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Water Quality Time-series Data of the Lower Brantas River, East Java, Indonesia: Results from an Automated Water Quality Monitoring Station

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Abstract: Using an automated water quality station in the lower Brantas River, East Java, Indonesia, highly time-resolved time series (1 min^{-1}) of main parameters that govern water quality have been measured (oxygen, chlorophyll-*a*, turbidity, nutrients, total inorganic and organic carbon) from 2003 to 2008. All parameters showed distinct seasonal variations related to dry and wet seasons. Due to the large input of organic material from sewage and industry into the river the most important parameter is the dissolved oxygen that displays a distinct seasonal behaviour with relatively large values during wet season and very low values in dry season. In addition, during dry season high variations between day and night were observed with zero oxygen concentrations at night. From highly time-resolved oxygen time series the main metabolic rates (primary production, respiration) together with atmospheric exchange rates could be calculated in a semi-quantitative way. From this, it could be estimated that the anthropogenic carbon input into the river has to be reduced from about 70 t/d BOD equivalents to at least 33 t/d in order to prevent anaerobic conditions.

Key words: Water quality, automated monitoring, time series, oxygen, BOD, respiration, atmospheric exchange, Indonesia, Brantas.

Introduction

Water quality management of rivers is not only an issue in highly industrialized countries but has become an important target in many developing countries. The increasing deterioration of water quality has especially led not only to ecological problems, e.g., loss of habitats and species but as well to many economic problems. Among those are a decrease of profit from fishing and fish farming, an increase of costs for drinking water processing and increased costs of health care system due to diseases caused by polluted water. In order to improve the water quality for a river system a reduction of discharge of domestic and industrial wastes is necessary. However, since this will influence the economy of the country it is of paramount importance to identify measures with the best cost-benefit relationship, i.e., to identify those dischargers for which a reduction will have a major effect on the entire ecosystem. For this a sound knowledge about the processes in the river system is necessary.

Typically, the control of water quality in a river system is carried out by regular, e.g., monthly, sampling campaigns at different locations. However, this approach has two disadvantages:

1. Due to the long time span between sampling illegal discharges or accidents that degrade the water quality, it will mostly go undetected.
2. From these infrequent data points it is not possible to gain a profound insight into the dominant processes

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that control water quality and to get data for running water quality models.

As a consequence, modern water quality control strategies comprise automated monitoring stations at strategic locations, in addition to the routine sampling. The advantages for automated monitoring stations are:
1. continuous and high resolution time series that allow the detection of events;
2. less human-resource allocation than for manual field campaigns; and
3. easy data processing (data are already automatically stored in data bases).

The disadvantages of automated stations are:
1. high investment costs;
2. technical skilled persons for operations and maintenance necessary; and
3. only for parameters that can be measured automatically (however, automated event-triggered samplers can be used for later lab analyses).

Following this strategy an automated monitoring station (MERMAID Brantas Station) was installed at the lower Brantas River in East Java, Indonesia. Since this station is among very few functioning stations in tropical rivers in the world, a thorough description that includes technical details, costs and availability is given in Schroeder et al. (2012).

In this paper the results of five years of operation of this station will be presented and discussed. Highly resolved time series will be discussed on different time scales (day-night, seasonal annual changes). With focus on the dynamics of oxygen concentrations, calculations of metabolic rates such as the net ecosystem production will be given. A rough valuation will be given about how much the anthropogenic organic carbon load has to be reduced in order to keep the oxygen values in the river above critical values.

Material and Methods

Study Area

The Brantas River basin is one of the largest river systems in Indonesia. It has a watershed of 11,800 km^2 and stretches 320 km from its spring at Mount Arjuna to the point where it branches into two rivers, Surabaya River and Porong River, both ending into the Madura Strait (Figure 1). Approximately 10 km upstream of Surabaya City the river branches into the Kali Mas with a low volume of water passing Surabaya City and the eastward-directed Wonokromo River which discharges into Madura Strait 30 km north of the Porong River (Figure 2). Due to high sediment loads, particularly during the wet season, the Porong has an expanding delta (Jennerjahn et al., 2004). The basin is located within the

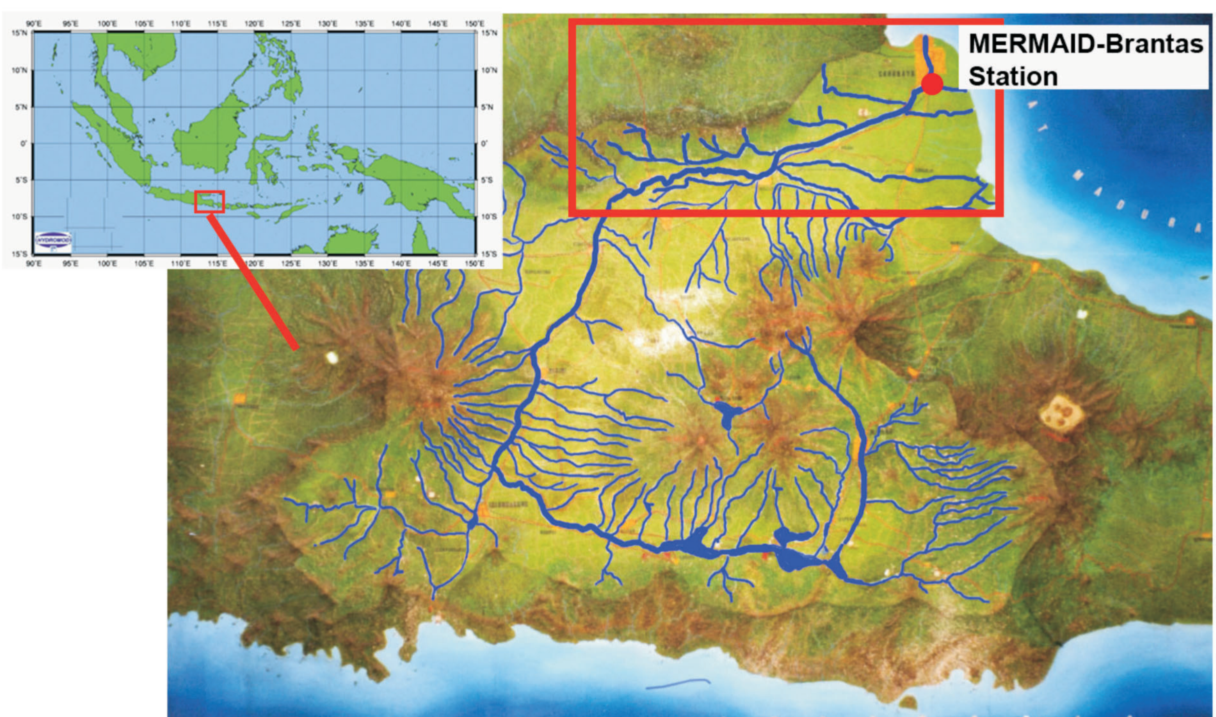

Figure 1: Catchment of the Brantas River in Java, Indonesia. The location of the MERMAID station is marked. The area in the red rectangle is magnified in Figure 2.

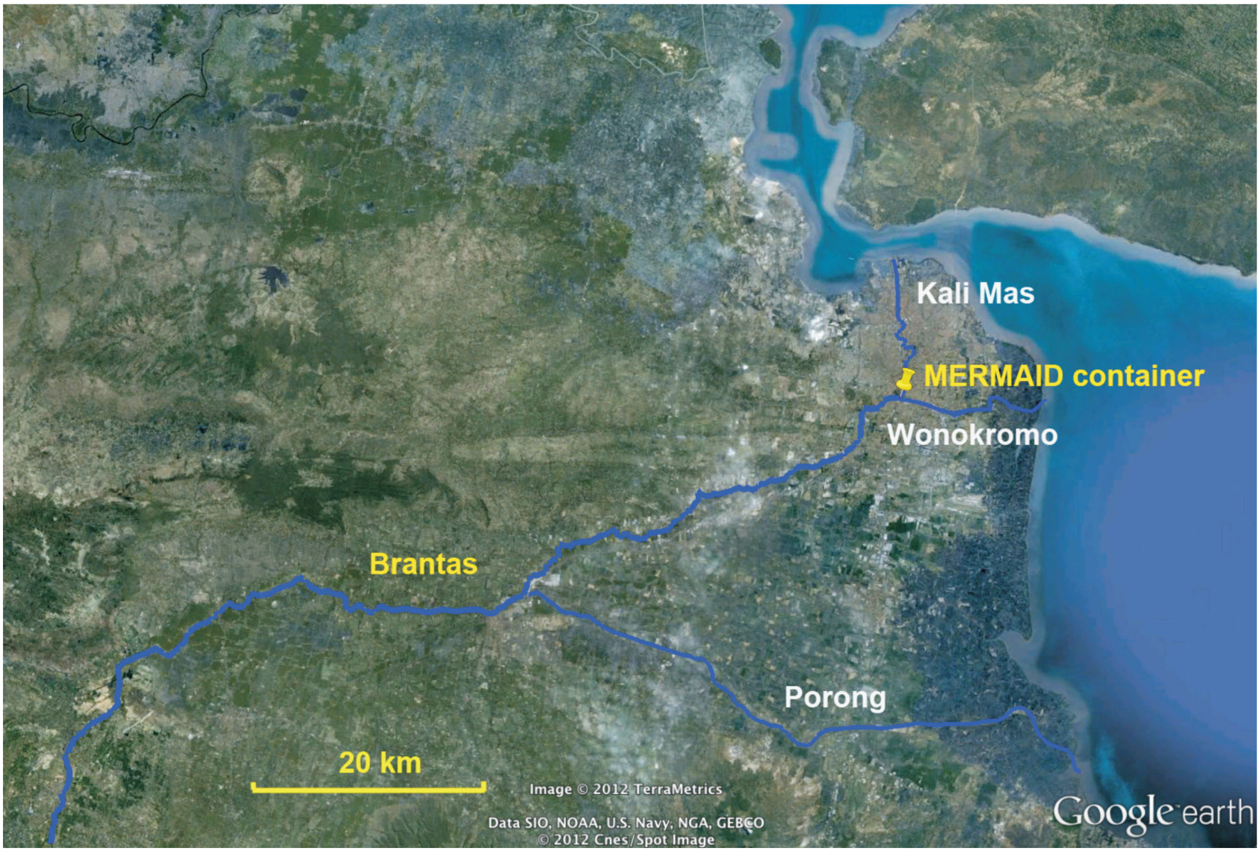

Figure 2: Map of the lower Brantas river with tributaries (magnified portion of Figure 1).

