area of forest and plantations decreased by 18% in the same time span. Major part of the hinterland of the western and central parts of the lagoon is used for the cultivation of rice under irrigation. The hinterland of the eastern lagoon is dominated by forest and to a lesser extent by dry land agriculture (Yuwono et al. 2007).

For the purpose of this study, the lagoon has been subdivided into three major geographical areas according to differences in hydrology and land cover and land use. Area W (West, 6 stations) represents the western part of the lagoon with the Plawangan channel connecting the lagoon to the sea and the Cibereum and Cikolang river mouths. It is characterized by high freshwater input coming from a mostly agricultural hinterland and intensive tidal exchange with the Indian Ocean. The Citanduy River in the west as being the major freshwater source makes up an additional station. Area C (Central, 5 stations) comprises the (western) central part of the lagoon which is bordered by mangroves. Tidal exchange and freshwater input occur mainly through area W. Area E (East, 9 stations) covers the

eastern part of the lagoon. Its freshwater input is low and hydrodynamics are governed by tidal exchange with the Indian Ocean. To the east area E is bordered by the city of Cilacap and its port facilities while land cover in the rest of the area is mangroves and dry land agriculture.

Sampling

Sampling campaigns in the lagoon were performed in May (transition) and November (wet) 2004, July (dry) 2005 and January (wet) and August (dry) 2006. Physico-chemical characteristics of the water column were measured in situ. Surface water was collected by a bucket and stored cool and dark in PE containers until return to the laboratory. Samples for nutrient analysis were filtered through single use membrane filters into prewashed PE bottles, preserved with mercury chloride solution (35 g l^{-1}) and stored dark and cool until analysis.

Sediment cores of maximum 50 cm core length were obtained from three mangrove stands in the lagoon (stations C24 and C26 in area C, station E16 in area E) with a handheld corer in January and August 2006. Four cores each were taken along a 90 m transect (30 m distance between cores) perpendicular to the waterline at low tide. Physico-chemical measurements were performed immediately after core recovery. The cores were stored cool and dark until return to the laboratory where they were subsampled for pore water and sediments. Pore water samples were obtained by carefully injecting permeable tubes (*Eijkelkamp* rhizon moisture sampling sets, 0.1 μM pore size) into the sediment through predrilled holes in the plexiglass sediment tubes (2 cm intervals where possible, sometimes 4 cm intervals). Pore water was then extracted into clean vacuum glass vials, preserved with mercury chloride solution (35 g l^{-1}) and stored dark and cool until analysis.

Analysis

Temperature, pH, salinity and dissolved oxygen (DO) concentration of water were determined with a WTW MultiLine F/Set-3 multiparameter instrument. Salinity is reported in dimensionless practical salinity units (psu). Because of technical problems with the probes pH and DO data are not available for August 2006. Redox potential, pH and salinity of pore water were determined with Hach probes in 5 cm intervals in August 2006. DO was determined with an luminescent dissolved oxygen (LDO) probe. The small pore water volume due to large grain size (sandy sediments) and high volume of roots did not allow salinity measurement in sediments at station 16 (area E; Pohlenga 2007). Water and pore water samples were analyzed for dissolved nutrients (nitrite, nitrate, ammonium, phosphate, silicate) using a continuous flow autoanalyzer and detected

spectrophotometrically as a colored complex (Grasshoff et al. 1999).

Data presentation

To be able to display the spatial and temporal variability of data collected in a manageable way results are presented as averages over areas with respective standard deviations. The latter can be high in some instances due to spatial variation within the respective area on the one hand and/or due to tidal variation on the other hand. Because of the large area of the lagoon it was not possible to sample all stations during the same tidal phase. Statistical evaluation of the sediment core data displayed no significant differences between cores of a single transect (Pohlenga 2007). Therefore, the cores were treated as replicates and average values and standard deviations are shown for the three mangrove stations.

Results

Physico-chemical parameters

Salinity displayed large spatio-temporal variations (Fig. 3). It was almost 0 at all times in the Citanduy River, except for August 2006. During that time salinity was 17.2 most probably due to extremely low river discharge resulting from zero precipitation (Fig. 2). Salinity displayed a spatial gradient with values increasing towards the east corresponding to the variation in freshwater input. It was generally higher during the dry than during the wet season. pH varied between 7.4 ± 0.2 and 8.1 without displaying any distinct pattern. DO varied between a minimum of 3.9 mg l^{-1} or 46% saturation in the Citanduy River and a
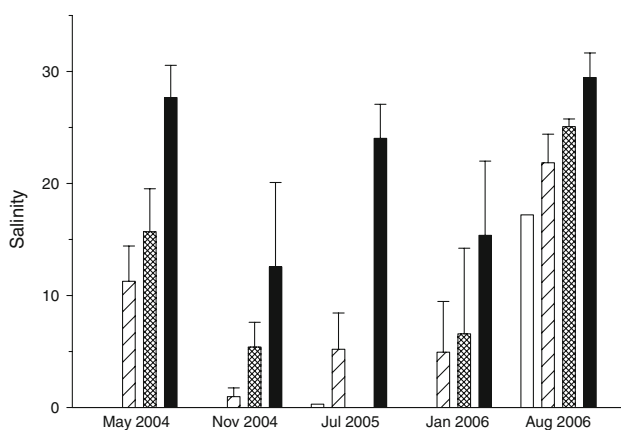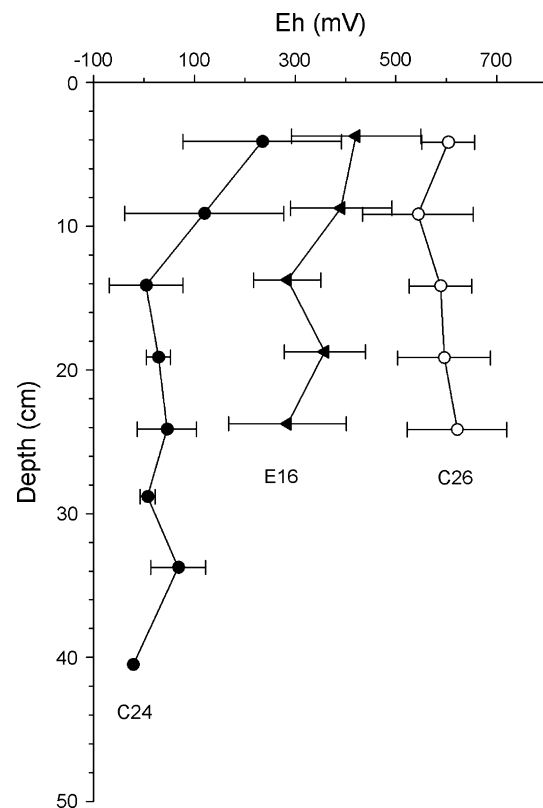

Fig. 4 Downcore variation of the redox potential (Eh) in mangrove sediments of the central (C24 = *filled circles*, C26 = *triangles*) and eastern Segara Anakan Lagoon (E16 = *open circles*) in August 2006. *Error bars* denote standard deviation from the average over four cores at each site

maximum of 6.8 ± 0.6 mg l^{-1} or $90 \pm 10\%$ saturation in area E also not displaying any distinct pattern.

