

Characteristics and Potential Usage of Dissolved Silica in Rice Cultivation in Sumani Watershed, Sumatra, Indonesia

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ABSTRACT

Research on watershed silica dynamics in Indonesia has been sparse as most of the focus on water environment has centred on suspended sediments, nitrogen and phosphorous. Thus, Si concentrations in rivers and their seasonal and spatial variations are not well understood. Silicon helps rice plants to overcome abiotic and biotic stresses by preventing lodging and increasing resistance against pests and diseases. Rice is one of the more important crops in the country, and information on Si concentrations in rivers is useful because river water is a primary irrigation source. In this study, we conducted a preliminary research on temporal and spatial variations in dissolved Si (DSi) concentrations at watershed scale to help achieve an efficient use of Si resources through irrigation water management. The Sumani Watershed, located approximately 50 km east of Padang City in West Sumatra, Indonesia, was selected as the target area. Lake Dibawah lies on the upstream end of the watershed, and water is discharged from the watershed into Lake Singkarak. The results verified that Lake Dibawah had a dam effect of naturally reducing DSi concentrations in water. In addition, the average DSi concentration from the samples obtained from rivers,

small channels, and ditches from October 2013 to December 2014 did not show strong seasonal patterns at each site but revealed clear spatial differences among sub-watersheds linked to the groundwater from Mt. Talang. The watershed has a high capability of supplying DSi to paddy fields via irrigation water.

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INTRODUCTION

Rice is a staple crop for over half of the world's population and it is grown on nearly every continent (Seyfferth et al., 2013). Rice production has been increasing since the mid-1960s, with the implementation of new rice cultivation systems known as green revolution technology (Pingali, 2012). By 2013, rice crops covered an area of about 165 million ha for an annual production of 741 million tons (FAO, 2013).

Rice is a typical silicon accumulator because of the high capability of its roots to take up Si from soil (Mitani & Ma, 2005). Silicon is an important beneficial nutrient for healthy and competitive growth of all cereals including rice (Brunings et al., 2009). Beneficial nutrients are equally important as macronutrients like nitrogen and phosphorus (Ahmad et al., 2013), and balancing these nutrients in rice cultivation can enhance the quality and yield of the crop (Ma, 2004). Thus, many studies have investigated the functions and mechanisms of Si in terms of plant pathology, plant physiology, as well as soil science and plant nutrition (Idris, 1975; Hso-Freng & Yann-Shee, 1978; Richmond & Sussman, 2003; Ma et al., 2006; Kraska & Breitenbeck, 2010; Dufey et al., 2014; Makabe-Sakaki et al., 2014).

Several studies have indicated that continuous rice cultivation affects the silica content of soil. Darmawan et al. (2006) reported that the average content

of available Si decreased from 707 ± 269 to 575 ± 260 kg ha⁻¹ in the 0–20-cm soil layer and from $3,121\pm 1,668$ to $2,755\pm 1,576$ kg ha⁻¹ in the 0–100-cm soil layer between 1970 and 2003, especially in the upper paddy fields. Additionally, Husnain et al. (2010) found that long-term fertilisation imbalances in the intensive rice-farming system led to surpluses of nutrients such as N and P and deficits of K and Si. This occurred because between 230 and 470 kg ha⁻¹ of Si was removed during rice harvest, while only 75–120, 20–25, and 23–257 kg ha⁻¹ of N, P, and K, respectively, were removed (Yoshida et al., 1981; Dobermann et al., 1996a,b; Casman et al., 1997). A lack of Si available to plants may have adverse effects on rice yield by decreasing resistance to lodging, diseases and pests (Winslow, 1992).

In Japan, silicate fertiliser containing several types of slag is applied to paddy fields to improve Si uptake in rice plants, although the application rate per unit area of paddy field is being gradually decreased to reduce production costs (Ma & Takahashi, 2002). In South and Southeast Asia, where most of the world's rice is grown, the straw and husks are typically removed from the field and used for various purposes, including animal fodder, fuel for stoves or burning (Savant et al., 1997). Since most Si taken up by rice is found within the straw and husk, the removal of rice straw accelerates soil desilication with no return of Si via biocycling (Seyfferth et al., 2013).

