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Geochemical methods for mapping available-Si distribution in soils in West Sumatra, Indonesia Aflizar a , * , Edi Syafri a , Jamaluddin a , Husnain b , Ahmad Fudholi c a Department of Agricultural Technology, Agricultural Polytechnic, Payakumbuh, West Sumatra 26271, Indonesia b Indonesian Agency for Agricultural Research and Development, Jakarta 12540, Indonesia c Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia – j o u r n a l h o m e p a g e : w w w . e l s e v i e r . c o m / l o c a t e / g e o d e r m a 1958) than do soils derived from alluvium material, particularly those in lowlands.

Many rice fields or sawah located in lowlands has parent materials that are mostly river sediment or alluvium, so the original SiO₂ availability is generally low (Aflizar et al., 2019). Rice is a typical Si- accumulator plant that takes up Si from soil solution through an active mechanism (Ma et al., 2001, 2007). According to Wu et al. (2009) , the solubility of Si is influenced by pH and iron (Fe).

Soil physical properties (texture, clay percentage, silt and sand) and soil chemical properties (pH, total carbon (TC), total nitrogen (TN), calcium (Ca), magnesium, potassium (K) and sodium (Na)) are used for sustainable land management in agriculture (Hartemink, 1998). Wang et al. (2009) reported that the distribution patterns of TN, total phosphorus (TP) and other nutrients significantly change with changes in land use, and distribution maps can be used to develop sustainable agriculture and improve the environment. Aflizar et al.

(2018) reported that the distribution of trace metal cadmium on a watershed is influenced by soil properties including pH, texture, TC, erosion and topographic factors. The Indonesian government does not believe and does not acknowledge that silica (Si)

deficiency has occurred in paddy soils in the country (Husnain et al., 2018; Darmawan et al., 2006). However, we hypothesise that there is an Si deficiency in the soil, especially in the Sumani watershed (SW).

Thus, the conditions of rice fields in Indonesia should be evaluated. Soil erosion is considered only as a carrier of adverse effects on the environment because it causes soil degradation and disasters for the environment and agriculture (Aflizar et al., 2010).

We hypothesise that soil erosion also has a good effect on the environment because it carries nutrient-rich soil sediments and precipitates them in lowland rice fields. Many farmers and agricultural practitioners in Indonesia assume that soil Si is not necessary for paddy sawah, so they believe that adding Si in artificial fertiliser is not necessary (Husnain et al., 2018; Darmawan et al., 2006). Moreover, the soil can sufficiently provide natural Si.

We hypothesise that Si in the soil is no longer sufficient for paddy sawah and that Si is contributed from irrigation water, river water (Somura et al., 2006) and sediments, which is then naturally distributed to the sawah. However, the content of Si is no longer sufficient; therefore, Si should be added in the form of fertiliser to the sawah soil.

The present study aimed to determine the factors influencing the distribution of available Si in the SW, where volcanic ash and Si fertiliser of irrigation water can be natural sources. We hypothesise that the pH, TC, TN, base cation (Ca, K, Na) and trace metal Fe are factors controlling Si availability in sawah soil. Accordingly, we conducted a study on the distribution of available Si in relation to land-use types and soil-erosion status in the SW, a main rice-production area in West Sumatra, Indonesia.

We have already previously observed that severe erosion occurred in the highlands of the watershed because of the land-use change from forest to agricultural field. Accordingly, we expected that these factors may influence available-Si distribution in the watershed. Soil erosion is generally regarded as a type of soil degradation. However, it may contribute to nutrient replenishment in sawah, especially in the lowlands, through the deposition of fine soil particles eroded from the highlands, as we discuss in this study.

2. Material and methods

2.1.

Study area and soil sampling This research was conducted in the SW in the Solok regency of West Sumatra (latitude 00° 36' 08" to 10° 44' 08" S, longitude 100° 24' 11" to 101° 15' 48" E). SW has an active volcano, Mount Talang (2500 m asl). Further information about the study area and sample locations are shown in Figs. 1 and 2.

On the east side of Mount Talang, we found a lake from which water flows through the lowlands and into lake Singkarak located at an altitude of 300 m asl. All the water of rivers and tributaries that flow into the SW also drain into lake Singkarak. According to data of climatological stations from 1996 to 2000. The SW has a humid tropical climate. The rainfall rate hovers at around 1669 and 3230 mm between altitudes of 300 and 2500 m.

Annual temperatures range from 19 °C to 30 °C varying from highlands to lowlands. The average annual humidity also varies from 78.1% to 89.4% (Farida et al., 2005). Fig.

1. Possible factors influencing the distribution of available Si in the SW. (a) Natural source of Si by volcanic ash, irrigation water and top soil. (b) Translocation of Si by topography and soil erosion. (c) Deficiency of Si in sawah soil. (d) Rich available Si in lowland.

(e) Available Si in sawah soil controlled by pH, TC, etc. Aflizar et al. We selected the SW for our research because of three reasons. First, we already have a database of its soil erosion. Second, the SW has various land-use types (rice fields, forests, mixed garden, garden vegetable - tables, weeds, and bush) suitable for our research (Fig. 2 b).

Third, this watershed is the central of rice-production area in West Sumatra. Fig. 2 a shows the soil sampling in the blue circle. The red circle represents the river-sediment sampling point. We present available Si in soil and collected soil samples from all land-use and soil types and topographical position of the various positions (Fig. 2).

A total of 23 soil samples were collected from stream sediments from the highlands to the lowlands. Soil samples were taken at depths of 0 – 20 cm and 20 – 40 cm. To view the distribution of soil vertically on highlands and lowland areas, soil samples were taken at a representative area to a depth of 100 cm. The watershed is divided into eight geology types, i.e., breccia andesit of Mt.

Talang, alluvium of andesit volcano, lava, colluvial deposit, welded tuff, quartz, slate shale part of tuah form, and lava andesit to basalt (Farida et al., 2005). SW consists of five subwatersheds, namely, Sumani (S1), Lembang (S2), Gawan (S3), Aripan (S4), and Imang (S5) (Aflizar et al., 2018). Located in the SW is the active volcano Mount Talang. Farmers Fig. 2. Sampling point (a) and land-use type (b) in the SW: field survey picture from: 1. sawah, 2.

forest, 3. mixed garden, 4. vegetables, 5. bush, 6. soil erosion, 7. river sediment. Aflizar et al. believe that this volcano enriches the soil through its frequent small eruptions and volcanic ash spread on agricultural land throughout the SW. According to Fiantis et al.

(2010), the element contents of volcanic ash are SiO₂ (57.61%), Al₂O₃ (16.16%), H₂O⁺ (6.92%), Fe₂O₃ (5.39%), CaO (4.79%), Na₂O (2.51%), MgO (1.88%), K₂O (1.84%), H₂O⁻ (1.62%), TiO₂ (0.67%), P₂O₅ (0.18%), and MnO (0.08%).

On 12 April 2005, Mount Talang erupted and ejected ash into the air that then fell and spread throughout the SW. The volcanic ash covered the summit and slopes of Mount Talang with a thickness of 5 and 0.1 cm, respectively, around the foot of Mount Talang. Fiantis et al. (2010) reported that the chemical characteristics of volcanic ash from Mount Talang are as follows: pH H₂O (1:5)(7.26), pH KCl (1:5)(7.12), P Bray 2 (68.02 mg kg⁻¹), P HCl 25% (498.12 mg kg⁻¹), CEC (5.75 cmolc(+) kg⁻¹), Ca (11.14 cmolc(+) kg⁻¹), Mg (2.18 cmolc(+) kg⁻¹), K (0.09 cmolc(+) kg⁻¹), Na (0.12 cmolc(+) kg⁻¹), base saturation (235%), P retention (52.84%), Si in allophone (11.50%), active Al (0.60%), and active Fe (1.99%).

Volcanic ash containing 57% SiO₂ is regarded as basaltic andesite. The mineralogy of volcanic ash is dominated by volcanic glass and labradorite. 2.2. Rice-farming systems In the SW, rice is mostly cultivated three times a year as long as irrigation water is available in lowland areas and two times a year in highland areas shifted with vegetables. Irrigation water is usually supplied through irrigation canals and river tributaries.