Inter-tropical Convergence Zone with distinct wet and dry seasons (November-April and May-October, respectively), During the wet season there are around 25 rainy days per month, compared to seven or fewer during the dry season. Annual precipitation is around 2000 mm on an average, with roughly 80% occurring in the wet season. Mean annual temperature is about 26°C (Adi, 2012).

The agricultural economy of the basin is centred on the cultivation of irrigated paddy fields. Other important food and cash crops include maize, cassava, soybeans, peanuts, tobacco, coffee and sugarcane. In this context, the Brantas River System functions as the most important source of water supply in the East Java Province (Sudaryanti et al., 2001). Almost all the water of the Brantas River in the dry season is utilized (Binnie, 1999). The population of the Brantas River basin is estimated at more than 16 million representing around 43% of the total population of East Java. In the Brantas River basin, industry production increased 184-fold within 30 years (Country Report Indonesia, 2001; Fujimoto, 2011; Bhat et al., 2005).

Water quality in the Brantas River is often poor, especially the Lower Brantas-Surabaya area. During the dry season, when the water discharge from upstream is low, a very poor water quality is reflected in low oxygen contents for most of the river. Biological Oxygen Demand (BOD_5) is ranging from 5 to 12 mg l^{-1} (Harnanto and Hidayat, 2000; Aldrian et al., 2008). Domestic wastewater is one of the important sources of organic materials, nutrients, and microbiological water pollution in Brantas River. The rapid population development and urbanization caused concentrated settlement especially in urban areas, such as Surabaya Metropolitan with 8149 inhabitants/km^2 of population density in 2000 (Harnanto and Hidayat, 2000).

The amount of population load from the densely populated areas is more than that of assimilative capacity in the river during the dry season. In semi-urban and rural areas, where infrastructures are rarely as well developed as in urban areas, sanitation facilities are usually insufficient and less maintained, if any. Domestic pollution load can be estimated by multiplying domestic pollutant load per capita by the population. This 'population equivalent' refers to the amount of oxygen demanding substances whose oxygen consumption during biodegradation equals the average oxygen demand of the waste water (BOD load) produced by one person (population equivalent for rural environment = 35 gram BOD/individual/day; for urban environment = 46 gram BOD/individual/day). Total domestic pollution load being produced is about 515 tons/day of BOD load in the whole basin (Harnanto and Hidayat, 2000).

In accordance with waste water treatment terminology (e.g., US Environmental Protection Agency), the terms ‘BOD load’ or ‘BOD equivalent’ in metric tons per day are used as an equivalent for the amount of easily degradable organic matter. One t/d BOD equivalent uses one t/d oxygen for organic matter degradation. Industrial wastewater is discharged from a number of industries. In 2000 about 483 industrial plants directly affected the Brantas River and major tributaries in terms of pollution from effluent and their total net load of organic carbon load contribution is estimated to be an equivalent of 125 ton BOD/day.

The following industries are mainly responsible for discharging organic matter into the river: yeast and derivative, sugar from cane, paper production from pulp, starch or sugar from tapioca, monosodium-glutamate production, tanneries and dyes and coconut-oil. Taking into account number of sites too, the top two categories discharging organic matter into the river are yeast and derivatives (five factories), and sugar (10 factories). Total BOD loads produced from these top two categories are about 158 ton/day and 128 ton/day, respectively (Harnanto and Hidayat, 2000). Contrary to these large figures the contribution of agriculture to the organic load can be assumed to be small. Since the return flow of the rivers from the irrigated areas is often nil during dry season, the input of nutrients by erosion from the fields will be important, especially in wet season. However, no estimation for these loads exists. In the Brantas Basin a governmental monitoring programme exists since several years. It is organised by Bappedal Propinsi Jawa Timur and carried out by Perum Jasa Tirta (www.jasatirta2.co.id). Within this context the Austrian company Verbundplan constructed 23 monitoring stations along the Brantas River. In the most downstream regions the oxygen concentrations fall below the critical value of 2 g/m^3 (Perum Jasa Tirta, 2007).

The water depth of the river is regulated manually by the authorities within ±20 cm by alternately opening and closing of weirs above and below the container location. During very low freshwater discharge (upstream) the water level is only regulated 1-2 times a day; during high discharge this occurs much more frequently. At the transition between wet and dry seasons the current velocity drops from 40 cm/s in March to near-zero value in October.

Sampling and Analysis

Before building the monitoring station some field campaigns have been carried out in order to get an overview of the pollution conditions. A field campaign together with the Federal Maritime and Hydrographic Agency (BSH) in Germany showed that no severe contamination with heavy metals, PAHs, chlorinated hydrocarbons and pesticides in water and sediment occurs (Nies et al., 2007). After the position of the monitoring station at the confluence of Kali Mas and Wonokromo had been chosen a field campaign clarified the nutrient conditions in the vicinity of the station in the Kali Mas and Wonokromo: in the rivers there is a gradient from land to sea for all three nutrients. In coastal waters with salinities above 30 the concentrations are comparatively large (NH_4: 0.1-0.4 mgN l^{-1} = 7-28 µmM; NO_3: 0.1-0.5 mgN l^{-1} = 7-35 µM, o-PO_4: 0.02-0.16 mgP l^{-1} = 0.6-5 µM). The conditions of the Porong River are different: While the concentrations of ammonium and o-phosphorus are lower than in the Wonokromo, high nitrate concentrations of upto 1.2 mg l^{-1} = 78 µM were found. These findings were consistent with those of Jennerjahn et al. (2004), in dry season.

Measurement Methods at the MERMAID Station

Location and Principle

The MERMAID Brantas monitoring station is located at the confluence of the Kali Mas and Wonokromo River, about 17 km from the ocean (see Figure 2). Due to infrastructure constraints its location is within the city of Surabaya. Many industrial and domestic discharges occur within 50 km upstream of the station. There are no sewage plants in the city, but many small channels discharge domestic sewage into the river. The MERMAID measuring system takes its water from the river by a pump and feeds it into a hydraulic loop that contains several sensors and chemical analysers. The system is fully automated, including cleaning and antifouling modules. The principle of the system is depicted in Figure 3; a detailed description can be found at Schroeder et al. (2012).

Instruments and Measurements Intervals

The following sensors are installed:

Conductivity:	4-conductor cell MECON-4R, MECOTEC, Elmshorn, Germany
Oxygen:	Membrane-covered electrode COS4 with electronic unit liquisys M COM 223, Endress & Hauser, Germany
Turbidity:	180° scattering at 800 nm, liquisys M CUM 223, Endress & Hauser, Germany

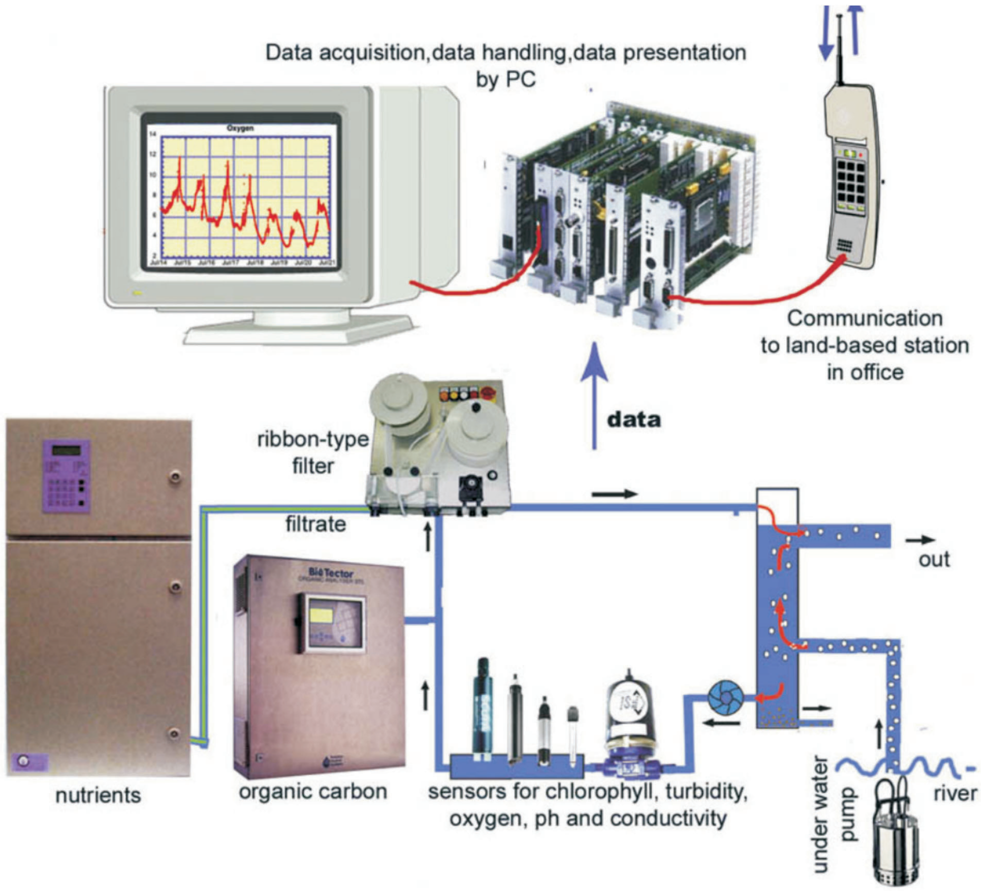

Figure 3: Measuring principle of the MERMAID system.

pH: Glass electrode orbsint CPS11 with electronic unit liquisys M CPM 223, Endress & Hauser, Germany

Chlorophyll-*a* -fluorescence: WETStar (Chl) fluorometer from WETLabs, USA

TOC & TIC: BioTector analyser (BioTector Analytical Systems Ltd, Ireland). Principle: TIC removal with HCl and oxidation of organic matter with ozone.

