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Spatio-temporal Variations in Nutrient Supply of the Brantas River to Madura Strait Coastal Waters, Java, Indonesia, Related to Human Alterations in the Catchment and a Mud Volcano

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Abstract: The Brantas River is a tropical mid-sized river with mountainous headwaters, covering a catchment area of around 11,050 km² at the east coast of Java, Indonesia. Its watershed is located in one of the most densely populated regions worldwide, facing alterations by agriculture, urbanization and aquaculture ponds. Additionally, one of the two major distributaries of the Brantas River in the lowlands, the Porong River is affected by inputs from the "LUSI" mud volcano since April 2006. We investigated spatio-temporal variations in inorganic nutrient biogeochemistry of the Brantas River, its major distributaries in the lower reaches and its coastal-estuarine regions and related them to land use and hydrology.

Highest nutrient loadings occurred during the wet periods (November to April) making up 80% and 87% of the annual dissolved inorganic nitrogen (DIN: NO_3^-, NO_2^-, NH_4^+) and phosphorus (PO_4^{3-}) loads, respectively, with the Porong River accounting for 90% and 82% of the annual DIN and PO_4^{3-} input. During wet periods the estuaries were flushed with DIN and PO_4^{3-} rich freshwater, leading to high concentrations in coastal waters. Much lower nutrient concentrations were observed in coastal waters during dry periods because of low river discharge and nutrient load. During dry periods an increased exchange time and increased biological activity were responsible for estuaries acting as a sink for NO_3^- and a source for NH_4^+ and PO_4^{3-}. In contrast, during wet periods most of the introduced NO_3^- was directly discharged into coastal waters without further processing and NH_4^+ and PO_4^{3-} fluxes were slightly lower. Variations in the DIN composition were mainly related to differences in land use with NO_3^- dominating the agriculture-dominated upper Brantas River and increasing NH_4^+ and NO_2^- content in the lower reaches affected by urban wastewater and aquaculture. The mud volcano affected parts of the Porong River showed drastic changes in the DIN composition and depletion of dissolved oxygen during low flow periods. In contrast, during wet periods most of the mud volcano input was diluted by the large freshwater and inorganic nutrient supply from the upstream regions. Our results suggest that the densely urbanized Brantas River with multiple anthropogenic nutrient sources (agriculture, urban sewage release, aquacultures) leads to an increased export of dissolved inorganic nitrogen and phosphorus into coastal waters. The enhanced nutrient export supports nutrient enrichment in coastal waters, can possibly affect the phytoplankton production and composition, leading to eutrophication within near-shore regions of the Madura Strait.

Key words: Nutrients, budget, eutrophication, biogeochemistry, environmental change, land use, Indonesia.

Introduction

Estuaries are important transition zones regulating the inorganic nutrient transport between terrestrial and marine systems. They face major chemical, biological and physical gradients over a relatively small area. In

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particular the exchange of inorganic nutrients such as N and P between terrestrial and marine ecosystems is important as both elements are essential nutrients limiting phytoplankton growth and primary production in estuarine and coastal waters (Ryther and Dunstan, 1971; Oviatt et al., 1995). The rate at which nitrogen is introduced into the terrestrial biosphere increased by more than two times in the past five decades by, for example, fertilizer production and use, fossil fuel combustion, and cultivation of leguminous crops (Galloway et al., 2004). The global production of agricultural fertilizers, for example, increased from <10 million tons of N (1950) to ca. 80 million tons (1990), and its production should exceed 135 million tons of N by 2030 (Vitousek et al., 1997b; Smith et al., 1999). The inputs of phosphorus has more than doubled as a consequence from mining, use of rock phosphate as fertilizer, detergent additives, animal feed supplement and other technical uses (Bennett et al., 2001; MacKenzie et al., 1998).

Rivers are the main source of nitrogen and phosphorus input to the world ocean (Froelich et al., 1982; Schlesinger, 1997). In particular during the last decades the discharge of these nutrients into the oceans has increased worldwide by more than two times, which is directly related to population growth in the catchment areas of the rivers and in coastal regions (Meybeck, 1998; Downing et al., 1999; Bricker et al., 2008) followed by an increased input of anthropogenic nutrient loading including wastewater, industrial processes, fertilizers and atmospheric deposition (Smith et al., 2003; Galloway et al., 2004; Seitzinger et al., 2005, 2010). Population density in coastal regions is increasing worldwide, which can have a strong effect on the estuarine and coastal ecosystems (Cohen et al., 1997). Land use changes have resulted in major modification of freshwater runoff, sediment transport, fluxes of carbon and nutrients to coastal systems (Syvitski et al., 2005). The increased export of inorganic nutrients can cause several negative environmental impacts, such as loss of habitat and biodiversity, increase in phytoplankton blooms resulting in hypoxia and increased fish mortality and increased blooms of toxic, harmful phytoplankton species (Billen and Garnier, 2007; Diaz and Rosenberg, 2008; Howarth et al., 1996; Rabalais, 2002; Turner et al., 2003; Seitzinger et al., 2010).

The Brantas River on the island of Java, Indonesia, is one example for a mid-sized tropical river showing large amplitudes in river discharge, a high population density and strong anthropogenic modifications along the whole watershed. It is one of Indonesia's most important catchment areas, which has undergone major changes since 1960, in over 20 infrastructure projects developing and managing the water resources in the Brantas catchment (Sudaryanti et al., 2001). Nowadays six reservoirs and dams are regulating the seasonal river flow in the catchment area. River water is used for irrigation, domestic and industry supply, flow maintenance and fisheries. Pollution of the Brantas system occurs from both point and non-point sources. With ~15.5 million people nearly 42% of East Java province's population is living in the Brantas catchment (Hidayat, 2009). The Gross Regional Domestic Product (GRDP) growth rates were 5-6% per year; however in the years from 1983 to 1995 it increased to 7-8% per year because of rapid industrialization in the area around Surabaya city. In total ~935 industries are registered in the Brantas basin; however, the majority of the labour force in the Brantas basin (53%) is engaged in agricultural activities (Hidayat, 2009).

In particular, tropical regions in South East Asia which are growing fast in terms of population and economy are facing major environmental problems due to the large anthropogenic impacts related to this growth. Thus knowledge about these impacts on the coastal nutrient biogeochemistry and water quality is important for estimating and preventing ecological and economic consequences due to possible eutrophication and hypoxia. In this study, we present the first detailed view of seasonal nutrient dynamics of the Brantas River estuarine system and adjacent coastal waters of the Madura Strait. Main objectives of our study are: (1) to characterize spatio-temporal variations of DIN and PO_4^{3-} patterns; (2) to determine the impact of possible nutrient release by (a) agriculture, (b) aquaculture and (c) urban wastewater; (3) to calculate how seasonal and spatial differences in the two main estuaries are affecting the seasonal nutrient budget; and (4) to examine the impact of the "LUSI" mud volcano on the water quality and biogeochemistry of the Porong river estuary and coastal waters of the Madura Strait.

Material and Methods

Study Area

The Brantas River (BR) is, with 320 km, the second largest river on Java covering a total catchment area of ~11,050 km^2. Originating near the volcanic, mountainous regions around Mt. Arjuno the BR is flowing around the volcanic regions receiving waters from many smaller tributaries above the delta. At Mojokerto (~30 kilometres upstream from the coastline) the BR divides into its two major branches the Surabaya River (later called Wonokromo River) which is heading to the northeast flowing across the city of Surabaya before entering the Madura Strait and the PR which is directly flowing eastwards to the coastal regions. Porong (PR) and Wonokromo River (WR) are the two major distributaries of the Brantas River (BR) discharging into the Madura Strait. Both rivers are located nearby Surabaya City (population ~2.9 million), East Java, Indonesia (7° 18' to 34' S, 112° 47' to 56' E; Figure 1). The transition zone between rivers and coastal waters of the Madura Strait were defined as the Wonokromo (PR-SMS) in the northern and Porong estuarine system (PR-SMS) in the southern regions of our study area. Additionally the MS receives waters by smaller tidal channels like the Kapetingan (KC) and Alo Channel (AC) which are used for draining and irrigation of the coastal regions between PR and WR. Both, KC and AC are part of a major drainage network in the lowlands receiving waters from the BR (Figure 1).

The catchment of the BR is dominated by agricultural land use (61%) mainly consisting of paddy fields, sugar cane, maize, soybeans and peanuts. Agricultural land use is followed by dry lands (12%), settlements (12%) and forests (4%) (Hidayat, 2009). In the 1970s and 1980s major dams and reservoirs were built along the BR for power generation, irrigation and flood control, hence river flow is regulated. The population along the whole catchment is accounting for around 15.5 million with a population density of 1260 inhabitants per km², largely concentrated in the lower reaches rather than in the higher, steeper mountain reaches making the area one of the most densely populated regions worldwide (Munawir and Vermeulen, 2007). The Australian Asian monsoon system is controlling climatic conditions on Java, showing one wet season with heavy rainfalls from October to April and a dry season from May to November. During the wet season ~80% of the freshwater discharge by the Brantas is directed into the Porong, its average discharge can be around 600 m^3 s^{-1}, and may rise to 1200 m^3 s^{-1} in extremely wet years. During the dry season, most of the river flow is directed to Surabaya and the discharge of the Porong is extremely low (Hoekstra, 1989). In the northern parts of our study area, the WE receives waters from the WR. Water supply from the BR system is mainly used for domestic (225 million m^3 y^{-1}), industrial (140 million m^3 y^{-1}) and irrigation supply (2.5 billion m^3 y^{-1}) and is actively regulated by a major dam and weir system, which was implemented in the last decades (Munawir and Vermeulen, 2007).