Nitrogen, phosphorus, and potassium are applied in the form of a single nutrient fertilizer (urea, SP-36, and KCl) or compound fertilizer with rates ranging within 46 – 184 kg N ha⁻¹, 36 – 72 kg P₂O₅ ha⁻¹, and 6.3 – 63 kg K₂O ha⁻¹ (information from surveyed farmers in study sites). However, KCl is rarely or even not applied in most sawah in the SW because farmers think KCl strengthens only the stalk of rice and farmers only need the rice grains.

Chemical SiO₂ fertilizer has been never applied to the soil, and SiO₂ has been supplied only from straw returned after harvesting. In terms of straw management in the SW, farmers preferred to burn the straw to shorten the time for the next planting season and thus prevent disease spread in some sites (personal comm. 2009). 2.3. Soil, plant, and water sampling We collected 146 soil samples based on land-use types and position in the watershed.

River sediments were also collected from 23 points to determine available Si. The samples were air dried, ground, and passed through a 2 mm sieve. Plant samples (rice flag leaf) were collected from several sites where soils were sampled. We collected water samples at five points along main rivers and determined the concentration of Si in water every month from August 2006 to February along the SW (Fig. 2) under collaboration

with local farmers and staff of Andalas University.

A total of 11 water sampling points in the SW were collected from the upper to lower streams of the rivers. 2.4. Soil chemical analyses We collected 146 soil samples based on land-use types and position in the watershed. River sediments were also collected from 23 points to determine available Si. The samples were air dried, ground, and passed through a 2 mm sieve.

Available Si was extracted using 1 mol L⁻¹ acetate buffer (pH 4.0) at a mixing ratio of 1:10 for 5 h at 40 °C with occasional shaking (Imaizumi and Yoshida, 1958). Then, the concentration of Si in the filtrate was measured by molybdenum-blue method at 810 nm.

TC was determined by the dry combustion method using a Yanaco CN Corder Model MT-700. Soil pH was measured using the glass-electrode method with a soil/water ratio of 1:2.5 (IITA, 1979; McLean, 1982). Exchangeable base cations (Na, Ca, and K) were extracted using 1 mol L⁻¹ neutral ammonium acetate (Thomas, 1982), and exchangeable Ca was determined using inductively coupled plasma – atomic emission spectroscopy (Shimadzu ICPS2000, Kyoto, Japan).

Exchangeable K and Na were determined using an atomic absorption spectrophotometer (Shimadzu AS 680). Percentage sand and clay were determined by pipette method (Gee and Bauder, 1986). Extractable Fe was extracted by 0.1 M HCl and measured with ICP (SSSA 1996). Rice plant was ground into powder, using a tungsten carbide vibrating mixer mill and digested with HNO₃ in a high-pressure Teflon vessel (Koyama & Sutoh, 1987). DSi concentration in water samples was determined with an atomic absorption spectrophotometer (Hitachi Z-5000). 2.5.

Estimation of soil-erosion rate by the USLE model Soil-erosion rate in the SW was estimated by USLE (Wischmeier and Smith, 1978). We estimated the soil-erosion rate in the SW using USLE (Aflizar and Masunaga, 2013), which expressed as: $E = R \times K \times L \times S \times C \times P$ (1) where P is a factor that accounts for the effects of soil-conservation practices (dimensionless), C is the crop cover factor (dimensionless), S is slope factor (dimensionless), L is length of the slope factor (dimensionless), K is the inherent soil erodibility (dimensionless), R is the rainfall erosivity factor (dimensionless), and E is the estimated soil loss (Mg ha⁻¹ y⁻¹).

The watershed was divided by 39 312 grids with 125 m × 125 m mesh size, and basic data were allocated or estimated in each grid by reading maps and a Landsat image for land-use types and altitude or the kriging method for precipitation and soil properties.

Based on these data, respective USLE factors were calculated in each grid unit. To calculate average soil erosion, we excluded the negative value of soil erosion.

We used the USLE model because other models require difficult collection of data of detailed rainfall and technical constraint. Detailed calculations of each USLE factor in the SW were have been described by Aflizar et al. (2010) . 2.5.1. Rainfall erosivity factor (R) and K-factor R-factor represents the potential ability of the rain to cause soil erosion.

To compute the monthly value of the R-factor (Aflizar and Masunaga, 2013): $R = 6.19(R_f) 1.21 (R_n) 0.47 (R_m) 0.53 (2)$ where and R_m is the maximum rainfall for a 24 h period in the observed month, R_n is number of rainy days per month, R_f is total monthly rainfall, and R is monthly erosivity. Table 1 shows the general monthly rainfall data and monthly values of the R-factor calculated with the above equation for two study periods.

No clear dry season appeared in the study area, and the monthly rainfall and R-factor showed no clear seasonal pattern, highly fluctuating year by year. The R-factor and soil erodibility (K)-factor are generally the most important factors requiring evaluation based on local conditions for the successful application of the model. Not all grids possessed their own data of precipitation or soil analyses to calculate R- and K-factors.

In this case, interpolation by the nearest-neighbor kriging method (Golden software 2002) assigned the value of the nearest grid possessing soil- analysis data. This method is useful and yields good results as re - ported by Aflizar and Masunaga (2013) and Goovaerts (2000) . The value for K-factor was computed using by Aflizar and Masunaga (2013) : $100K = 2.713M 1.14 (10^4) (12 a) + 3.25(b^2) + 2.5(c^3) (3)$ where M is given by $[(St - Svf)/100] - Cf$; a is the percentage of soil organic matter content; b is the structural code; c is the permeability class code of the soil; and St , Svf , and Cf are the percentage of silt, very fine sand, and clay fractions, respectively. Details are found in the study of Aflizar et al.

(2010) . Aflizar et al. Table 1 Available SiO₂ (mg/kg) and erosion-factor analyses in sampling sites in the Sumani watershed. Location Sub watershed Land use GPS reading Erosion Mg/ ha/yr SiO₂ (0–20) mg SiO₂ /kg SiO₂ status in soil East South R K LS C P
 Jawi-jawi 1 Sumani Sawah 681,009 9,898,946 2452 0.1 0.064 0.01 0.4 5 204.64 d
 Jawi-jawi 2 Sumani Sawah 681,007 9,898,924 2452 0.1 0.064 0.01 0.4 5 559.71 | Jawi-jawi
 3 Sumani Sawah 680,846 9,899,016 2452 0.1 0.064 0.01 0.4 10 138.86 d Gantung ciri 1
 Sumani Sawah 679,766 9,900,725 2452 0.3 0.001 0.01 0.4 0.1 258.86 d Gantung ciri 2
 Sumani Sawah 679,906 9,900,722 2452 0.3 0.001 0.01 0.4 0.1 308.79 | Gantung ciri 3
 Sumani Sawah 679,994 9,900,676 2452 0.3 0.001 0.01 0.4 5 271.93 d Kelok Duri Sumani
 Sawah 682,301 9,909,213 2452 0.1 0.064 0.01 0.4 2 207.86 d Selayo Sumani Sawah

682,677 9,909,496 2452 0.1 0.064 0.01 0.4 2.5 127.07 d Sawah sudut 1 Sumani Sawah
682,689 9,909,403 2452 0.1 0.064 0.01 0.4 2 201.64 d Sawah sudut2 Sumani Sawah
682,753 9,909,451 2452 0.1 0.064 0.01 0.4 2 200.79 d Gawan-sungai 1 Sumani Sawah
682,988 9,911,695 2452 0.3 0.001 0.01 0.4 15 145.5 d Gawan-sungai 2 Sumani Sawah
683,204 9,911,613 2452 0.3 0.001 0.01 0.4 10 148.29 d Gawan-sungai 3 Sumani Sawah
683,159 9,911,560 2452 0.3 0.001 0.01 0.4 15 250.71 d Batu Banyak 1 Lembang Sawah
690,240 9,894,285 1665 0 0.611 0.01 0.4 5 157.07 d Bukik Sileh 2 Lembang Sawah
690,168 9,894,089 1665 0 0.611 0.01 0.4 5 168 d Anau kadok 4 Lembang Sawah 690,190
9,894,077 1665 0 0.611 0.01 0.4 5 331.07 I Bukik Sileh 4 Lembang Sawah 690,146
9,894,586 1665 0 0.611 0.01 0.4 7.5 230.14 d Koto Lawas 1 Lembang Sawah 690,485
9,898,085 2452 0 1.744 0.01 0.4 0.2 148.07 d Koto Lawas 2 Lembang Sawah 690,385
9,898,220 2452 0 1.744 0.01 0.4 0.2 308.14 I Koto Lawas 3 Lembang Sawah 690,391
9,898,224 2452 0 1.744 0.01 0.4 10 241.71 d Batu banyak Lembang Sawah 689,859
9,899,180 2452 0.1 0.064 0.01 0.4 15 203.57 d Koto Anau Lembang Sawah 687,948
9,902,605 2452 0.5 0.064 0.01 0.4 5 124.29 d Sawah Durian 2 Lembang Sawah 687,963
9,902,709 2452 0.5 0.068 0.01 0.4 5 192.64 d Sawah Durian 3 Lembang Sawah 688,040
9,902,988 2452 0.3 0.064 0.01 0.4 5 165.21 d Pandan Putih 1 Aripas Sawah 684,981
9,909,986 2452 0.3 0.064 0.01 0.4 5 339.86 I Pandan Putih 2 Aripas Sawah 684,868
9,910,153 2452 0.3 0.064 0.01 0.4 5 249.64 d Rawang sari Aripas Sawah 684,560
9,910,295 2452 0.3 0.064 0.01 0.4 5 427.07 I Pandan ujung 1 Aripas Sawah 685,806
9,912,702 2452 0.1 0.001 0.01 0.4 5 89.36 d Pandan ujung 2 Aripas Sawah 685,820
9,912,612 2452 0.1 0.001 0.01 0.4 5 164.79 d Pandan ujung 3 Aripas Sawah 685,664
9,912,492 2452 0.1 0.001 0.01 0.4

