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Dissolved silica dynamics and phytoplankton population in Citarum Watershed, Indonesia

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Abstract

Silicon is an essential and a beneficial nutrient for aquatic and terrestrial primary producers, respectively. Previous research reported that low silica available in lowland sawahs (a leveled and bounded rice field with an inlet and outlet for irrigation and drainage) in the Citarum watershed was partially associated with low dissolved silica (DSi) concentrations in irrigation water. DSi dynamics and the effect of phytoplankton were studied in the reservoirs of three major dams on Citarum River. The concentrations of DSi and other essential nutrients, as well as phytoplankton diversity and density, were monitored at several sites in the Citarum basin from September 2006 to November 2007. DSi concentrations were highest in the upstream reaches, including the furthest upstream reservoir (Saguling), and decreased downstream. Dams contributed to a decrease of approximately 49-58% in DSi concentrations. The DSi reduction is associated with rising diatom densities ($P<0.05$), which utilize silica in the construction of frustules. The lowest DSi concentration was measured in Jatiluhur reservoir where diatoms were very abundant. High NO_3-N and PO_4-P concentrations in upstream and reservoirs which ranged from 1.3 to 18.3 mg L^{-1} and 0.06 to 2.3 mg L^{-1}, respectively, were probably derived from drainage of industries and houses in upstream and feeding materials used for fish culture in the reservoirs. This condition may enhance the growth of phytoplankton including diatom. Diatom was a major species in the reservoirs, while Cyanophyceae was dominant in all segments of Citarum River. Increasing diatom population could retain more DSi as diatom accumulate abundant silica in its cell wall and depleted Si supply from irrigation water into sawah in lowland.

Key words: dam, diatom, DSi, phytoplankton, reservoir, silica retention.

Introduction

Dissolved silica (DSi) is derived mainly from the weathering of minerals [27], and carried to surface water bodies and ground water. A large amount of silica (Si) is accumulated in lake sediments [18], but much remains in lotic systems where it is steadily transported downstream and eventually to oceanic sink [43]. Silicon is typically present as monosilicic acid, H_4SiO_4 and is usually referred to as DSi. Silica plays an important role in the ecology of aquatic systems as it is an essential element for diatoms (Bacillariophyceae), comprising 26-69% of cellular dry weight [39]. Si is also a beneficial element for rice [11,28]. Irrigation water supplies approximately 30% of the Si taken up by rice in a sawah [28]. The concentration of DSi in rivers and streams, or irrigation water is affected by water regulation structures, such as dams [1], weathering of rock and soil in the watershed [33]. The effect of damming on water quality depends on several factors, namely dam location, water depth, depth of the outlet, surface area, age of the dam, quality of the incoming water and climate [4].

Reservoirs, created by dams, are a major source of agricultural irrigation water. Irrigation water contains significant amount of Si, Ca, S, K and Mg which are taken up by rice plant [31]. Ironically, expanded crop production is often accompanied by significantly higher fertilizer use as well as higher rates of industrial and urban growth, all of which contribute to increased nutrient loads and eutrophication of water bodies [5,37]. Eutrophication may cause a dramatic increase of the diatom population, which can deplete DSi in surface water [23]. Several studies have focused on the effect of impoundment on DSi depletion through Si accumulation by diatoms, and the subsequent decrease of Si levels in near-shore oceanic waters of Finland, Yugoslavia, Japan, America and Europe[1,7,12,19,22]. The lower DSi concentrations adversely impact marine food webs [1,7,12,19,22-24,38] and river water quality [34].

In addition to the potential negative effects on marine ecosystems, reduced DSi levels in irrigation water can have adverse effects on rice, sugarcane and other higher plants, for which Si is an important beneficial element. Since rice plants require Si in higher amounts than nitrogen and other nutrients [40], Si removed during rice harvest ranged from 230 to 470 kg Si ha^{-1} while the amount of N, P and K removed ranged from 75 to 120 kg N ha^{-1}, 20 to 25 kg P ha^{-1} and 23 to 257 kg K ha^{-1}, respectively [6,8-9,47]. The critical level of available Si in soils is 300 mg kg^{-1} [44]. Rice roots uptake Si much faster than other nutrients [45]. In addition, about 30% of Si needed for rice plant growth is derived from irrigation water. However, there is no information on the critical level of DSi in irrigation water. DSi concentration in irrigation water was depleted by time due to change in environmental condition such as increase of dams and concrete canal, and etc. [33]. The concentration of Si in irrigation water in Yamagata, Japan from 1956 to 1996 was depleted about 57% [32]. The presence of sufficient DSi in irrigation water is critical in maintaining healthy plants and achieving a satisfactory harvest. Despite the importance of DSi, there is no report that has quantitatively evaluated the influence of dams and DSi retention in reservoirs on irrigation water quality.