935 industries are located in the Brantas Basin; however just 483 of these directly release effluents into the Brantas River and major tributaries with a total net BOD load contribution to the Brantas River of 125 tons per day (Binnie & Partners (Ovevseas) Ltd., 1999). Most of these industries are located in the lower reaches of the Brantas Delta and the main contributors for pollution loadings are (1) pulp and paper (13%), (2) sugar cane (35%) and mono sodium glutamate (48%) industries (Binnie & Partners (Ovevseas) Ltd., 1999). Domestic pollutions are released into the river as "grey water" (from domestic usage, except toilet wastes) and "black water" (from toilet usage) via drainage channels or partly from wastewater treatment plants (Binnie & Partners (Ovevseas) Ltd., 1999). The WR (up to the city of Surabaya called Surabaya River) is heavily influenced by these drainage waters from domestic households and industry as it is flowing across the city of Surabaya (Binnie & Partners (Ovevseas) Ltd., 1999). The PR, KC and AC are discharging into the southern PE. The smaller KC and AC originate from irrigation system in the low-gradient areas of the Brantas river delta and flow partly through densely urbanized areas, lowland rice fields and coastal aquaculture ponds. Drainage waters from the coastline covering aquaculture ponds are actively released either directly into the KC and AC or being introduced into smaller channels which are all heading into KC and AC.

As the PR serves as a sediment drain during the wet periods, its lower reaches are almost completely diked with nearly no exchange with the surrounding aquaculture ponds. Just a few smaller inlets can be found near the river mouth. Additionally, in contrast to the WR the PR is less associated with densely urban regions heading seawards. The whole coastline of the MS is covered by a small belt of mangrove forests and a large area of brackish water aquaculture ponds (fish and shrimp) covering an area of around 17,900 ha (FAO, 1982) around the cities of Surabaya and Sidoarjo (Figure 1), established at most parts of the coastline from the northern WR to the southern PR opening. In May 2006 a mud volcano erupted in Surabaya-Sidoarjo, nearby the PR. Since April 2007 part of the mud is artificially released into the nearby PR for flushing most of the sediments directly into coastal waters of the Madura Strait. The mean monthly river discharge of WR and PR exhibited strong seasonal and spatial variations (Figure 2) from January 2007 to December 2008. Highest river discharge occurred from November to April while low river flow was observed from May to October (Figure 2). In the wet month's river discharge of WR

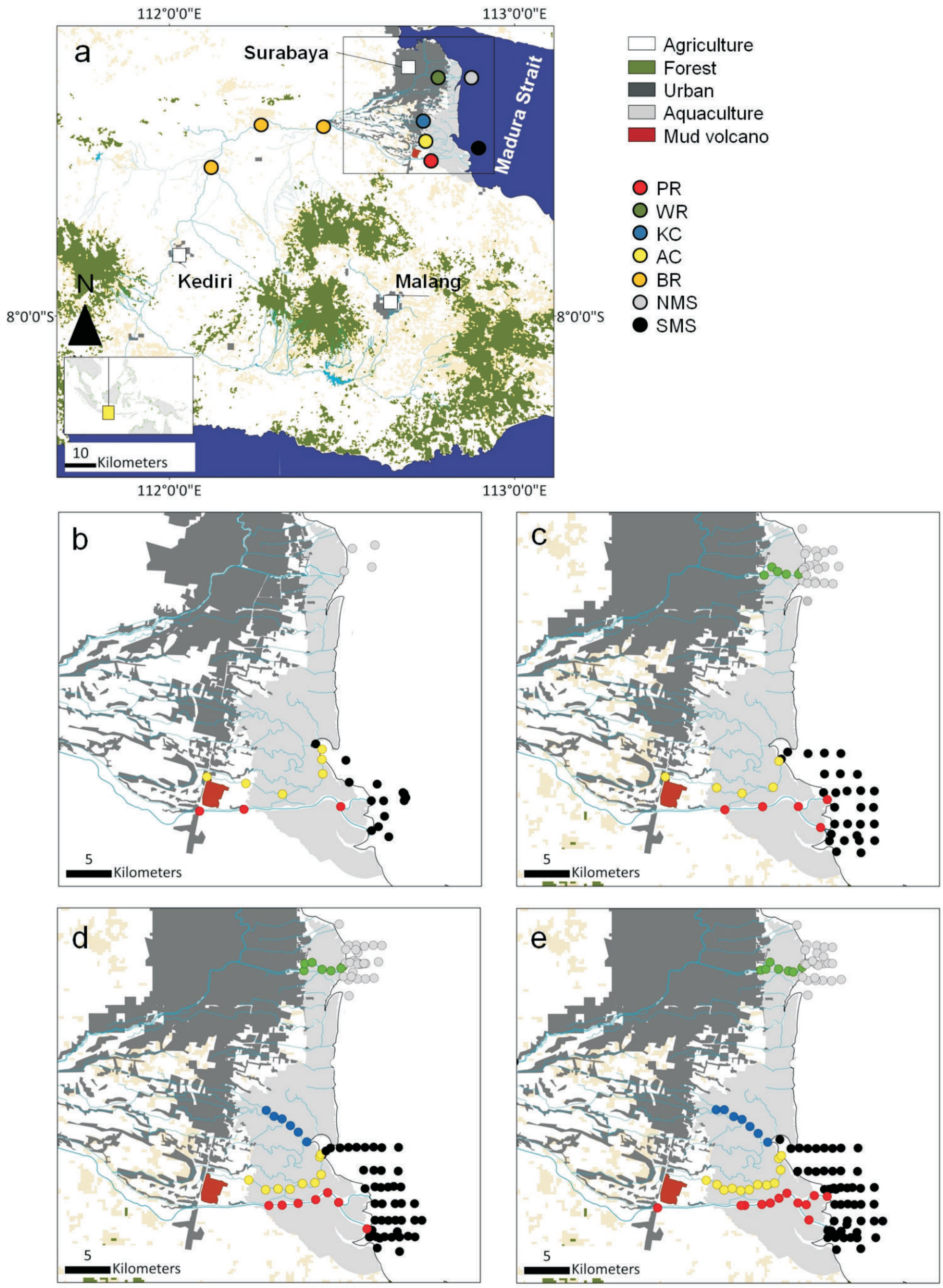

Figure 1: Map of the BR watershed and study area. Map (a) shows the locations of sampling stations in the BR taken in March and August 2008 and the sampling groups in the lower reaches and coastal waters. Maps (b-e) show the sampling locations in the lower reaches and coastal waters of the study area during each sampling campaign in: (b) wet season 2007 (April 2007), (c) dry season 2007 (September 2007), (d) wet season 2008 (March 2008) and (e) dry season 2008 (August 2008). River coastal transects of WR (green), PR (red), KC (blue) and AC (yellow) as well as coastal sampling stations in the NMS (grey) and SMS (black) are shown in circles.

and PR increased rapidly from 11.1 $m^3 s^{-1}$ to 67.2 $m^3 s^{-1}$ (WR) and from < 1 $m^3 s^{-1}$ to 513.1 $m^3 s^{-1}$ (PR; Figure 2). As seen in the discharge charts, the PR was dominating the annual freshwater input to the MS (~80% of the total annual inflow).

Sampling and Chemical Analyses

Four sampling campaigns were carried out in April and September 2007 and in March and August 2008. Samples were taken along four river-coastal transects (WR, PR, KC and AC). For spatial comparisons we grouped all

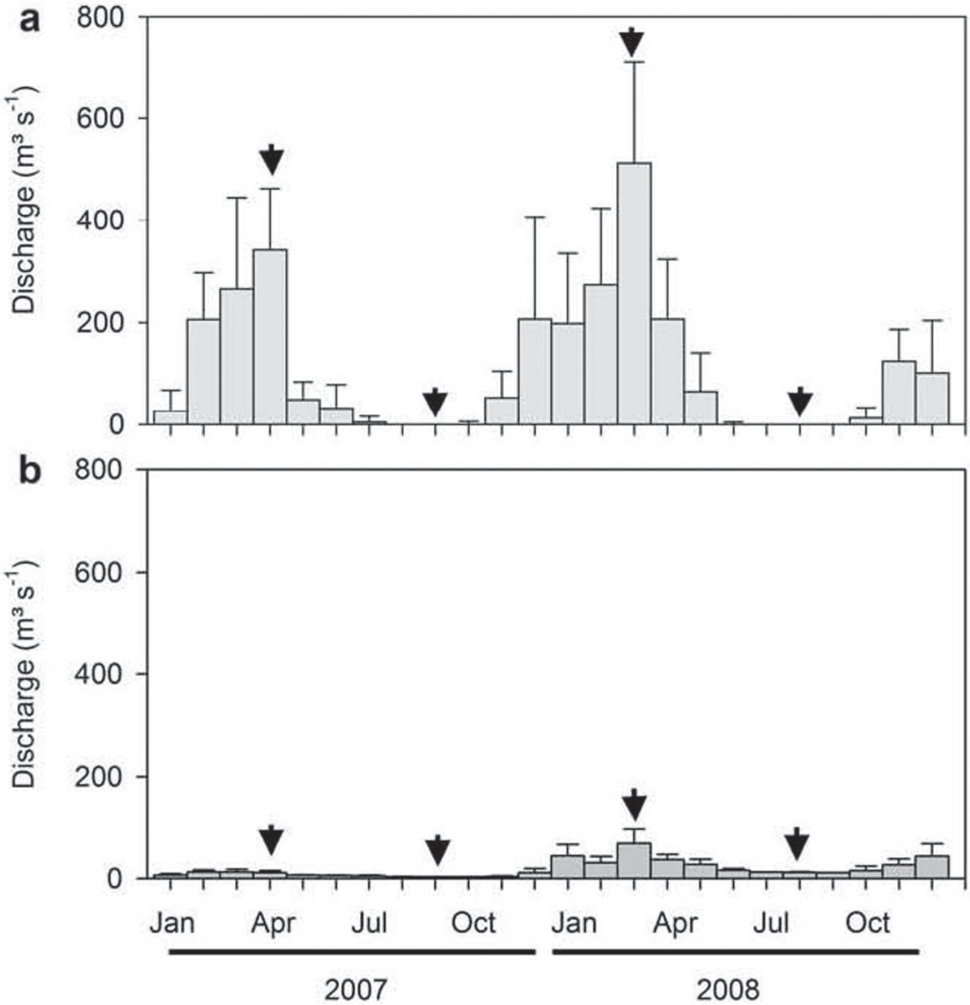

Figure 2: Mean monthly river discharge of (a) Porong (PR) and (b) Wonokromo River (WR) during the investigated period from January 2007 to December 2008. Sampling expeditions are indicated as dark arrows.

sampling stations geographically and divided the whole sampling area into (1) middle reaches (consisting of river stations in the BR), (2) lower reaches (river stations of each river: WR, PR, KC and AC) and (3) coastal waters (stations in open Madura Strait), divided into northern area (NA) around the WR and southern area (SA) around the PR (Figure 1).

