ASSESSMENT OF SOIL EROSION AND SEASONAL WATER QUALITY CHARACTERISTICS IN SOCIAL FOREST–DOMINATED WATERSHEDS, LAMPUNG, INDONESIA

(インドネシア・ランプン州の社会林業が支配的な流域における土壌侵食と季節的な水質特性の評価)

RAHMAH DEWI YUSTIKA

2020

THE UNITED GRADUATED SCHOOL OF AGRICULTURAL SCIENCES,
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Approval Sheet

This thesis enclosed herewith, "ASSESSMENT OF SOIL EROSION AND SEASONAL WATER QUALITY CHARACTERISTICS IN SOCIAL FOREST–DOMINATED WATERSHEDS, LAMPUNG, INDONESIA", prepared and submitted by, Rahmah Dewi Yustika, in partial fulfillment of the requirement for the award of degrees of Doctor in Philosophy, is hereby approved as to style and contents.

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I dedicate this work:

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CHAPTER 1

GENERAL INTRODUCTION

1.1. Social Forestry

The growing population in Indonesia influences land demand for agriculture that accelerates converting of the land use from forest to agricultural land. A national forest area in Indonesia covers 63% of its total area (MoEF, 2018). The term forest according to the Indonesian Forestry Act 1999 is a united ecosystem predominantly by tree communities found in the natural environment (Republic of Indonesia, 1999). The contribution of Indonesia in United Nations Framework Convention on Climate Change (UNFCCC) modified forest definition into forest "working definition" that stated, "a land area of more than 6.25 hectares with tree higher than 5 meters at maturity and a canopy cover of more than 30 percent" (MoEF, 2016).

It is important to protect the forest from deforestation and forest degradation, as forest has functions in supporting biodiversity (flora and fauna), determining hydrological characteristics, and supporting life for communities. Local communities surrounding forest areas have a strong bonding with the forest as they depend on forest resources for living. The utilization of forest areas by local communities often rise conflict of forest tenure. Local communities that live surrounding the forest area have a potential on forest management to ensure forest functions. Therefore, forest management policy for giving legal access to local communities is a solution to use forest resources in order to support economic growth and reduce conflicts with consideration in maintaining forest functions.

Social forestry is the system of forest management that empowers local communities by giving legal access to forest resources. This policy gives equity to local communities for increasing prosperity and economic development, for balancing the relationship between environment and dynamic social culture, and for maintaining sustainable forest function (Ministry of Environment and Forestry, 2016). Besides that, legal access to forest tenure can reduce deforestation and improve rehabilitation. Social forestry program consists of community forests (*Hutan Kemasyarakatan, HKm,* is a type of social forestry that the main purposes are for empowering local community by giving legal access to forest area), forestry partnerships (*Kemitraan Kehutanan* is cooperation between local community and forest managers, the holders of forest service, the holders of forest land use rights, and the holders of primary forest industry), *adat* forests (*Hutan Adat* is a forest that located in an *adat* law community's area), village forests (*Hutan Desa* is a type of social forestry which is managed by village officials for the welfare of village community), and community plantation forests (*Hutan Tanaman Rakyat* is a type of social forestry that allows local community to access the forest to establish timber plantation in a production forest through application of silviculture to ensure forest sustainability).

In Tanggamus Regency, Lampung, Indonesia, the coffee plantation is predominant land use and cultivated by smallholder in the social forestry area. Local community around the forest in Tanggamus Regency area has legal access to use forest in order to increase their livelihoods and welfare through community forest and forestry partnership programs but on another side, they have to maintain forest function. Coffee cultivation becomes one of the important sources to support economic growth. Indonesia is the fourth largest coffee producer after Brazil, Vietnam, and Colombia (International Coffee Organization, 2019). Coffee is the largest export from the agricultural and forestry sector in Lampung Province, with a value USD 435,288,000 (Statistics of

Lampung Province, 2017a) and a production of 131,501 ton (Statistics of Lampung Province, 2017b) in 2014.