However, the supply of Si from irrigation water may slow the rate of Si depletion (Darmawan et al., 2006). Imaizumi

and Yoshida (1958) reported that irrigation water supplied approximately 30% of the Si taken up by rice in a paddy field in Japan. Silicon is the second most abundant element in the Earth's crust (Conley, 2002). Silicon in rivers, reservoirs, and lakes mainly originates from rock weathering, a process enhanced by high temperatures, moisture and active vegetation (Cochran & Berner, 1996; Conley, 2002; Humborg et al., 2006; Billen and Garnier, 2007), while direct input of Si through urban or industrial wastewater is minor (Sferratore et al., 2006; Garnier et al., 2006). Thus, the management of irrigation water in terms of Si and macronutrient supply and water quantity may help farmers to stabilise rice quality and production.

Indonesia is the third largest producer of rice in the world (FAO, 2013), and because of the importance of macronutrients for rice growth, Si in irrigation water has received limited attention. Research on DSi dynamics in the watersheds of Sumatra Island has not yet been conducted. In this study, therefore, we investigated temporal and spatial variations in DSi concentrations at the watershed scale to improve the efficiency of Si resource use for rice cultivation through irrigation water management.

STUDY AREA

Sumani Watershed is located approximately 50 km east of Padang City in West Sumatra, Indonesia (Figure 1) and covers about 586 km². Lake Dibawah lies on the upstream

end of the watershed, and water flows from the watershed into Lake Singkarak. The average annual precipitation is 2,201 mm (Farida et al., 2005), and the watershed lies between 338 and 2,739 m.a.s.l. The watershed is situated in a humid tropical zone (Aflizar et al., 2010a), with average annual temperatures ranging from 19 to 30°C, and varying along an altitudinal gradient. The average annual humidity ranges from 78.1 to 89.4% (Aflizar et al., 2010b).

The various land uses of the watershed are summarised according to the GIS data of the Ministry of Forestry in Indonesia (2010) in Table 1. This range of land uses includes primary and secondary forests, tree crop gardens (mixed gardens, coconuts and tea gardens), vegetable gardens, *sawah*, bushes (shrubs, grasses, and alang-alang or *Imperata cylindrica*) and settlements (Aflizar et al., 2010b). A *sawah* is a levelled and bounded rice field with an inlet and outlet for irrigation and drainage (Wakatsuki et al., 2009). In a mixed garden, perennial crops, primarily trees such as coconut, clove, coffee, teak, mahogany, avocado, melinjo (*Gnetum gnemon*), rubber and cinnamon are planted in combination with annual crops (Karyono, 1990). Chilies (*Capsicum annum* L.), onions (*Allium cepa* L.), soybeans (*Glycine max* L.), corn (*Zea mays* L.) and sweet potatoes (*Ipomea batatas* L.) are the major crops in vegetable gardens (Aflizar et al., 2010b).