During our field campaigns the depth of the rivers and estuarine transects were measured using an echo sounder at each sampling station, showing that both estuaries are shallow in depth (averaging ~3.6 to 5.2 m). The area of PE and WE (Figure 1) used for calculations of the LOICZ budget was estimated covering in total ~260 km². The volume of both estuaries has been estimated for around 26×10^9 m³ and water-level changes are corresponding to a micro-mesotidal cycle (Hoekstra et al., 1989). At each sampling station dissolved oxygen (DO) and salinity were estimated using a HACH-Lange multi-probe sensor. Surface water samples for measurement of dissolved inorganic nutrients (NO_3^-, NO_2^-, NH_4^+ and PO_4^{3-}) were taken from a depth of 0.5 m. Samples were filtered through Sartorius Minisart filter (0.45 µM pore size) in 50 ml LDPE (low-density polyethylene) bottles, and preserved with a mercuric chloride solution. Afterwards samples were stored cool until analysis. Inorganic nutrients were determined on a Skalar-autoanalyzer following Grasshoff protocols (Knap et al., 1996).

Samples for chlorophyll-*a* (chl-*a*) were taken on Whatman GF/F filters by using a low pressure vacuum pump. The filters were stored frozen and in the dark until further processing in the laboratory. In the laboratory filters were extracted overnight in 90% acetone at 4°C in the dark, afterwards chl-*a* was determined using a

Shimadzu spectrophotometer (Strickland and Parsons, 1972). The WR and PR daily discharge data from 2007 to 2008 were obtained from PT Jasatirta, the Brantas and Bengawan Solo River Basin Management Agency (http://www.jasatirta1.co.id).

LOICZ Nutrient Budget Calculations

Loadings for dissolved inorganic nitrogen (DIN: NO_3^-, NO_2^-, NH_4^+) and dissolved inorganic phosphorus (PO_4^{3-}) introduced into estuaries by the PR and WR (2007, 2008) were calculated from daily loads. The daily inputs of dissolved inorganic nutrients (DIN, PO_4^{3-}) were calculated by multiplying the mean seasonal freshwater flow with mean inorganic nutrient concentrations measured at low salinity stations (< 1) in the PR and WR. We used a simplified biogeochemical box model developed by the Land Ocean Interactions in the Coastal Zone (LOICZ) project (http://nest.su.se, Gordon et al., 1996; Smith and Hollibaugh, 1997; http://nest.su.se/mnode/Toolbox/LOICZ_Toolbox.htm) to calculate water exchanging time of the estuaries and nutrient budgets. Both estuaries were treated as well mixed one dimensional boxes, which can be assumed to be in a steady state. This model can also be found in other studies in a more detailed description (Liu et al., 2009). Calculations were made using the LOICZ budget toolbox (http://nest.su.se/mnode/Toolbox/LOICZ_Toolbox.htm) by inserting mean values of river discharge, volume, salinity and inorganic nutrient concentrations.

A convenient summary of the LOICZ budget is the following:

1. Water budget: The first step was to establish a water budget for the system. Changes in the water mass balance were determined by the sum of all the average flows into (V_{in}) and out (V_{out}) of the system:

$$\Delta V = V_{in} - V_{out} = -V_Q - V_P - V_G - V_R + V_E$$

V_{in} and V_{out} are the mean river discharge values discharging water into and out of the systems. V_Q, V_P, V_G, V_E are the mean river discharge, precipitation, groundwater and evaporation. V_R is the residual flow that balances the other sources of water entering the system. This flow has usually a negative value due to the water flow out to the adjacent ocean. As V_Q is usually the dominant variable in the system and we didn't obtain data for the other sources, we reduced the mass balance of our system to calculations made with the river discharge.

2. Salt budget: The second step was to include the salt water budget, as coastal marine systems have flows across the system boundaries in addition to V_R. The salinity balance includes additional exchange flows associated with tides, winds, density and circulation patterns (Strobel et al., 2009). The salinity balance in the system was calculated by:

$$V_X(S_1 - S_2) = S_R V_R$$

with $$S_R = (S_1 + S_2)/2$$

S_1 are the mean salinities observed in the estuarine system of interest and S_2 the mean salinities measured in adjacent coastal waters, respectively. Both salinities were measured during wet and dry period expeditions in 2007 and 2008. V_X is the exchange flow of water masses between estuarine system of interest and adjacent coastal waters. The exchange time (τ) of water (t, in days) was estimated by:

$$\tau = V_S/(V_R + V_X)$$

where V_S is the volume of the system.

3. Nutrient exchange: In summary, the exchange of inorganic nutrients (ΔN) between the systems of interest and adjacent coastal waters can be estimated based on the water budgets, salt budgets and nutrient concentrations:

$$\Delta N = \Sigma\text{out} - \Sigma\text{in}$$
$$= V_R C_R + V_X C_X - V_Q C_Q - V_P C_P$$

where C_Q, C_1, C_2, C_R and C_X are the mean concentrations in the river, system of interest, adjacent coastal waters, residual-flow boundary [$C_R = (C_1 + C_2)/2$] and mixing flow ($C_X = C_1 - C_2$), respectively (Liu et al., 2011). A negative sign of ΔN indicates that the system of interest acts as a nutrient sink, whereas a positive sign indicates that the system is a source for inorganic nutrients, respectively (Liu et al., 2011).

Results

Physicochemical Properties

Corresponding to seasonal changes in river discharge, salinities in the rivers/tidal channels and coastal regions of the estuaries varied considerably (Figure 3, Table 1). During the wet periods all five rivers were dominated by freshwater with mean salinities occurring in a narrow range between 0.1 and 1.6 (Table 1). The mean salinity in coastal waters was 16.9 ± 12.3 (Table 1). In general salinity was low near the river mouth openings and increased with distance to the coastline (Figure 3). During the dry periods freshwater input was low and the salinity in the rivers/tidal channels was consistently higher than during wet periods, ranging between mean values of 0.2 and 15.2 showing a landward shift in the salinity gradient

(Figure 3, Table 1). The mean salinity in coastal waters was 31.2 ± 4.9, which was considerably higher than during the wet periods. The mean DO concentrations in the mid reaches were around 6.9 ± 0.1 and 7.8 ± 0.2 mg l^{-1} (Table 1) during the wet and dry seasons, respectively showing in general the highest mean DO concentrations of all rivers/tidal channels. During wet periods DO concentrations decreased rapidly in the WR, KC and AC

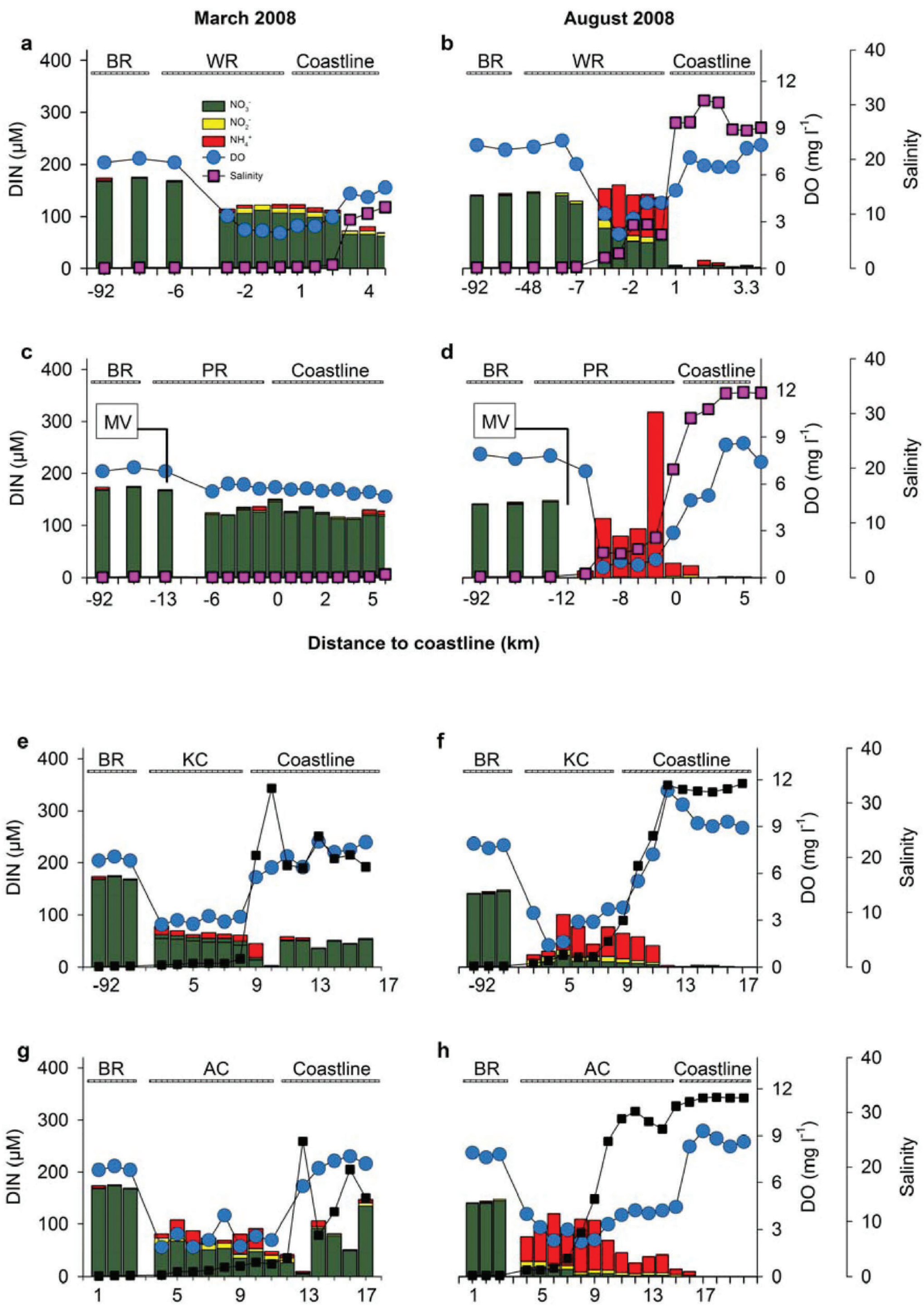

Figure 3: Spatial variations of DIN (NO_3^-, NO_2^-, NH_4^+), DO and salinity at sampling stations along the: (a, b) Brantas-Wonokromo river, (c, d) Brantas-Porong river, (e, f) Brantas-Kapetingan channel and Brantas-Alo channel, and (g, h) transects during wet season (March) and dry season expeditions (August) in 2008.