Salinity in pore water varied around 7 at station C26 while it varied around 17 at station C24 and displayed little downcore variation in both cases. pH also displayed little downcore variation and varied around 5.7 at stations E16 and C26 and around 6.5 at station C24. DO and the redox potential displayed distinct differences between the stations. Minimum values and little downcore variation were observed at station C24 while stations E16 and C26 displayed a downcore decrease (Fig. 4).

Dissolved inorganic nutrients

Dissolved inorganic nitrogen (DIN = nitrite + nitrate + ammonium) major part of which occurred in the form of nitrate displayed large spatio-temporal variations (Fig. 5). Maximum concentrations were found in the Citanduy River and decreased towards the east. While seasonal variability was low between May 2004 and January 2006 DIN concentrations were much lower in the entire lagoon during the extremely dry August 2006. Phosphate was always <1.5 μM except for the Citanduy in May 2004.

Fig. 3 Spatio-temporal variation of salinity in the Segara Anakan Lagoon. *Vertical bars* denote from left to right average salinity ± 1 SD in the Citanduy River (*white*), western (*hatched*), central (*cross-hatched*) and eastern lagoon (*black*)
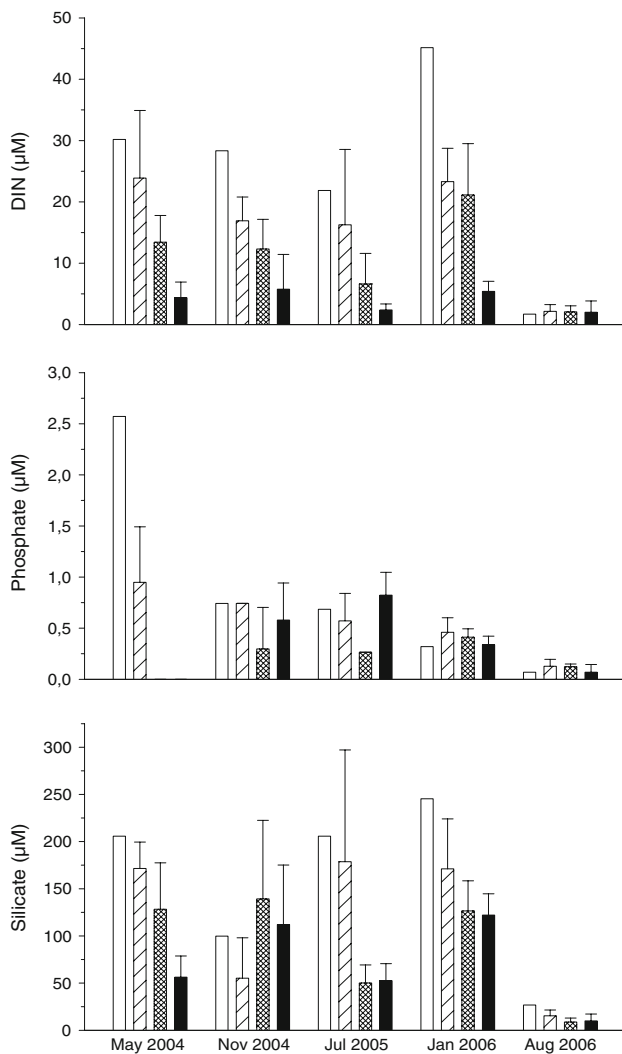
Fig. 5 Spatio-temporal variation of DIN (*upper panel*), phosphate (*middle panel*) and silicate (*lower panel*) in the Segara Anakan Lagoon. *Vertical bars* denote from left to right average ±1 SD in the Citanduy River (*white*), western (*hatched*), central (*cross-hatched*) and eastern lagoon (*black*)

Minimum concentrations throughout the entire lagoon were measured in August 2006. Silicate also displayed a W–E gradient with higher concentrations in the Citanduy and in area W than in the other areas except for November 2004 when silicate concentrations were slightly higher in the central and eastern parts of the lagoon.

Pore water nutrients displayed distinct spatio-temporal variations. Nitrite was almost 0 at all times. Silicate concentrations were highly variable within cores and displayed a downcore decrease only at stations E16 and C26 in August 2006 (Fig. 6). During the wet season in January 2006 nitrate concentrations with a few exceptions were <10 µM and showed little variation downcore (Fig. 7). At the surface ammonium varied between 40 and 60 µM at stations E16 and C26 and between 40 and 100 µM at

station C24. It decreased with depth at all stations. Phosphate displayed no distinct trends with depth (Fig. 8). It varied around 1 µM at station E16, around 0.5 µM at station C26 and between approximately 1–5 µM at station C24.

During the dry season in August 2006 nitrate was high at the surface and then decreased downcore at stations E16 and C26 (Fig. 7). At station C24 nitrate concentrations were <11 µM in the upper half of the core and then increased slightly with depth. Ammonium profiles were almost similar to those of January except for station C24 where it varied around 20 µM in the upper cm and then slightly increased with depth. Phosphate varied around 0.5 µM at station C26, displayed a distinct downcore decrease at station E16 and an inconsistent pattern at station C24 (Fig. 8).

Discussion

The observed spatio-temporal variations in the distribution of dissolved nutrients in the lagoon are probably the result of a seasonally varying interaction of natural (hydrology, geomorphology, soils, vegetation) and anthropogenic (land use, urbanisation) factors which will be discussed in the following. Potential nutrient sources of the lagoon are the rivers, mainly the Citanduy, the Indian Ocean, the mangroves and the city of Cilacap. Additionally, diffuse surface runoff and groundwater discharge may add to the nutrient inventory of the lagoon.