The three dams located along the Citarum River, Jatiluhur, Cirata and Saguling, have been operating since 1967, 1988 and 1996, respectively. Cirata and Saguling dams are operated primarily for hydroelectric power while the Jatiluhur reservoir supplies irrigation water to about 240,000 ha of sawah [26]. The Citarum river watershed has experienced rapid land use changes, particularly since the 1980s, when industrial and urban developments began a cascade of environmental degradation that has left segments of the Citarum River highly polluted. Recently, eutrophication has been reported upstream of the three major Citarum dams [10, 14, 20], a likely consequence of excess nitrogen (N) and phosphorus (P) loads from the upper Citarum basin. Higher N and P loads often contribute to higher densities of phytoplankton, including diatoms. Eutrophication increased diatoms population, eventually decreased the DSi concentration [22]. As reservoirs become eutrophic, diatom populations grow and sequester DSi into biological structures. The characteristic frustules of diatoms are built from silica and thus an adequate supply of Si is necessary for robust diatom populations. The silica uptake mechanism of diatoms has been well described [15]. Basically, silica (SiO_2) is accumulated by the cell and hydrated to form amorphous silica or opal ($SiO_2 . n H_2O$). The hydrated silica is used in the formation of frustules, which are highly insoluble. The rate of Si uptake by diatom ranges from 15×10^{-3} to 60×10^{-3} $\mu g\ SiO_2\ cell^{-1} h^{-1}$. Silica frustules are very distinctive and their shape and structure are unique in the identification of individual taxa. The frustules are also highly durable and will persist in sediment, virtually unchanged, for thousands years [15], thus acting as a long-term silica sink. Their maximum growth rate ranges from 1 to 3.2 $\mu g\ day^{-1}$ [15].

The goal of this study was to collect quantitative data on the concentrations of DSi and other nutrients in the Citarum River, and to document taxonomic and density changes of phytoplankton populations and compare with same data in the Kaligarang River, a smaller river basin that, unlike the Citarum, is not dammed. The significant differences in morphology and hydrodynamics between the two river systems allows for a quantitative comparison of the impacts of impoundments on river chemistry and DSi supply into lowland sawah.

Materials and methods

Description of the study area: The Citarum river catchment area is located between 6°00"00' and 7°00"00' S and 107°00"00' and 108°00"00' E in the West Java Province, Indonesia and it's watershed covers 6,080 km^2, and includes 269 km of river channel flowing from Mt. Wayang, at 1,700 m above sea level (ASL), to the Java Sea (Fig. 1). The Saguling, Cirata and Jatiluhur dams are located at 643, 220 and 107 m ASL, respectively, on the main stream of the Citarum River. The Kaligarang River and its tributaries, with approximately 30 km of stream channel, have a much smaller watershed (220 km^2) in compared to Citarum River. Unlike the Citarum, the Kaligarang River is free-flowing and empties into the Java Sea without any impoundment. The Kaligarang is located east of the Citarum River, between 7°00"00' and 7°15"00' S and 109°20"00' and 109°30"00' E (Fig. 1). The mean annual rainfall and mean annual temperature in the study area are 2,230 mm and 23.7°C for the Citarum watershed (1970-2000) and 1,856 mm and 25.8°C for the Kaligarang watershed (1990-2000). The highlands of Kaligarang watershed are the steep slope area of Mt. Ungaran with elevations between 400–2,050 m ASL and slopes range from 15–40% [3]. Although the catchment areas of the two watersheds are very different, land use and vegetative cover are similar, being dominated by forest and plantations in the uplands and sawahs in the lowlands.