1.2. Effects of land use changes

Land use changes from forest to other land use effects on environmental problems that influence ecosystem services such as soil erosion. The land that suffers from soil erosion will have problems with decreasing soil quality, agricultural productivity, and sedimentation. Besides, land use changes also cause problems of reducing water quality. Agriculture land use usually applies chemical fertilizer to increase crop productivity. The excessive amount of fertilizer application has resulted in decreased water quality that caused eutrophication, the harmful effects for human consumption, and the declined aesthetics of water quality.

1.2.1. Soil erosion

Soil erosion is transporting of soil particles from one place to other places by wind or water that occurred naturally or accelerated by human intervention. Natural soil erosion or geological erosion is soil erosion that occurred naturally and slowly to complete equilibrium between soil forming and soil removing. Human-accelerated erosion is soil erosion influenced by human activities due to forest conversion to agricultural land and improper management.

Soil erosion in the tropics area dominantly promoted by water. The mechanism of soil erosion initiated by precipitation caused the detachment of soil particles from soil surfaces. The intensity of precipitation influences soil erosion as raindrops power determines the detachment of soil particles from soil mass. Raindrop affects soil erosion up to 86.8% and play roles in soil aggregate loss (Lu et al., 2016). The next process is raindrops will splash causes transportation of soil. The transportation of soil particles becomes intense in the sloping area and deposits in lower elevation.

Soil erosion promoted by water has various forms such as sheet erosion, rill erosion, and gully erosion (Weil and Brady, 2017). Sheet erosion occurs when soil removes uniformly from the soil surface. Increasing sheet flow will make concentrated flow into tiny channels which is called rill erosion. Gully erosion was found when the rapid water flow cuts deeper into the soil and make larger channels. Continuous concentrated water flow will result in deeper grooves with V shaped or U shaped.

The effect of soil erosion play role in decreasing nutrient and organic matter above soil surface and reducing soil productivity. Measuring soil erosion could be conducted by USLE equation that consists of various factors such as erosivity, erodibility, slope, crop, and land management (Wischmeier and Smith, 1978). The equation of USLE:

$$A = R \times K \times LS \times C \times P \quad (1)$$

where *A* is erosion (Mg ha^{-1} $year^{-1}$), *R* is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$), *K* is the soil erodibility factor (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), *LS* is the slope length factor (dimensionless), *C* is the crop factor (dimensionless), and *P* is the soil management factor (dimensionless).

R factor is the effect of precipitation to cause the erosion which this depend on intensity and duration, also mass, diameter, and velocity of raindrops (Morgan, 2005). *K* factor reflects the sensitivity of soil characteristics (textures, organic matter, permeability and structure) to erosion. *LS* consists of the slope-length factor (*L*) and the slope steepness factor (*S*) and represents topographic impacts on the soil erosion rate. While *C* factor represents the influence of cover crop type and the *P* factor represents the influence of soil management practices to soil erosion rate.

Measurement of soil erosion in the field is costly and time-consuming. In recent days, adopting process-based model becomes alternatives to access soil erosion, evaluate tillage practices, make plans for best management practices, and comply with environmental regulations. Process-based model such as Annualized Agricultural Non–Point Source (AnnAGNPS), Hydrological Simulation Program–Fortran (HSPF), Areal Nonpoint Source Watershed Environment Response Simulation–Continuous (ANSWERS–Continuous), and Soil and Water Assessment Tool (SWAT) could be applied to identify long term effects of hydrological changes and land management within watershed (Borah and Bera, 2003). These tools could help users for planning land management in watershed and giving alternatives for applying best management practices. The assessment of sediment yield and runoff from these models compares with yield measurements presents that result of these models were acceptable (Shen et al., 2009). The monitoring and assessment of water quality help policymakers in making regulations for sustainable natural resources management.