Nutrients: NH_4^+, NO_3^- and o-PO_4^{3-} are measured with automated analyser Micromac C, Systea, Italy: Loop flow automated wet analysis after automated filtration with ribbon-type filter. Analysis after the method of Strickland and Parsons (1972), described in detail in Grunwald et al. (2007) and Azzaro and Galletta (2006).

A weather station is installed above the roof of the container. Due to large trees in the vicinity the wind velocity may be disturbed.

Global irradiation: Pyranometer CMP11 from Adolf Thies GmbH, Germany

Wind velocity/-direction: Wind sensor Classic from Adolf Thies GmbH, Germany

The measurement intervals for conductivity, oxygen, turbidity, pH and chlorophyll were 1 s^{-1}. However for practical purposes the values were averaged over one minute. The nutrients and the TOC/TIC were measured every second hour only.

Calibration Methods

Oxygen: Water saturated air, monthly

Conductivity: KCl solution, once a year

Turbidity: Formazin standard, monthly

pH: pH standards, bi-weekly

Chlorophyll-*a*-fluorescence: Comparison with a chlorophyll-*a* standard, once a year

TOC/TIC: Reference standard from OI Analytical, USA, once a year

Nutrients: Samples were filtered through single use membrane filters and stored cool and dark until analysis. The analyses were carried out in the lab of Dinas Pengeiran with standard photometric methods (Grasshoff et al., 1999), every six months

Whereas all sensors are regularly calibrated directly in the station, nutrient measurements were compared with samples and consecutive lab analyses. In order to test the function of the filtration and automated nutrient analyses a comparison for nitrate and ammonia was carried out in October 2003 (Figure 4). The samples for lab analyses were taken from the hydraulic loop of the MERMAID station prior to filtration and processes as described above. Considering the different types of filters used the agreement is satisfying.

Representativeness

Since the station gets its water from near the banks of the river the representativeness of the location for the whole river cross-section had to be demonstrated. For this purpose, samples from the station were compared with those from the middle of the river (taken from a bridge) in October 2003 (Figure 5). Shown are samples/lab analyses from the station in front of the automatic filter (Sf) and from the bridge in the middle of the river (B) together with automated measurements from the nutrient analysers (MM) over a whole day. Whereas in general, the agreement is satisfying, differences of the automated nitrate measurements at the beginning are unclear. Presumably this was caused by some transient effect of the analyser after change of reagents. However, this was not observed during other comparisons. Due to a malfunction of the ammonia analyser measurements only exist from the afternoon.

Data Analysis

The time series from the MERMAID stations were analysed in different time scales: on an annual basis to assess the seasonal variations, monthly or weekly to show the transition between dry and wet seasons and daily to get more information on the biogeochemical processes

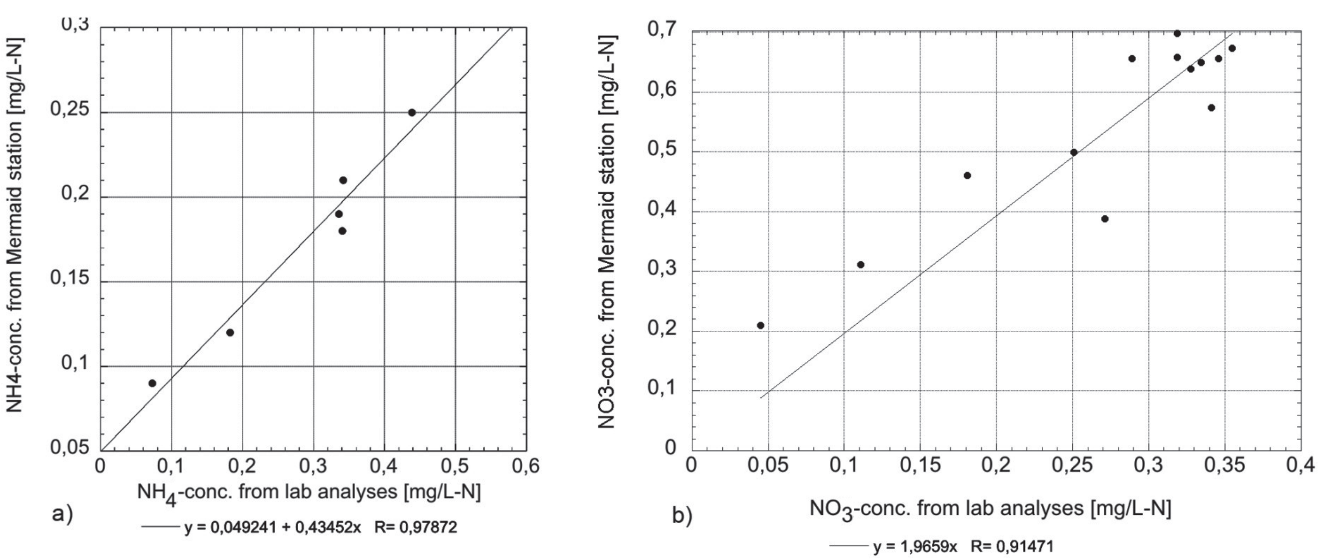

Figure 4: Comparison of automated nitrate and ammonium measurements with lab analyses. The lab samples were taken from the MERMAID hydraulic loop before the filter unit.

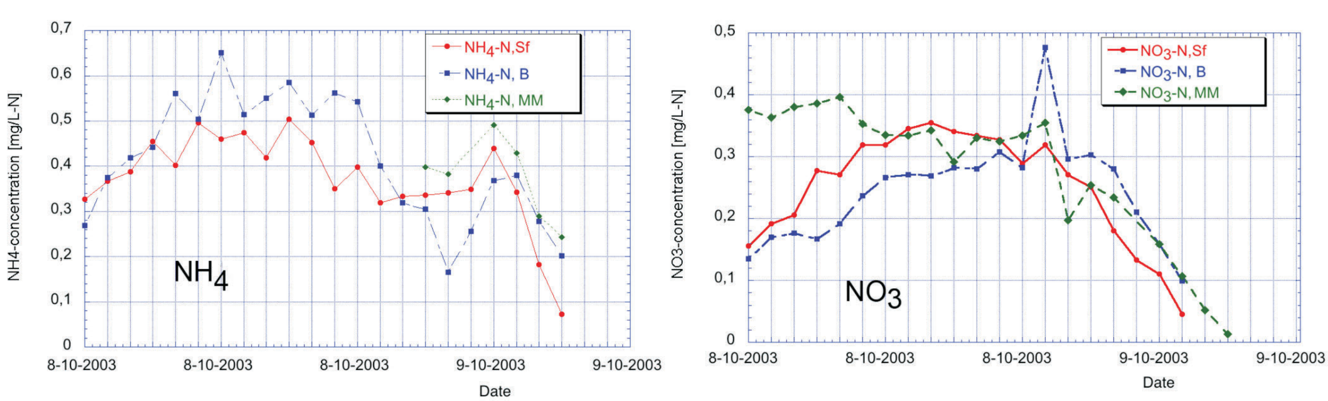

Figure 5: Representativity of the MERMAID station: Comparison of lab nutrient analyses from the bank of the river (Sf), from a bridge in the middle of the river (B) and from automated MERMAID measurements (MM).

that occur with day-night cycles. In addition statistical values such as median and min/max values were calculated with the annual data in order to get information on the frequency of regular events such as oxygen depletion.

Calculation of the Average River Cross-section and Travel Times

Since only few data on the Brantas topography exist, the average river cross-section has to be estimated for further interpretations. This was carried out by comparison of conductivity measurements from the two Verbundplan stations Jrebeng (km 273) and Canggu (260) with the MERMAID Station (km 300). Structures in the time series that occurred at the upstream stations could be found several hours later at the MERMAID station. From this the flow velocity and the average cross-section could be estimated. The river cross-section results as 50 m^2 with an average water depth of 2 m. From this the travel time τ of the water body between km 260 and km 300 in dependence on the freshwater discharge V can be calculated:

$$\tau = q \times L/V \tag{1}$$

where L is travel length, q = average cross-section (width × depth), and V is freshwater discharge.

With $q = 50 \times 2 = 100$ m^2 and L = 40,000 m the following travel time result:

Dry season: Typical discharge = 11 m^3/s
travel time = 4.3 days
Wet season: Typical discharge = 80 m^3/s
travel time = 0.6 days

For future studies of the coastal waters this will be important since from these travel times it depends if degradable carbon will reach the coastal waters or if it is consumed within the river, only leaving the mineralised nutrients.