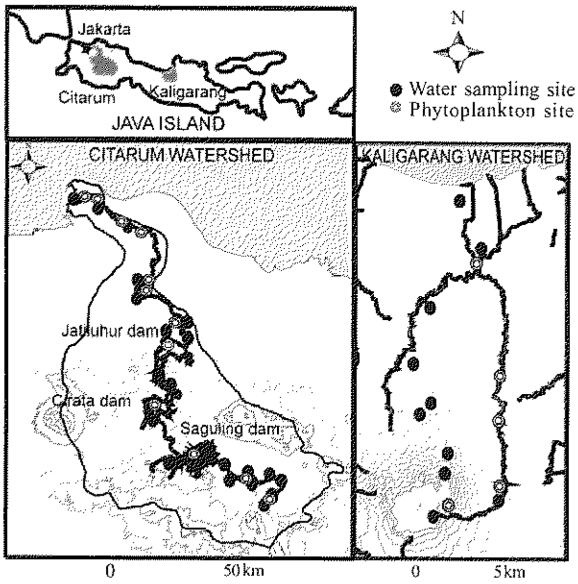

Figure 1. Citarum and Kaligarang Watersheds map showing water sampling stations and phytoplankton observation sites.

Sample collection: To investigate the dynamics of DSi, surface water samples for chemical analysis were collected monthly from September 2006 until November 2007 at eight upstream sites, seven reservoir sites and four downstream sites in the Citarum watershed (Fig. 1). Phytoplankton taxonomy samples were collected on January 23-25, 2007 at two upstream, four reservoir sites and six downstream sites in the Citarum watershed. At each of the three major impounded segments upstream of the dams, phytoplankton samples were collected at five depths: 0-0.5 m, 1-2 m, 2-3 m, 5-7 m and 7-9 m. Phytoplankton taxonomy samples were also collected upstream of an additional small dam (Walahar), which is located near Jatiluhur reservoir. In the Kaligarang watershed, monthly water samples were collected at two upstream sites, five midstream sites and three downstream sites. Phytoplankton taxonomy samples were collected on July 21, 2006 at five sites located in the Kaligarang river watershed (Fig. 1). The samples for chemical analyses were collected using water dipper then kept in a clean, 100 mL polyethylene bottle and refrigerated until analysis. Phytoplankton samples were collected using a 200 mL water sampler [35] and 1 mL of buffered formalin was added to each sample before preserving prior to identification [46].

Phytoplankton identification: The collected phytoplankton water samples were poured into graduated cylinders, but were not filtered, covered with aluminum foil, placed in a dark room and allowed to settle undisturbed for four days. After four days, water in the graduated cylinder was gently siphoned off, without agitating the settled material, until 20 mL of the sample remained. Phytoplanktons in the concentrated samples were identified to the lowest practical taxon.

Laboratory analysis: Water samples were analyzed for pH, DSi, nitrate (NO_3-N), phosphate (PO_4-P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), iron (Fe) and manganese (Mn) content. pH was determined using a pH meter and glass electrode. The concentrations of DSi, Ca, Mg, Fe and Mn were determined using inductively coupled plasma-atomic emission spectroscopy (ICPS-2000; Shimadzu, Kyoto, Japan), while K and Na were measured using an atomic absorption spectrophotometer (Shimadzu AS 680; Kyoto, Japan). Nitrate and PO_4-P concentration in water samples in upstream to downstream Citarum were determined by spectrophotometer (Hitachi-U 2001; Tokyo, Japan) for monthly water samples and by ion chromatography (Dionex DX-120; Suanyvale, USA) for other water samples.

Results and Discussion

DSi concentration: The mean DSi concentrations at the upstream sites, reservoirs and the downstream locations of the Citarum River ranged from 8.15 to 17.14, 4.14 to 10.25 and 3.96 to 14.04 mg Si L^{-1}, respectively (Fig. 2). Mean DSi concentrations in the Kaligarang River were notably higher than that of Citarum, ranging from 12.28 to 18.66 mg Si L^{-1} in the upstream segment and 6.95 to 19.62 mg Si L^{-1} in the downstream segment of the river (Fig. 2). The elevated DSi concentrations in the Kaligarang were most likely related to the geological history and existing lithology of the basin[25]. In the Kaligarang watershed, volcanic ash is distributed throughout the length of the river channel, but in the Citarum watershed, volcanic ash generally found only in the upstream areas [29-30].