1.2.2. Water quality

Water quality is observed through physical characteristics (odor, color, dissolved solids, floating matters, sediment load, turbidity and clarity, suspended organic, and inorganic materials), chemical characteristics (pH, salinity, dissolved oxygen, chemical oxygen demand, heavy metals, dissolved organic matter and organic nitrogen, dissolved load of chemical constituents), and biological characteristics (organism, biomass, pathogens, cyanobacteria, phytoplankton and zooplankton, biological oxygen demand) of water (Sahrawat et al., 2005). The standard of water quality is different according to purposes such as drinking water, industrial, agricultural land, and recreation.

Within the watershed, water quality is influenced by many factors such as land use, fertilizer application, industrial center, sewage system, tillage practices, best management practices, and pesticide application. Agriculture land use changes could affect water quality (Lin et al., 2015). Soil tillage and vegetation cover influence soil erosion that play role in suspended sediment. Laufer et al. (2016) showed that intensive tillage had the highest sediment concentration compared to reduced tillage and strip tillage.

Intensive agriculture activities could decline water quality in stream water (Rodrigues et al., 2018; Rothwell et al., 2010) due to fertilizer and pesticide application. Soil degradation cause by land activities results in the declining of organic matter which lead to soil deterioration. Declining soil fertility leads to reductions of yield on agriculture land (den Biggelaar et al., 2003). Therefore, farmers use chemical fertilizer to increase yield. Runoff during precipitation could transport fertilizer above soil surface. Eutrophication occurs because of excessive fertilizer application which results in nutrient enrichment in water body. Eutrophication could reduce water quality and change functions of the aquatic ecosystem.

Land use and seasonal pattern could influence water quality (Rodrigues et al., 2018). Moreover, water quality characteristics differ between rainy and dry seasons. Shi et al. (2017) presented that river water quality in the rainy season has higher level of electrical conductivity (EC), ammonium nitrogen ($NH_4^+ - N$), nitrate nitrogen ($NO_3 - N$), and total suspended solids (TSS) while in dry season has higher concentration of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO). Shabalala et al. (2013) revealed that nitrate concentration was higher in rainy season than dry season due to agricultural applications of manure and fertilizers.

Water quality also got influence from geology. Research in Java in Indonesia demonstrated higher Si availability in river with areas consisting parent material of tuff and volcanic ash rather than clay sediment (Husnain et al., 2008). S. Yu et al. (2016) presented that the phosphate concentration in stream water had influence from geological factors that contain different orthophosphate backgrounds. Low pH water was influenced by igneous lithologies (granite, lavas and volcanic tuff) while high pH water was affected by calcareous geology (Rothwell et al., 2010).

Primary water quality USEPA standard (United States Environmental Protection Agency [USEPA], 2009) regulates contaminants that could have effects on human health. While secondary water quality USEPA standard regulates contaminants that determine aesthetic qualities such as appearance, taste, and odor. In Indonesia, Ministry of Health Republic Indonesia issues regulation about water quality of environmental health standard and water health requirement for sanitation hygiene, swimming pool, *solus per aqua*, and public bathing. Rivers are very important in supporting human activities for irrigation, drinking, bathing, generating power plant, and transportation. Therefore, it is important to maintain water quality to ensure rivers function.

1.3. Best Management Practices

Best management practices (BMPs) conserve soil and water within the watershed by reducing soil erosion and nutrient loss from agricultural land. The adoption of BMPs help farmers to maintain soil quality to support crop production. There are some BMPs that can be applied in watersheds such as buffers, agroforestry system, terraces, contour cropping, and cover crops.

1.3.1. Buffers

Riparian buffers are the strip of trees, shrubs, or grass along the stream water that provide transitions zone between water and agricultural land and have functioned as a filter to reduce soil erosion, surface runoff, and nutrient loss. Riparian buffer could be used to handle non-point source pollution. Besides, riparian buffer also has functioned as flood mitigation, stabilize bank erosion, and as wildlife habitat.