5 192 d Pandan ujung 6 Aripas Sawah 685,437 9,912,538 2452 0.1 0.001 0.01 0.4 5
184.71 d Parambahan 1 Aripas Sawah 690,900 9,902,399 2452 0.3 0.611 0.01 0.4 1.8
306.43 I Parambahan 2 Lembang Sawah 690,786 9,902,411 2452 0.3 0.611 0.01 0.4 1.8
280.5 d Parambahan 3 Lembang Sawah 690,734 9,902,391 2452 0.3 0.064 0.01 0.4 0.2
227.14 d Sungai janih Lembang Sawah 686,383 9,898,559 2452 0.1 0.064 0.01 0.4 15
113.36 d Gunung Talang Lembang Sawah 686,155 9,898,931 2452 0.1 0.064 0.01 0.4

10 162.64 d Batu Bajanjang Lembang Sawah 686,201 9,898,830 2452 0.1 0.064 0.01 0.4
10 120.86 d Air angek 1 Lembang Sawah 684,168 9,898,356 2452 0.3 0.064 0.01 0.4 5
500.57 I Anau Kadok 2 Lembang Sawah 684,089 9,898,413 2452 0.3 0.064 0.01 0.4 5
139.5 d Anau Kadok 3 Lembang Sawah 684,138 9,898,260 2452 0.3 0.064 0.01 0.4 10
243.21 d Pasar usang Lembang Sawah 684,550 9,903,109 2452 0.3 0.064 0.01 0.4 5
374.57 I Panyalaian Cupak Lembang Sawah 684,404 9,903,287 2452 0.3 0.064 0.01 0.4

0.2 364.71 I Kubu Gawan Mixed Garden 679,336 9,910,716 2452 0.3 2.512 0.2 0.5 640
534.86 I Parak gadang Gawan Mixed Garden 680,767 9,911,154 2452 0.3 0.064 0.2 0.5 45

445.29 | Gunung Talang Sumani Mixed Garden 681,796 9,902,683 2452 0.1 0.064 0.2 0.5
30 476.79 | Gantung Ciri Sumani Mixed Garden 679,878 9,903,305 2452 0.2 0.064 0.2 0.5
5 211.71 d Curang gadang sasak Sumani Sawah 677,000 9,902,000 2452 0.1 2.512 0.01
0.4 115 262.29 d Kayu aro Sumani Tea 680,022 9,890,308 1665 0.1 0.064 0 1 20 326.79 |
Pasar usang guguk Lembang Mixed Garden 682,500 9,898,000 2452 6.1 0.064 0.2 0.5 45
679.07 h Koto baru Lembang Sawah 683,508 9,905,910 2452 0.2 0.064 0.01 0.4 3 508.07
h Lembang Aripan Bush 681,302 9,914,208 2452 0.2 0.001 0.95 0.4 1 543 h Jawi-jawi
Sumani Mixed Garden 679,878 9,903,305 2452 0.2 0.064 0.2 0.5

5 955.71 h Sukarami BPTP Sumani Bush 680,390 9,895,606 1665 0.1 0.064 0.29 1 15
447.86 | Danau kamar Sumani Tea 680,586 9,890,624 1665 0.1 0.064 0 1 15 217.93 d Air
batumbuk Lembang Bush 685,164 9,886,435 1665 0.2 0.064 0.29 1 85 260.79 d Bungo
tanjung Lembang Mixed Garden 693,126 9,883,658 1665 0.1 1.744 0.2 0.5 5 382.71 | Air
tawar Lembang Mixed Garden 691,000 9,887,152 1665 0.1 2.512 0.2 0.5 30 497.79 | Bukik
sileh Lembang Sawah 688,906 9,894,277 1665 0 2.138 0.01 0.4 5 509.14 | Koto anau
Lembang Sawah 687,977 9,902,100 2452 0.2 0.001 0.01 0.4 5 245.79 d Air Mati Aripan
Bush 684,848 9,912,166 2452 0.3 2.138 0.95 0.4 1 616.29 h Bukik gompong Sumani
Mixed Garden 681,722 9,895,558 1665 0.1 2.138 0.2 0.5 85 576.64 | Kampung jawa 1
Sumani Mixed Garden 682,165 9,894,832 1665 0.1 2.138 0.2

0.5 65 857.14 h (continued on next page) Aflizar et al. Table 1 (continued) Location Sub
watershed Land use GPS reading Erosion Mg/ ha/yr SiO₂ (0–20) mg SiO₂ /kg SiO₂
status in soil East South R K LS C P Kampung jawa 2 Sumani Mixed Garden 682,148
9,894,165 1665 0 3.613 0.2 0.5 10 227.36 d Tower TVRI 2 Sumani Forest 682,440
9,893,752 1665 0 2.877 0 1 40 316.5

| Tower bukik gompong Sumani Forest 683,120 9,893,547 1665 0.1 2.877 0 1 5 358.29 |
Laing 1 Aripan Grass 680,718 9,915,222 2452 0.1 0.001 0.29 1 2.5 89.36 d Laing 2 Aripan
Forest 685,090 9,917,469 2452 0.5 2.138 0 1 3.5 560.79 | Laing 3 Aripan Grass 685,251
9,917,230 2452 0.5 2.138 0.29 1 285 243.86 d Laing 4 Aripan Mixed Garden 685,283
9,917,147 2452 0.5 2.138 0.2 0.5 270 98.57 d Saok laweh Aripan Sawah 686,353
9,912,829 2452 0.1 0.001 0.01 0.4

5 261 d Ganangan Lembang Mixed Garden 684,733 9,906,341 2452 0.2 0.064 0.2 0.5 10
437.36 | Balai pinang Lembang Sawah 685,276 9,905,296 2452 0.3 0.064 0.01 0.4 0.2
289.29 d Guguk rantau Lembang Bush 682,703 9,906,436 2452 0.2 0.064 0.29 1 5 372 |
Koto baru Lembang Forest 682,595 9,906,283 2452 0.2 0.001 0 1 5 791.14 h Sawah
suduk Sumani Bush 682,276 9,908,944 2452 0.1 0.064 0.29 1 5 313.29 | Pakan senayan
Sumani Mixed Garden 680,780 9,906,663 2452 0.1 0.064 0.2 0.5 1.6 201.21 d Selayo
Gawan Sawah 679,843 9,907,068 2452 0.3 0.064 0.01 0.4 5 264.43 d Durian X koto