Spatio-temporal variation of dissolved nutrients related to hydrology and catchment processes

Maximum silicate concentrations were observed in the Citanduy River. In most cases it varied around 200 µM which is in the range of rivers from the wet tropics and high on a global scale. Silicate weathering rates in wet tropical Asia are among the highest observed worldwide (Gaillardet et al. 1999; Jennerjahn et al. 2006). The most important factors for the high weathering rates, hence the high silicate load of rivers in tropical Asia are the relatively young geology, active tectonism, steep gradients and high precipitation, high runoff and high temperature (Jennerjahn et al. 2006). All of these should be particularly high on the island of Java because of its location on an active continental margin with intense tectonism and in the center of the wet tropics. Silicate stems almost exclusively from natural sources, no direct inputs can be expected from anthropogenic activities. Therefore changes in riverine silicate basically result from hydrological alterations and/or changes in land use/cover in the catchment like, for example, river damming and deforestation (Jennerjahn
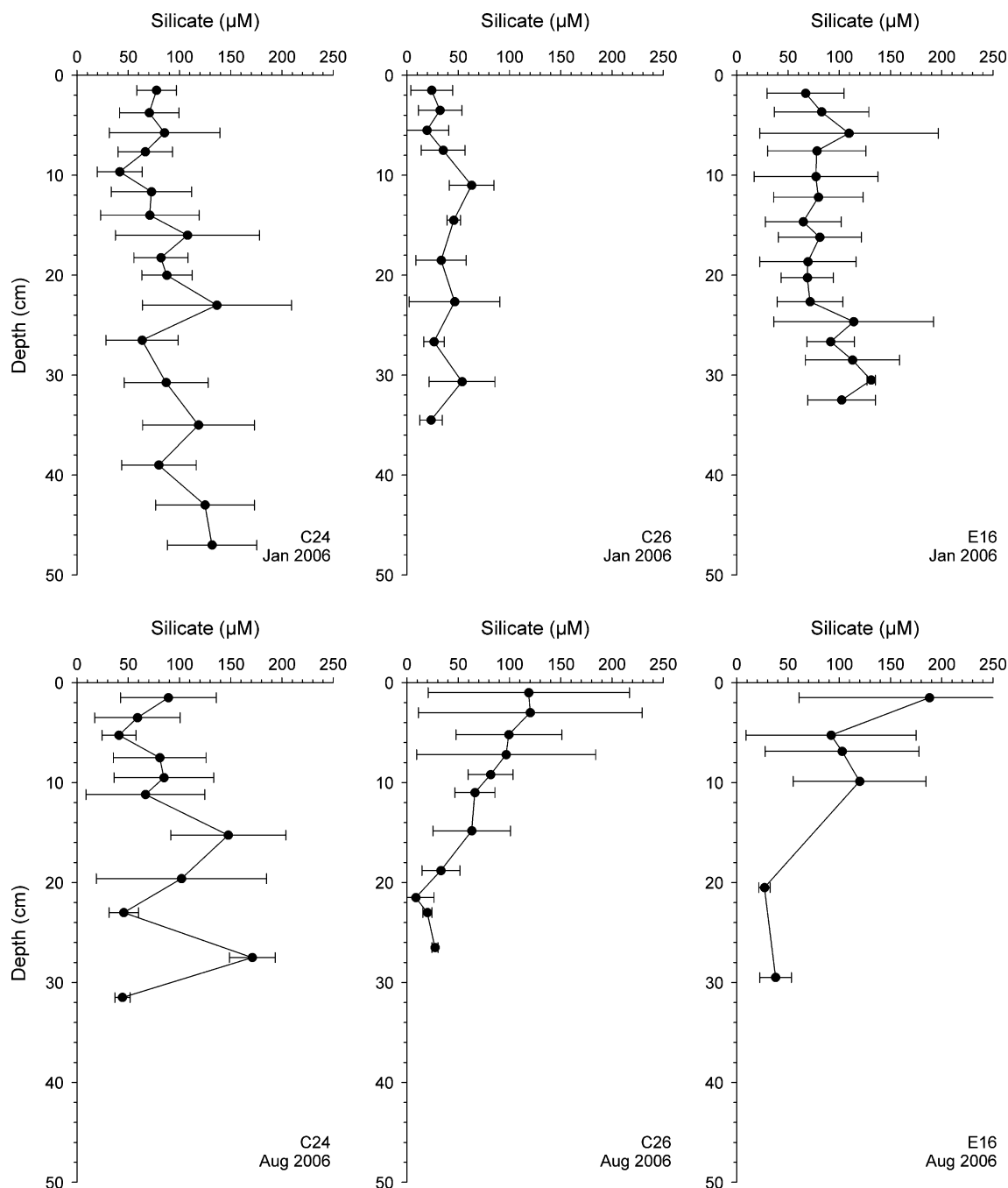
Fig. 6 Downcore variation of pore water silicate in mangrove sediments of the central (C24, C26) and eastern Segara Anakan Lagoon (E16) in January 2006 (*upper panel*) and August 2006 (*lower panel*). *Error bars* denote standard deviation from the average over four cores at each site

et al. 2006). Unsustainable land use practices in the Citanduy River catchment going on for decades, i.e. deforestation and conversion to agricultural land, are held responsible for high sediment loads of the river which are contributing to the rapid shrinking of the lagoon area (Yuwono et al. 2007). As such, this anthropogenically enhanced erosion could also contribute to the high silicate concentrations in the Citanduy River through increased

supply of mineral surface area and hence increased chemical weathering.