The highest DSi concentrations measured in the upstream segments of the Citarum and Kaligarang rivers were 23.46 and 28.83 mg Si L^{-1}, respectively, which occurred during a period of minimal precipitation (September 2006) (data not shown). Conversely, the lowest DSi concentrations in the upstream reaches of both the Citarum River (5.28 mg Si L^{-1}) and Kaligarang River (6.42 mg Si L^{-1}) were detected in samples collected during a wet period in November 2007. Despite these low and high DSi data, and the concurrent precipitation levels, there was no clear relationship between the temporal DSi changes and seasonal precipitation over the 15-month sampling period. During some months when precipitation was high (e.g., March 2007), DSi concentration were also high. However, during high precipitation (e.g January 2007 and November 2007) DSi concentrations were significantly lower (Fig. 2). A similar inconsistence correlation between DSi levels and precipitation was also reported [41]. However, a relationship between precipitation and DSi is reasonable since rainfall would tend to dilute DSi concentrations in upstream reaches. However, this trend does not necessarily follow in the reservoirs and downstream river segments. Impoundment of river water and the associated nutrient dynamics may aggravate the dilution effect of precipitation in the reservoirs and downstream areas. Dissolve Si concentrations declined in the reservoirs by 49-58% over the study period, except from September to December 2006. From September to November 2006, precipitation was relatively low. Rainfall began to increase in mid-December 2006.

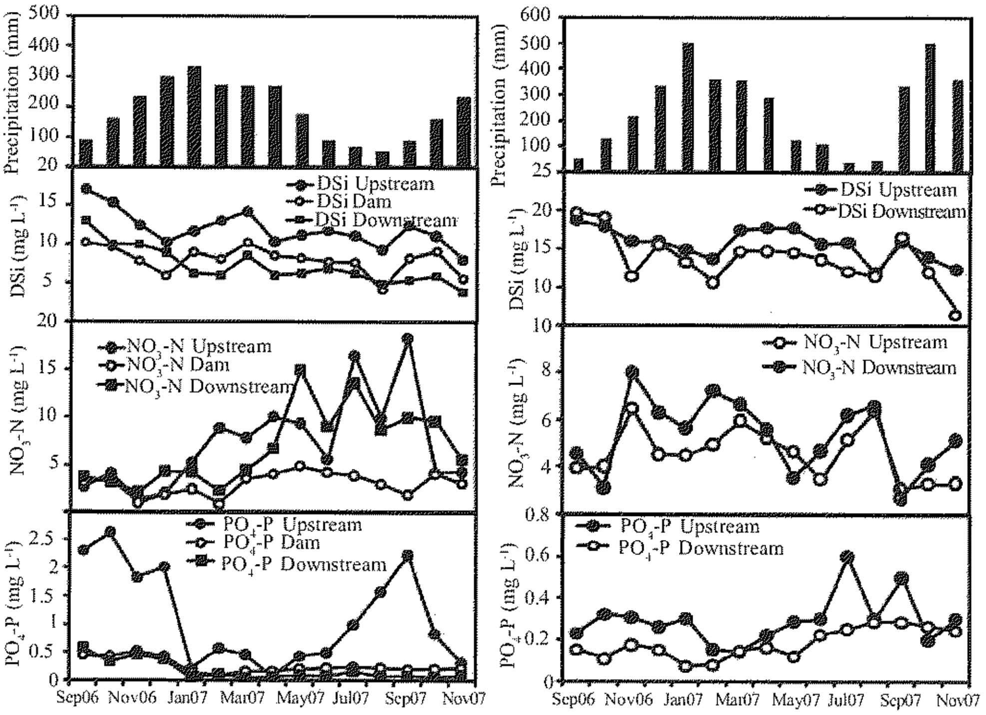

Figure 2. Fluctuation of precipitation, DSi, NO_3-N and PO_4-P in upstream, dams and downstream Citarum River (left) and Kaligarang River (right) from September 2006 until November 2007.

During the wet season, precipitation can be erratic, often delivering heavy rain over a relatively short period of time. Si supplies may be enhanced when rainwater percolates into the soil of the basin, carrying minerals to the river channel. There are multiple forces acting during the rainy season, including mobilization of minerals from watershed rocks and soils, erosion and dilution of existing concentrations. These, sometimes opposing, factors contribute to the lack of correlation between DSi concentrations and rainfall patterns. However, the data collected during this study do show that the unidirectional, downstream decrease in DSi in the Citarum River did not occur in the Kaligarang River system.