The type of vegetation and the width influence the effectiveness of riparian buffer. The recommendation width of riparian forest buffer for sediment removal, nutrient removal, and flood mitigation were 50 – 160 ft, 30 – 140 ft, and 65 – 225 ft, respectively (USDA Forest Service, 1997). Grass has higher effectiveness in reducing sediment and nutrient losses than shrubs and forest, while forest can give the highest protection of flood mitigation (Lehigh Valley Planning Commission, 2011). Riparian buffer that consists of trees, shrubs, and grass are more effective in filtering sediments and nutrients loss compared to just one type of vegetation.

1.3.2. Terrace

Terrace is soil conservation practices used on the sloping area by reducing slope gradient and length for facilitating agricultural crops. People build terraces also for reducing soil erosion, slope stabilization, and reducing surface runoff. Application terraces with crop residue and grass strip at terrace lips could reduce soil erosion rate higher than just terrace application (Suyana et al., 2010).

This practice was applied in many areas in the world and used for various crops (rice, maize, wheat). Terrace practice was applied since ancient times in southern Peru by Inca (Londoño, 2008). Need to consider design terraces, periods of use, waterways, and width for tillage machine before build the terrace because building the terrace is costly. Besides, terraces need to be maintained and well manage to conserve its function for reducing landslide risk (Tarolli et al., 2014).

1.3.3. Agroforestry

Agroforestry is the management of agricultural crops with other trees that could decline pressure on protected areas, support life for biodiversity, and support rural income (Ashley et al., 2006). Agroforestry with high shade of canopy cover and less management will have similar conditions with forest (Bhagwat et al., 2008). Application of agroforestry in corn-soybean rotation could reduced runoff, nutrient, and sediment (Udawatta et al., 2001) especially in the second and third year of experiment due to increasing of vegetation cover and vegetation roots.

Application of agroforestry could improve soil organic matter through litter from plant residue and leaves, contribute to soil biological activities, and support water availability in the root zone (Hairiah et al., 2003). The existence of organic matter will improve soil properties in the upper layer such as bulk density. The bulk density in agroforestry buffer is lower than in grass buffer and row crop while hydraulic conductivity in agroforestry and grass buffer was higher than row crop treatments (Seobi, et al., 2005).

1.3.4. Contour cropping

Contour cropping is planting trees according to elevational contour lines in order to reduce soil erosion and surface runoff. Alegre and Rat (1996) presented that contour hedgerow reduced soil erosion and surface runoff. Besides, the application of residue from hedgerow could repair soil properties by lowering bulk density and increasing hydraulic conductivity in intercropping than sole cropping. Contour application could reduce mean sediment and phosphorus loss (Stevens et al., 2009). Tadesse and Morgan (1996) stated that the effectiveness of contour grass strip in reducing sediment depends on grass species, slope, and intensity of runoff.

1.3.5. Cover crop

Cover crop is crops grown in soil surface that could reduce soil erosion, surface runoff, nutrient losses, and soil water evaporation. Cover crop play role in reducing soil erosion because it minimizes soil particle detachments from raindrop which decline aggregate breakdown. Further, cover crop enhances soil aggregate stability, soil organic C, and total N (Liu et al., 2005). Coarse root axes and high rooting density of cover crops could increase hydraulic conductivity and reduce runoff (Y. Yu et al., 2016).

The residue from cover crops could increase soil organic matter and increase plant–available soil water relationships. In addition, residue from cover crop enhances infiltration rate and decline evaporation (Unger & Vigil, 1998). Type of cover crops are *Pueraria javanica, Centrosema pubescens, Calopoginium mucunoides, Arachis pintoi,* and others. Leguminous cover crops can promote biologically fixed nitrogen (Dabney et al., 2001) and provide nitrogen for the following crops. Application of cover crops should consider about enhance risks of disease, need labor cost for planting and pruning, increase pest attacks, allelopathy, and disturb tillage practice (Dabney et al., 2001).