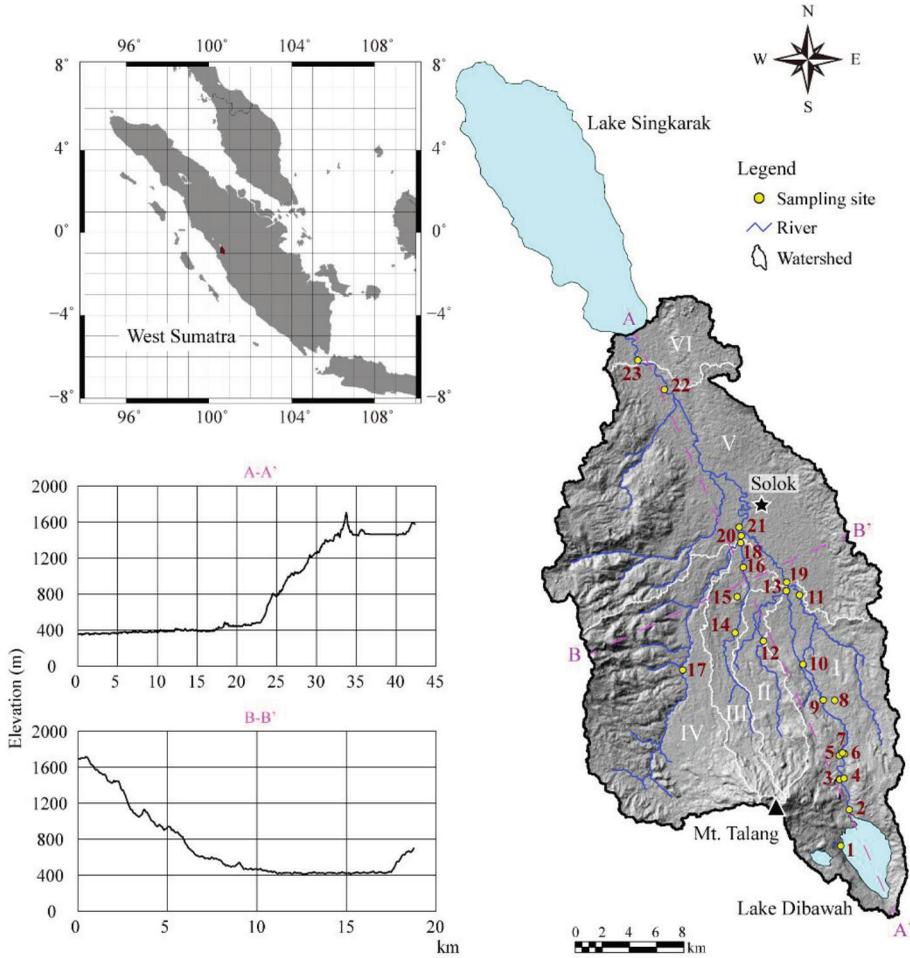


Figure 1. Location of the Sumani Watershed and sampling sites

Table 1
Landuse characteristics of Sumani Watershed

	Forests	Tree crop gardens	Vegetable gardens	Paddy fields/ sawah	Settlements	Water
Sub-watershed I	9%	1%	37%	40%	3%	10%
Sub-watershed II	27%	15%	4%	51%	3%	0%
Sub-watershed III	24%	10%	2%	48%	16%	0%
Sub-watershed IV	57%	15%	12%	14%	2%	0%
Sub-watershed V	16%	18%	36%	26%	5%	0%
Sub-watershed VI	0%	82%	0%	14%	4%	0%

Source: Ministry of Forestry, Republic of Indonesia (2010)

METHODOLOGY

Field sampling was conducted once per month between October 2013 and December 2014 (with the exception of March 2014). Water samples from rivers, irrigation channels and ditches, and a paddy field were collected from 23 sites. Due to the lack of detailed information on river locations and low road accessibility in the area, sampling points were increased with knowledge gained throughout the field investigation in this study. Thus, sampling occurred at only 11 sites in October 2013, 16 sites between November 2013 and January 2014, and 22 sites in June and July 2014. All the sites were sampled in the remaining months, except for March 2014 when road and weather conditions were not suitable for any fieldwork. In total, 287 water samples were collected. Of these, 263 were collected from rivers, channels and ditches. Additional samples were obtained from a paddy field (site no. 8) and spring water (site no. 15). Surface waters of paddy fields were also sampled at five sites downstream, eight sites midstream, and five sites upstream in the watershed in November 2013.

The water samples were filtered through a 0.45- μm membrane filter (Advantec Dismic-25CS, Japan). The concentration of DSi was measured using inductively coupled plasma atomic emission spectroscopy (ICP-AES, Shimadzu ICPE-9000).

All the statistical analyses were performed with EZR (Saitama Medical Centre, Jichi Medical University, Saitama, Japan), which is a graphical user interface

for R (The R Foundation for Statistical Computing, Vienna, Austria).

RESULTS AND DISCUSSION

Roles of Lake Dibawah in DSi concentration

Lake Dibawah, which is located on the upstream end of the watershed, is primarily precipitation- and spring-fed and it provides the main water source for streams. A portion of the lake's water is allocated for irrigation via small channels at the outlet of the lake. Of the small ditches along the lake, one from Mt. Talang was selected as a regular sampling site because of its accessibility (site no. 1). Figure 2 compares the DSi concentration at this site with that at the outlet of the lake (site no. 2). The average DSi concentrations were 35.8 mg L⁻¹ (n = 14) at site no. 1 and 6.21 mg L⁻¹ (n = 14) at site no. 2. The standard deviations were 1.75 and 0.41 mg L⁻¹ at site nos. 1 and 2, respectively. The concentrations at both sites were relatively stable during the research period from month to month. A comparison of the two sites indicated that water with high DSi concentrations flowed into the lake, while water with low concentrations was discharged from the lake ($p < 0.001$).