Table 1: Average values for salinity, DO, inorganic nutrient concentrations (DIN, NO^{3-}, NO^{2-}, NH_4^+, PO_4^{3-}), and chl-*a* concentrations along the sampling groups in the rivers and coastal waters

	Salinity	*DO* *(mg l^{-1})*	*DIN* *(µmol l^{-1})*	*NO_3^-* *(µmol l^{-1})*	*NO_2^-* *(µmol l^{-1})*	*NH_4^+* *(µmol l^{-1})*	*PO_4^{3-}* *(µmol l^{-1})*	*chl-a* *(µg l^{-1})*
Wet seasons (2007, 2008)								
BR	0.2 ± 0.1	6.9 ± 0.1	176.0 ± 3.3	169.1 ± 3.5	1.6 ± 0.1	1.7 ± 2.4	4.7 ± 0.1	2.7 ± 0.0
PR	0.1 ± 0.0	6.1 ± 0.6	139.2 ± 13.1	120.6 ± 13.1	2.9 ± 0.5	2.0 ± 1.7	4.8 ± 2.1	5.3 ±
WR	0.3 ± 0.0	2.7 ± 0.4	124.6 ± 6.0	104.0 ± 5.4	9.2 ± 0.5	5.6 ± 2.8	3.3 ± 0.6	4.3 ± 3.0
KC	0.8 ± 0.4	3.0 ± 0.2	72.1 ± 6.2	49.3 ± 4.7	7.2 ± 0.4	10.4 ± 3.5	5.4 ± 0.8	7.5 ± 3.0
AC	1.6 ± 1.0	2.5 ± 0.8	103.6 ± 17.6	38.5 ± 22.0	9.2 ± 7.8	26.0 ± 24.7	5.4 ± 3.7	7.9 ± 5.9
NA	24.5 ± 11.3	6.7 ± 2.1	36.6 ± 39.5	25.3 ± 26.4	2.6 ± 2.4	8.7 ± 10.6	1.8 ± 1.0	6.9 ± 4.3
SA	10.4 ± 9.9	6.5 ± 1.8	79.7 ± 45.4	71.8 ± 39.8	2.6 ± 1.1	5.4 ± 4.5	2.9 ± 2.1	4.5 ± 4.3
Dry seasons (2007, 2008)								
BR	0.2 ± 0.0	7.8 ± 0.2	148.1 ± 3.2	141.5 ± 2.9	2.0 ± 0.8	0.9 ± 1.5	5.7 ± 1.3	1.4 ± 0.6
PR	15.2 ± 10.1	3.9 ± 2.8	151.7 ±172.9	1.0 ± 1.0	1.4 ± 1.4	146.9 ±173.2	1.6 ± 1.0	15.8 ± 10.3
WR	10.5 ± 12.3	3.6 ± 1.8	136.1 ± 49.0	51.3 ± 34.9	11.7 ± 6.9	31.4 ± 33.0	7.7 ± 3.2	12.2 ± 9.6
KC	4.8 ± 6.3	4.1 ± 1.2	34.8 ± 22.4	9.3 ± 5.7	6.4 ± 2.8	10.6 ± 18.4	7.0 ± 3.2	20.5 ± 7.9
AC	13.5 ± 12.2	3.4 ± 1.1	73.4 ± 32.0	8.1 ± 9.9	8.0 ± 6.5	40.9 ± 27.4	4.4 ± 5.7	21.0 ± 16.7
NA	31.7 ± 3.2	7.8 ± 1.2	5.0 ± 6.0	1.4 ± 1.4	1.0 ± 1.3	2.5 ± 3.4	2.3 ± 2.3	9.4 ± 6.9
SA	32.1 ± 3.0	8.2 ± 1.7	5.6 ± 10.4	0.7 ± 1.1	1.1 ± 1.7	3.7 ± 7.6	1.4 ± 0.8	8.3 ± 7.6

after reaching the densely urbanized and aquaculture dominated regions. The average DO concentrations measured here ranged between 2.5 ± 0.8 mg l^{-1} (AC) and 3.0 ± 0.2 mg l^{-1} (KC) (Table 1). In contrast the mud volcano affected PR had just slightly lower DO concentrations of 6.1 ± 0.6 mg l^{-1}. DO concentrations in coastal waters varied between 6 and 7 mg l^{-1} with lower values in low salinity regions of the river plumes (Figure 3, Table 1).

During the dry periods DO concentrations in the lower reaches were clearly lower than the sampling stations in the middle reaches (Table 1). In WR, KC and AC, oxygen concentrations decreased rapidly after reaching the urban and aquaculture dominated regions around Surabaya city showing mean values between 3.4 ± 1.1 mg l^{-1} (AC) and 4.1 ± 1.2 mg l^{-1} (KC) (Table 1). The strongest seasonal change in the DO levels could be observed in the mud volcano affected PR where mean values decreased down to 3.9 ± 2.8 mg l^{-1} (Table 1). As seen in the transect profiles from August 2008 DO concentrations decreased rapidly down to values of 0.9 mg l^{-1} downstream of the mud volcano station. In all four rivers/tidal channels in the lower reaches showed increasing DO levels seawards corresponding to increasing salinity. Coastal waters showed in general high mean DO concentrations (Figure 3, Table 1).

Distribution Patterns of DIN and PO_4^{3-}

Mean DIN concentrations in the rivers and tidal channels varied between 51.7 ± 25.7 µM and 201.3 ± 132.2 µM (Table 1). The highest values of 201.3 ± 132.2 µM were found in the mud volcano affected PR during the dry periods and the agriculture-dominated mid reaches of the BR with mean values of 174.2 ± 15.6 µM (Table 1) during the wet periods. The DIN composition in the mid reaches was generally dominated by NO_3^- (NO_3^- 98%, NO_2^- 1%, NH_4^+ 1%; Figure 5) in both seasons. During wet periods the mean DIN concentrations in rivers/tidal channels of the lower reaches ranged from 72.1 ± 6.2 µM (KC) to 139.2 ± 13.1 µM (PR) (Figures 3 and 4, Table 1), of which 52-96% occurred in form of NO_3^- and 2-35% of NH_4^+ and 2-13% of NO_2^- showing an increase in the NH_4^+ and NO_2^- fraction compared to stations in the mid reaches of the BR. In particular the urban and aquaculture mud volcano affected KC and AC had a higher content of NH_4^+ and NO_2^- followed by the urban affected WR, whereas the DIN composition in the mud volcano affected PR changed just slightly (Figures 3 to 5, Table 1). Similar to changes in the DIN composition, DO concentrations decreased strongly in the WR, KC, AC and just slightly in the mud volcano affected PR. During wet periods DIN concentrations in coastal waters of the study area were generally high. The mean DIN concentrations were 101.6 ± 46.1 µM (Table 1) and were dominated by NO_3^- (NO_3^-: 80%, NO_2^-: 5%, NH_4^+: 15%; Figure 5). The highest concentrations were found at low salinities in nearshore waters and decreased with increasing distance to the coastline and increasing salinity.

During the dry periods the average DIN concentrations in rivers/tidal channels of the lower reaches ranged from 51.7 ± 25.7 µM to 201.3 ± 132.2 µM (Figures 3 and 4, Table 1). The DIN concentrations were in general highest in freshwater regions of the rivers/tidal channels and decreased with increasing salinity showing much lower DIN concentrations varying between 2 and 12 µM at the river mouths. In contrast to the high NO_3^- content in the agricultural dominated mid reaches of the BR the DIN composition in the lower reaches showed an increasing percentage of NH_4^+ and NO_2^- (Figures 3 to 5). The highest NH_4^+ content was associated with the mud volcano affected PR, followed by the urban and aquaculture affected KC and AC. In all four rivers/tidal channels in the lower reaches the increasing NH_4^+ content was associated with a general decrease in the DO concentrations. During dry periods, DIN concentrations in coastal waters were considerably lower than in the wet periods, showing mean concentrations of 13.7 ± 15.4 µM (Table 1) and a higher contribution of NH_4^+ and NO_2^- (NO_3^-: 15%, NO_2^-: 21%, NH_4^+: 64%; Figure 5).

Mean phosphate (PO_4^{3-}) concentrations varied between 1.6 and 8.4 µM. During wet periods the highest mean concentrations in the rivers were found in the AC (5.4 ± 3.7 µM) and KC (5.4 ± 0.8 µM) and lowest in the WR (3.3 ± 0.6 µM). During the dry periods mean PO_4^{3-} concentrations were highest in the urban and aquaculture affected KC (7.0 ± 3.2 µM) and WR (7.7 ± 3.2 µM) and lowest in the mud volcano affected PR (1.6 ± 1.0 µM). In coastal waters PO_4^{3-} concentrations did not differ clearly between wet and dry period varying between 2.5 and 3.1 µM (Table 1).

Distribution Patterns of Chlorophyll-*a*

Mean chl-*a* concentrations ranged between 1.4 and 21.0 µg l^{-1} at all sampling stations during all expeditions (Table 1). In the rivers and tidal channels the mean chl-*a* concentrations were considerably higher during dry periods ranging between 1.4 and 21.0 µg l^{-1} compared to wet periods when mean chl-*a* concentrations ranged between 2.7 and 7.9 µg l^{-1}. In coastal waters chl-*a* concentrations were slightly higher in both sampling areas during the dry periods (Table 1).