Phosphate did not display large spatio-temporal variations except for a high concentration in the Citanduy River in May 2004. In contrast, despite fairly high variability within areas, DIN and silicate generally displayed a spatial gradient with highest concentrations in the Citanduy River and a decrease towards the east. This is most probably due
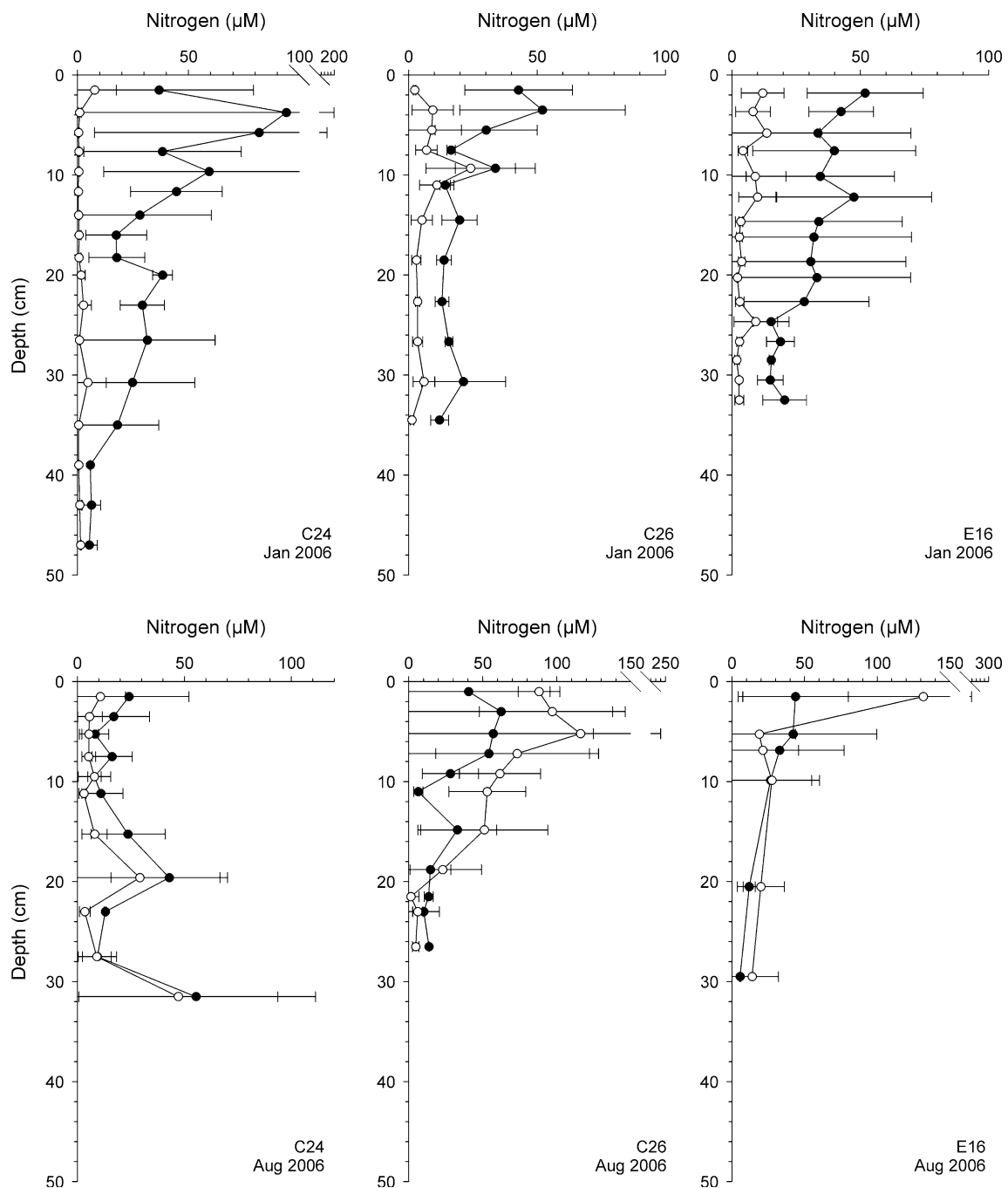
Fig. 7 Downcore variation of pore water nitrate (*open circles*) and ammonium (*filled circles*) in mangrove sediments of the central (C24, C26) and eastern Segara Anakan Lagoon (E16) in January 2006 (*upper panel*) and August 2006 (*lower panel*). *Error bars* denote standard deviation from the average over four cores at each site

to a similar gradient of freshwater inflow from the hinterland of the lagoon. Perennial rivers supply the western part of the lagoon with silicate-laden freshwater throughout the year. The eastern part of the lagoon receives a significant input of freshwater only through surface runoff during the rainy season. Nevertheless, the observed silicate concentrations in area E were much higher than those observed in the adjacent Indian Ocean (Hebbeln et al. 2006). Extremely

low concentrations of all nutrients coinciding with maximum salinities were observed throughout the entire lagoon in August 2006. Because of El Niño conditions the dry season was extremely dry during that year and precipitation was zero in August. As a consequence the supply of land-derived nutrients was also very low. The N/P ratio was almost in the range of the Redfield ratio of 16 (Redfield et al. 1963) or below it in the eastern part of the lagoon.
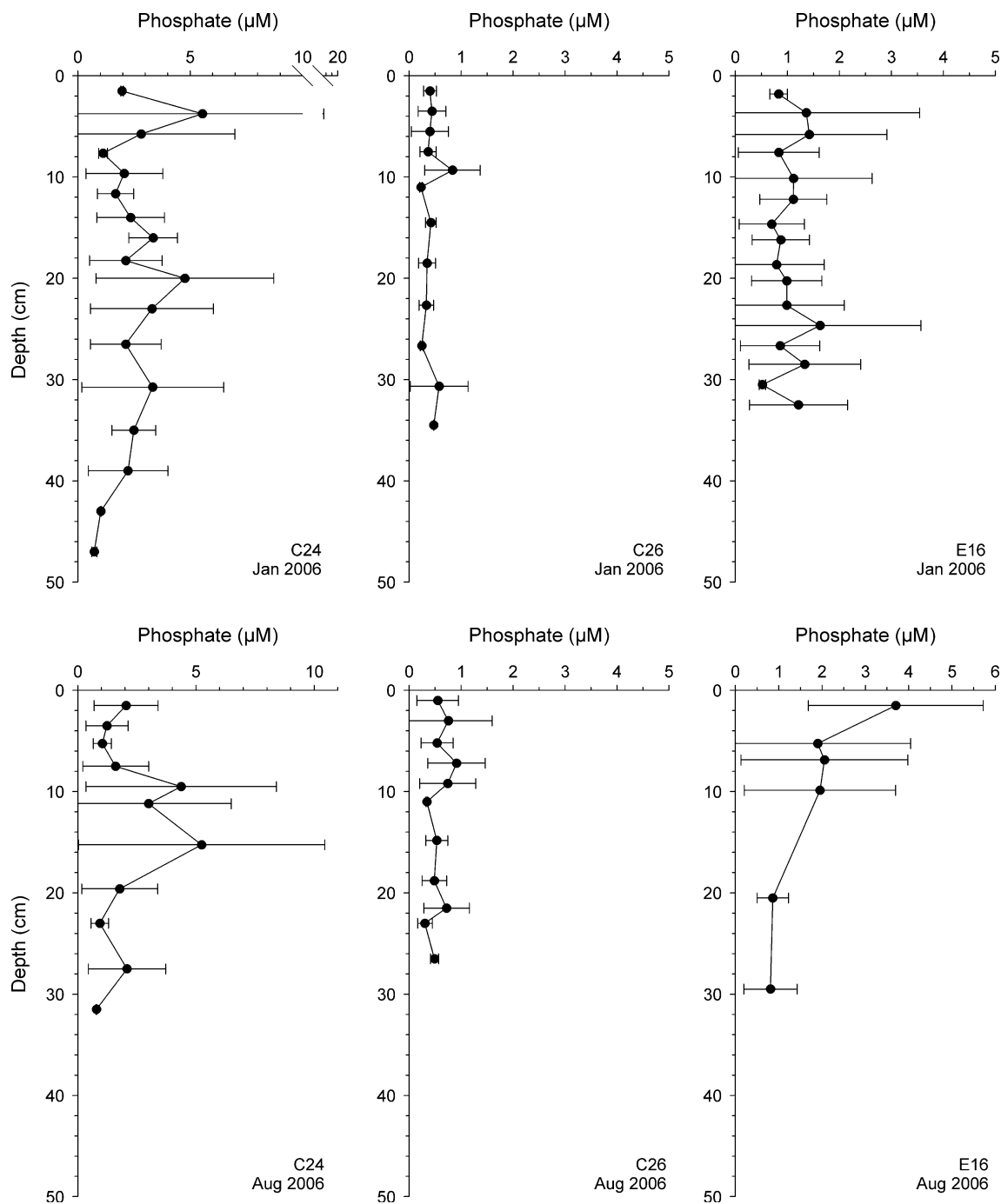
Fig. 8 Downcore variation of pore water phosphate in mangrove sediments of the central (C24, C26) and eastern Segara Anakan Lagoon (E16) in January 2006 (*upper panel*) and August 2006 (*lower panel*). *Error bars* denote standard deviation from the average over four cores at each site

It was mostly higher in the other regions indicating P limitation of primary production in the western and central parts of the lagoon mainly due to the high nitrate inputs of the Citanduy River.