In the Citarum river reservoirs, DSi concentrations were generally consistent throughout all depths that were sampled (Table 1). However, longitudinal differences were apparent as DSi concentrations decreased from the upstream to the downstream reservoirs. The DSi concentrations in Saguling, Cirata and Jatiluhur reservoirs were 11.26 to 11.58, 9.97 to 10.07 and 8.86 to 9.04 mg Si L^{-1}, respectively (Table 1). Generally DSi concentrations decrease from upstream to downstream because of DSi retention in the reservoir or the impoundment water by sedimentation or taken up by diatom. In Jatiluhur reservoir, with the lowest DSi concentration displayed the highest diatom concentration (Table 2). The differences in vertical distribution of DSi concentrations were not, however, significant. The relationship between diatom population and DSi concentration in surface water along Citarum river watershed was shown in Fig. 3 and the differences were significant ($P<0.05$).

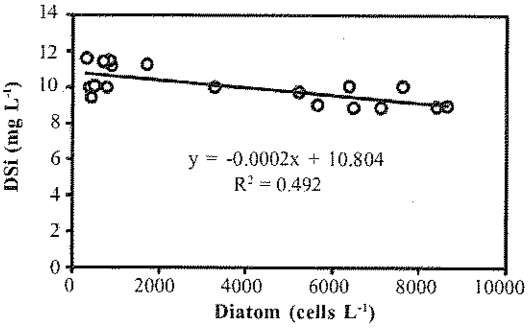

Figure 3. Relationship between diatom population and DSi concentration in Citarum river basin.

Nitrate concentration was not significantly different among the three dams, ranged from 1.6 to 1.9 mg L^{-1}. The concentration of PO_4-P was significantly lower in Jatiluhur reservoir. This result indicated high upload of N and P in upstream which probably derived from vegetable farming in upland and textile factories along Citarum River. Other elements, such as K, Na, Mg and Fe, showed a similar trend of decreasing concentrations in the downstream reservoirs. Manganese concentration remained relatively unchanged or increased slightly, from upstream to downstream sampling sites. Barring the presence of any toxic chemicals, phytoplankton growth is generally limited by essential nutrients which are present in lower concentration than relative to need. Calcium, Mg, K, Na, Fe and Mn are usually present in excess and thus rarely limit algal growth in freshwater ecosystems [42]. The concentration of NO_3-N, PO_4-P and DSi in the reservoirs are not a limiting factor for phytoplankton growth.

Table 1. Nutrient concentrations in Saguling, Cirata and Jatiluhur reservoirs.

Location (m asl)*, depth (m)	pH	DSi	NO_3-N	PO_4-P	K	Na	Ca	Mg	Fe	Mn
		mg L^{-1}							µg L^{-1}	
Saguling reservoir (643)										
0- 0.5 m	7.90	11.26	1.60	0.07	6.41	56.39	19.78	6.12	10.90	1.40
1- 2 m	7.91	11.45	1.81	0.08	6.53	56.63	19.98	6.16	9.00	0.90
2- 3 m	7.93	11.40	1.80	0.09	6.40	57.51	20.06	6.11	8.40	1.60
5- 7 m	7.95	11.58	1.82	0.08	6.68	57.89	20.22	6.19	9.50	0.90
7- 9 m	7.55	11.53	1.90	0.08	6.46	56.30	20.26	6.11	11.00	1.50
Mean	7.85a	11.44a	1.79a	0.08a	6.50a	56.94a	20.06a	6.14a	9.76a	1.26b
SD	0.15	0.11	0.11	0.01	0.10	0.64	0.17	0.03	1.03	0.30
Cirata reservoir (220)										
0- 0.5 m	7.28	9.97	1.71	0.07	5.52	28.61	16.32	5.37	7.50	4.20
1- 2 m	7.32	10.04	1.70	0.08	5.43	28.24	16.35	5.40	9.30	1.30
2- 3 m	7.32	10.07	1.89	0.08	5.30	28.43	16.34	5.42	9.50	3.70
5- 7 m	7.15	10.01	1.80	0.06	5.44	27.65	15.61	5.33	10.00	2.80
7- 9 m	7.28	10.05	1.90	0.08	5.49	27.88	17.52	5.57	10.80	2.50
Mean	7.27a	10.03a	1.80a	0.07a	5.44a	28.16a	16.43a	5.42a	9.42b	2.90a
SD	0.06	0.03	0.09	0.01	0.08	0.35	0.61	0.08	1.09	1.01
Jatiluhur reservoir (107)										
0- 0.5 m	7.45	8.92	1.61	0.06	4.71	24.75	19.08	5.14	7.40	1.30
1- 2 m	7.47	8.86	1.79	0.05	4.64	24.55	18.50	5.02	11.30	2.30
2- 3 m	7.33	8.96	1.88	0.04	4.44	24.87	19.24	5.17	7.40	1.40
5- 7 m	7.28	8.87	1.89	0.06	4.58	24.73	18.86	5.07	10.30	3.00
7- 9 m	7.16	9.04	1.77	0.06	4.43	24.83	20.23	5.29	9.40	2.10
Mean	7.34a	8.93a	1.79a	0.05b	4.56b	24.75a	19.18a	5.14b	9.16c	2.02b
SD	0.11	0.07	0.11	0.01	0.11	0.11	0.58	0.09	1.56	0.62