1.4. Objectives of the study

The objectives of this study are:

1. To determine total sediment solids and assess soil erosion by utilizing the USLE, also recommended best management practices (BMPs) for the study area.
2. To determine the seasonal water quality characteristics in river under human activities and natural processes impacts.

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CHAPTER 2

Assessment of soil erosion in social forest-dominated watersheds in Lampung, Indonesia

2.1. Introduction

Increasing human population as well as rapid economic growth have resulted in increased demand for land in Indonesia (Liu and Yamauchi, 2014). The availability of land is closely linked to the intensity of economic activities, which subsequently impact forest areas. In particular, deforestation can be attributed to illegal logging activities and conversion to agricultural land, plantations, and settlements (Kubitza et al., 2018; Malahayati, 2018; Margono et al., 2014). Conversion of forest land to other land-use types contributes to nonpoint source pollution and significantly threatens water quality in aquatic systems (Gunawardhana et al., 2016).

Forest areas in Indonesia should be sustainably managed by utilizing both canopy and understory vegetation. This would not only maintain the ecological functions of forests but also enhance infiltration, which would decrease the rapid discharge of water as well as the subsequent erosion from mountainous areas to downstream watersheds. The political reformation period of 1998 significantly impacted land use change in the forested areas of Indonesia (Sunderlin, 2002) . Presently, the Indonesian government is attempting to reduce the effects of deforestation by implementing equitable economic policies through a social forestry program. According to the Ministry of Environment and Forestry (2016), social forestry consists of community forests (*Hutan Kemasyarakatan, HKm*), forestry partnerships (*Kemitraan Kehutanan*), adat forests (*Hutan Adat*), village forests (*Hutan Desa*), private forests (*Hutan Rakyat*), and community plantation forests (*Hutan Tanaman Rakyat*). The social forestry policy aims to empower communities surrounding forest areas through provision of environmental services and maintenance of forest functions. This could potentially contribute to local economic growth and improve sociocultural dynamics near forests.

Community forestry and forestry partnerships were implemented in the Sekampung Hulu and Sangharus watersheds in Lampung Province, Indonesia as part of the social forestry policy. The primary land use in these watersheds is coffee plantation, with nearly 131,501 tons of coffee produced in Lampung Province in 2014 (Statistics of Lampung Province, 2017b). Land use changes inside the forests likely influence the environmental functions of the forests. Moreover, a reservoir downstream of the target watersheds contributes to irrigation of paddy fields and supports electricity generation. Thus, erosion hazards in the upstream area could influence the water capacity of the reservoir dam as well (Ran et al., 2013).

Because land use changes can trigger soil erosion and sedimentation (Pilgrim et al., 2015), the conversion of forests to coffee plantations in the study area likely increased soil erosion, which is an indicator of environmental disturbance. Soil erosion is detrimental to optimal soil properties (Ebeid et al., 1995) and causes nutrient loss from soil surfaces (Su et al., 2010). Soil erosion rates depend on the amount and intensity of precipitation (Canton et al., 2001), topographic conditions (Hessel and Jetten, 2007), soil characteristics (Panagos et al., 2014), and vegetation (Nicolau et al., 1996). The focal area for this study is characterized by high precipitation and steep slopes in the hilly or mountainous areas (Prawiradisastra, 2013).

Assessment of soil erosion can help address land management issues at the plot or watershed scale. In addition, such assessment enables stakeholders to evaluate erosion risks and subsequently determine suitable crop types for the watershed. Furthermore, this information allows government agencies to implement agricultural regulations and forest management policies to minimize land degradation and address related environmental concerns. Soil erosion can be estimated through the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), which is simple and user friendly. The application of the USLE at the watershed scale can be supplemented by geographic information system (GIS) analysis (Ahmad and Hagos, 2016). Recently, GIS has been utilized in studies of natural resource management for efficient data management. The integration of the USLE with GIS allows assessment of soil erosion for each spatial unit.