Spatial variations in amount and composition of the nutrients are probably related to regional differences in land use/cover. The low Chl *a* in area E of 6.1 µg l^{-1} in

May 2004 and of 9.3 µg l^{-1} in November 2004 indicates low primary productivity and hence low nutrient uptake (Yuwono et al. 2007; Erwin Riyanto Ardli personal communication). The fairly low concentrations of DIN and phosphate observed over the years therefore suggest a moderate to low input of nutrients from the environs. The prevailing forest in combination with the lack of perennial

rivers draining the hinterland appears to be responsible for this as well as the dilution with low-nutrient seawater through tidal exchange with the Indian Ocean.

Conditions are different in the western (area W) and central (area C) parts of the lagoon. There, a number of rivers drain a large hinterland mainly used for cultivation of rice. The fairly high DIN concentrations in the Citanduy most probably resulted from agricultural effluents. It is conceivable that excess nitrogen derived from fertilizer application was washed into the river from the bordering paddy fields. Interestingly, phosphate was always <1 µM and the DIN/P ratio >24 in the Citanduy except for May 2004. This is probably related to the land use management (i.e. fertilizer-use efficiency) and the specific characteristics of the soil and bedrock of the lagoon's hinterland. The soils of central Java are mostly acidic Andosols, the parent material of which is basically andesitic volcanic ash (Supriyo et al. 1992; Van Ranst et al. 2002). They have a high P-retention capacity which may affect the efficiency of fertilizer uptake in a way that added P is rapidly adsorbed to mineral surfaces and hence not available for plant uptake (Olk et al. 1999; Dobermann et al. 2002). The effect of nutrient stress among other factors on yields of rainfed lowland rice was investigated in field experiments with application of N, P and K fertilizers in Jakenan, central Java. There, yield reduction due to N omission was 42%, to K omission 33–36% and to P omission 3–4%. An application of 120–22–90 kg ha^{-1} of N–P–K fertilizer significantly increased the rice yield, whereas there was no further increase in yield under application of higher rates of fertilizer (Boling et al. 2004). Nitrogen appears to be the most important control of rice yield and the amount of N applied will be by far the largest among all added nutrients. Fertilizer application without an efficient nutrient management in the hinterland of Segara Anakan therefore bears the potential of polluting the lagoon with excess nutrients, particularly nitrogen. The specific soil conditions, in contrast, foster the retention of P through adsorption on mineral surfaces. It is conceivable that elevated concentrations of DIN in the Citanduy and the western lagoon (area W), occasionally in the central lagoon (area C), are the result of fertilization in the rice-dominated agricultural hinterland. Phosphorus retention in the acidic volcanic soils prevailing around the entire lagoon is probably the major factor for the generally low phosphate concentrations and resulting high DIN/P ratios in the lagoon.

Mangroves as a source of nutrients

Silicate concentrations in pore water of the investigated mangrove sites were lower than in lagoon water in January 2006, but much higher than in the lagoon in August 2006 (Fig. 6). While no downcore trends were observed in January 2006, silicate concentrations displayed strong gradients with elevated surface concentrations in August 2006 at stations E16 and C26. Long exposure of these sediments and hence high evaporation during that extremely dry month may have been an important factor for the enrichment of silicate in pore water of the uppermost sediment layers. In general, silicate concentrations were at the lower end of the range of silicate concentrations observed in pore water of an Australian mangrove (Coral Creek, Hinchinbrook Island; Alongi 1996). Unusually high pore water silicate concentrations of 200–500 µM measured in a mangrove in the Fly Delta, Papua New Guinea, were ascribed to originate to a large extent from the decomposition of belowground biomass (Alongi et al. 1993). The very low particulate biogenic opal (<1%, unpublished data) available for dissolution in Segara Anakan mangrove sediments may to some extent explain the fairly low pore water silicate when compared to other mangroves (Alongi et al. 1993; Alongi 1996). Despite the lack of flux measurements it is conceivable that silicate was released from mangrove sediments to lagoon water during the dry season of 2006.

Concentrations of nitrate and ammonium were much higher in mangrove pore water than in lagoon water during that time. In contrast to the lagoon where nitrate prevailed, ammonium was in the same range or even higher than nitrate in pore water. Differences in concentrations between sites as well as temporal variations are probably related to seasonal and site-specific variations in inundation frequency and related redox conditions in the sediments. Nitrate and ammonium concentrations were in the same range as observed in pore water from an African (Gazi Bay, Kenya; Middelburg et al. 1996), an Asian (Phuket, Thailand; Kristensen et al. 1988) and an Australian mangrove (Coral Creek, Hinchinbrook Island; Alongi 1996). DIN flux into the sediments was directly measured or postulated for all these locations.

Microbial reworking of OM is the likely source of ammonium in Segara Anakan sediments. Nitrification may then have led to the formation of nitrate, the amount of which depended mainly on the availability of oxygen. Nitrate was generally lower during the rainy season in January 2006 than in August 2006 and generally lower at station C24 than at stations E16 and C26, most likely because of less exposure of the sediments to oxygen and hence less nitrification. More intensive evaporation in August 2006 may have additionally contributed to the high concentrations of nitrate. Uptake by roots may also be an important control of DIN in mangrove sediments. Alongi (1996) found uptake of nitrate and, more important, of ammonium by prop roots of *Rhizophora* spp. Maximum uptake was measured in the lower section of the roots which were heavily colonized by micro- and macroalgae

while the middle and upper sections were only sporadically colonized. It suggests that algae rather than the roots themselves were responsible for the observed nutrient uptake. In Segara Anakan little algal cover of mangrove roots was observed (Nordhaus personal communication). Therefore nutrient uptake by plants is probably less important than in other mangroves. This and the much higher DIN concentration in pore water than in the lagoon suggest that mangrove sediments may have been a source of DIN to the lagoon during the dry season in August 2006. During the wet season in January 2006 DIN input into the western and central lagoon resulted mainly from the Citanduy and it is unlikely that mangrove sediments contributed significantly to the DIN pool. However, in the eastern lagoon nitrate concentrations of $<5\ \mu M$ in lagoon water suggest that mangrove sediments contributed to the DIN pool during that time.