Discussion

Seasonal Biogeochemistry of Nutrients Derived from the Rivers

The DIN and PO_4^{3-} concentrations in the mid reaches of the BR were generally high throughout the year, showing no clear seasonal trend, suggesting a continuous input of inorganic nutrients. The DIN composition in the mid reaches of the BR was dominated by NO_3^- accounting for more than 95% of the total DIN during both seasons (Table 1). The lower reaches of the sampling area are characterized by a densely urbanized region around Surabaya, with major industries and large aquaculture pond systems along the whole coastline. In contrast, the middle and upper reaches of the Brantas basin are dominated by agriculture land use, causing differences in the release of inorganic nutrients. Large areas of the mountainous watershed of the BR have undergone strong alterations like deforestation and transformation into agriculture dominated land. Recently 61% of the upper catchment is used for agriculture; in particular wet- and dryland rice fields are dominating the agricultural land use in the Brantas basin with ~25% of the total harvested area.

Concentrations of NO_3^- (141.5–169 µM) and PO_4^{3-} (4.7–5.7 µM) in the BR were much higher as observed in less-disturbed rivers in the world (Meybeck, 1982) such as the Amazon and the Yenisey, but comparable to concentrations observed in more polluted and eutrophic European, North American and Asian rivers, e.g., the Mississippi, Yangtze, Po, Rhine, Loire (Liu et al., 2003; Guillaud et al., 2007; Turner and Rabalais, 1991; Zhang et al., 2003), suggesting that inorganic nutrients are primarily derived from anthropogenic sources in the upper watershed. NO_3^- concentrations in pristine rivers are usually lower than 10 µM (Meybeck, 1982; Humborg et al., 2003), whereas for example NO_3^- in anthropogenic disturbed rivers like the Mississippi and Yangtze could vary between 70 and 114 µM (Rabalais et al., 1996; Liu et al., 2003; Guo et al., 2004).

High NO_3^- concentrations are a general trend mainly caused by an increased use of agricultural fertilizers and enhanced industrial and domestic waste (Meybeck, 1982; GESAMP, 1987). In agricultural dominated regions, large amounts of NO_3^- can leach into the groundwater or can be released into nearby streams and rivers due to surface runoff. In North America, major parts of the Mississippi watershed mud volcano are used for intensive agriculture, and most parts of Europe are also used intensively for agriculture, resulting in high nutrient loadings of the major river catchments all across the continent (Verhoeven et al., 2006). Agriculture dominates the whole watershed of the BR, which can be assumed to be the major source for inorganic nutrients. This increased nutrient release could also be observed in other tropical river systems as seen in the Citanduy River, Indonesia where increased deforestation and changes to agriculture land use caused an enhanced input of inorganic nitrogen from mainly paddy fields resulting in elevated NO_3^- concentrations in the river (Jennerjahn et al., 2009).

In the BR basin the increased usage of chemical fertilizers and perennial irrigation caused an increase in the rice yields from 1.11 million tons (1965) to 2.26 million tons (2004). Fertilizer application can enhance nitrogen mineralization and soil N pools in terrestrial ecosystems and can thus contribute additional NO_3^- to stream water via erosive runoff or by the release of nutrient enriched drainage waters from the agricultural dominated watershed. Surprisingly, NO_3^- and PO_4^{3-} concentrations decreased only slightly in the mid reaches during the dry periods suggesting that inorganic nutrient input was continuously high throughout the year most probably due to a combination of (1) perennial irrigation work in the agricultural dominated upper and middle catchment areas of the BR enabled by modifications in the river flow and (2) multiple point sources along the whole urban affected watershed.

Nutrient Sources and Seasonal Nutrient Supply from the Lower Catchment

Impact of Urban and Aquaculture Sources

Comparisons of surface waters among BR, PR, WR, KC and AC showed generally higher NH_4^+ concentrations in the densely urbanized and by aquaculture ponds affected WR, KC and AC. This trend could in particular be observed during the dry periods as NH_4^+ concentrations increased considerably in the WR, KC and AC (Figures 3 and 5, Table 1) suggesting a release by urban sewage or drainage waters from pond system. Average NH_4^+ concentrations in the lower reaches of our study area (Table 1) were in the range of concentrations measured in the Thames (~40 µM) (Middelburg et al., 2000) and Tamar estuaries (0 to 45 µM) (Owens, 1986), but lower than those found in the strongly urbanized European systems like the Scheldt (100 to 1000 µM) (Somville, 1978) and Colne estuaries (up to 500 µM) (Robinson et al., 1998), where NH_4^+ was the dominant form of DIN introduced by sewage effluents. Main pollution from industries originate from pulp and paper (13%), sugar cane (35%) and mono sodium glutamate industries (48%) (Binnie & Partners (Ovevseas) Ltd., 1999). Based on our data and the fact that most of the industries at the Brantas basin and densely urbanized areas are located in the deltaic regions around Surabaya city, it is suggested that the high NH_4^+ content in the WR, KC and AC resulted from the input of wastewaters.

The low-lying coastal areas of the watershed are densely urbanized, particularly around Surabaya city, and large parts are covered by aquaculture ponds. In particular the smaller drainage channels of KC and AC are connected to the coastal pond system (Figure 1). Surabaya is the second largest city in Indonesia, with a population of about 2.9 million. Due to the lack of adequate wastewater treatment most of the domestic sewage is directly released into the nearby Surabaya River and WR (Binnie & Partners (Ovevseas) Ltd., 1999). In general, household wastewater ("grey waters" + "black waters") components were estimated to 4-5 kg capita^{-1} yr^{-1} for nitrogen and 0.7 kg capita^{-1} yr^{-1} for phosphorus (Malisie, 2008).

Calculated for the total 2.9 million inhabitants of Surabaya, this sums up to a daily input of 32-40 tons N and six tons P into the drainage system and rivers. For comparison, an effluent input of 80 tons per day into the upper Danshuei River on Taiwan significantly increased the NH_4^+ and PO_4^{3-} concentrations in the receiving river water (Wen et al., 2008). Additionally, input of NH_4^+ and PO_4^{3-} in the WR, KC and AC can originate from the release of inorganic nutrients by the large areas of aquaculture ponds covering the whole coastline as was also found in other studies (Gowen, 1994; Folke et al., 1997). Aquaculture can enhance N and P fluxes by recycling of the high organic matter load in their sediments (Gilbert et al., 1997; Karakassis et al., 1999).

As seen in the transect profiles NH_4^+ concentrations in the WR were elevated straight after the urban regions (Figures 3 and 4) at sampling sites before entering the aquaculture affected areas suggesting that the main input of NH_4^+ was originating from urban sources. However, for the KC and AC the relationships between urban and aquaculture sources were not as clear. Effluents released into KC and AC were one reason why these tidal channels had the highest concentrations of NH_4^+, since they were major draining of the aquaculture pond regions around Sidoarjo. This and by comparing with other rivers like the Danshuei we can conclude that wastewater release from urban regions was mainly responsible for the increasing NH_4^+ content in the WR, KC and AC. In particular the smaller drainage channels covering the coastal aquaculture ponds can introduce additional nutrients into coastal waters, which was also observed in recent studies made on the Chinese island of Hainan showing that aquaculture ponds can be a significant source of nitrogen, particularly NH_4^+ (Liu et al., 2011).

Impact of the Mud Volcano

In contrast to the WR, the PR is completely diked in the lower reaches and therefore has almost no contact with the surrounding watershed except for a few smaller outlets of aquaculture ponds. During low flow periods the DIN composition in the PR changed drastically corresponding to a nearly total depletion of DO falling to values below 1 mg l^{-1} (Figure 3). NO_3^- which was dominating the DIN fraction before reaching the mud volcano affected river segment of the PR was almost totally depleted at the last sampling station before the mud volcano incident which was corresponding to decreasing PO_4^{3-} concentrations, suggesting that most of the nutrient supply was utilized by bacteria or phytoplankton. Sediment input by the mud volcano resulted in a drastic increase in the suspended sediment concentrations by nearly 130 times (Jänen, 2012). In the mud volcano affected river segment NH_4^+ concentrations increased and was dominating the DIN composition, suggesting a direct release of NH_4^+ from the mud volcano porewater and/or an introduction organic matter degradation, which increased drastically in the heavily affected regions (Jänen, 2012). A good indicator for the input from organic matter degradation was the strong oxygen depletion observed after the MV incident and corresponding to increasing NH_4^+ concentrations. Further downstream NH_4^+ concentrations decreased again which can be attributed to dilution with marine waters reaching into the PR during low discharge periods, as seen in the salinity mixing plots (Figure 6). In contrast, during wet periods the PR showed little change in the DIN composition and just a slight decrease of DO (Figure 3), suggesting that the large supply of NO_3^- rich freshwater from the upstream regions was dominant and thus diluted the local mud volcano release.