* asl (above sea level); Means followed by the different letter in the same column are significantly different ($P<0.05$) using Tukey's honestly significant different test; SD (standard deviation).

Table 2. Phytoplankton population and identification of dominant species in dams and downstream river along Citarum watershed.

Location (m asl*) and depth (m)	Bacyllarophyceae		Cyanophyceae		Chlorophyceae		Xanthophyceae		Total
	cells L^{-1}	(%)	cells L^{-1}	(%)	cells L^{-1}	(%)	cells L^{-1}	(%)	cells L^{-1}
Upstream River									
Citarum upstream (720 m*)	0	0	2,904	44	66	1	0	0	6,600
Cileuncak Lake (696 m*)	900	3	7,600	21	0	0	0	0	36,000
Saguling dam (643 m*)									
0-0.5 m	1,710	19	5,310	59	0	0	0	0	9,000
1-2 m	840	21	2,360	59	0	0	0	0	4,000
2-3 m	702	9	4,992	64	0	0	0	0	7,800
5-7 m	320	4	6,640	83	0	0	0	0	8,000
7-9 m	0	0	3,850	70	0	0	0	0	5,500
Cirata dam (220 m*)									
0-0.5 m	396	18	748	34	0	0	0	0	2,200
1-2 m	504	18	980	35	0	0	0	0	2,800
2-3 m	6,320	30	6,603	31	0	0	0	0	21,300
5-7 m	3,289	23	5,720	40	0	0	0	0	14,300
7-9 m	7,622	74	1,854	18	0	0	0	0	10,300
Jatiluhur dam (107 m*)									
0-0.5 m	8,399	37	5,902	26	0	0	0	0	22,700
1-2 m	6,490	55	3,540	30	0	0	0	0	11,800
2-3 m	8,640	48	6,840	38	0	0	0	0	18,000
5-7 m	7,120	40	5,969	32	0	0	0	0	17,800
7-9 m	5,655	65	2,697	31	0	0	0	0	8,700
Walahar Dam (50 m*)	5,220	30	10,440	60	0	0	0	0	17,400
Lower stream River									
Citarum, Cadassari (48 m*)	786	3	23,580	90	0	0	786	3	26,200
Citarum, Karawang (40 m*)	0	0	9,207	99	0	0	0	0	9,300
Citarum, Kertasari (32 m*)	0	0	48,192	96	0	0	502	1	50,200
Citarum Majasetra (29 m*)	490	5	9,310	95	0	0	0	0	9,800
Citarum, R.dengklok (27 m*)	428	4	9,844	92	0	0	0	0	10,700
Citarum, Bekasi (20 m*)	0	0	2,277	99	0	0	0	0	2,300

*asl (above sea level).