Estimation of Stream Metabolism

Primary production and respiration are the major metabolic pathways by which organic matter is produced and destroyed. Gross primary production (GPP) is the gross fixation of inorganic C by photosynthesis, respiration (R) is the remineralization of organic C to CO_2. Net ecosystem production (NEP) is the difference between GPP and R. NEP, which can be positive or negative, represents the overall metabolic balance of an ecosystem (Howarth et al., 1996). When NEP is positive, GPP exceeds R, and the system can export or store organic carbon (Schindler et al., 1998). When NEP is negative, R exceeds GPP and the system respires more organic C than was produced by primary production within the system's boundaries. Sustained negative values of NEP, or GPP/R ratios imply that a system's respiration is subsidized by organic matter that was imported from outside of its boundaries. In rivers such as the Brantas the ecosystem receives organic carbon from multiple autochthonous and allochthonous sources that uncouples ecosystem respiration from planktonic primary production (Wetzel, 1972; Howarth et al., 1996).

Diurnal profiles of measured oxygen concentration as measured with the MERMAID station can be applied for an estimation of the different process rates. One of the first detailed evaluation of oxygen profiles was carried out by Odum (1956). The method is based on a graphical evaluation of diurnal oxygen concentrations. This is due to the fact that the oxygen curves result as a combination of the following processes:

1. Release of oxygen into the water as a result of photosynthetic primary production by phytoplankton during daylight.
2. Uptake of oxygen from the water as a result of the respiration of benthic organisms, planktonic organisms, and (bio)chemical oxidation.
3. Exchange of oxygen with the air in a direction depending on the saturation gradient.

In form of an equation this is:

$$\Delta c_{ox}/\Delta t = \mathrm{GPP} - R - A \tag{2}$$

where $\Delta c_{ox}/\Delta t$ is change of measured oxygen concentrations with time, GPP = gross primary production, R = algal and bacterial respiration (includes degradation of the organic carbon discharged by domestic and industrial sources), A is exchange rate with atmosphere (= flux through surface, F_{ox}, divided by mean depth H) [g/(m^3 day)].

Therefore, the slopes of the oxygen curve give information on gross primary production, respiration and the exchange coefficient with atmosphere. In order to evaluate the curves in a quantitative way it has to be assumed that:

(a) The respiration of plankton and bacteria does not change very much over the day due to dispersion or mixing with other water masses (identical changes in dissolved oxygen will occur simultaneously throughout the water mass which will pass the point of measurement during the diurnal period).
(b) The respiration in the night is the same as during daylight.
(c) The water column is well mixed.
(d) Diffusion into or out of the water depends primarily on the saturation gradient. Since diffusion is related

directly to stream velocity, variations in velocity are small.

While assumptions (a) and (c-d) will be valid for the Brantas, assumption (b) cannot be fully met since the respiration at low oxygen values is somewhat dependent upon oxygen concentrations (Staehr et al., 2010) and in the Brantas the oxygen concentrations reach 0 during the night. Other authors refined the Odum methods (Pomeroy, 1938; Seeley, 1969). Chapra and Di Toro (1991) developed the "delta method" which uses the average dissolved oxygen deficit, the daily range in the deficit, and the time of minimum deficit in a graphical approach to estimate respiration rate, gross primary production rate, and re-aeration rate, respectively. A similar method was used by Williams et al. (2000). Later Mulholland et al. (2005) extended the methods and, for example, found a good correlation between the amplitude of the diurnal dissolved oxygen deficit profiles and gross primary production.

The oxygen flux between atmosphere and water can be calculated by the following formula (Staehr et al., 2010):

$$F_{ox} = K_2 \times H \times (c_s - c_{ox}) \qquad (3)$$

where K_2 is aeration coefficient [d^{-1}], H = water depth [m], c_s = oxygen saturation concentration and c_{ox} is actual oxygen concentration [g/m^3]. At 30°C c_s is about 7.5 g/m^3 (fresh water). K_2 depends on different parameters, e.g., flow velocity, turbulence (wind) etc. In the literature a parameterization for K_2 has been carried out with data of many streams, for example O'Connor and Dobbins (1958) for moderately deep to deep channels, Parkhurst and Pomeroy (1972), Bansal (1973), Dobbins (1964), Churchill et al. (1962), Bennet and Rathbun (1972) (evaluation of 13 equations from literature), and many other authors. The parameterizations under the conditions of the Brantas during dry season (H = 2 m, flow velocity ~0.1- 0.2 m/s) give values of k_2 between 1 and 1.7 d^{-1}, resulting in calculated oxygen fluxes at night (anaerobic conditions, c = 0) between 15 and 25 $g/(m^2 \times d)$ (= 0.6-1.04 $g/(m^2 \times h)$). For further considerations a value of 1.5 d^{-1} will be used.

The net ecosystem production, NEP, that is shown in Figure 13e, calculates during day time (Staehr et al., 2010):

$$NEP_{daytime} = \Delta c_{ox}/\Delta t - F_{ox}/H \ \ [g/(m^2 \times h)] \qquad (4)$$

where $\Delta c_{ox}/\Delta t$ is hourly changes in oxygen concentration [$g/(m^3 \times h)$], F = atmospheric flux [$g/(m^2 \times h)$] and H is mean water depth.

Results and Discussion

Overview: Time Series Measurements between 2003 and 2008

Measurements from the MERMAID Brantas station were carried out from 2003 until the end of 2008. As an overview the complete time series of oxygen is presented in Figure 6. The freshwater discharge at the Wonokromo River is depicted on top and the oxygen concentrations are shown below. The discharge changes between 7 m^3/s during dry season (white areas) and up to 100 m^3/s during wet season (grey areas). At some years the same temporal pattern can be seen in the oxygen concentrations: During dry season the concentrations fluctuate (on a daily basis) between zero at night and 3-4 mg l^{-1} during day (compare Figure 11). During wet season the minima seldom reach values below 1 mg l^{-1} at night and mostly are above 2-3 mg l^{-1} during daytime. However, apart from this general scheme there are interannual differences and many fluctuations that may be caused by different cloud coverage, changing river currents and varying pollution (input of organic materials). In order to interpret the oxygen fluctuations and get a better insight into the involved processes higher time-resolved time series have to be analysed.

Time Series January 2003 until April 2004

The following diagrams show results of time series measurements for the period January 2003-March 2004. In Figure 7 the one-year time series of freshwater discharge at Gunungsari (10 km upstream, taken from Jasa Tirta database, daily values) are depicted together with the daily medians and daily minima and maxima of the following parameters: water temperature, conductivity, turbidity, chlorophyll-*a*, and oxygen. In addition, the two-hourly concentrations of ammonium, nitrate, o-phosphate and total inorganic carbon (TIC) are shown. In the discharge curve the wet and dry seasons can clearly be identified. All other variables show more or less a dependence on the dry/wet season as well. Water temperature shows more daily fluctuations during dry season with higher values during early afternoon: Due to the slow current velocities in dry season the water can warm up and cool down faster. Remarkable is the increase at the end of the dry season and the fast drop of temperature when the first rain start. Conductivity as a measure for salinity is slightly higher during dry season and drops when the rain starts (dilution). Turbidity shows high fluctuation with large peaks in wet season until mid-May and from mid-November. It remains very low until mid-November when the wet season starts. Chlorophyll-*a*

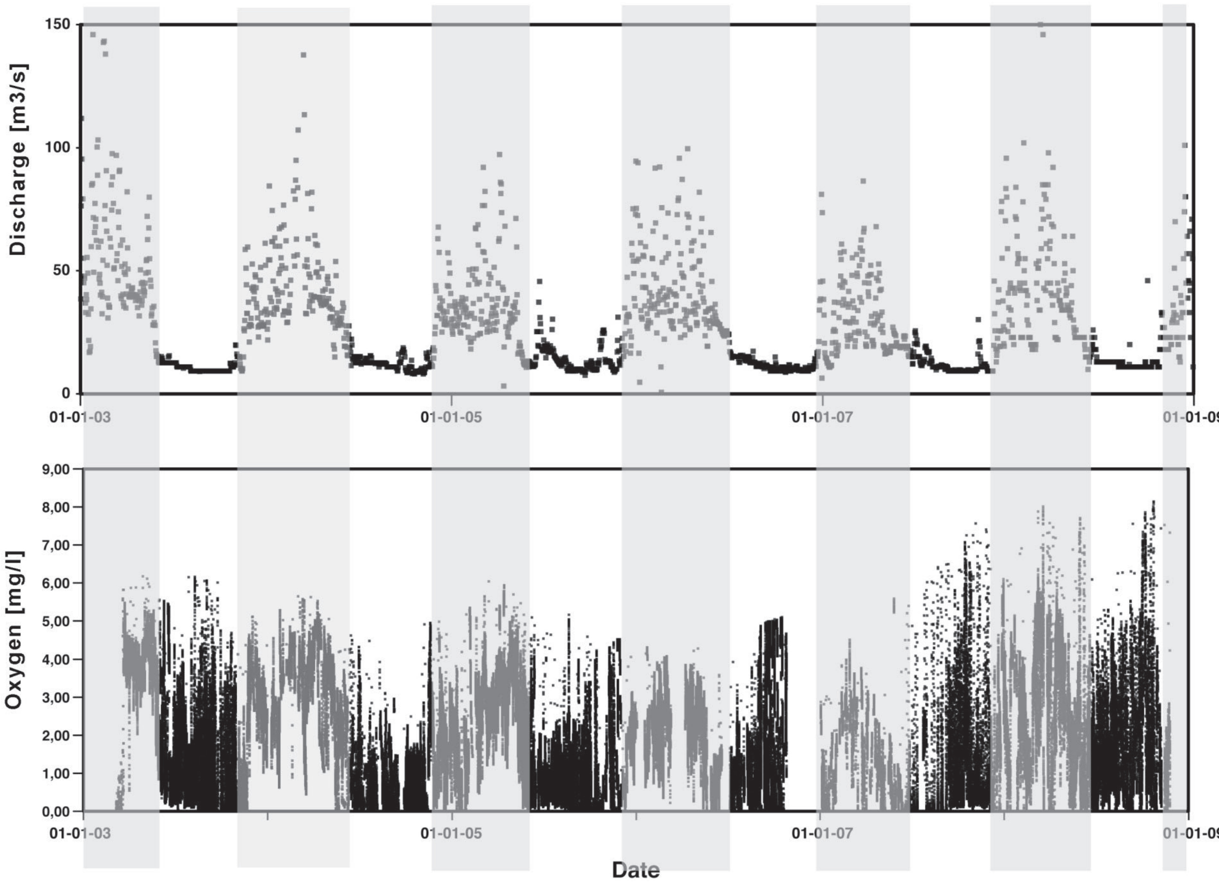

Figure 6: Overview of the oxygen conditions in the years 2003-2009. Top: Discharge (Data from Jasa Tirta). Bottom: Measured oxygen concentrations.