Biogeochemical Mixing and Transformation Processes of Inorganic Nutrients along the Estuarine Gradient during High and Low Rainfall Periods

East Java is influenced by the Australian Asian monsoon system with generally heavy rainfalls during the wet periods and reduced rainfalls in the summer months. During the investigated expeditions, wet periods were characterized by a strong freshwater input into coastal waters forming two river plumes in front of the WR and PR mouths. Low salinity (< 5) water was taken from all

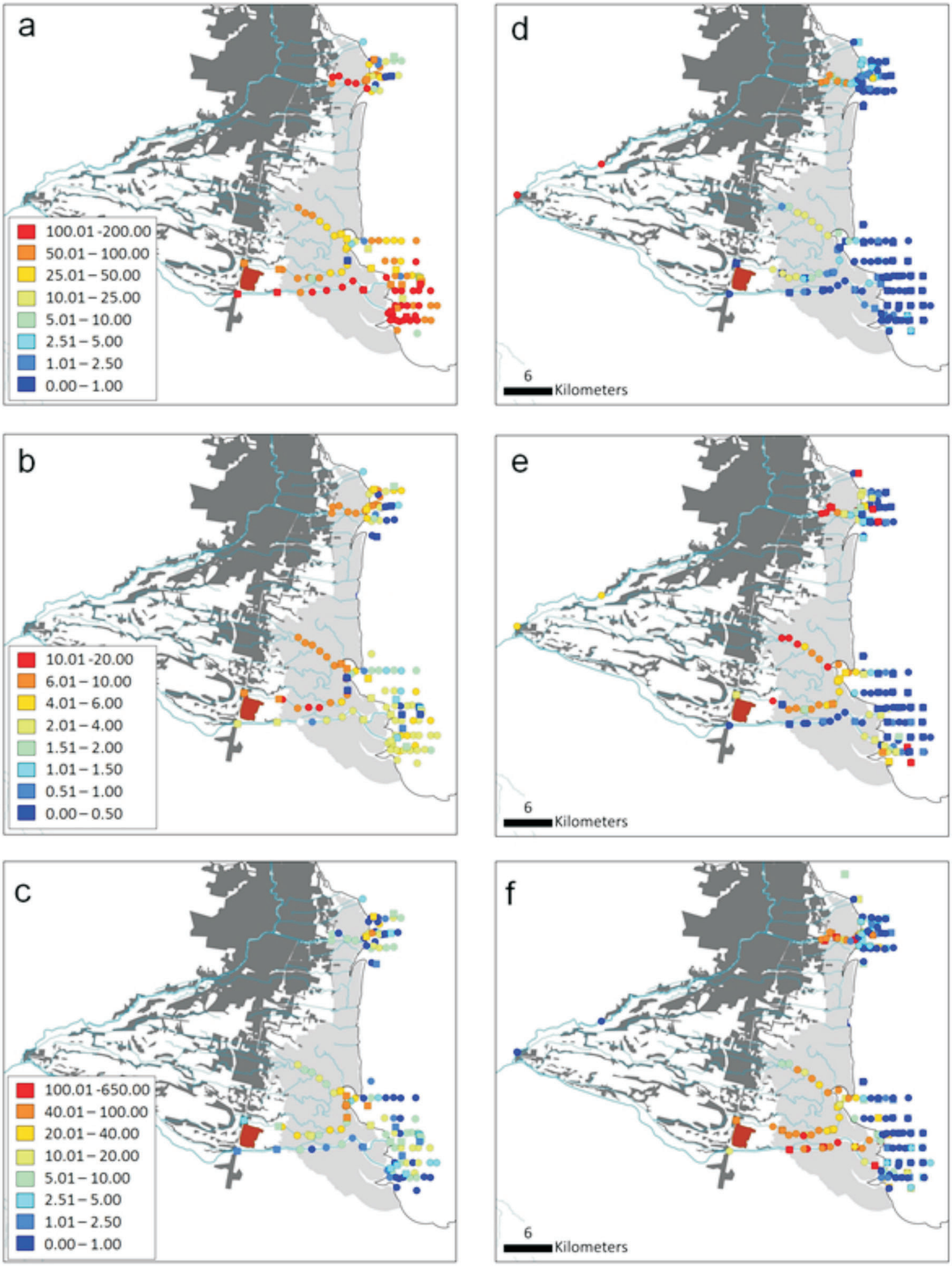

Figure 4: NO_3^- (a, d), NO_2^- (b, e) and NH_4^+ (c, f) concentrations (µM) in surface water samples obtained during each sampling campaign in: (a, b, c) the wet seasons 2007 and 2008 (April 2007 [squares], September 2008 [circles]) and (d, e, f) dry seasons 2007 and 2008 (September 2007 [squares], August 2008 [circles]).

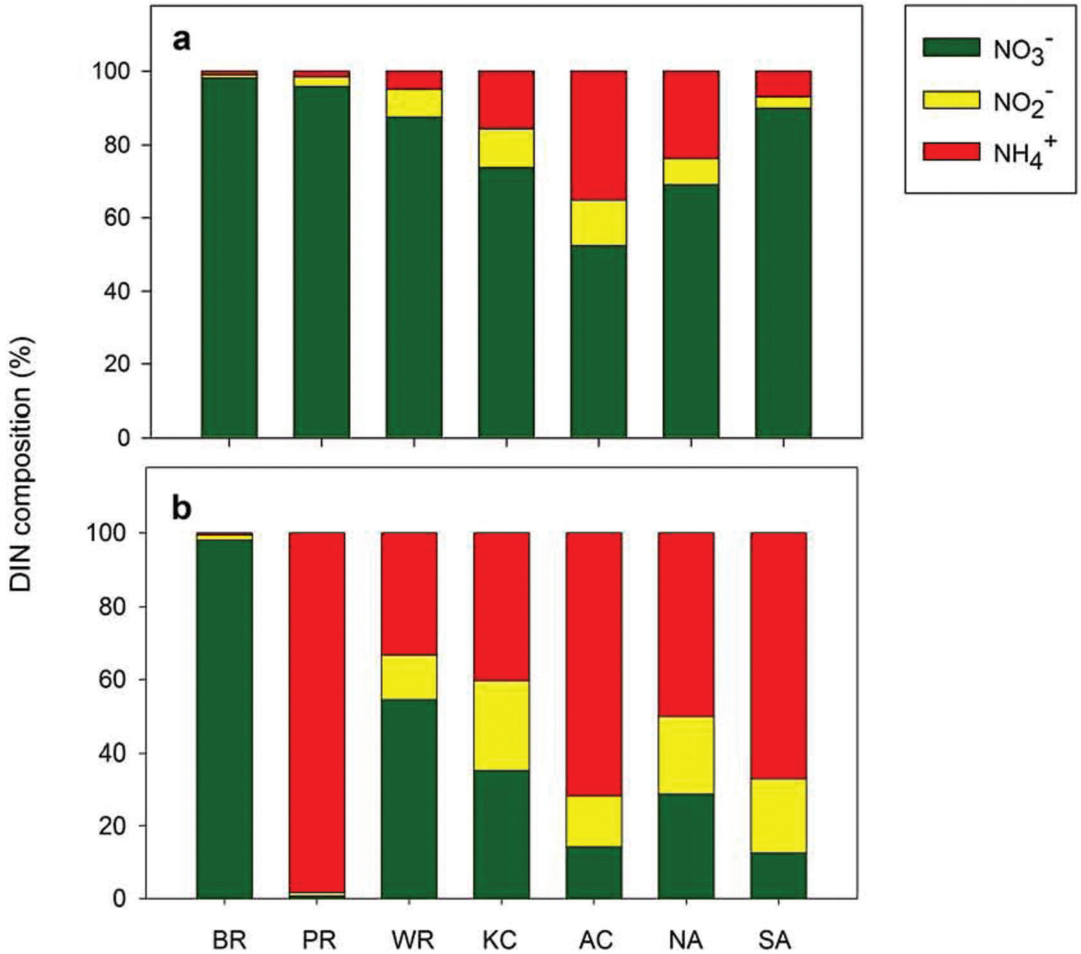

Figure 5: Mean DIN composition for rivers (BR, WR and PR), tidal channels (KC and AC) and coastal waters (NA, SA) for all expeditions during the: (a) wet periods and (b) dry periods.

rivers and near the Porong and Wonokromo mouths to the NMS and SMS. Both river plumes extended eastwards into the MS introducing inorganic nutrients into coastal regions.

In coastal regions mean DIN concentrations were high, ranging between 36.6 ± 39.5 µM (NMS) and from 79.7 ± 39.8 µM (SMS) and for PO_4^{3-} from 1.8 ± 1.0 µM (NA) to 2.9 ± 2.1 µM (SMS). These concentrations could be found upto a distance of ~10 km in front of the PR and upto a distance of ~5 kilometres in front of the WR mouth. The observed DIN and PO_4^{3-} concentrations in coastal waters were comparable to concentrations found in coastal waters of the human altered Rhone River Delta (50-120 µM) (Pastres et al., 2004), but high compared to pristine rivers like the Amazon (DeMaster and Pope, 1996). NO_3^-, PO_4^{3-} and NH_4^+ in both systems, the WR-NMS and PR-SMS showed a similar pattern along the salinity gradient. Specifically, nutrient concentrations were high in low salinity waters of the WR-NMS and PR-SMS systems and decreased conservatively with increasing salinity (Figure 6), suggesting that nutrient uptake by biological processes such as phytoplankton utilization was low. This was also indicated by low chl-*a* concentration (Table 1) and high TSM concentrations (Jänen, 2012) in low salinity regions indicating that a sufficient nutrient uptake by phytoplankton can be neglected, as light limitation and strong high river discharge. Thus low residence time prevents the nutrient uptake and occurrence of a stable phytoplankton community. High NO_2^-, NH_4^+ and low DO levels, especially observed in low salinity regions of the estuaries suggest increased nitrification, as a result from the recycling of organic matter and nitrification of dissolved NH_4^+ introduced into the estuaries. The strong NO_3^- input from the agricultural dominated hinterland accompanied by nitrification processes and relatively low NO_3^- uptake in the estuaries was most likely responsible for the dominance of NO_3^- in the DIN pool of coastal waters.