The study of the effects of land use change on water quality could aid watershed management and planning (Kibena et al., 2014; Xu and Zhang, 2016). Somura et al. (2019) conducted a preliminary study on the total suspended solids (TSS) in the target watersheds and concluded that TSS concentrations for the Sekampung Hulu River were higher than those for the Sangharus River. However, this study was conducted during the rainy season (March–May), but detailed investigation of the primary rainy season characteristics and the causes of the apparent differences in TSS concentrations was not conducted. Thus, this study aimed to determine the water quality of the Sekampung Hulu and Sangharus Rivers based on annual estimates of their TSS concentrations for 2016. Subsequently, soil erosion was assessed by utilizing the USLE. Best management practices (BMPs) were also recommended for the study area. The evaluation of soil erosion in both watersheds could potentially aid sustainable land management in the study area.

2.2. Materials and methods

2.2.1 Study area

The Sekampung Hulu and Sangharus watersheds are located in the Tanggamus Regency, Lampung Province, Indonesia. These two major watersheds supply water to the Batutegi Dam reservoir (Figure 2.1). The study area is situated between latitudes 5°5’37” S and 5°15’58” S and longitudes 104°30’34” E and 104°42’56” E. The Sekampung Hulu and Sangharus watersheds are spread over 141.3 km^2 and 117.2 km^2, respectively. The study region covers an area of 258.5 km^2, of which social forestry constitutes 244.3 km^2. The remainder area of 14.2 km^2 is private land, which is predominantly located in the Sangharus watershed.

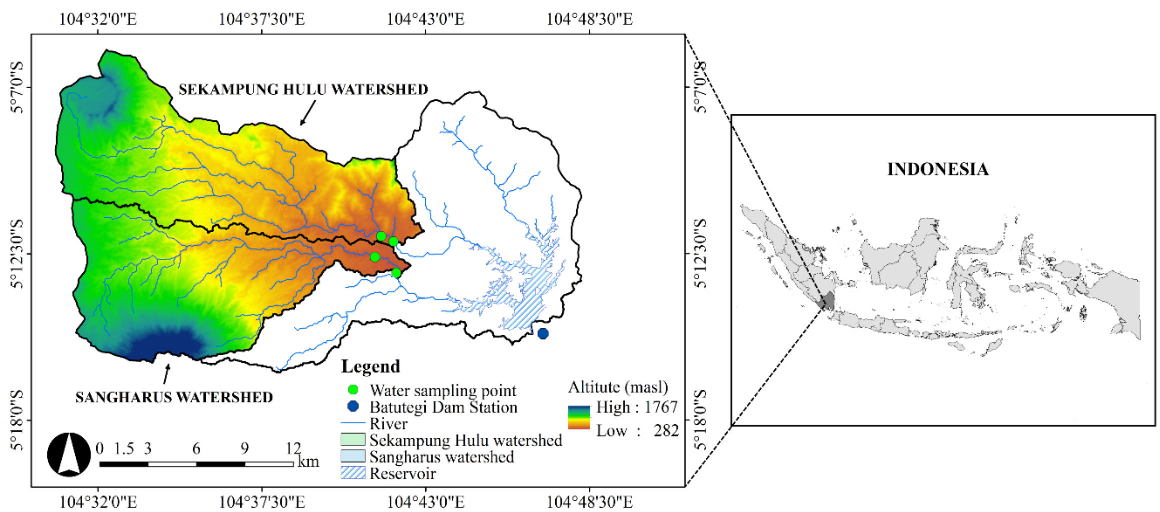

Figure 2.1 Location of study area.