Gawan Forest 680,026 9,914,546 2452 0.1 0.001 0 1 0 153.64 d Koto sani Imang Bush
678,451 9,916,455 2452 0.3 0.001 0.29 1 0.2 309 I Aie angek Imang Mixed Garden
678,169 9,915,663 2452 0.2 2.512 0.2 0.5 123.2 355.71 I Sumani 1 Imang Sawah 677,426
9,921,191 1288 0.1 0.001 0.01 0.4 5 292.5 d Panyalaian Cupak Lembang Sawah 684,275
9,903,267 2452 0.3 0.064 0.01 0.4 5 299.36 d Sumani 2 Aripan Sawah 677,681 9,921,448
1288 0.1 0.001 0.01 0.4 5 128.36 d Aur Duri Imang Sawah 678,648 9,919,152 1288 0.1
0.064 0.01 0.4 25 392.14 I Belimbing Imang Sawah 678,905 9,916,775 2452 0.3 0.001 0.01
0.4 3 313.5 I Durian Aripan Sawah 680,453 9,914,773 2452 0.1 0.001 0.01 0.4 4 295.93 d
Sawah Parit Aripan Sawah 685,480 9,910,916 2452 0.3 0.064 0.01 0.4 10 182.36 d Guguk
Dama Aripan Sawah 685,080 9,909,609 2452 0.3 0.064 0.01 0.4 5 228.64 d Batu Juriang
Aripan Sawah 686,098 9,908,995 2452 0.2 0.064 0.01 0.4 10 288.86 d Muaro Paneh
Aripan Sawah 687,639 9,906,755 2452 0.2 0.064 0.01 0.4 4 120.64 d Koto Gadang Koto
Anau Lembang Sawah 687,895 9,903,389 2452 0.3 0.064 0.01 0.4 5 200.57 d Koto Anau
Lembang Sawah 688,034 9,902,271 2452 0.2 0.064 0.01 0.4 5 235.93 d Koto Laweh
Lembang Sawah 690,464 9,898,410 1665 0 1.744 0.01 0.4 3 200.79 d Bukit Sileh
Lembang Sawah 691,249 9,895,502 1665 0.1 0.064 0.01 0.4 20 196.7

d Bukit Sileh 2 Lembang Vegetable 691,275 9,895,481 1665 0.1 0.064 0.4 0.5 20 203.79 d
Kampung Batu Lembang Sawah 691,024 9,893,027 1665 0.1 0.064 0.01 0.4 5 310.29 I
Kampung Batu 2 Lembang Vegetable 691,156 9,891,364 1665 0.1 0.064 0.4 0.5 50 102.43
d Dilam 1 Lembang Sawah 692,432 9,900,886 1665 0.3 3.399 0.01 0.4 10 157.5 d Dilam 2
Lembang Sawah 692,462 9,900,828 1665 0.3 3.399 0.01 0.4 10 152.79 d Dilam 3
Lembang Sawah 692,483 9,900,815 1665 0.3 3.399 0.01 0.4 10 189.43 d Sumani 3 Aripan
Mixed Garden 677,030 9,921,312 1288 0.1 0.001 0.01 0.4 0 412.07 I Aripan 1 Aripan
Mixed Garden 676,813 9,922,182 1288 0.1 0.001 0.2 0.5 0 355.29 I Aripan 2 Aripan Mixed
Garden 678,613 9,919,968 1288 0.1 0.064 0.2 0.5 1 1115.36 h Aripan Pompa Aripan
Mixed Garden 679,004 9,919,123 1288 0.1 0.064 0.2 0.5 1 756.43 h Tanjung Bingkung
Aripan Mixed Garden 680,785 9,916,791 2452 0.3 0.611 0.2 0.5 56 427.93 I Bbanda
pandan Aripan Mixed Garden 681,581 9,913,781 2452 0.2 0.001 0.2

0.5 1 633 h Kota Solok Aripan Mixed Garden 684,026 9,911,713 2452 0.3 0.064 0.01 0.4 1
634.5 h Batu kualo Lembang Mixed Garden 684,727 9,909,217 2452 0.2 0.064 0.2 0.5 5
296.36 d Muaro paneh Lembang Mixed Garden 686,990 9,906,478 2452 0.2 0.064 0.2 0.5
5 200.79 d Lembang atas Lembang Mixed Garden 688,122 9,900,659 2452 0.1 0.611 0.2
0.5 28 391.5 I Bukik sileh Lembang Mixed Garden 690,986 9,894,498 1665 0.2 3.4 0.2 0.5
200 389.79 I Batu banyak Lembang Mixed Garden 691,380 9,891,131 1665 0.1 0.611 0.2
0.5 14 794.14 h Kubung Lembang Mixed Garden 684,313 9,907,711 2452 0.2 0.064 0.2
0.5 5 166.93 d Bukik kili 1 Lembang Mixed Garden 684,276 9,906,492 2452 0.2 0.064 0.2
0.5 5 375 I Bukik Kili 2 Lembang 683,659 9,905,507 2452 0.3 0.064 0.2 0.5 0 329.14 I
(continued on next page) Aflizar et al.2.5.1.1. Slope length and steepness factor (LS).

Sawah 679,659 9,910,488 2452 0.3 0.611 0.01 0.4 1 220.07 d Ketaping 4 Gawan Mixed Garden 679,437 9,910,599 2452 0.3 0.064 0.2 0.5 5 137.57 d Gawan 1 Gawan Forest 679,098 9,910,622 2452 0.3 2.51 0 1 1 136.29 d Bukit kili 1 Gawan Forest 678,850 9,910,573 2452 0.1 2.51 0 1 1 130.29 d Bukit Kili 2 Gawan Sawah 682,115 9,911,144 2452 0.3 0.064 0.01 0.4 1 255.86 d Aripan 4 Aripan Sawah 682,803 9,913,171 2452 0.2 0.001 0.01 0.4 5 127.29 d Aripan 5 Aripan Mixed Garden 682,701 9,914,550 2452 0.2 0.001 0.2 0.5 0 150.21 d Destamar 1 Aripan Mixed Garden 682,863 9,916,064 2452 0.1 0.001 0.2 0.5 0 94.07 d Destamar 2 Aripan Mixed Garden 682,652 9,917,803 2452 0.4 0.064 0.2 0.5 100 113.36 d Destamar 3 Aripan Mixed Garden 682,652 9,917,803 2452 0.4 2.14 0.2 0.5 100 263.57 d Gantung Ciri 1 Sumani Sawah 680,501 9,903,987 2452 0.1 0.064 0.01 0.4 1 309.86 l Gantung Ciri 2 Sumani Sawah 679,916 9,904,572 2452 0.2 0.001 0.01 0.4 1 292 d Pulauan 1 Sumani Mixed Garden 679,772 9,904,605 2452 0.2 0.064 0.2 0.5 1 421.93 l Pulauan 2 Sumani Sawah 679,503 9,904,591 2452 0.2 0.064 0.01 0.4 1 313.5 l Pulauan 3 Sumani Mixed Garden 679,278 9,904,592 2452 0.2 0.611 0.2 0.4 14 194.36 d Bukik Singo-singo Sumani Mixed Garden 679,032 9,904,638 2452 0.2 0.611 0.4 0.5 56 178.71 d Bukik Singo-singo 2 Sumani Mixed Garden 680,264 9,904,469 2452 0.2 0.611 0.01 0.4 28 274.07 d Mean 299.8 Median 259.83 Max 1115.36 Min 89.36 SD 177.21 Where, d is deficiency concentration of Si; l is low concentration of Si; h is high concentration of Si. Aflizar et al.2.6.

Data processing for 3D mapping Overall data processing involving USLE was conducted using Surfer[®] 8 (Golden software 2010) dealing with factors gained from a detailed soil survey, digital elevation model, and land-use map. The map of available Si, soil erosion, and land use were computed subsequently using block kriging by taking account of the data within the range.

Block kriging was used instead of punctual kriging because it enables the evaluation of the regional pattern of variation rather than local details owing to the construction of smoother maps with smaller estimation variance (Aflizar et al., 2010). Surfer[®] 8, produced by Golden Software, Inc. (Golden Colorado), is a relatively inexpensive and user-friendly counteracting and three-dimensional surface mapping software for scientists and engineers.

Basic proficiency with Surfer[®] 8 can be achieved with a few hours of self-tutoring. Various editions of Surfer[®] 8 have been applied to the modelling and evaluation of soil heavy-metal contamination and other environmental data (Pazmandi and Tuba 2003). Reported applications typically use Surfer tool as an interface with other software rather than as a stand-alone analytical tool (Aflizar et al., 2010).

Surfer software is extensively used but not well documented, with only limited

reference to its application to environmental data existing in scientific literature. In this study, we used universal kriging that assumed a constant and unknown mean. As shown in Fig. 1, samples were collected throughout the study area, with the exception of the area at the very steep slope and common land-use forest at the west side of SW because of lack of access to the area. Thus, a polygon with boundaries limiting the area of sampling was used, and estimates were generated only for the area inside it.