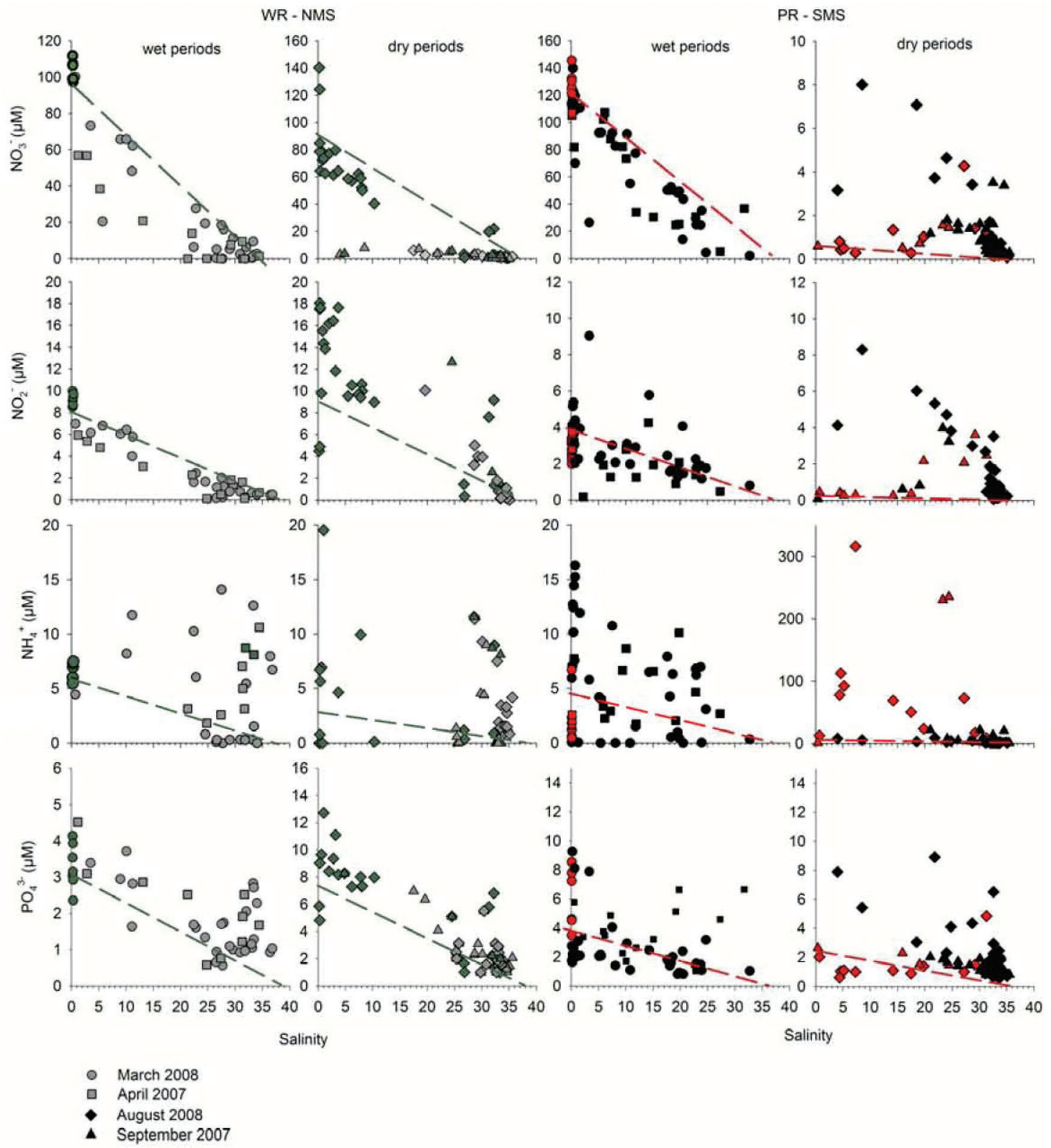

Figure 6: Surface water concentrations of dissolved inorganic nutrients along the WR (green), NMS (grey) and PR (red), SMS (black) during wet and dry periods in 2007 and 2008. The end-member mixing line indicates nutrient concentrations expected from conservative mixing of fresh and marine water masses.

High nitrite levels found in the WR-NMS estuary can also be an indicator for increased denitrification. Especially in a organic matter rich turbid estuary as found in the WR-NMS (Jänen, 2012) enhanced degradation of additionally introduced organic matter from anthropogenic drainage waters from urban and aquaculture sources can cause strong DO consumption by bacteria most likely increasing the probability of denitrification processes in the water column.

The high PO_4^{3-} concentrations in freshwater regions are probably a result of the increased fertilizer usage in the watershed with subsequent leaching from agricultural soils during the wet periods. PO_4^{3-} and NH_4^+, as shown by the salinity mixing diagrams (Figure 6) seem to be released into estuarine water in particular at intermediate to high saline waters. This suggests the regeneration of organic matter along the whole estuarine gradient as also observed in the Mississippi river plume (Wawrik et al., 2004). This regeneration process would also fit to the low oxygen concentrations in the mixing waters of the WR-NMS and PR-SMS system.

In summary, wet periods are characterized by a strong rainfall driven nutrient input into the estuaries causing a flushing and a strong export of inorganic nutrients into the outer estuaries and adjacent coastal waters of the MS, so that during wet periods the BR system acted as a strong nutrient source towards the coastal sea. Additionally, the regeneration of inorganic nutrients could also be observed along the estuarine mixing gradient acting as an additional nutrient input, possibly fuelling phytoplankton growth in the adjacent coastal waters of the Madura Strait.

With decreasing rainfalls river discharge of the PR and WR decreased strongly during the dry periods; as a result the estuaries were more influenced by marine salt waters and the system itself shifted from a river dominated towards a marine dominated estuary. The salinity of the WR and PR inlet stations increased from ~1 during the wet periods to 30 during the dry periods and marine waters could intrude into the tidal channels shifting the estuarine mixing zone landwards. Coastal waters were dominated by marine waters and the concentrations of DIN in NMS and SMS decreased nearly totally, suggesting biogeochemical transformation processes along the estuaries affecting the input of DIN into the Madura Strait. In particular in freshwater and mixing salinities the WR-NMS and the PR-SMS showed strong differences, most probably caused by the influence of the MV at the PR.

NO_3^- still dominated the DIN pool in freshwater regions of the WR-NMS system with concentrations from ~60 to 80 μM. The high amount of NO_3^- can be explained by the input from the agriculture dominated hinterland. However along the estuarine gradient an increased uptake at salinities between 10 and 20 and low concentrations in high salinity waters (Figure 6) were observed indicating a change in the DIN source. Decreasing NO_3^- concentrations can be attributed to nutrient uptake by freshwater phytoplankton indicated by 3 to 5 times higher chl-*a* concentrations in the inner low saline regions of the estuaries (Table 1). This was also indicated by changes in the organic matter composition which are suggesting an additional input of more labile organic matter, most likely originating from freshwater phytoplankton. Increased phytoplankton growth can be explained by better light conditions during the dry periods, due to a reduced suspended matter input from agriculture soil and thus decreasing particle concentrations in low saline waters of the WR-NMS system (Jänen, 2012).

However, in coastal waters the amount and concentrations of NO_3^- in the DIN pool decreased considerably and was replaced by NH_4^+. This shift was most likely caused by the combination of direct and fast NO_3^- utilization from freshwater (in the inner estuaries) as well as marine phytoplankton (outer estuaries, coastal waters) and input from NH_4^+ from organic matter regeneration. The dominance of NH_4^+ in the DIN pool of coastal high saline waters was accompanied with increased concentrations of NO_2^- and PO_4^{3-} which are both additionally indicating that the DIN composition organic matter undergoes increased regeneration and nitrification along the estuarine gradient (Figure 6). In coastal waters, resuspension of estuarine sediments and associated release of NO_3^- and NH_4^+ from sediment pore water into the water column was probably the major source of DIN. Surprisingly, PO_4^{3-} concentrations were relatively unaffected with clearly higher concentrations along the estuarine gradient than in the wet periods. This increase can be attributed to additional human sources and/or a possible input by sediment release in the low oxygenated zones and by estuarine mixing (Upchurch et al., 1974). For instance, under anaerobic conditions PO_4^{3-} can be released by the reduction of Fe (III) hydroxyoxide (Mortimer et al., 1941; Baldwin et al., 2002) as well as orthophosphate release can occur from facultative heterotrophic bacteria (Gächter et al., 1988).

Nutrient Budget

Daily freshwater input to this studied system included 19.4×10^6 m^3 d^{-1} and 4.8×10^6 m^3 d^{-1} of river discharge from the PR and WR, respectively, with a total river water discharge of 24.2×10^6 m^3 d^{-1} (V_Q), thus the water mass balance shows a net water exchange (V_R) from the studied system to the MS with a residual flow of 24.2×10^6 m^3 d^{-1}. The freshwater input was clearly dominated by rainfall driven discharge in the wet periods accounting for ~89% of the annual discharge and most of the freshwater introduced into the MS was derived by the PR during this period of the year. The volume of the PR-SMS and WR-NMS system (V_S) is 623.35×10^6 m^3 and 42.30×10^6 m^3, respectively and the total water exchange time (τ) of the studied system was calculated from the ratio $V_S/(V_R + V_X)$. The estimated exchange time varied between 3.9 and 70.2 and was in both systems higher during dry periods which can be easily explained by the decreasing river discharge during this time of the year. However, as water is artificially directed by multiple dams and weirs most of the river discharge during dry periods is directed towards the WR which explains why the exchanging time increased just a bit compared to the PR. Calculations made with the salt balance showed that in total, the water exchange flow from the MS to the studied systems (V_X) was 38.11×10^6 m^3 d^{-1}. Nutrient fluxes from the WR and PR to the MS can be estimated as a sum of the net residual flux ($C_R V_R$) and mixing flux ($C_X V_X$) (Liu et al., 2009; Liu et al., 2011).