concentrations show the opposite behaviour with high and fluctuating values during the dry season. In wet season the daily median values are below 10 µg l^{-1}. They increase starting from mid-May until November (dry season) with a high variability: at night concentrations are mostly 10 µg l^{-1} and day concentrations rise up to 40 µg l^{-1}. The reasons for this are good growing conditions mainly due to high light availability, low turbidity and high solar irradiation during daylight. The oxygen concentrations show a very distinct seasonal behaviour: During wet season the median values are between 2 and 5 mg l^{-1} with the median only slightly below the middle between max and min values. During dry season the concentrations vary between 0 and 2 mg l^{-1} with the median very near the min values. The reasons for this are:

1. Large consumption processes (mainly carbon-BOD), that bring down the oxygen concentrations during night to near zero values.
2. Large primary production during daylight that increases the oxygen concentrations up to 4 mg l^{-1} and compensate the consumption.
3. Small input of atmospheric oxygen by small atmosphere-exchange due to small current velocities and little wind so that the near-zero concentrations at night cannot be increased.

The seasonal variations of ammonium, nitrate, o-phosphate and TIC are not so distinct. However, especially ammonium (NH_4) concentrations are elevated during dry season. Presumably, this is caused by a decrease of nitrification due to low oxygen values during night so that ammonium can accumulate despite larger uptake by the increased phytoplankton. Total inorganic carbon is larger during dry season since carbonates formed by decomposition of organic matter can accumulate due to larger residence times of the water bodies during dry season. This is consistent with data from Aldrian et al. (2008).

For a better view on the transition between dry and wet seasons in Figure 8 the relationships are depicted for the period between November 15 and November 29, 2003. It can be seen that all variables change, but with different time delay in comparison to the discharge. For example, the variables TIC, water temperature and

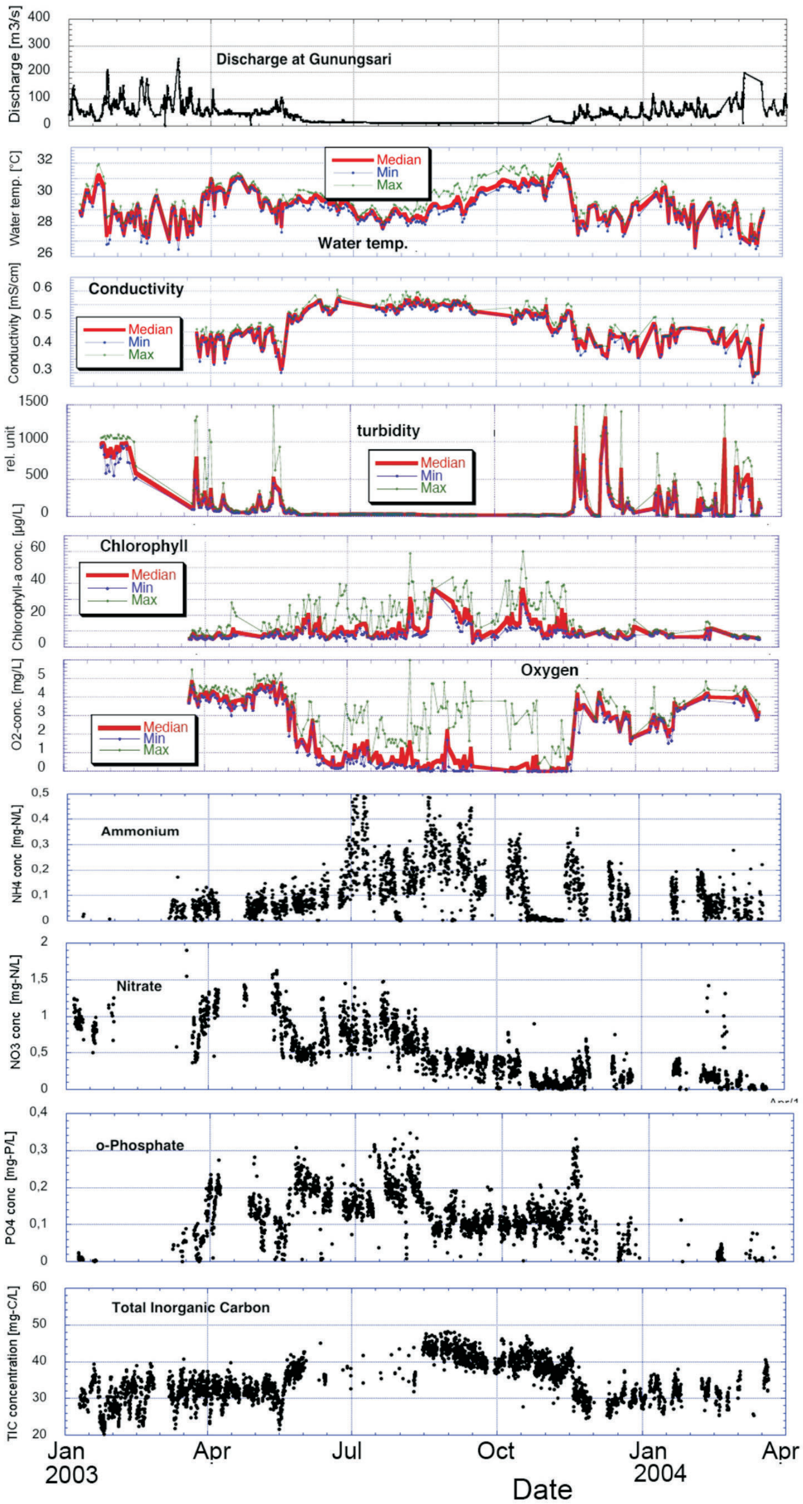

Figure 7: Daily median and min/max values of continuously measured parameters from January 2003 until April 2004. From top: fresh water discharge (daily values), water temperature (median), electric conductivity (median), turbidity (median), chlorophyll-*a*-fluorescence (median), dissolved oxygen (median). For nutrients and organic carbon single data measured every second hour are shown: ammonium, nitrate, o-phosphate, total inorganic carbon. Red: Daily median values, Green: Daily maximum values, Blue: Daily minimum values.

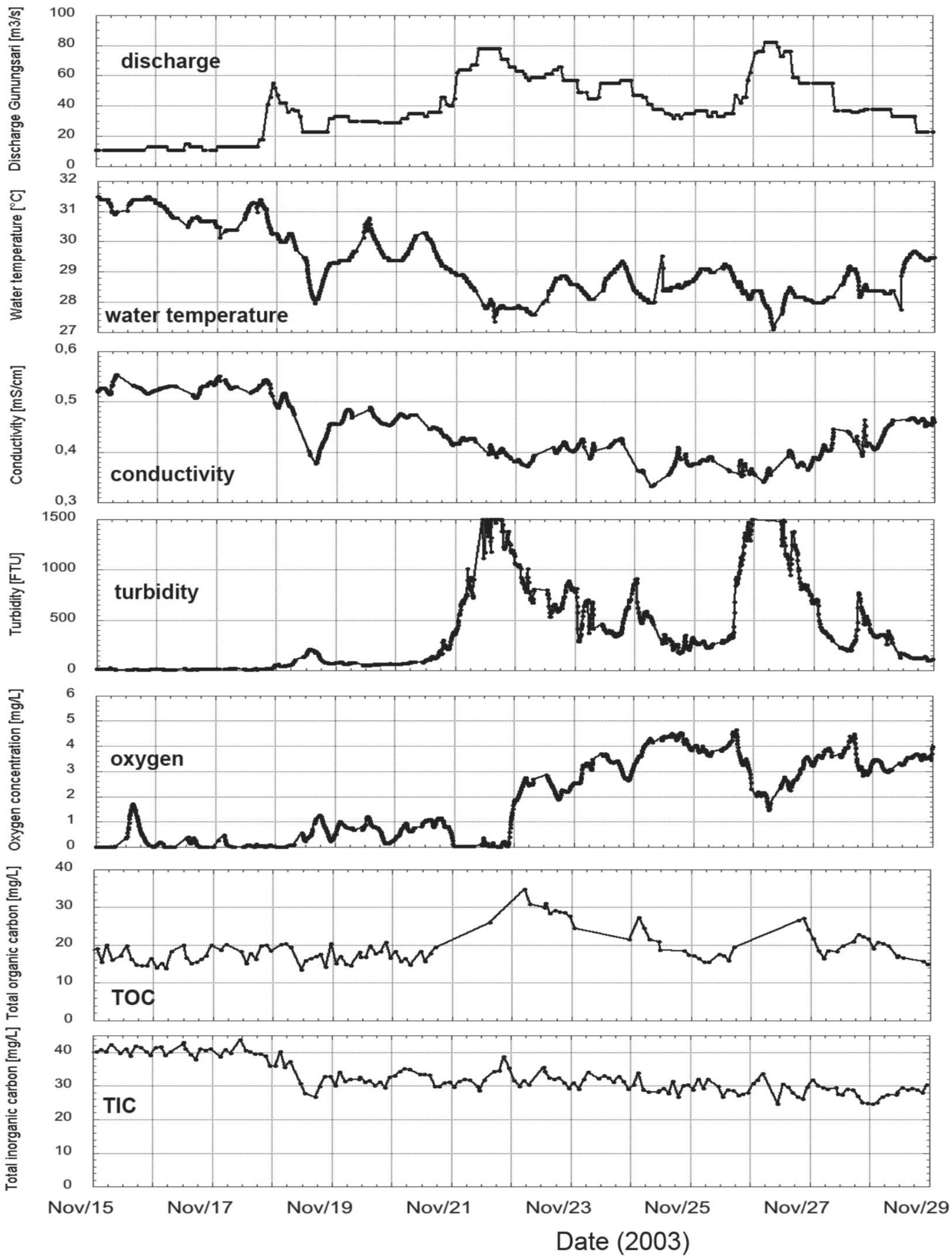

Figure 8: Daily median values of different parameters from November 15, until November 29, 2003.