It has been previously reported that the construction of large dams leads to decreased input of Si into coastal zones because of increased water residence times and net losses of Si to the sediments within reservoirs (Conley et al., 1993; Garnier et al., 1999; Friedl et al., 2004; Koch et al., 2004; Ahearn et al., 2005; Humborg

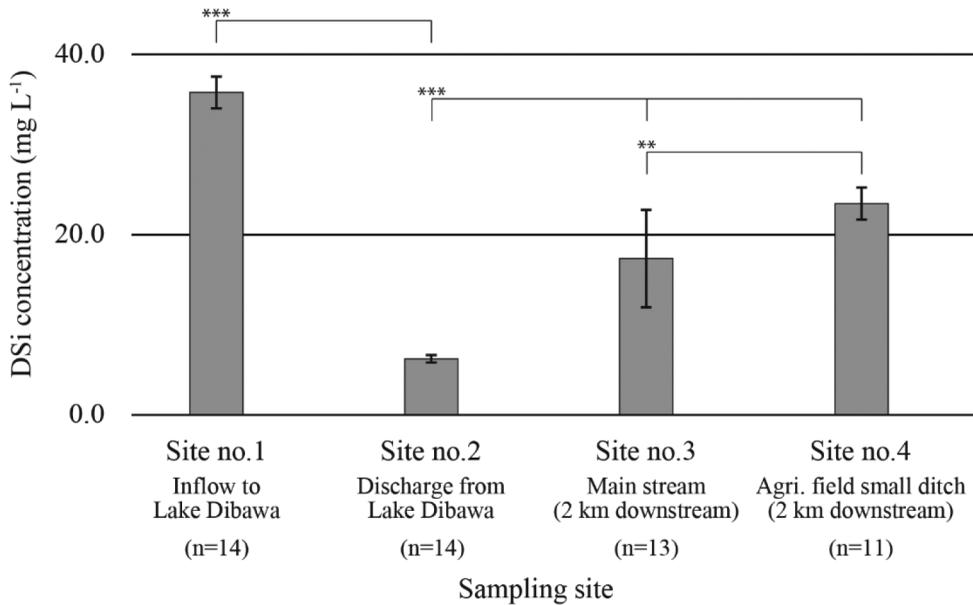


Figure 2. Average DSi concentrations and standard deviations. Statistical analysis was performed using Welch t-Test against site nos. 1 and 2. In addition, Kruskal-Wallis Test with the Bonferroni adjustment was applied against site nos. 2, 3 and 4. ** $p < 0.01$, *** $p < 0.001$.

et al., 2006). Development, such as dam construction or concrete canal installation within a watershed, was found to result in a decrease in Si concentrations in irrigation water (Ma and Takahashi, 2002). Thus, the lake naturally becomes akin to a dam reservoir, and dilution through precipitation, consumption of Si through diatom growth, and subsequent settling of diatom frustules in the lake might occur.

These natural functions may have adverse effects on rice, sugarcane and other tall plants because of reduction of Si levels in irrigation water. However, the concentrations of DSi 2 km downstream of the lake outlet (site no. 3) were higher than at site no. 2 ($p < 0.001$). These differences varied from 1.37 to 19.4 mg L⁻¹ during the

research period and exceeded 10 mg L⁻¹ in all, except for four months (November 2013 and May, November, and December 2014). In addition, at site no. 4, which is also located about 2 km downstream of the lake outlet and close to sampling site no. 3, containing a small ditch flowing through an upland field, the DSi concentrations averaged 23.4 mg L⁻¹, with a maximum of 26.1 mg L⁻¹ and a minimum of 20.5 mg L⁻¹. These relatively high concentrations exhibited little variation, with a standard deviation of 1.78 mg L⁻¹. These results pointed to a possible Si source for river water between site nos. 2 and 3. As the DSi concentrations were consistently higher at site no. 4 than site no. 3 ($p < 0.01$), agricultural fields were also likely to contribute Si to the water.