Phosphate concentrations did not display distinct downcore trends in January 2006, but were much higher than in lagoon waters at stations C24 and C26. Similar patterns were observed in August 2006 (Fig. 8). Maximum concentrations were observed at station C24 with the lowest redox potential and minimum concentrations at station C26 with the highest redox potential. Pore water concentrations of phosphate in Segara Anakan were in the same range or slightly higher than in other mangroves (Alongi et al. 1993; Alongi 1996; Alongi et al. 2000; Middelburg et al. 1996). Phosphate fluxes between $3\ \mu M\ m^{-2}\ h^{-1}$ out of the sediment to $7\ \mu M\ m^{-2}\ h^{-1}$ into the sediment were measured in mangrove forests of the Fly River delta in Papua New Guinea. Phosphate concentrations in pore water were $<0.2\ \mu M$ (Alongi et al. 1993). In the Gazi Bay mangrove phosphate concentrations were always $<1\ \mu M$ in pore water as well as in the overlying tidal water (Middelburg et al. 1996).

Although mechanisms are debated, phosphate release from anoxic sediments has been observed (Golterman 2001). In sediments from shallow, eutrophic Lake Arreskov (Denmark), for example, phosphorus and iron release were higher under anoxic than under oxic conditions and iron-bound phosphorus was the most important fraction for phosphorus loss from sediments (Andersen and Ring 1999). Iron hydroxides were also responsible for phosphate release under anoxic conditions from sediments of the brackish Méjèan Lagoon (France; Gomez et al. 1999). It is therefore conceivable that this process is responsible for the fairly high phosphate concentrations in pore water at station C24 of the Segara Anakan Lagoon. At stations E16 and C26 with its higher redox potential and dissolved oxygen part of the phosphate released during OM degradation was probably immobilized through the formation of iron hydroxides and/or adsorption onto mineral surfaces. Uptake by roots and microbes may be another important

factor (Alongi 1996; Middelburg et al. 1996). A phosphate flux out of the sediment is likely, particularly during the dry season (August 2006) when freshwater input is low and low-nutrient seawater dominates the lagoon (average salinity 21.9–29.5, Fig. 3). The degree of P recycling in mangrove sediments may vary with redox conditions with P release being higher from frequently inundated sub- to anoxic sediments in the northern central part of the lagoon (station C24). This is also important for the bioavailability of recycled nutrients. The average N/P ratio at station C24 (January 2006: 15, August 2006: 25) was near to the Redfield ratio of 16, the ratio in which phytoplankton take up N and P (Redfield et al. 1963). It was much higher at stations E16 (January 2006: 38, August 2006: 33) and C26 (January 2006: 76, August 2006: 141) indicating P limitation of phytoplankton uptake there.

Status of the lagoon in terms of nutrient pollution

The Segara Anakan Lagoon is affected by human uses for many years. Dramatic changes of the land use and land cover in the wider Segara Anakan region occurred in the past decades (White et al. 1989; Olive 1997; Ardli and Wolff, this volume). The lagoon and mangrove area has been shrinking and the area of cultivated land (mainly irrigated rice) has been increasing (Olive 1997; Ardli and Wolff, this volume). Consequently, eutrophication or nutrient pollution has been considered a serious problem for the lagoon by many. However, the scarcity of data constrained the creation of a respective assessment. Another general constraint in this respect is the frequent use of the terms 'eutrophication' and 'nutrient pollution' without referring to commonly used criteria and threshold values. This, in turn, is complicated by the fact that eutrophication is a complex environmental problem that requires developing conceptual models with specific cause–effect relationships which most likely will go beyond simple application of threshold values. Additionally, reviews of the pertinent literature have shown that there are differences between marine and freshwater ecosystems (e.g. Nixon 1995; Jørgensen and Richardson 1996; Smith et al. 1999; Cloern 2001).

For the purpose of assessing the status of the Segara Anakan Lagoon and the Citanduy River in terms of nutrient pollution we chose the approach of Smith et al. (1999), who have collected specific criteria for the various aquatic ecosystems from the literature (Table 1). The state of the Citanduy is oligotrophic to mesotrophic when applying the stream criteria to its nitrate and phosphate concentrations. It is at the higher end of the range measured in rivers under little human impact while it is at the lower end of the range of rivers heavily affected by human activities (Fig. 9; Table 2). For a quantitative assessment the best estimate of global

Table 1 Trophic states of aquatic ecosystems and related average nutrient concentrations (*TN* total nitrogen, *TP* total phosphorus) as collected by Smith et al. (1999). The trophic states oligo-, meso-, eu- and hypertrophic correspond to systems receiving low, medium, high and excessive nutrient inputs

	Trophic state	TN (μM)	TP (μM)
Lakes	Oligotrophic	<25	<0.4
	Mesotrophic	25–47	0.4–1.1
	Eutrophic	47–86	1.1–3.6
	Hypertrophic	>86	>3.6
Streams	Oligotrophic	<50	<0.9
	Mesotrophic	50–107	0.9–2.7
	Eutrophic	>107	>2.7
Marine	Oligotrophic	<19	<0.4
	Mesotrophic	19–25	0.4–1.1
	Eutrophic	25–29	1.1–1.4
	Hypertrophic	>29	>1.4

nutrient inputs into the ocean available to date indicates a triplication of nitrogen and phosphorus inputs from the 1970s to the 1990s (Smith et al. 2003). This triplication is ascribed to dramatic increases of human activities during that time. From the statistical evaluation of data sets from 165 rivers they concluded that the DIN and dissolved inorganic phosphorus (DIP) load (total flux) and yield (flux per unit area) can be parameterized as functions of population density and runoff. With regard to a population density of >1,000 inhabitants km^{-2} (central Java province; Badan 2006), intensive agriculture in the hinterland and urban and industrial wastewater disposal, high nutrient inputs to the lagoon can be expected. According to the global scale assessment of Smith et al. (2003) the island of Java is generally a high-yield low-load region in terms of nitrogen and phosphorus input into the ocean.