Figure 7 and Table 2 summarise calculations made for the daily inorganic nutrient fluxes averaged for wet and dry periods of 2007 and 2008 at the WR and PR. The total discharge weighted DIN and PO_4^{3-} load into the estuaries was 1453.4 x 10^3 mol d^{-1} and 66.8 x 10^3 mol d^{-1}, respectively. Highest nitrogen and phosphorus inputs were estimated for the wet periods with 2279.5 x

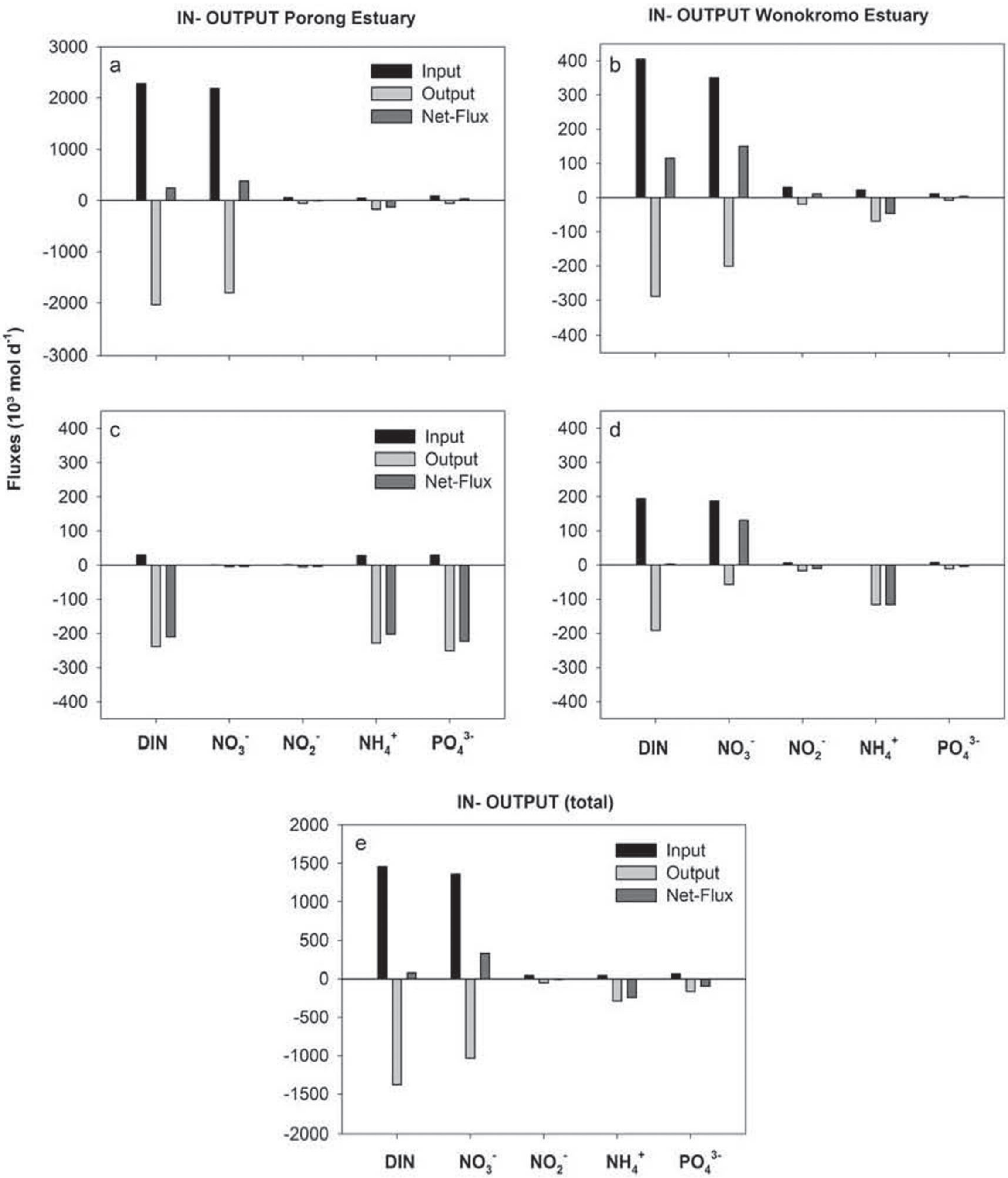

Figure 7: Daily dissolved inorganic nitrogen (DIN), nitrate (NO_3^-), nitrite (NO_3^-), ammonium (NH_4^+) and phosphate (PO_4^{3-}) inputs (IN-) and outputs (OUT-) and net fluxes (NET-FLUX) for the WR-NMS and PR-SMS during the: wet periods (a, b), dry periods (c, d) and in total (e) for all expeditions.

Table 2: Surface area, salinity and daily nutrient budgets (10^3 mol d^{-1}) for the WE and PE

		DIN 10^3 *mol* d^{-1}	NO_3^- 10^3 *mol* d^{-1}	NO_2^- 10^3 *mol* d^{-1}	NH_4^+ 10^3 *mol* d^{-1}	PO_4^{3-} 10^3 *mol* d^{-1}
Wet seasons						
PR-SMS						
	Estuary	2279.5	2188.1	51.7	39.7	86.4
	Marine	-2036.6	-1803.2	-62.1	-171.3	-58.6
	Sink/Source	242.9	384.9	-10.4	-131.5	27.8
WR-NMS						
	Estuary	405.0	351.5	31.0	22.5	11.1
	Marine	-289.5	-200.9	-20.0	-68.6	-8.1
	Sink/Source	115.5	150.6	11.0	-46.1	3.1
Dry seasons						
PR-NMS						
	Estuary	28.7	0.5	1.5	26.7	28.5
	Marine	-238.7	-4.3	-5.5	-228.9	-251.7
	Sink/Source	-210.0	-3.8	-4.0	-202.2	-223.2
WR-SMS						
	Estuary	193.6	187.0	6.6	0.0	7.5
	Marine	-191.0	-57.7	-17.0	-116.2	-11.8
	Sink/Source	2.6	129.3	-10.4	-116.2	-4.2
Entire study period						
	Total Input	1453.4	1363.5	45.4	44.5	66.8
	Total Output	-1377.9	-1033.1	-52.3	-292.5	-165.1
	Sink/Source	75.5	330.4	-6.9	-248.0	-98.3

10^3 mol d^{-1} and 86.4 x 10^3 mol d^{-1} (Table 2), respectively, and decreased with decreasing river discharge. In total 95% of the DIN introduced into the estuaries was exported into the adjacent MS, mainly introduced during wet periods most probably as a result of the ~8 times higher river discharge. Spatial differences in the input and output of inorganic nutrients of both estuaries show that the total import and export was driven by the PR, because of its ~4 times higher river discharge compared to WR. This suggests a fast flushing of the estuaries. During wet periods heavy rainfalls cause a strong import and export of inorganic nutrients across the estuarine system. According to the high river discharge, thus low exchanged time and biogeochemical transformation processes were restricted. Especially biological processes like phytoplankton uptake can be neglected along the estuaries because of light limitation induced by the high suspended matter load and the fast flushing of nutrients into adjacent coastal waters.

Both estuaries showed higher retention of DIN during the dry periods, suggesting that the water exchanging time of the estuaries was a main reason affecting the DIN fluxes. Most probably, the increased retention of DIN can be attributed to the utilization of inorganic nitrogen by freshwater and marine phytoplankton. Additionally, the low oxygen concentrations observed in both estuarine systems can be used as an indicator for possible denitrification processes occurring in the estuaries causing a loss of DIN. Both the PR-SMS and WR-NMS showed a net gain of NH_4^+ and PO_4^{3-} suggesting an additional source of nitrogen and phosphorus in the estuaries, which can be attributed to either local anthropogenic sources (urban, aquaculture ponds, mud volcano) or by the recycling of organic matter. In particular during the dry periods most of the DIN exported to coastal waters was consisting of NH_4^+, which would suggest an increased input by transformation processes such formed by organic matter degradation.

Our DIN budget shows a spatial difference between the WR-NMS and PR-SMS, suggesting that the mud volcano played an additional role in the total N budget, especially during the low discharge periods. Compared to the WR-NMS the NO_3^- input was clearly reduced and the NH_4^+ output was 2-3 times higher during the dry periods which was strongly connected to the local position of the mud volcano, as seen in the decreasing NO_3^- concentrations along the PR transect. This loss of NO_3^- is most probably a result of microbial consumption and denitrification as DO levels decreased drastically in the affected river segment. Due to the reduced freshwater supply during the dry periods, the additionally introduced NH_4^+ can have a stronger impact on the general DIN budget compared to wet periods when NO_3^- rich freshwater was dominant.

Annual yields and loads for the net output of both estuaries based on the calculated LOICZ budget and a catchment area of 11,050 km^2 were calculated with discharge data from 2007 to 2008. On a global scale, the annual loads were low compared to large river systems (Smith et al., 2003). However, the estimated nutrient yields for the BR basin were 45.5 x 10^3 mol km^{-2}year^{-1} for DIN and 3.2 x 10^3 mol km^{-2} year^{-1} for PO_4^{3-}, which were according to Smith et al. (2003) within an intermediate range for DIN and DIP (in our study PO_4^{3-}) yields. High predicted DIN and DIP yields for example in Europe and the northeast United States is mainly due to high anthropogenic N and P inputs in these regions. Indonesia is in particular interesting as many Indonesian basins are in the top 10% for all elements and forms (Seitzinger et al., 2005) due to a combination of high runoff, high relief, and high levels of anthropogenic activity. This could also be partly found in the BR, which has a high relief structure in the upper regions of the watershed, a highly irrigated, agricultural dominated watershed and a very densely populated watershed (>1000 inhabitants per km²). Nevertheless we have to bear in mind that river discharge during the dry periods was reduced drastically; hence DIN and PO_4^{3-} yields could be even higher. Assuming a continuous flow during the whole year would cause increased nutrient yields for the BR. In particular DIN yields (87.5 x 10^{3}mol km^{-2} year^{-1}) of the BR would be much higher as estimated for a wet and dry season year. In contrast the PO_4^{3-} yields (3.2 x 10^3 mol km^{-2} year^{-1}) would increase just slightly showing the importance of nutrient recycling within the estuaries during the dry periods.

Summary and Conclusions

The Brantas River Estuary is a highly dynamic system characterized by strong variations in seasonal river discharge and massive anthropogenic alterations along the whole watershed, with a densely urbanized and agricultural dominated upper watershed and large areas of aquaculture ponds coating the whole coastal area. In particular the DIN composition in the rivers and tidal channels of the study region were coupled to variations in the anthropogenic altered landscape, showing an additional input of NH_4^+ in the densely urbanized lower reaches. The mud volcano had a strong local and temporal effect on the PR, as during low flow periods the DO levels decreased drastically in correlation with a strong shift in the DIN composition indicating a high release of NH_4^+ into river waters.

Nutrient input into the estuaries was strongly controlled by the seasonal and spatial discharge patterns of the WR and PR with highest loads of NO_3^- and PO_4^{3-} being introduced by the PR during the wet periods. Variations in the exchange times and nutrient budgets suggest that the main parts of NO_3^- were directly exported to the Madura Strait during the wet periods. In contrast, the increasing residence time causes a higher retention of DIN during dry periods mainly controlled by phytoplankton uptake. Seasonal comparisons showed a net release of NH_4^+ and PO_4^{3-} in both seasons, especially during dry periods indicating that benthic recycling may additionally fuel the nutrient pool in the estuaries.

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