Variations in the DSi concentrations

The average DSi concentration for the whole watershed, obtained from river, channel and ditch samples was 18.0 mg L^{-1} ($n = 263$). The concentrations varied over $4.2\text{--}38.3 \text{ mg L}^{-1}$ during the research period, with a standard deviation of 7.1 mg L^{-1} . Husnain et al. (2010) reported that the DSi concentration of irrigation water in the Citarum Watershed of Java, Indonesia, was $13.64 \pm 3.13 \text{ mg L}^{-1}$ ($n = 15$) from September 2006 to November 2007, with monthly sampling. Thus, the average DSi concentrations of the Sumani and Citarum Watersheds exhibited similar tendencies.

Figure 3 provides a histogram and standard statistical values of DSi concentrations. For this analysis, the samples at site nos. 1, 8, and 15 were excluded. This is because water at site no. 1 flows into the lake, where high DSi concentrations appeared to be diluted. Water is then discharged from the lake as river water and irrigation water. Thus, the concentrations at sampling site no. 1 were not influenced by downstream water quality in sub-watershed I. Additionally, the samples at site nos. 8 and 15 were not collected from a river or small ditch, but rather from the surface water on a paddy field and spring water, respectively. In order to compare DSi characteristics among sub-watersheds, four independent sub-watersheds (sub-watersheds I through IV) were selected. In this comparison, sub-watershed V was excluded because its water was influenced to an unknown degree by water from the other four sub-watersheds. For this discussion, the individual sub-watersheds were divided into

two groups based on the DSi concentration levels. The group with lower concentrations included sub-watersheds I and IV, and that with higher concentrations included sub-watersheds II and III. Sub-watershed I had an average concentration of 13.7 mg L^{-1} and a standard deviation of 5.00 mg L^{-1} , with measurements frequently falling between 10 and 15 mg L^{-1} . The average concentration in sub-watershed IV was 17.0 mg L^{-1} , and the standard deviation was 4.62 mg L^{-1} . Measurements were concentrated between 15 and 20 mg L^{-1} . On the other hand, in sub-watersheds II and III, the average DSi concentrations were 26.2 and 24.0 mg L^{-1} , respectively. Measurements between 25 and 30 mg L^{-1} were most frequent in sub-watershed II, and those from 20 to 25 mg L^{-1} were most frequent in sub-watershed III.

The DSi concentrations in sub-watershed V were determined by inflow quantity and quality from sub-watersheds I through IV. In this study, as river discharge was not observed, the impact ratios of each sub-watershed against the concentration in sub-watershed V were unknown. In sub-watershed V, the average DSi concentration was 17.6 mg L^{-1} , and the standard deviation was 2.0 mg L^{-1} . Measurements tended to fall between 15 and 20 mg L^{-1} . The concentrations in sub-watershed V were similar with those in sub-watershed IV, but fluctuations were smaller in sub-watershed V than in sub-watershed IV.

In order to investigate possible sources of differences in the DSi concentrations among the sub-watersheds, we examined groundwater. For the preliminary analysis,