The elevation in the study area ranges from 282 to 1767 masl. The local mean annual precipitation is 1826 mm (Directorate General of Operation and Maintenance Water Resources Mesuji Sekampung [DGOMWRMS], 2017). The mean monthly precipitation during the periods 1998–2010 and 2013–2016 is presented in Figure 2.2. No precipitation data is available for 2011–2012 because the equipment was not working.

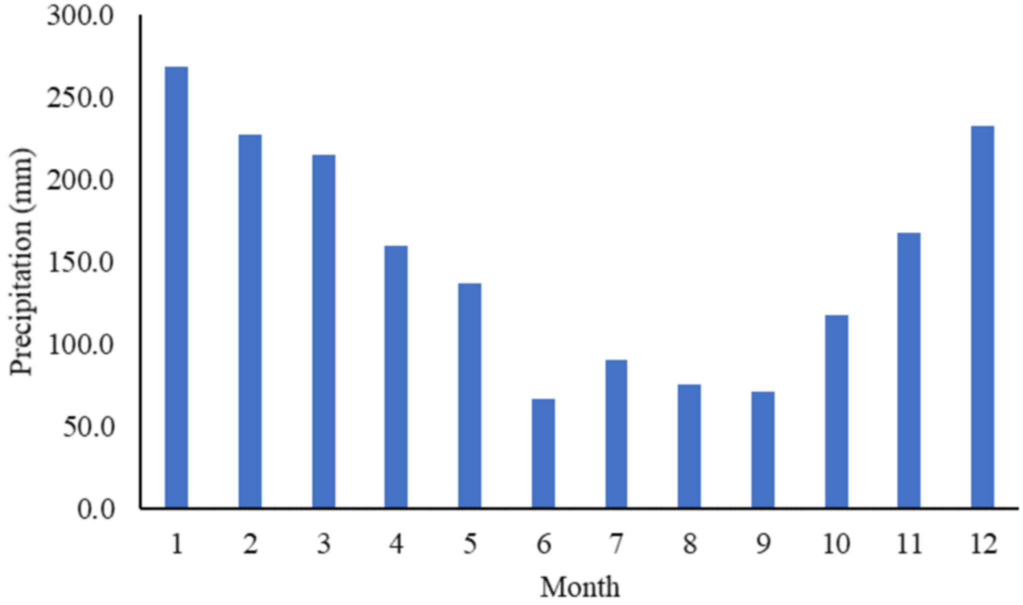

Figure 2.2 Mean monthly precipitation, 1998–2010 and 2013–2016.

Based on data from the National Land Agency (2017) and from field observations, land use in the Sekampung Hulu watershed comprised forest (5.8%), young coffee (25.7%), agroforestry coffee (33.9%), shade coffee (34.3%), and river (0.3%), while that in the Sangharus watershed comprised forest (4.6%), young coffee (3.3%), shade coffee (66.3%), agroforestry coffee (25.6%), and river 0.2% (Figure 2.3a). Young coffee has less canopy coverage because of the early stage of growth. Shade coffee describes coffee plantations also planted with shade trees such as *Gliricidia sepium*, *Paraserianthes falcataria*, and others. Agroforestry coffee describes multistory coffee plantations with fruit and timber trees such as durian (*Durio spp.*), avocado (*Persea americana),* cloves (*Syzygium aromaticum*)**,** dogfruit (*Archidendron pauciflorum*), mahogany (*Swietenia mahagoni*), sonokeling (*Dalbergia latifolia*), *Albizia chinensis*, and others. Agroforestry coffee is distinguished from shade coffee by the inclusion of more than five different shade tree species.