We used cross-validation to estimate the kriging density through different approaches.

3. Result 3.1. General soil physicochemical properties Tables 1 and 2 show general soil physicochemical properties in the SW. The soil had high silt and clay contents (values of silt and clay contents) and organic matter content of about 5%, which high value (Balai Penelitian Tanah, 2009). Soil permeability and erodibility were high. According to Wischmeier and Smith (1978), soils with K-factor > 0.04 are generally susceptible to soil erosion.

Soil susceptibility to erosion is highly influenced by different climatic, physical, hydrological, chemical, mineralogical, and biological properties (Veihe, 2002). Total nitrogen and available Si are low, whereas TC, extractable Fe and Zn are high. Exchangeable base cations (Ca, Mg, K, and Na) were relatively high. Soil physicochemical properties had some correlation with available Si in the SW (Table 2).

Table 2 reveals that the physical properties of the soil in the form of 32% clay content and 55% silt are quite high as an indicator of good soil physical condition for sawah. Medium to high levels of TC, TN, Ca, K and Na as macronutrients for sawah are good for supporting sustainable management of sawah. However, after analysing available Si in the soil in SW, the concentration of Si was 80% (< 300 mg SiO₂ kg⁻¹), indicating deficiency.

This occurred because since the introduction of the Green Revolution in Indonesia in 1974, the Indonesian government only recommended the use of N, phosphate and K fertilisers; pesticides; and irrigation in sawah. This practice is still being continued to date (Aflizar et al., 2018). Hence, with our current findings, the sawah in the SW and Indonesia requires Si (silicate) fertilisation because the Si levels are already deficient to low.

In accordance with the minimum law, Liebig states that growth is not controlled by the total available resources but is controlled by the fewest resources or nutrients (limiting factors) (Warsi and Dykhuizen, 2017). In the SW, the current growth and production of paddy sawah is determined by available Si in the soil at the deficiency level (Table 1).

Unfortunately, the Indonesian government has not recommended the use of Si fertiliser, only N, P and K (Aflizar et al., 2019). 3.2. Available Si and other general soil properties Table 3 shows the average Si concentrations available in sawah soil (262.4 mg SiO₂ kg⁻¹ in deficiency levels). For sawah to produce well, available Si in the soil must be > 600 mg SiO₂ kg⁻¹. Then, where did the supply of 337.6

mg SiO₂ kg⁻¹ come from so that sawah in the SW could still produce 5 tons ha⁻¹. Tables 2 – 4 and Fig. 4 reveal that the contributor of available Si to rice fields is from Si from the soil depth of 0 – 20 cm (262.4 mg SiO₂ kg⁻¹), river water and irrigation (34.7 mg SiO₂ kg⁻¹) and river sediments from erosion products (393.7 mg SiO₂ kg⁻¹).

To obtain a high production of Sawah (> 5 tons ha⁻¹ to 9 tons ha⁻¹), the paddy soil must have an Si content of 600 mg SiO₂ kg⁻¹, equivalent to an Si content in 1 ha = 600 mg SiO₂ kg⁻¹ × 2 × 106 kg ha⁻¹ × 0.9 g cm⁻³ = 1080 kg SiO₂ ha⁻¹. Thus, the lack of Si in sawah in 1 ha is = 1080 kg SiO₂ ha⁻¹ - 437.5 kg SiO₂ ha⁻¹ = 5.52 kg SiO₂ ha⁻¹ - 472.32 kg SiO₂ ha⁻¹ = 164.66 kg SiO₂ ha⁻¹.

Therefore, the figure of 165 kg SiO₂ ha⁻¹ is a recommendation for Si fertiliser that must be added to the sawah, so that its production increases due to the achievement of Si concentration available in 600 kg SiO₂ ha⁻¹ in sawah soil. The main source of Si in this paddy soil can be taken from coal fly ash and organic matter (Darmawan et al., 2006) or from Si fertiliser directly.

Table 4 shows the average Si available in soil at 0 – 20 cm depth in the SW and 5 subwatershed (S1, S2, S3, S4, and S5). The Si concentration was lower than that in the Citarum watershed, Kaligarang Watershed on Java Island, and Seedfarm and Non-Seedfarm sawah on Java Island (Darmawan et al., 2006; Husnain et al., 2008). This finding may be due to the different numbers of growing seasons of sawah and the soil geology.

The intensive rice cultivation has led to Si mining and exportation through harvesting processes (Darmawan et al., 2006). Differences in the parent material also appeared to be the major factor influencing Si in soils at the watershed scale (Darmawan et al., 2006; Husnain et al., 2008). 3.3. Relationships between soil chemical properties and availability of SiO₂ in the SW pH showed a positive relationship with the availability of Si, i.e.,

Si availability increased with increased pH. This phenomenon may be due to the high availability of Si in high-pH soil possibly because of the Table 2 General soil physicochemical properties in the Sumani watershed. Mean Criteria (Range) SD r a Sand (%) 9.0 (0.4 – 58.0) 11 0.08 Very fine sand (%) 2.0 (0.4 – 9.0) 2 0.01 Silt (%) 55.0 (0.0

– 85.0) 20 0.02 Clay (%) 33.0 (9.0

– 95.0) 20 0.05 Organic matter (g kg⁻¹) 54.0 h (21.0 – 111.0) 24 0.01 Soil permeability (cm h⁻¹) 93.0 (0.0 – 1506.0) 286 0.01 Soil erodibility (K) 0.22 h (0.0 – 0.5) 0.1 0.17* Bulk density (g cm⁻³) 0.9 (0.5 – 1.3) 0.2 0.01 Soil pH H₂O 1:2.5 5.5 a (4.2 – 7.2) 0.5 0.32** Total Carbon (g kg⁻¹) 34.6 h (7.2 – 151.4) 27.6 0.01 Total Nitrogen (g kg⁻¹) 3 m (0.4 – 9) 0.17 0.01 Exchangeable Ca (cmolc (+) kg⁻¹) 10.6 m (0.023 – 29.7) 6.1 0.45** Exchangeable K (cmolc (+) kg⁻¹) 0.4

m (0.1 – 1.9) 0.4 0.38** Exchangeable Na (cmolc (+) kg⁻¹) 0.9 h (0.002 – 3.7) 0.7 0.28** Extractable Fe (mg kg⁻¹) 204.2 h (0.02 – 1500.6) 289 0.17* Available Si 0 – 20 cm (mg SiO₂ kg⁻¹) 300.0 l (89.4 – 1115.4) 177 **, P Value < 0.01 and *, P value < 0,05; SD is standar deviation; r is correlation; h is high; m is medium; l is low; a is acid. Aflizar et al. influence of volcanic ash from Mount Talang. According to Fiantis et al. (2010), Mount Talang volcanic ash contains CaO (4.79%), exchangeable Ca (cmol 11:14 (+) kg⁻¹), and pH H₂O 1:5 (7:26). Volcanic ash very rapidly decays and releases nutrients compared with primary minerals.

The weathering process of volcanic ash releases Ca and other elements, including available Si and K as indicated by an increase in pH (Fig. 3). Ca, K, and Si from volcanic ash are released into the soil, where the nutrients become available to the plants through the process of exchange with free hydrogen protons in the soil. 3.4. Soil-erosion map and distribution of Si availability The soil-erosion map in the SW in 3D is presented in Fig. 4 .

The average rate of erosion in the SW was 58.91 Mg ha⁻¹ y⁻¹ . However, soil erosion was much greater than the average erosion in the highlands where the lands sloped. In the hilly area adjacent to Mount Talang (highland areas S1 and S2), soil erosion ranged within 100 – 200 Mg ha⁻¹ y⁻¹ . Meanwhile, in the hilly area that lies on the west side (upper position of S2, S3 and S5), soil erosion exceeded 200 Mg ha⁻¹ y⁻¹ .

Conversely, in the lowlands (particularly S1, S2, S3, S4, and S5) soil erosion was very low. According to Aflizar et al. (2010), the highest soil erosion occurs in hilly areas in the SW highlands caused by land-use change from forest to agriculture and by natural factors such as erodibility added soil and high rainfall. Meanwhile, soil erosion in the lowlands was low because a sawah generally had a band to prevent erosion.