Phytoplankton populations: Phytoplankton densities in the upstream, reservoirs and downstream reaches of the Citarum River ranged from 6,600 to 36,000, 2,200 to 22,700 and 2,300 to 50,200 cells L^{-1}, respectively (Table 2). The dominant taxonomic group of phytoplankton in all segments of the Citarum River was Cyanophyceae, historically referred to as blue-green bacteria or algae. Cyanophyceae densities ranged from 748 to 48,192 cells L^{-1}, followed by diatoms at 3 to 8,640 cells L^{-1} (Table 2). Other phytoplankton groups, including Chlorophyceae and Xanthophyceae, were not found or were present at very low numbers. *Mycrocistis* sp. was the dominant Cyanophyte (70%); *Synedra* sp. was the dominant diatom (10-35%) (data not shown). Cyanophyceae was found at all sampling locations in the Citarum river system, while diatoms were found primarily in impounded waters that more closely resembled lentic ecosystems. Diatoms were also found in the downstream reaches, although these cells may have been carried downstream from Jatiluhur reservoir. The diatom population in Jatiluhur reservoir was the highest (8,640 cells L^{-1}) of the three Citarum reservoirs studied, and accounted for 37% to 65% of the total phytoplankton population. Diatoms accounted for 18 to 74% of the population in Cirata reservoir and 4 to 21% of the population in Saguling reservoir. A study conducted during low precipitation (July, 2003) in Cirata reservoir has found that secchi disk depths were only from 0.9 to 1.4 m and the surface water contained chlorophyll *a* up to 48 μg L^{-1} [21], reflects a very low transparency and high organic material presence. Phytoplankton densities during the wet season (January 23-25, 2007) were not as high as in the period of lower rainfall, a pattern also reported in other studies [18, 36]. The density of Bacyllarophyceae in Jatiluhur reservoir was reported ranged from 808 to 14,707 cells L^{-1} in May 2002, a relatively dry month, accounting for approximately 58.3 % to 80.4 % of the total population in Jatiluhur reservoir at the time of the study [15]. Although total phytoplankton density in May 2002 [14] was about twice as high as during the wet period in the present study, the relative abundance of Bacyllarophyceae in the two studies was approximately the same. In the Kaligarang watershed, Cyanophyceae was the dominant phytoplankton group (Table 3). Higher downstream densities were probably related to nutrient enrichment from nonpoint sources within the Kaligarang watershed.

Bacyllarophyceae are an important component of the silica cycle in natural waters; the only other algal group to have a quantitative role in the silica cycle is Chrysophyceae [36]. Among 11 diatom taxa studied, approximately 41.4% of their dry weight was silica [37]. While

Table 3. Density and proportion of blue-green bacteria (Cyanophyceae) in the Kaligarang watershed.

Location (m asl)*	Cyanophyceae	
	(cells L^{-1})	(%)
Upstream		
Waterfall (Curug lawe) (753)	0	0
Kaligarang (462)	890	50
Midstream		
Kedung doro (351)	7,500	100
Kedung doro (292)	22,220	100
Downstream		
Kali kreo (128)	24,000	100

*asl (above sea level).

the cell walls of Cyanophyceae, Chlorophyceae and Xanthophyceae algae consists mainly of peptydoglycan, cellulose and chrysolaminarin, respectively, diatom cell walls are constructed of silica [42]. Some Xanthophyceae (yellow-green algae) also possess silica valves [42], although little data are available on silica uptake by this, or other, non-diatom taxa.

Higher nutrient concentrations promote the growth of diatoms, which use significant quantities of Si, thus making Citarum river reservoirs silica sinks. Other study in Japan reported that the rate at which silica was retained by Lake Biwa was equivalent to about 80% of the annual input of DSi into the lake [17]. Silica retention behind dams results in a decline of DSi concentrations in the lower reaches of the river, including water diverted for irrigation purposes.

Nutrient loading to reservoirs: Retention of DSi by dams may cause diatom blooms in impounded waters where N and P are also retained [22,24] (Fig. 2). The nutrients that build up in the Citarum River originate from factories and effluent drainage water from high density housing in the watershed. Most of factories in this area are textile factories which release high concentration of NO$_3$-N and PO$_4$-P [13] and heavy metal such as Pb, Ni, Cu, Cr, Cd [2,16]. Saguling reservoir, uppermost in the river, receives N and P from the city of Bandung and from food given to the caged fish that are raised in the reservoir[20]. Nitrate and phosphate fertilizer from vegetable farming in upland Citarum are also contributed to the nutrient loading into the reservoir. As shown in Fig. 2, NO$_3$-N and PO$_4$-P concentration in upstream Citarum were high especially during the period with less precipitation. It was depleted in the reservoirs and downstream, but that was not seen in the Kaligarang River. However, the concentration of NO$_3$-N and PO$_4$-P in Citarum River were relatively high than those in Kaligarang River (Fig. 2), indicated high nutrient loading in upstream Citarum. The NO$_3$-N and PO$_4$-P in upstream Citarum were ranged from 1.3 to 18.3 mg L^{-1} and 0.06 to 2.3 mg L^{-1}, respectively, while in upstream Kaligarang it was ranged of 3.1 to 6.47 mg L^{-1} and 0.14 to 0.6 mg L^{-1}, respectively. Cirata reservoir is reported to be eutrophic [10], as is Jatiluhur reservoir [14], the most downstream of the three. As expected, discharge through the dams is higher during periods of high rainfall (February to June) and low when rainfall is less (July to January, except for November 2007). Over the same period there was little change in the influx of PO$_4$-P, which remained low. The influx of DSi and NO$_3$-N did vary over time, but showed little difference among the three reservoirs (Fig. 4). However, in Cirata reservoir, during high water discharge through the dam outlet, DSi influx was high, but NO$_3$-N influx was low. Conversely, during low water discharge, NO$_3$-N influx exceeded that of DSi.