We calculated the yields and loads of DIN and phosphate for the Citanduy River based on our own nutrient measurements, a catchment area of 3,380 km^2 (Whitten et al. 1996) and discharge data from 1978 to 1984. The annual average discharge amounted to 5.51 km^3 $year^{-1}$ for that period (Sutopo Purwo Nugroho personal communication). The DIN and phosphate loads of the Citanduy River are estimated to 172.9 × 10^6 and 6.0 × 10^6 mol $year^{-1}$, respectively. On a global scale these are minimum values in accordance with the coastal zone predictions by Smith et al. (2003). The respective yields are estimated to 51 × 10^3 mol km^{-2} $year^{-1}$ for DIN and to 2 × 10^3 mol km^{-2} $year^{-1}$ for phosphate. These fall into a medium range in the Smith et al. (2003) categories and do not match the predicted high yields (85–170 × 10^3 mol km^{-2} $year^{-1}$ for DIN, 5–10 × 10^3 mol km^{-2} $year^{-1}$ for DIP). Despite the possible uncertainties in our calculations it appears that the nutrient concentrations and yields of the Citanduy River fall inbetween those of pristine and heavily impacted rivers (Table 2) and hence can be rated 'moderate' with regard to 'nutrient pollution'.

With respect to Smith et al.'s (1999) classification of aquatic ecosystems the Segara Anakan lagoon lies between 'lakes' and 'marine' systems. Because of the generally fairly high salinity we chose to apply the lower 'marine' trophic state boundaries of nutrient concentrations to the lagoon water. When applying these criteria to the DIN and phosphate data of the lagoon, Segara Anakan falls into the oligotrophic to mesotrophic range. Compared to other lagoons around the globe, many of which are heavily polluted ones in Europe, nutrient concentrations in Segara Anakan were low (Fig. 9; Table 2). Within the lagoon a W–E gradient in trophic state was observed. Highest DIN concentrations were observed in the western lagoon (area W), mostly in the oligo-/mesotrophic range, occasionally eu-/hypertrophic. DIN was always in the oligotrophic range in the eastern (area E) and central lagoon (area C) with one exception in the latter in January 2006 when DIN fell in the

Fig. 9 Trophic state of the Citanduy and other world rivers (**a**) and Segara Anakan and other lagoons (**b**) based on concentrations of dissolved nutrients. *Boxes* denote trophic states for streams (**a**) and the coastal marine environment (**b**) according to Table 1. *Filled circles* represent the Citanduy in (**a**) and Segara Anakan in (**b**) and *open circles* represent other world rivers in (**a**) and other lagoons in (**b**) according to Tables 2 and 3
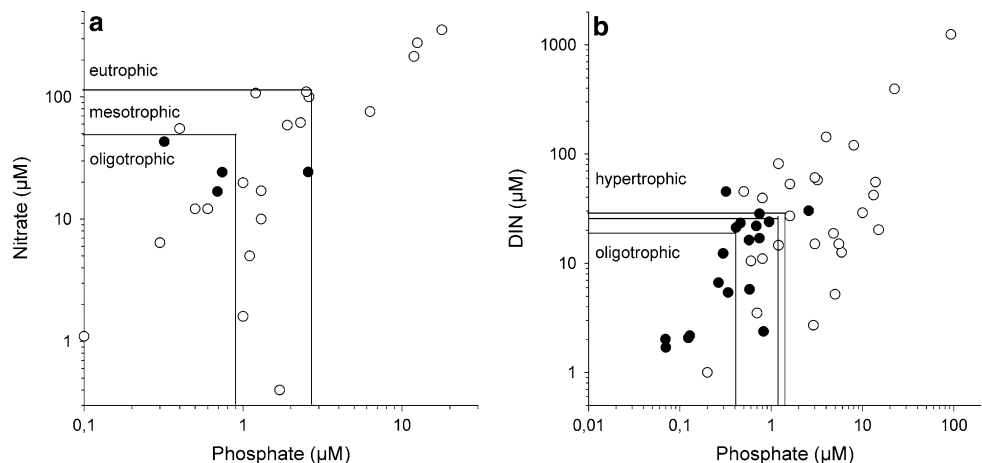
Table 2 Dissolved nutrients and respective atomic ratios in the Segara Anakan Lagoon, world rivers under heavy human impact and world rivers under little human impact

	Nitrate (μM)	Phosphate (μM)	Silicate (μM)	N/P	References
Segara Anakan					
Citanduy	0.6–42.9	0.1–2.6	27–245	11.7–141.1	*
Area W	0.4–20.8	0.1–1.0	15–179	19.7–55.7	*
Area C	0.2–17.8	<0.1–0.4	9–139	16.6–8946.5	*
Area E	0.2–5.3	<0.1–0.8	10–122	3.1–27.1	*
World rivers under heavy human impact					
Brahmaputra (Bangladesh)	58.6	1.9	130	31.2	1
Ganges (Bangladesh)	61.4	2.3	128	26.2	1
Mississippi (USA)	75.7	6.3	127	12.1	1
Changjiang (China)	55.0	0.4	232	125.7	1
Huanghe (China)	12.1	0.5	128	24.3	1
Ebro (Spain)	107.1	1.2	177	92.7	1
Elbe (Germany)	214.3	11.9	67	18.0	1
Po (Italy)	100.0	2.6	67	38.1	1
Rhine (Germany)	277.1	12.5	87	22.2	1
Weser (Germany)	353.6	17.8	67	19.8	1
Paraiba do Sul (Brazil)	19.8	1.0	110	19.2	2
Brantas (Indonesia)	110.0	2.5	180	44.0	3
World rivers under little human impact					
Amazon (Brazil)	12.1	0.6	115	19.4	4
Tocantins (Brazil)	1.1	0.1		11.4	4
Mackenzie (Canada)	10.0	1.3	50	8.0	4
Lena (Russia)	6.4	0.3	97	20.6	4
Contas (Brazil)	1.6	1.0	75	1.6	4
Mahaweli (Sri Lanka)	5.0	1.1	77	4.5	5
Kidogoweni (Kenya)	0.4	1.7	429	0.2	6
Mkurumuji (Kenya)	17.0	1.3	279	13.1	6

Human impact classification was conducted according to natural nutrient concentrations given by Meybeck (1993) and description of human activities in the various sources cited. Data sources: *, This paper; 1, Global Environmental Monitoring System (2000); 2, Carneiro (1998); 3, Jennerjahn et al. (2004); 4, Jennerjahn et al. (2006); 5, Silva et al. (2005); 6, Mwashote and Jumba (2002)

meso-/eutrophic range. This gradient in trophic state is probably related to the combined effect of freshwater-related input of land-derived nutrients and tidal dynamics.