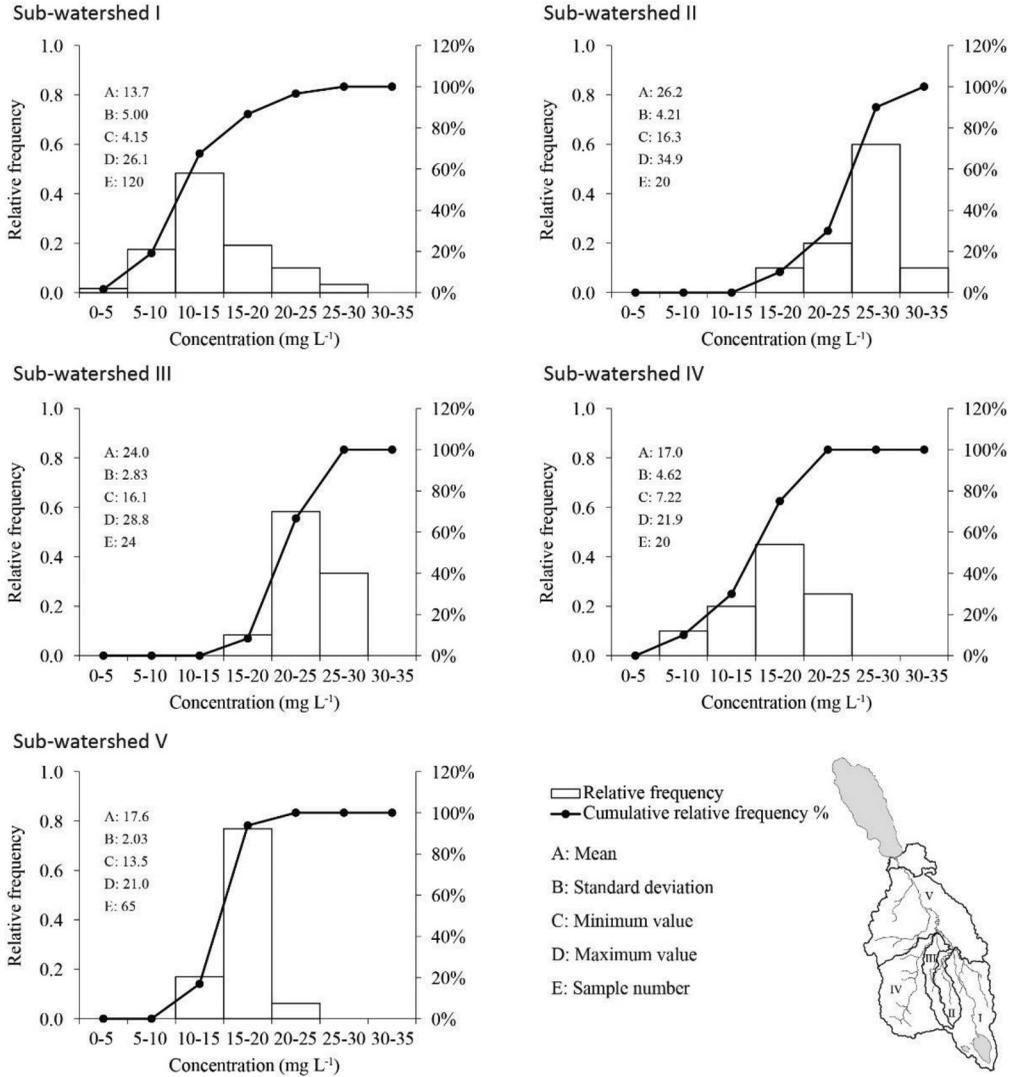


Figure 3. Histogram and statistical values of DSi concentrations among sub-watersheds, excluded site nos. 1 (Inflow water to Lake Dibawa), 8 (Surface water of a paddy field), and 15 (Spring water). Kruskal-Wallis Test with the Bonferroni adjustment was applied against sub-watersheds I to IV. $p < 0.001$ in sub-watershed I vs. sub-watersheds II and III, and in sub-watershed IV vs. sub-watersheds II and III. No statistically significant difference was detected between sub-watersheds II and III.