The higher DSi loads during periods of high precipitation and elevated water discharge may be related to the release of Si from soil and rocks within the watershed, which is accumulated upstream of the dam. Nutrients, particularly NO$_3$-N and PO$_4$-P, probably originate not only from upstream point and nonpoint sources, but also from excess amounts of fish food in the reservoirs themselves. In Saguling reservoir, about 57% of N and 69% of P were derived from upstream sources, while internal loading, including the artifacts of fish culturing, contributed as much as 43% of N and 31% of P [20]. This issue of internal nutrient loading related to fish culturing is probably exacerbated at Cirata and Jatiluhur reservoirs where the use of floating net cages for raising fish is even more prevalent. The nutrient load of each successive downstream reservoir is also due in part to down gradient transport of nitrogen and phosphorus from upstream fish culture operations.

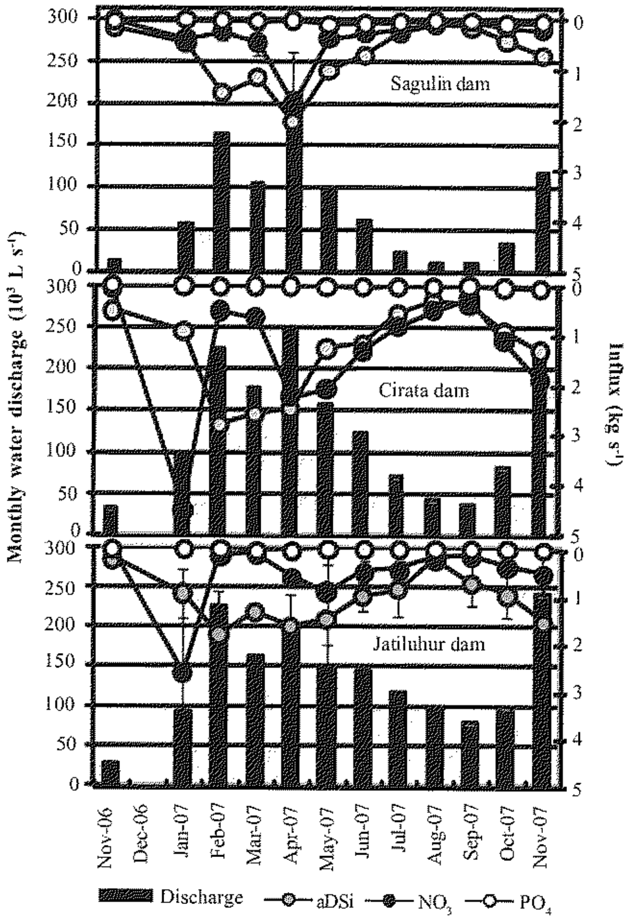

Figure 4. Monthly mean influx of DSi, NO$_3$ and PO$_4$ (kg s^{-1}) in Saguling, Cirata and Jatiluhur dams.

Eutrophication of these reservoirs occurred, which was probably caused by contamination of drainages from industries, houses and feeding materials of fish culture. This eutrophication increased phytoplankton population, particularly Diatom, of which cell wall contains 26-69% silica. As a result, there was a decrease in the DSi concentration of post-impoundment river or irrigation water supplied. Irrigation water is an important source of DSi that supplied about 30% of Si required for rice plant growth [27]. The decreasing of Si supply from irrigation water resulted in the decrease of Si available for rice plant [24] in lowland sawahs. However, there have been no studies on the influence of Si availability in sawah on rice yield in Indonesia. The phenomenon found on Si dynamics in Citarum watershed might influence rice productivity in the sawahs in West Java. Although we could not discuss relationship between DSi concentration in river and irrigation water and the rice yield in the present study

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