The average annual erosion in the SW is 58.91 Mg ha⁻¹ y⁻¹ , which has produced as much sediment in the SW is 6.18 Mg ha⁻¹ y⁻¹ with an average of SDR is 10.5%. This finding indicated the accumulation of eroded soil particles in the flat bottom of the

watershed area where the land is sawah. Fig. 5 shows the 3D distribution of Si availability in the SW.

In the highlands S1 and S2 (located near Mount Talang), Si availability was relatively higher than those in the western side of the SW, which includes the areas on the upper positions (S1, S3, and S5). We compared Fig. 3 with 4 and found high soil erosion on both sides. However, in the hilly area near the Mount Talang (the highlands S1 and S2), Si availability was relatively higher than those in the west areas.

This finding may be due to the fact that the area around Mount Talang received fresh volcanic ash from its eruption, and the surrounding soil type is andisol derived from basalt andesite. Fiantis et al. (2010) reported that the eruption of Mount Talang on April 12, 2005 belched 5 cm-thick volcanic ash into the air before falling over the surrounding areas.

Volcanic ash contains approximately 57.61% SiO₂, and the main mineral is volcanic glass and labradorite. Qafoku et al. (2004) reported that volcanic glass is more brittle and elements are more easily released to the soil solution compared with primary minerals. Fig. 6 shows the vertical distribution of Si availability in the highlands and lowlands.

We found lower availability of Si on the soil surface than in the subsoil because more Si was consumed by plants or leached into the subsoil. This result also indicated the influence of soil erosion on the distribution of Si. To examine the effect between the Si consumption by plants or Si loss by soil erosion, we attempted a simple calculation and found that the total annual production of vegetable crops, mixed gardens, and rice in the SW was 27 Gg y⁻¹, whereas the total erosion and total river sediment each year were 3436 Gg y⁻¹ and 360 Gg y⁻¹, respectively. The average Si in rice leaves in Java was 120350 mg SiO₂ kg⁻¹ (Husnain et al., 2008), and Si in the soil in the SW was 300 mg SiO₂ kg⁻¹.

Thus, the SiO₂ lost each year through plant consumption was 3252 Mg y⁻¹, whereas the SiO₂ lost through soil erosion was 1031 Mg y⁻¹. Thus, these data illustrated that erosion greatly influenced soil Si. Table 3 Mean of available Si and other general soil properties in the SW.

Sampling point	pH	TC	Available Si	Exchangeable Ca	Exchangeable Na	Exchangeable K	Extractable Fe (g kg ⁻¹)	(mg SiO ₂ kg ⁻¹)	(cmolc kg ⁻¹)	(mg kg ⁻¹)																																					
Sawah (n = 78)	5.5	34.6	262.4	9.88	1.14	0.26	298	Mixed garden (n = 48)	5.6	45.2	375.9	13.89	0.31	0.72	114	Vegetables (n = 2)	4.6	26.7	153.1	7.32	0.29	1.28	104	Tea (n = 2)	5.3	123.9	272.4	6.07	0.25	0.22	16.3	Forest (n = 8)	5.8	57.3	319.5	13.24	0.38	0.31	19.2	Bush (n = 7)	5.6	38.2	290.9	10.57	0.40	0.30	18.7

River Sediment (n = 23) 5.5 34.6 393.7 9.88 1.14 0.26 298 262.4 Criteria of available Si level in sawah soil Deficiency level (Matichenkov, 2002) 300.0 Low level (Sumida, 1992) 600.0 Table 4 Average available Si in 0 – 20 cm soil depth of some selected sawah in the SW and other watersheds in Indonesia. Study (reference) Location Area (km²) n soil sample Available Si in soil (0 – 20 cm) depth (mg SiO₂ kg⁻¹) Sumani subwatershed (S1) Sumatera Island 176.70 19 241.63 Lembang subwatershed (S2) Sumatera Island 191.80 34 261.01 Gawan subwatershed (S3) Sumatera Island 80.40 6 219.32 Arian subwatershed (S4) Sumatera Island 70.40 16 210.57 Imang subwatershed (S5) Sumatera Island 64.00 3 332.71 Sumani Watershed (SW) Sumatera Island 583.3 78 253.05 Citarum Watershed (Husnain et al., 2008) Java Island 6949 6 504.83 Kaligarang Watershed (Husnain et al., 2008) Java Island 210 6 460.33 Sededfarm (Darmawan et al., 2006) Java Island 18 1283.00 Non-Sededfarm (Darmawan et al., 2006) Java Island 22 1202.00 Sededfarm lowland (Darmawan et al.,

2006) Java Island 12 1804.00 Sededfarm upland (Darmawan et al., 2006) Java Island 6 1005.00 Non-Sededfarm lowland (Darmawan et al., 2006) Java Island 13 1187.00 Non-Sededfarm upland (Darmawan et al., 2006) Java Island 6 1226.00 Aflizar et al. loss, and we expected to lose ground in SiO₂ from the watershed scale. We expect that the transfer layer of topsoil is eroded by erosion. Consistent with the increased erosion every year owing to changes in land use (Aflizar et al.,

2010), the loss of SiO₂ in the watershed scale continued to increase every year. Fig. 7 explains the direction of material movement due to soil erosion in the watershed, where the direction of movement Sumani material is indicated by blue arrows. The arrow was made based on altitude and slope degree in the SW simulation by using a vector in Surfer[®] 9.

The material apparently moved from highlands S1 and S2 and then accumulated sediment in the lowland S2. Material from the upper position while S2, S3, S4 and S5 collected in lowland S3, S4, and S5. Benefits received by the lowland area is the discovery of the availability of high Si at lower positions. This fact, probably due to the transport surface soils containing high SiO₂ through soil erosion.

We also suspected that erosion increased the content of Si in river water and irrigation because the soil contained particles in the form of sediment. We subsequently observed SiO₂ in river and irrigation water. 3.5. Concentration of DSi in river water and irrigation Dissolved Si in river and irrigation water in the Sumani watershed as shown in Fig. 8 .

DSi in rivers and irrigation water on average ranged from 5 to 54 mg kg⁻¹ SiO₂ in the

interval of observation from August Fig. 3. Relationship between available Si and soil chemical properties of soils; (a) pH, (b) Fe, (c) total carbon in the SW, (d) total carbon in sawah, (e) Na, (f) Ca, and (g) K. Aflizar et al. 2006 until February 2007. DSi was higher in the lowlands than in the SW highlands.

In the SW, DSi concentrations in water were higher than those in the DSi in the Citarum watershed, Indonesia (12.6 – 36.6 mg SiO₂ kg⁻¹) (Husnain et al., 2006). DSi in the second watershed was generally low because no SiO₂ fertilizer was present in the SW. Thus, DSi from rivers and irrigation water can be a source of SiO₂ fertilizer. As reported Fig. 4. 3D soil-erosion map in the SW. Fig. 5.

Distribution of available Si in soil. Aflizar et al. by Imaizumi and Yoshida (1958), the 30% SiO₂ sources for rice is derived from river water and irrigation water. Fiantis et al. (2010) performed laboratory experiments and found that phosphorus and other elements including Si in volcanic ash of Mount Talang are leached out within 3000 days through water as leaching agent and within < 2000 days by using organic acids (citrate and oxalic acid).

In summary, available-Si distribution was influenced by various factors, as shown in Fig. 9. Table 5 shows that the average Si concentration in the river at SW was greater than those in the rivers in the Citarum and Kaligarang watersheds, as well as other Asian countries (Thailand, Malaysia, Sri Lanka, and Japan).

The average Si in irrigation water in the SW was also greater than that in Java Island and irrigation water in Japan. This finding may be due to the fact that SW has a natural Si source in the highlands of Mount Talang, which greatly contributes Si to springs and rivers and irrigation. High Si concentrations in river water and irrigation in the SW are the largest contributors of Si to sawah as a counterweight to Si in the soil.

The contribution of natural SiO₂ resources as irrigation water reportedly play important roles in maintaining the available-Si concentration in soil (Darmawan et al., 2006). Kawaguchi and Kawaguchi and Kyuma (1977) found moderate Si concentration in river water, which are the dominant sources of irrigation in Java Island, Indonesia.

3.6. Cross-validation of field measurements Before using a simulation map and optimizing a mathematical model, the accuracy of the simulation map or the model with the original data should be verified (Theodossiou et al. 2006).