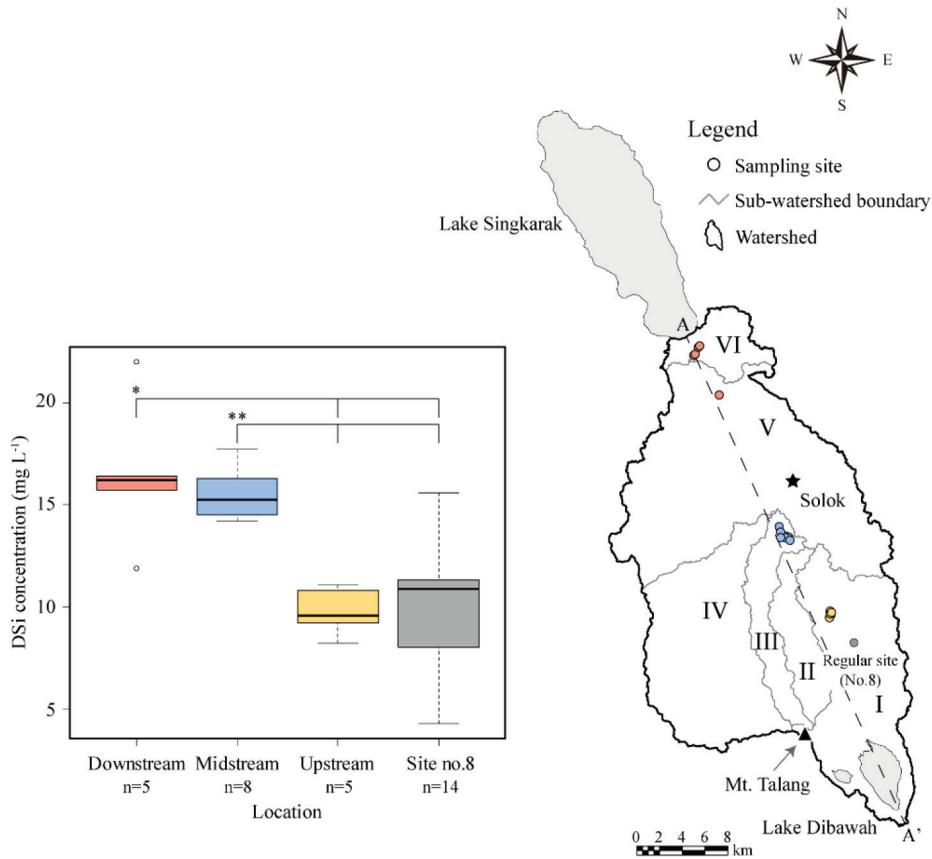


Figure 4. DSi concentrations in the surface water of paddy fields. Box=25th and 75th percentiles; bar=minimum and maximum values. Kruskal-Wallis Test with the Bonferroni adjustment, * $p < 0.05$, ** $p < 0.01$.

DSi concentrations in spring water upstream of sub-watershed II were analysed on-site in February 2014 using the pack test (DPM-SiO₂). The average concentration was 72.1 mg L⁻¹ (n = 2), indicating that spring water might be a source of Si in the area. Thus, to examine variations in DSi concentration in spring water (groundwater), the highly accessible spring water of site no. 15 located in sub-watershed III was sampled. The averaged DSi concentration of this site

was 62.1 mg L⁻¹ (n = 10), with a standard deviation of 2.8 mg L⁻¹. This finding indicated that water with high concentrations of DSi was steadily discharged as spring water with little variation.

Based on the consistently high DSi concentrations at site nos. 1 and 15, it was concluded that water from Mt. Talang provided a source of Si through groundwater to surface water within the watershed.

Spatial Distribution of DSi concentrations in the Surface Water of Paddy Fields

The DSi concentrations in the surface water of upstream through downstream paddy fields in the watershed were studied in November 2013 (see Figure 4). The water samples were collected along the longitudinal (A-A') line from Lake Dibawah (upstream) to Lake Singkarak (downstream). As variations in the growth stages of rice on each paddy field might affect DSi concentrations of surface water, the water samples were collected under conditions similar to those before and after transplanting of rice seedlings and during the growing stages as much as possible. The upstream sampling sites were located in sub-watershed I, midstream sites in sub-watershed III and downstream sites in sub-watersheds V and VI. The average DSi concentrations were 9.8, 15.5, and 16.4 mg L⁻¹ for upstream, midstream and downstream sites, respectively. Most of the DSi concentrations between 5 and 10 mg L⁻¹ occurred in upstream paddy fields, while those between 15 and 20 mg L⁻¹ occurred more frequently downstream. For the midstream fields, values were concentrated between 10 and 20 mg L⁻¹. Along the A-A' line, there were clear differences in these intervals between upstream and downstream sites ($p < 0.05$). Our findings indicated that water with relatively low DSi concentrations from Lake Dibawah provided irrigation water via small channels for upstream areas. Downstream, river water mixed with water with high DSi concentrations from sub-

watersheds II and III, and was allocated to the paddy fields.

Moreover, the DSi concentrations of surface water at a regular sampling site (no. 8) exhibited a trend that is similar to that of the upstream sampling from November 2013. The concentration at this site was relatively low, with an average of 10.1 mg L⁻¹. The DSi levels seemed to be lower during the rainy season and higher during the dry season, especially in June and July. Although the cause of this phenomenon is not quite clear, the dilution of surface water by precipitation in the rainy season and the long retention time of water in the soil during the dry season might provide an explanation.

Si Supply from Irrigation Water

Irrigation water may provide an important source of Si for rice. Thus, the amount of Si delivered to a paddy field via irrigation was estimated. Ma and Takahashi (2002) reported that paddy soil was irrigated with an average of 1,400 mm (14,000 m³ ha⁻¹) of water during the single growth period of rice. Average Si concentrations from 380 rivers in Japan ranged from 4.0 to 19.5 mg L⁻¹, with an overall average of 10.1 mg L⁻¹. From these results, Si supply from irrigation water in Japan was estimated to be 141.4 kg ha⁻¹, or about 30% of the crop requirement. In this study, the amount of irrigation water was also assumed to be 1,400 mm because of the lack of information on irrigation water levels in the area. DSi load to the paddy fields was then estimated from this irrigation

water value for an average of 238 ± 81.2 kg ha⁻¹ per rice cultivation period (Table 2), accounting for $53.6 \pm 18.3\%$ of the Si taken up by rice.