While DIN is introduced into the lagoon by the Citanduy and other rivers in area W almost throughout the entire year, there is almost no such input in the eastern lagoon because of the low freshwater input. Despite the fact that major part of the Citanduy load of dissolved and particulate substances is exported into the Indian Ocean, part of it can reach the central lagoon. The magnitude of the river-derived nutrient input into the central lagoon largely depends on the hydrodynamics. Computer simulations have shown that seawater cannot enter the western and central part of the lagoon during neap tides in the rainy season (Holtermann et al., this volume). During that time high amounts of dissolved nutrients and suspended sediments can reach the central lagoon simply because of the

high freshwater input as was observed in January 2006 after 2 months of high precipitation (Figs. 2, 5). Particularly during the dry season, however, spring tides bear the potential to push the Citanduy plume towards the central part of the lagoon as we have observed and computer simulations have confirmed (Holtermann 2007). The magnitude of nutrient inputs into the central lagoon may be generally lower during the dry season because of the lower land-derived inputs. With increasing dryness the combined effects of tidal dynamics and recycling in mangroves gain importance for the nutrient budget of the central lagoon.

The low Chl *a* concentrations in Segara Anakan when compared to those of other lagoons state that the biotic response to nutrient inputs is moderate as well (Yuwono et al. 2007). For example, nutrients and Chl *a* in Segara Anakan are one to two orders of magnitude lower than in the highly eutrophied coastal lagoons of Viladecans, Spain

Table 3 Concentrations of dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and chlorophyll *a* (Chl *a*) in Segara Anakan and other lagoons

	DIN (µM)	DIP (µM)	Chl *a* (µg l^{-1})	References
Segara Anakan				
Citanduy	1.7–45.2	0.1–2.6	1.8	*, 1
Area W	2.2–23.9	0.1–1.0	2.8	*, 1
Area C	2.1–21.1	<0.1–0.4	4.6	*, 1
Area E	2.0–5.8	<0.1–0.8	6.1	*, 1
Lac Mellah, Algeria	3.1–5.2	1.0–5.0		2
Urbino, France	10.5	0.6		2
Biguglia, France	11.0	0.8		2
Prévost, France	12.6	5.9		2
Venice, Italy, 1978	143.0	4.0		3
Venice, Italy, 1999	39.4	0.8		3
Sacca di Goro, Italy	20.2	15		2
Thau, France	55.1	13.9		2
Rhône Delta, France	50–120	3–8		2
Albufera Valencia, Mediterranean	45.2	0.5	486	4
Massona, Mediterranean	2.7	2.9	250	4
Encanyissada, Mediterranean	27.0	1.6	2.4	4
Golf Prat, Mediterranean	57.7	3.2	18.4	4
Remolar, Mediterranean	393.3	22.4	48	4
Brac Vidala, Mediterranean	28.9	10.0	284	4
Murtra, Mediterranean	1243.2	92.7	24	4
Sant Climent, Mediterranean	41.9	13.2	313	4
Reguerons, Mediterranean	18.7	4.8	223	4
Celestun, Mexico	14.6	1.2		5
El Verde, Mexico	15	5.5	27	6
Longoni Bay, coral lagoon, Mayotte	1.1–9.1		0.3	7
Ofu, American Samoa	1.0	0.2		8
Olosega, American Samoa	0.1	1.7		8
Bundala, Sri Lanka	81.4	1.2		9
Embilikala, Sri Lanka	60.7	3.0		9
Malala, Sri Lanka	52.9	1.6		9
Chiku, Taiwan	15	3.0		10
Saquarema, Brazil	3.5	0.7	14–94	11

Chl *a* data in the Segara Anakan Lagoon are from May 2004. Data sources: *, This paper; 1, Yuwono et al. 2007; 2, De Casabianca et al. 1997 and references therein; 3, Pastres et al. 2004; 4, Lucena et al. 2002 and references therein; 5, Herrera-Silveira 1996; 6, Flores-Verdugo et al. 1988; 7, Vacelet et al. 1999; 8, Garrison et al. 2007; 9, Piyankarage et al. 2004; 10, Hung and Kuo 2002; 11, Carmouze et al. 1991

(Table 3; Lucena et al. 2002). The data available for Segara Anakan hardly indicate any signs of nutrient pollution and eutrophication. The reason for this may lie in the availability of nutrients and light and the bathymetry and the hydrodynamics of the lagoon. Highest nutrient concentrations were observed in Area W during the wet season. There, the suspended matter concentration is generally higher than in the central and eastern parts of the lagoon. It can be as high as several hundreds of mg l^{-1} in the western lagoon and up to 1,114 mg l^{-1} in the Citanduy River (Yuwono et al. 2007). Despite the availability of nutrients

Chl *a* was low in the Citanduy and the western lagoon. It indicates that phytoplankton uptake rates must have been low, most probably because of light limitation. An increase of Chl *a* towards the central and eastern lagoon may be related to lower suspended matter contents and hence higher light penetration (Table 3; Yuwono et al. 2007).

Major part of the lagoon is very shallow with a water depth of <2 m. It has a semidiurnal tide with a maximum spring tide amplitude of 1.4 m and a water residence time of 1–3 days near its western and eastern outlets and of about 12 days in its central part (Holtermann et al., this

volume). For estuaries and lakes at the land–sea margin of the North Atlantic Nixon et al. (1996) have demonstrated that the portion of nitrogen and phosphorus retained in the system is a function of the water residence time. The longer it is, the higher is the portion of N and P retained in the system. For Segara Anakan with its very short residence time it would mean that about 75% of N and about 80–90% of P could be exported to the coastal ocean.

Conclusion

The nutrient inventory of the Segara Anakan Lagoon is controlled by a complex mixture of anthropogenic and natural sources and processes. It is basically maintained by inputs from the Citanduy and other rivers and the tidal exchange with the Indian Ocean. These vary spatially related to the magnitude of the freshwater input which is high in the western part of the lagoon and decreases towards the east. Temporal variations are in the range of semidiurnal (high–low tide) to a full lunar month (spring-neap tide, approximately 29.5 days) with respect to the tidal exchange and on the order of months with respect to the seasonally varying precipitation and freshwater input. In combination these factors are determining the hydro-dynamics of the lagoon which control the dispersal of substances in the lagoon and export to the Indian Ocean. During times of low input of freshwater and land-derived nutrients (July–September) the release from mangrove sediments appears to contribute to the nutrient inventory of the lagoon.

Despite the extremely high population density and intensive agriculture in the hinterland the level of nutrient pollution and eutrophication in the lagoon is low to moderate when compared on a global scale. The short residence time of the water in the shallow lagoon indi-cates that major part of the land-derived nutrient input is rapidly exported to the sea. Although Segara Anakan is a highly perturbed system for decades it appears that still natural processes exert major control on the nutrient inventory of the lagoon.

The mismatch of the river-derived N and P yields we calculated with those simulated by Smith et al. (2003) shows that extrapolations from global scale assessments can be insufficient on a local scale. It underscores that more local to regional scale knowledge on cause–effect rela-tionships and quantification of nutrient fluxes based on these is required particularly for management purposes. Our study contributes to the understanding of Segara Anakan's ecosystem structure and functions. It is a pre-requisite for developing measures for a sustainable management of Segara Anakan's natural living resources.

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