conductivity follow nearly immediately the increase of discharge from 15 to 60 m^3/s on 18.11.03 since they are related to the water phase (dissolved). Turbidity and TOC follow only three days later (21.11.03) together with the second step of freshwater increase. This can be expected since the increase of turbidity (= increase of suspended matter concentration) is due to resuspension/erosion of suspended particles by the rain – either from the reservoirs or from soil from upstream fields. The TOC concentrations increase together with turbidity since the suspended particles contain relatively high amount of organic matter. The increase is not so large because presumably the suspended matter contains less particulate organic matter during high discharge. TIC, on the other hand, is mostly related to dissolved carbonates (which originate from organic carbon degradation) that decrease immediately with the increasing water discharge due to dilution.

Oxygen shows another behaviour: After the first increase of discharge the concentrations increase slightly to 1 mg l^{-1} and then fall down again to near-zero values for one day together with the increasing suspended matter. Only later uncritical values of >3 mg l^{-1} are reached. It seems that the first water body coming from upstream with the increased turbidity and TOC has a higher oxygen demand which cannot be compensated for by the higher exchange with atmosphere caused by the increased current velocity.

Interannual Variability (2005/2006)

For clarity, the discussions above were conducted for the year 2003-04 only. To demonstrate the similarity between the different years Figure 9 shows a comparison between the years 2005 and 2006 for the daily medians of turbidity and oxygen. In 2006 the station was not running between October 28 until the end of the year due to malfunction of a computer. In both years the median values of the turbidity were between 300 and 500 during wet season and about 10-30 during dry season. In 2005 the wet season stopped about three weeks earlier than in 2006. In 2005 the second wet season started in November. The dynamic of oxygen was comparable in the two years with slightly smaller median concentrations during wet season in 2006. During dry season the median oxygen concentrations were larger in 2006. Since the maximum concentrations are not shown in this figure, the large daily variations during dry season are not visible (see next paragraph). The spikes that occur occasionally, originate from some maintenance operations during which the data acquisition was not stopped by mistake.

Day-night Variability

From the prior discussions it became clear that there is a high daily variability of oxygen during dry season. In Figure 10 the oxygen concentrations are depicted for the period July to November 2003. The concentrations during daylight are drawn in red and the concentrations during night in blue. As can clearly be seen the night concentrations are nearly always below 1 mg l^{-1}, while the daily maxima reach 3 mg l^{-1}. However, in the morning hours and in the afternoon the concentrations are low as well. In order to look in detail at these dynamics the

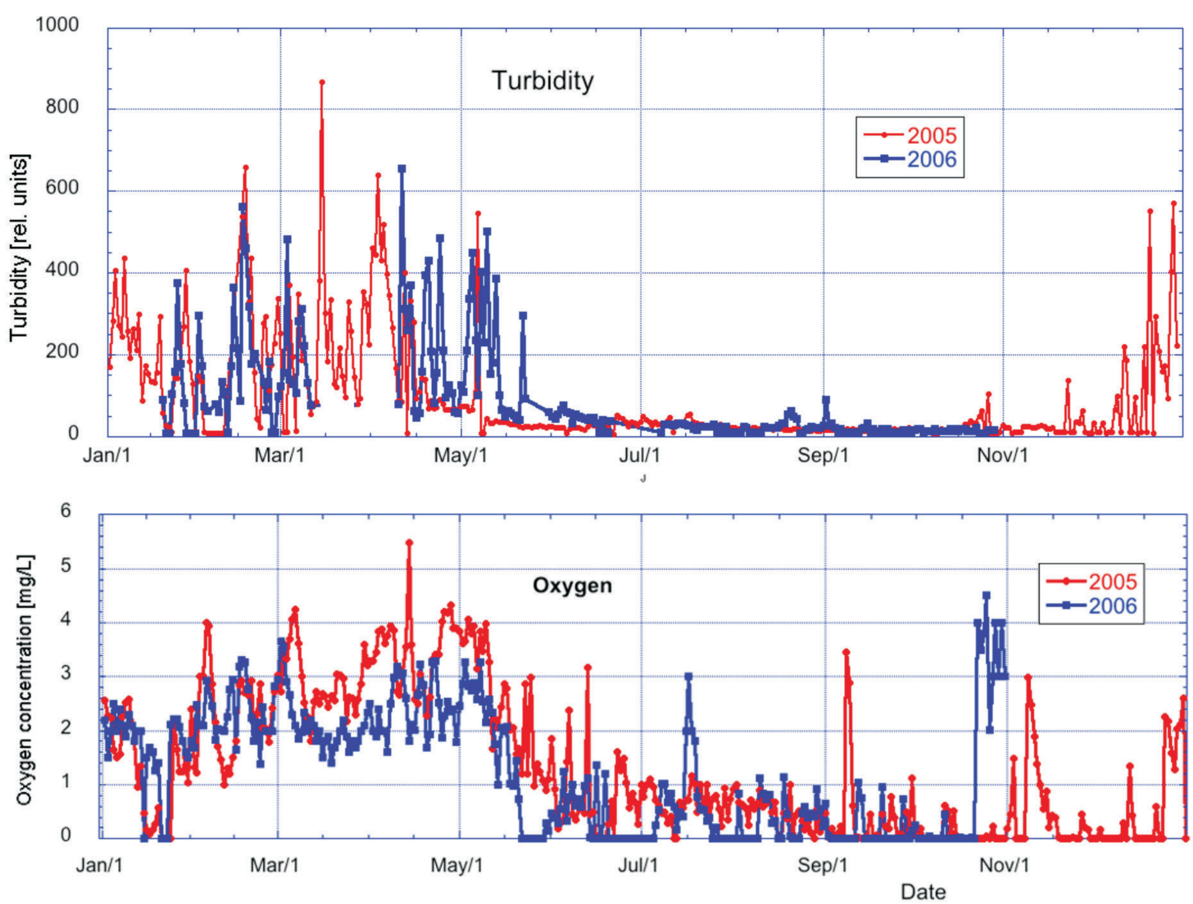

Figure 9: Comparison of daily median values of turbidity (top) and turbidity (bottom) between the years 2005 and 2006. Red: 2005, blue: 2006.

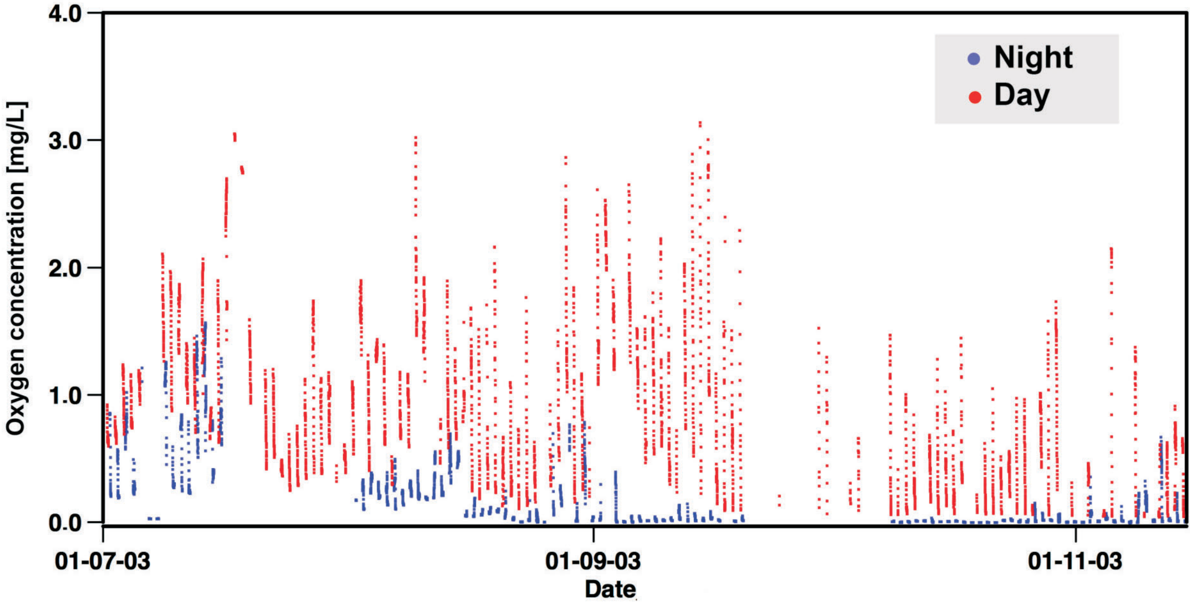

Figure 10: Dissolved oxygen concentrations for July to November 2003. Red: Values during day light, blue: During night time.

oxygen dynamics are plotted in a higher resolution in Figure 11 for different time intervals in 2004. The upper graph (a) shows oxygen in May, at the end of the dry season. The values are still relatively high with little variability and no oxygen depletion during night. The reasons for this are: (i) still high freshwater flow with high current velocities that enhance the exchange with atmosphere and enhances the turbidity, and (ii) cloudy weather with occasional rain together with the high turbidity in the water that prevents oxygen increase by primary production. In July (b) at early stages of the dry season distinct day-night cycles exist. However, only during some hours in the night oxygen concentrations of zero are observed. In September (c) and October (d) regular day-night patterns can be seen. The oxygen concentrations reach zero in the afternoon and increase only several hours after sunrise.