On average, 141.4 kg ha⁻¹ of DSi is supplied by irrigation water in Japan, and 30 ± 15 kg ha⁻¹ of DSi is supplied by irrigation in France (Desplanques et al., 2006). Thus, the Sumani Watershed has a higher capacity for supplying Si to paddy fields via irrigation. DSi loads varied among the sub-watersheds. The highest DSi load occurred in sub-watershed II at 366.8 ± 58.8 kg ha⁻¹. The spring water at site no. 15 had a DSi load of 869.4 ± 39.2 kg ha⁻¹, constituting approximately $195.8 \pm 8.8\%$ of the crop requirement. Thus, Si input via irrigation could increase with the efficient introduction of spring water into paddy fields. Numerous beneficial effects of Si have been reported; these include prevention of lodging (falling over), increased photosynthetic activity, increased insect (e.g., brown planthopper) and disease (e.g., rice blast) resistance,

reduced mineral toxicity, improvement of nutrient imbalance, enhanced drought and frost tolerance, and improved grain yield (Deren et al., 1994; Kim et al., 2002; Ma, 2004). Therefore, aggressively introducing Si via irrigation water may enhance the stability of rice production and quality in the region.

CONCLUSION

The dynamics of DSi concentrations in Sumani Watershed were investigated for the first time between October 2013 and December 2014. From this research, it was found that Lake Dibawah had a dam effect of naturally reducing DSi concentrations in the water, based on a comparison between inflow and outflow concentrations. Further, it was revealed that the average DSi concentration of samples obtained from rivers, small channels and ditches was 18.0 mg L⁻¹, with the levels varying from 4.2 to 38.3 mg L⁻¹ during the research period. Among the sub-watersheds, there

Table 2
DSi loads supplied by irrigation and spring water in Sumani Watershed. The load was assumed as 1,400 mm irrigation water per cultivation period.

	DSi load (kg ha ⁻¹)	DSi concentration (mg L ⁻¹)	Standard deviation (mg L ⁻¹)	Sample number
Whole watershed	238.0 ± 81.2	17.0^a	5.8	249
Sub-watershed I	191.8 ± 70.0	13.7^b	5.0	120
Sub-watershed II	366.8 ± 58.8	26.2	4.2	20
Sub-watershed III	336.0 ± 39.2	24.0^c	2.8	24
Sub-watershed IV	238.0 ± 64.4	17.0	4.6	20
Sub-watershed V	246.4 ± 28.0	17.6	2.0	65
Spring water (no. 15)	869.4 ± 39.2	62.1	2.8	10

^a average value of DSi concentrations in the watershed, excluding site nos. 1, 8, and 15.

^b average value of DSi concentrations in sub-watershed I, excluding site nos. 1 and 8.

^c Average value of DSi concentrations in sub-watershed III, excluding site no. 15.

were significant differences in the DSi concentrations, with higher concentrations in sub-watersheds II and III than other sub-watersheds. Based on an analysis of spring water, the differences in DSi concentrations among sub-watersheds may be closely related to the groundwater from Mt. Talang. In addition, it was understood that spatial variation in DSi concentration existed upstream to downstream in the surface water of paddy fields. Then, by using the measured DSi concentrations and a literature review, it was determined that more than 50% of Si taken up by rice can be provided from irrigation water in the area based on the average DSi concentration value. Moreover, from the highest average DSi concentration ($26.2 \pm 4.2 \text{ mg L}^{-1}$) from sub-watershed II, up to 69-96% of Si taken up by rice may be supplied from the irrigation water.

Although the total Si absorbed by rice in a growing season is easily determined, no study has yet investigated which Si source (soil or irrigation water) is the most critical for the absorption of Si during a rice cultivation period. Additionally, the relationship between the spatial distribution of Si concentrations and rice quality in this watershed is not yet understood. Thus, such research should be conducted as the next step to help produce high-quality rice through the efficient allocation of irrigation water.

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