The verification is not intended to prove the model accuracy but to ensure the absence of systematic errors, which play important roles in bias estimation (Kitanidis, 1983).

The verification procedures were implemented as follows. The concentration of available Si from 146 soil-sample points were analysed in the laboratory through the same methods and equipment.

With the help of kriging method in Surfer[®] 8, the estimated distribution map of available Si was created. Then matched back with the result of analysis of available Si in the laboratory. The differences between the results of analyses available Si in the laboratory and the estimated values were recorded.

The distribution map is considered unbiased in the sense that if the basic assumptions made were true, then the difference between the analyses of available Si map would be zero. In any other case, the estimated value would be conditionally biased. An example of this is found in the greater estimation value or smaller value measured in laboratory. Fig.

10 shows the correlation of the concentration of available Si measured with the estimation map of available Si. The result can easily be observed that the available Si was distributed around a straight line at 45°. This finding showed that the estimation map of available Si was unbiased.

The isolated points were located below 45°, indicating that the estimated value was incorrect or soil samples in locations required more soil samples. This fact explains the observation on that area needs to be a lot of soil sample, especially in the area have different in geology, land use and topography. Theodossiou and Latinopoulos (2007) reported when using kriging, the occurrence of a large difference between the laboratory and estimated values should not depend on the actual value but only on the location of soil sample, which was representative area that can be simulated (or not) by measuring the actual value. Fig.

11 shows the distribution diagram of the correlation between the estimation error (the difference between Fig. 6. Vertical distribution of available Si. Fig. 7. Direction of material movement in the SW. Aflizar et al. Fig. 8. Dissolved Si in river and irrigation water in the SW. Fig. 9. Diagram of available-Si distribution influenced by various factors. Aflizar et al. available Si and estimated value) and estimates of available Si.

Again, this can be seen easily that the value is distributed around the horizontal straight line which demonstrates that the estimated error value is almost zero. The estimated value of the large error did not depend on the actual estimated values. 4. Discussion According to Matichenkov and Calvert (2002) and Sumida (1992), available Si at < 600 mg SiO₂ kg⁻¹ and < 300 mg SiO₂ kg⁻¹ is considered to be low and deficient,

respectively, for growth and rice production.

As shown in Table 1, the USLE C factor in the paddy field is the smallest value compared with other plants, and the estimated soil erosion is also small. Table 1 shows that the natural causes of erosion in the SW are due to the large R, K and LS values of the USLE factor. Soil erosion in the SW can be controlled by reducing the parameters of USLE C and P factors. In general, Si is available in sawah soils at deficient levels.

The erosion status is also low. The available Si in soils ranges from deficient to low levels, indicating that the status of soil erosion in sawah is so low that it does not have a significant effect on the cause of available Si in sawah soils at the level of definition ($< 262.4 \text{ mg SiO}_2 \text{ kg}^{-1}$).

This means that the available Si is more influenced by the practice of rice management. Si concentrations are generally available in the SW at low to deficient levels. From 77 samples of sawah soil at a depth of 0 – 20 cm, 83% concentration of available Si in soils was found at a deficient level, 17% at a low level and 0% at a high level. Deficient levels of available Si in the soil are found in subwatershed Lembang (S2), Sumani (S1), Aripan (S4), Imang (S5) and Gawan (S3).

Significant Si deficiency has occurred in the sawah in the SW (Table 1). Thus, adding Si in the form of fertilisers is needed in sawah. The aim is to increase sawah production by more than 5 tons ha⁻¹ to 9 tons ha⁻¹ (Aflizar et al., 2019). Table 1 shows that the available Si concentrations in soil $> 600 \text{ mg SiO}_2 \text{ kg}^{-1}$ are found in mixed gardens, forests and shrubs in sub-watershed Lembang (S2), Sumani (S1) and Aripan (S4) because these plants do not need much Si for production. According to Ma et al.

(2007), sawah desperately needs available Si in the soil for growth, production and protection against diseases. Sawah has deficient levels of Si due to intensive rice farming (3 times a year), burning of straw and the absence of Si return in the form of fertiliser to rice fields (Darmawan et al., 2006).

The available Si concentration in sawah, vegetables and shrubs is less than $300 \text{ mg SiO}_2 \text{ kg}^{-1}$, indicating that the sawah level is deficient. This is a sign why in sawah soils Si deficiency affects production and blast disease (Aflizar et al., 2009), whereas in mixed gardens and forests, vegetables and tea do not show a significant effect because sawah are Si accumulator, whereas other agricultural crops are not. The concentration of DSi in water in the SW is higher because in SW there is additional Si from volcanic ash of Mount Talang (Fiantis et al.,

2010) and warm springs that have high DSi water content, which are located in the highlands of SW (Somura et al., 2017). Therefore, to increase rice production in SW, the Si should be more than 5 tons ha⁻¹ to 9 tons ha⁻¹, and blast disease in rice fields should be eliminated. Based on the data in Tables 2 and 5, Si management is needed in sawah soil in the form of Si fertiliser because there is not enough natural contribution of Si from topsoil and DSi from irrigation water, river water and sediments to reach available Si at concentrations of > 600 mg SiO₂ kg⁻¹.

To achieve sustainable Si management in sawah, an average addition of Si fertiliser of 165 kg SiO₂ ha⁻¹ is required. At present, the Si deficiency in sawah soils can no longer be improved from natural fertilisers sourced from irrigation water, river water and Table 5 Average Si concentration (mg SiO₂ L⁻¹) in irrigation and river water from Sumani Watershed, Java Island, and other Asian countries.

Study (reference)	Location	Area (km ²)	SiO ₂ concentration (mg SiO ₂ L ⁻¹)
	Irrigation water in Sumani Watershed (SW)	Sumatera Island, Indonesia	583.3 32.65
	River water in Sumani Watershed (SW)	Sumatera Island, Indonesia	583.3 40.94
	Lake Dibawah in Sumani Watershed	Sumatera Island, Indonesia	5.96
	Irrigation water in Java (Darmawan et al., 2006)	Java Island, Indonesia	14.00
	River water in Java (Kawaguchi and Kyuma, 1977)	Java Island, Indonesia	29.82
	River water Citarum Watershed (Husnain et al., 2008)	Java Island, Indonesia	6949 24.05
	River water Kaligarang Watershed (Husnain et al., 2008)	Java Island, Indonesia	210 37.28
	River water in Thailand (Kawaguchi and Kyuma, 1977)	Thailand	17.19
	River water in West Malaysia (Kawaguchi and Kyuma, 1977)	Malaysia	13.01
	River water in Sri Lanka (Kawaguchi and Kyuma, 1977)	Sri Lanka	13.07
	River water in Japan (Kawaguchi and Kyuma, 1977)	Japan	19.00
	Irrigation water in Japan (Kumagai et al., 2002)	Japan	10.20

Correlation between measured available Si in the laboratory and estimated value. Fig. 11. Correlation between the estimated available Si and estimated error. Aflizar et al. sediments alone because 60% of the total land in SW suffer from Si deficiency, 31% have low Si levels, and 10% have high Si levels (Table 1 and Fig. 5). The problem of Si deficiency in sawah is very urgent (Table 1 and Fig. 5).

Considering that Indonesia's population is increasing every year, the loss of rice fields to non-agricultural uses is high. Table 3 shows the mean soil properties of the land-use types. According to Bollich and Matichenkov (2002) and Sumida (1992), available Si levels less than 600 and 300 mg SiO₂ kg⁻¹ are considered to be "low" and "deficient" for rice plant growth.

Based on these criteria, most of the sites were grouped into the categories of "low" and "deficient," indicating that soil in the SW was generally low in available Si. This finding may explain the blast diseases frequently observed in this watershed. Tea plantation showed a high TC, and vegetable garden showed a low pH. In the SW, the low Si availability may be associated with the intensive agricultural practices and the absence of additional Si fertilizer by farmers, in addition to the high rainfall that transports Si from the surface soil through erosion and runoff. This region has the annual contribution of volcanic ash from Mt. Talang to the agricultural area on the island of Java as mentioned by Kawaguchi and Kyuma (1977).

However, the high activities of rice farming and vegetable and tea planting have resulted in the mining and transport of Si through the process of harvesting (Darmawan et al., 2006). Referring to Fig. 3, the concentration of hydrogen protons from soil decreased with increased concentrations of Ca, K, and available Si, resulting in increased pH.