From these curves that are not always so smooth due to disturbances originating from wind or weir manipulations (short increases of local current velocities) information about primary production and oxygen consumption processes can be derived. Part (e) of Figure 11 shows the whole month of November. It is evident that between November 9 and 14 there are no longer daily maximum values from primary production due to very cloudy weather at the station. Starting from November 15 the current velocity increases due to increased freshwater discharge (rains upstream in the mountains). However, during the time span November 15-20 the turbidity is still small enough for primary production (daily maxima). Only when the eroded/re-suspended material from upstream reaches the station, no daily maxima can occur mainly due to high turbidity. No nightly oxygen depletion takes place due to: 1. Smaller residence time of the water body that results in less oxygen consumption (before the oxygen consuming substances are totally decomposed they have already left the investigation area), 2. Enhanced exchange with atmosphere that "fills up" part of the oxygen deficit and 3. Less "fresh" and easy decomposable material from algae and less algal respiration.

In order to have a better insight into the processes that occur during the dry season Figure 12 shows very high resolved data of global irradiation, oxygen, chlorophyll-*a* and nitrate for October 2003. Times (in UTC) with daylight are indicated by grey areas. As can be seen, the oxygen concentrations increase several hours after sunrise, have their maximum value at sunset and reach already zero values several hours after sunset. In a general way, chlorophyll-*a* follows this pattern – with production during daylight and sedimentation during night – but has some additional peaks during the night; presumably due to flow irregularities by operation of upstream weirs. In view of the missing light this has no consequence on oxygen.

Nitrate shows maxima during daylight until late evening. The reason for this behaviour is the occurrence of nitrification as long as enough oxygen is available. Unfortunately no ammonium time series are available for this time period in 2003, but measurements in 2004

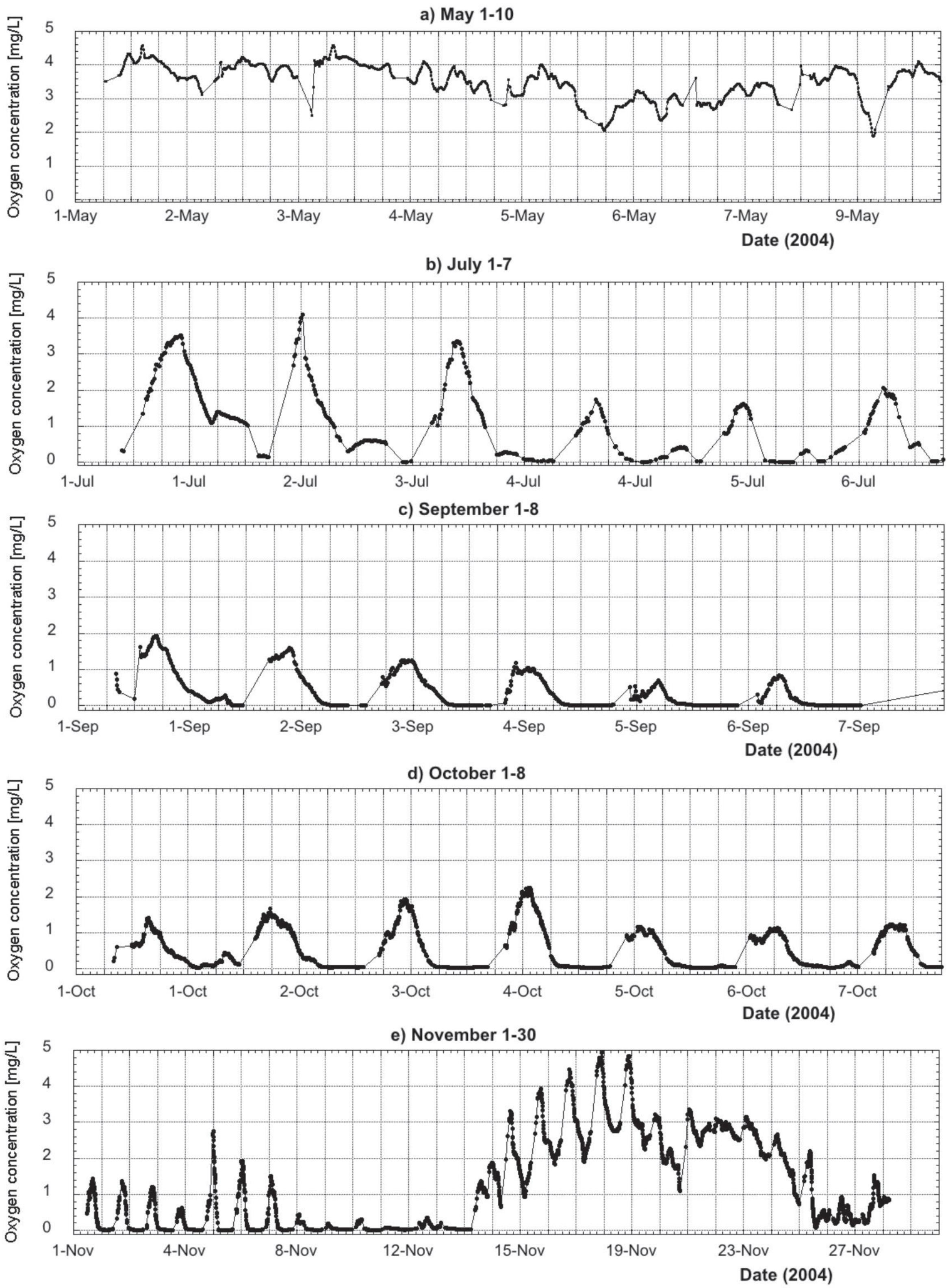

Figure 11: Seasonal time-resolved time series of dissolved oxygen in 2003 for the transition betwen dry season and wet season: (a) 1.5.2003-10.5.2003 (end of wet season), (b) 1.7.2003-7.7.2003 (dry season), (c) 1.9.2003-8.9.2003 (dry season), (d) 1.10.2003-8.10.2003 (end of dry season), (e) 1.11.2003-28.11.2003 (beginning of wet season).

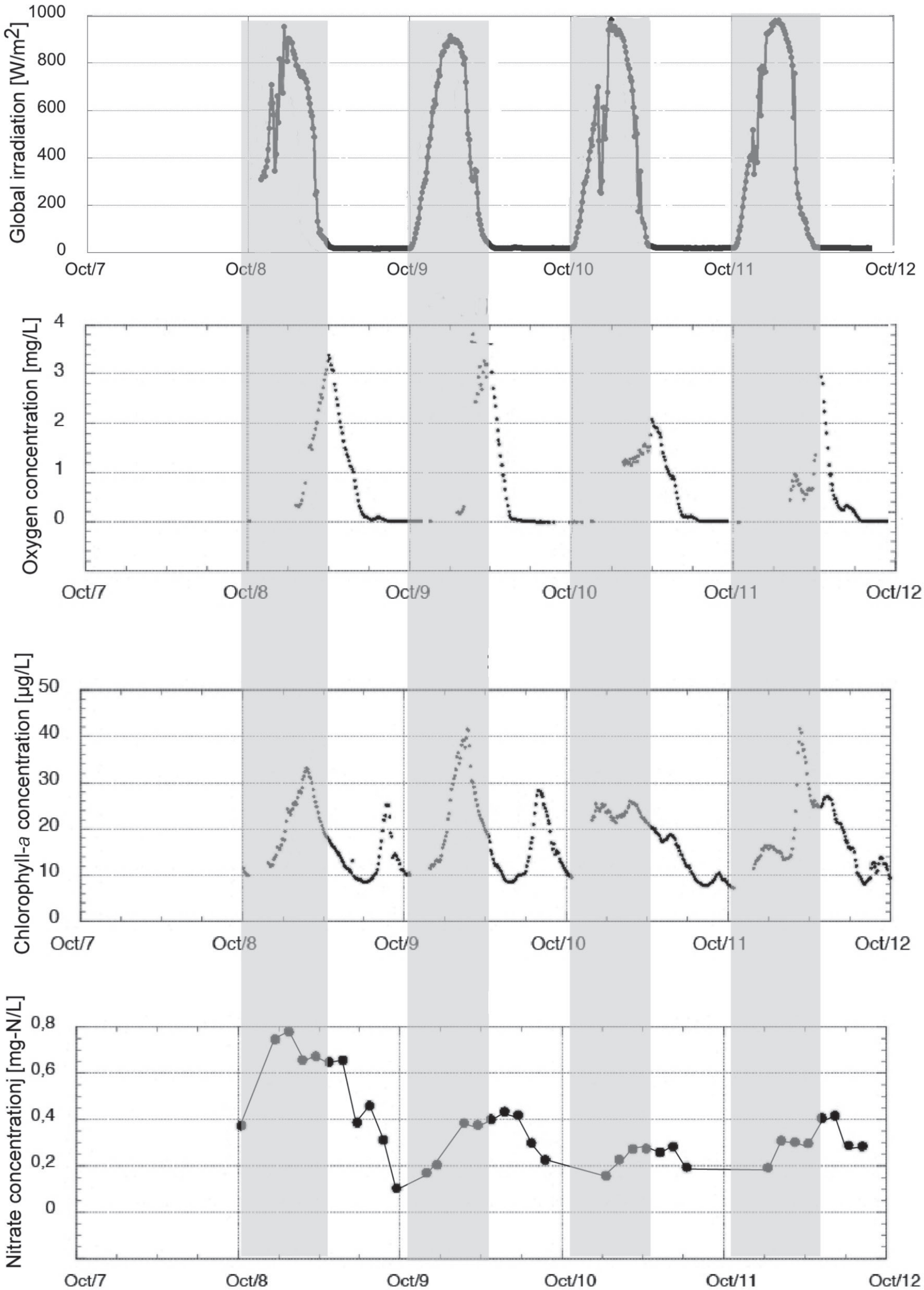

Figure 12: Highly time-resolved time series for 2003, October 7-12. From top: Global irradiation, dissolved oxygen, chlorophyll-*a* and nitrate concentrations. Daylight times are indicated in gray.