This process may have occurred throughout the entire SW. To enable the process of release of nutrients needed by plants from volcanic ash, sourcing a substantial amount of hydrogen protons is necessary. In the SW can originate from inorganic acids released from the eruption of Mount Talang which always occurs in small and medium scale in the past until now.

In addition, organic acids derived from the exudates of biota can be a source of hydrogen protons (Fiantis et al., 2010; Dahlgren et al., 1999). The weathering of volcanic ash occurs through surface exchange with aqueous hydrogen ions (Shoji et al., 1993). The main sources of protons for the weathering of volcanic ash include acidic aerosols, carbonic and organic acids.

Acidic aerosols comprise sulphuric acid (H_2SO_4), hydrochloric acid (HCl), fluoric acid (HF), and nitric acid (HNO_3), which originate from the eruption plume, whereas carbonic and organic acids originate from biota (Dahlgren et al., 1999). Besides an increase in the concentration of silicon in the soil because it deals with pH, Ca and K.

extractable Fe and Exchangeable Na is the opposite effect, namely reducing the availability of Si concentration in the soil. The highly extractable Fe showed a negative correlation with Si availability. This finding may have been due to the indirect effect of soil pH, where Fe solubility was high at low pH and the low pH was related to the solubility of Ca, K, and Si. Jansen et al. (2003) reported that the solubility of Fe (III) was higher at pH 4 and 5. Conversely, the solubility of Fe (II) and Al was high at pH 3.5.

Exchangeable Na led to increased concentrations and thus to the low availability of Si. This finding was most likely due to the Na **in the form of** sodium carbonate (Na_2CO_3) reacting with SiO_2 and the liquid form of sodium silicate (Na_2SiO_3) and CO_2 (Greenwood and Karpinets, 1997). We suspected that Na_2SiO_3 was a form of Si unavailable to plants.

Si is available for plants in the form of $\text{Si}(\text{OH})_4$ (Saccone et al., 2006), H_4SiO_4 (Tian et al., 2008). The solubility of Si in soil solution ranged from pH 2 to 9, and Si typically comes **in the form of** orthosilicat. We speculated that Na_2CO_3 formed from the reaction of Na ions with carbonate ions. Regarding TC, we found no significant correlation for all land-use types.

However, when we extracted sawah soil, a negative correlation was found between TC and Si availability. This finding was due to the high TC in sawah soil because of the high rice production. Darmawan et al. (2006) reported that the TC of sawah soil has increased by 13.7% during the 30 years of intensive cultivation of rice in Java, Indonesia.

The high production of rice meant that Si was highly consumed. They changed from Si in a form available for plants to be biogenic Si **in the form of Si** which is not available for plants. Si in the remaining plants so that decomposes organic material is a form of Si which is generally **in the form of** biogenic Si, which in form is not available as plants (Imaizumi and Yoshida, 1958). Changes **in the form of** available Si as biogenic Si may explain why soil with high TC had decreased available Si. Darma - wan et al.

(2006) reported that intensive rice without Si fertilizer and mining Si has resulted in the soil through the process of harvesting. Thus, **the availability of Si in sawah in** Java soil decreased by 11% – 21% within 30 years. For the hilly areas far from Mount Talang, Figs. 4 and 5 illustrate high soil erosion with low content of Si (upper positions of S2, S3, S4, and S5) and low erosion with relatively high availability of Si (lowlands **S1, S2, S3, S4,** and S5). Vegetable land mostly had low Si availability (Table 2 and Fig. 3), where the show is located at the highest regional rate of erosions.

Severe soil erosion can carry away available Si on the soil surface. Conversely, **the availability of Si** was relatively high at sawah and generally distributed in the lowlands (Figs. 3 and 4), where most sediment accumulation occurs (Fig. 3). Aflizar et al.

(2010) re - ported the results of the estimation method for the location kriging deposition of eroded in sawah, which numerous eroded soil particles on the topography of the watershed that were transported and accumulated **at sawah in the** lowlands. At lowland soil layers deeper than the Upland area. We believe that **this finding may be**

due to the accumulation of particles eroded from highlands in the lowlands.

Local farmers also believe that the lowlands originated from the eroded soil of the highlands (Personal communication, 2009). Lowland areas of geology data showed that soil derived from basaltic andesite colluvial deposit from Mount Talang in the highlands was transported in large quantities through soil erosion one hundred years ago. Based on calculations from the data in Table 3 and Fig.

5, the basis for making Si fertiliser recommendations is to achieve an available Si concentration of $> 600 \text{ mg SiO}_2 \text{ kg}^{-1}$ in the soil. Thus, the calculation of Si fertiliser is based on $600 \text{ mg SiO}_2 \text{ kg}^{-1}$ reduced by the concentration of Si from Si input from top soil (0 – 20 cm), irrigation water, river water and sediment.

The result of this reduction will be the recommendation of Si fertiliser needed by the soil to reach a concentration of $600 \text{ mg SiO}_2 \text{ kg}^{-1}$ and to produce rice $> 5 \text{ tons ha}^{-1}$ to 9 tons ha^{-1} . The fertiliser recommendations are obtained based on a 3D map of the distribution of available Si (Fig. 5), which has been mapped: Sawah soil with available Si concentration: Si = $50 - 150 \text{ mg SiO}_2 \text{ kg}^{-1}$, then recommended Si fertiliser = $299 - 236 \text{ kg SiO}_2 \text{ ha}^{-1}$, Si = $150 - 300 \text{ mg SiO}_2 \text{ kg}^{-1}$, then recommended Si fertiliser = $236 - 141 \text{ kg SiO}_2 \text{ ha}^{-1}$, Si = $300 - 450 \text{ mg SiO}_2 \text{ kg}^{-1}$, then recommended Si fertiliser = $141 - 47 \text{ kg SiO}_2 \text{ ha}^{-1}$, Si = $450 - 600 \text{ mg SiO}_2 \text{ kg}^{-1}$, then recommended Si fertiliser = $47 - 0 \text{ kg SiO}_2 \text{ ha}^{-1}$ and Si = $600 \text{ mg SiO}_2 \text{ kg}^{-1}$, then recommended Si fertiliser = $0 \text{ kg SiO}_2 \text{ ha}^{-1}$. However, Si management is sustainable in the paddy fields in SW through the recommendation of balanced Si fertilisation.

It can be achieved by paying attention to the high soil erosion status in SW (Fig. 4). In other words, soil erosion in SW must be controlled because it is found in mixed vegetable and mixed gardens in the highlands of SW (Fig. 4), which can cause leaching of Si fertiliser given to the sawah. Therefore, in order to have good Si management, the soil erosion distribution map in Fig.

4 is very useful and can be used as a guide to determine soil and water conservation actions that will be given to the SW. Aflizar and Masunaga (2013) reported that areas that have high soil erosion must be given soil and water conservation in the form of contour plantings and making of terraces.

The availability of 3D visual maps of the available Si distribution in the soil and distribution of soil erosion and DSi in irrigation and river water and Si sediment is very helpful for sustainable agricultural development and management of Si in paddy soils. It can also be used to improve the environment on a watershed scale in Indonesia. 5.

Conclusions Soil depth (0 – 20 cm) and Si from irrigation and sediment was a major source of Si in the SW. Soil erosion transported soil surface rich in Aflizar et al. SiO₂, making it available to lowlands sawah. Meanwhile, the river water in the surrounding highlands had high erosion and low SiO₂ availability.

Low pH, high extractable Fe, and high exchangeable Na showed relatively low availability of SiO₂. Given these factors, the availability of Si distribution in the SW. When Si availability in sawah soil was low, we found rice blast disease. Generally, Si availability in the SW was low.

However, in areas close to Mount Talang, is the height of the addition of SiO₂ from volcanic ash, also in the lowland areas through irrigation water. However, on the west side of the SW, the area we found the availability of SiO₂ sawah deficiency especially at high topography on the west side of the SW, which is now found in many diseases according to the results of interviews with farmers.

Blast disease occurred based on our observations but not in the area surrounding Mount Talang. This finding may be due to the contribution of SiO₂ from volcanic ash Mount Talang. For the sake of a sustainable management of watershed, we recommend the addition of SiO₂ to rice fields with doses 230 kg/ha.

Possible sources of SiO₂ include coal fly ash because it is so widely available in Indonesia. Declaration of Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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