confirm this assumption: In dry season the ammonium concentrations exhibit minima during daylight (not shown here). During night the nitrate concentration decrease presumably due to high denitrification rates. This is not mirrored in the ammonium values since the main reduction path goes to gaseous nitrogen. This is the only pathway that really abstracts nitrogen from the system and reduces the nitrogen load that reaches coastal waters. The other path that reduces nitrate concentrations is the uptake by phytoplankton that will be remineralized later in the coastal zone. However, the decrease of nitrate at the end of the night militates in favour of denitrification.

River Metabolism

In order to demonstrate how the evaluation of metabolic rates from highly resolved oxygen time series was carried out in this study, in Figure 13 the above mentioned contributions of different processes to the oxygen balance are depicted. Curve (a) shows the measured oxygen concentrations on October 15th over the aerobic period. In order to calculate the slope the curve has to be smoothened (b). Part (c) shows the hourly changes in oxygen that are positive during daylight and negative during night time. In part (d) the atmospheric flux F_{ox} [g/(m^2 × d)] between atmosphere and water (re-aeration) is given. The atmospheric flux varies over the day between 0.6 and 0.9 g/(m^2 × h)). In part (e) the net primary production, calculated according to equation (3) is shown for this day. As can clearly be seen from the figure the primary production during daylight (light grey area) is only a relatively small fraction of the night time respiration (deep grey area). Therefore, the contribution of primary production to the total oxygen balance over the day is small, although one has to keep in mind that by primary production fresh autochthonous organic material is built that later (in coastal areas) will consume oxygen as well. The gross primary production, GPP, is assumed to be zero during the night, and therefore the respiration R is equal to the calculated NEP (Staehr et al., 2010; Cole et al., 2010): $NEP_{night} = R_{night}$.

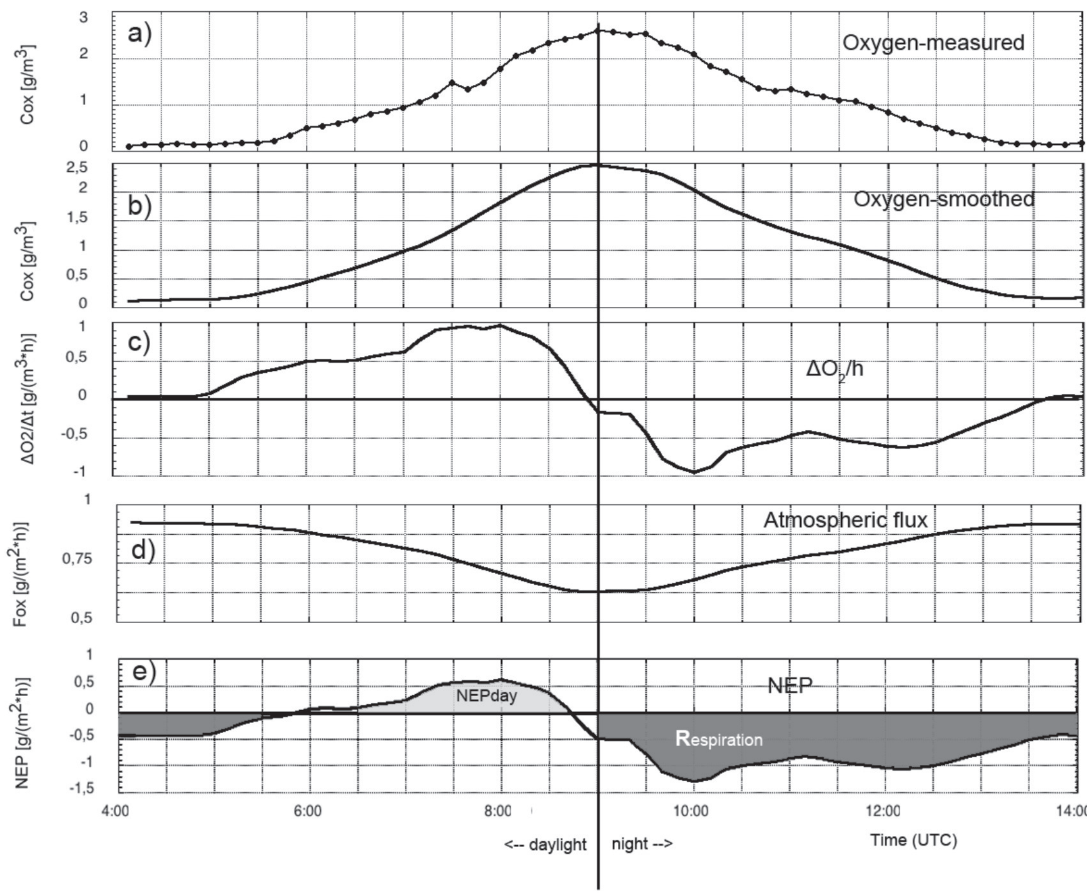

Figure 13: Measured oxygen concentrations on October 15, 2003 and resulting metabolic rates: (a) measured oxygen, (b) smoothened oxygen curve, (c) hourly oxygen changes, (d) atmospheric flux, Fox, (e) net ecosystem production, NEP. During daylight = net primary production (light gray). During night = respiration (dark gray). The time is in UTC.

If one assumes that the respiration during day and night is equal (which is not strictly true because the respiration will change under small or zero oxygen conditions which can be seen in curve 13e from 13:00 hours) and taking a mean hourly respiration flux of 0.7 g/($m^2 \times h$) over the whole day, the total respiration of the Brantas between km 260 and km 300 can be estimated as ≈70 tons/day (with a volume of 40 km length × 50 m width × 3 m mean depth). This is 70% of the value estimated by the monitoring authorities BAPPEDAL which claim that about 100 t/d of BOD equivalents are discharged into the Brantas in this river region (data from Bappedal Propinsi Jawa Timur for 1999, pers. comm.), respectively 56% of the 125 tons/day given by Binnie and Partners (1999). The evaluation of the time series shown here only for October 15th was carried out for several other days of dry season and in principle gave the same results. However, due to fluctuations in the curves that presumably were caused by upstream weir operations not all days could be used.

Estimation of the Necessary Reduction of Organic Carbon Input

An estimation shall be carried out, by how much the carbon input of 70 t/d BOD equivalents would have to be reduced in order to sustain aerobic conditions even at low discharge rates. For this we demand that the dissolved oxygen concentration in the river shall never be below 2 g/m^3 (fish critical value). Under these conditions the atmospheric flux F_{crit} is, using eq. (4):

$$F_{crit} = K_2 \times H \times (c_s - c_{crit}) = 1.5 \times 2 \times (7.5 - 2) = 16.5 \text{ g/(m}^2 \times \text{d)}$$

The total (maximum) atmospheric oxygen input into the area, E_{crit} [t/d], is the atmospheric flux, F_{crit}, multiplied with the surface area (L × W):

$$E_{crit} = F_{crit} \times L \times B = 16.5 \times 40000 \times 50 = 33 \text{ t/d}$$

Since 33 t/d of oxygen are introduced into the river by atmospheric exchange, only an organic load that consumes this amount should be discharged into the river in order to keep the oxygen concentrations above 2 g/m^3. Therefore, the organic carbon input should be kept below 33 t/d BOD equivalents instead of 70 t/d as it is now. This will be quite an administrational/political challenge considering that the domestic sewage is about 2/3 of the total organic carbon discharge and that there is no central sewage system in Surabaya that could be connected to a purification plant.

Conclusions

This study has demonstrated that for environmental monitoring of rivers the evaluation of highly time-resolved time series over the seasonal cycle is an excellent method for the quantitative assessment of the processes that control nutrient and organic matter pollution. Although many similar studies have already been carried out at rivers and lakes in temperate regions in this study this could be demonstrated for a heavily polluted tropical river that is heavily polluted by domestic and industrial organic (degradable) waste. At the same time the evaluation of the time series showed the difficulties that occur when using highly resolved oxygen time series with regular anaerobic conditions. Another difficulty was fluctuations in the time series due to upstream weir operations that hampered the evaluation of data during several short time periods. By gaining insight into the main processes “primary production”, “respiration” and “atmospheric exchange” an estimation of necessary reductions in anthropogenic input could be given that would prevent anaerobic conditions in the river even under worst conditions. In order to calculate the necessary load reductions in a more quantitative way a numerical model has to be applied.

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