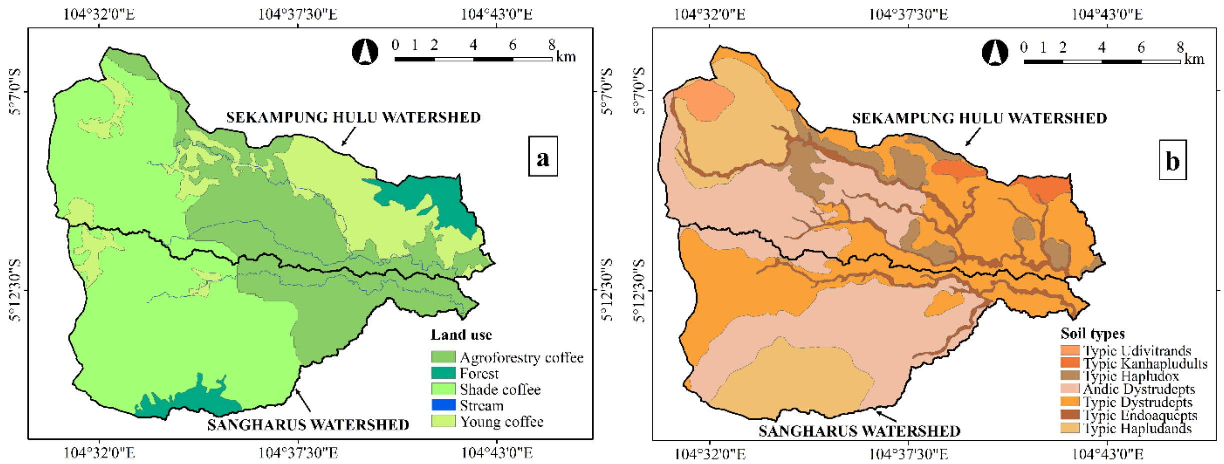

Figure 2.3 (a) Land use and (b) soil types in the study area.

Soil type classifications (Figure 2.3b) for the Sekampung Hulu and Sangharus watersheds were obtained from the Indonesian Center for Agricultural Land Resources Research and Development (ICALRD, 2016). The Sekampung Hulu watershed comprised the following soil types: Andic Dystrudepts (28%), Typic Dystrudepts (30.6%), Typic Hapludands (16.5%), Typic Hapludox (11.6%), Typic Kanhapludults (3.1%), Typic Udivitrands (2.9%), and Typic Endoaquepts (7.2%). The soil types in the Sangharus watershed consisted of Andic Dystrudepts (43.5%), Typic Dystrudepts (33.2%), Typic Hapludands (19.5%), and Typic Endoaquepts (3.7%). The dominant soils in both watersheds were Andic Dystrudepts and Typic Dystrudepts, which are categorized as Inceptisols.

2.2.2 Water sampling

In this study, water samples were collected from the main streams of the Sekampung Hulu and Sangharus Rivers at two sites each (Figure 2.1) and TSS concentrations were subsequently determined. All water samples were collected composite at a depth approximately 20–30 cm below the water surface. At each site, the water samples were stored in bottle with size 250 ml. The water samples were kept in cool box with ice gel inside during transportation from sampling sites to the laboratory.

Water sampling was conducted four times during the 2016 rainy season (once in October, twice in November, and once in December). Additionally, data regarding TSS concentrations from March to May 2016 were obtained from a previous study (Somura et al., 2019) to ensure a comprehensive analysis. A well-mixed samples were filtered and the residue left in the filter was dried in a universal oven (UN55, Memmert) at 105°C, and weighed with an analytical balance (AUY220, Shimadzu). The TSS parameter was analyzed based on the methods proposed by the American Public Health Association (1999).

2.2.3 Assessment of soil erosion

Soil erosion assessment for the Sekampung Hulu and Sangharus watersheds was conducted using the USLE method (Wischmeier and Smith, 1978), which has been applied in several previous studies focusing on the prediction of soil erosion in watersheds (Devatha et al., 2015; Huang, 2018; Pham et al., 2018). The USLE equation is expressed as:

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is erosion (Mg ha^{-1} year^{-1}), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K is the soil erodibility factor (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the slope length factor (dimensionless), C is the crop factor (dimensionless), and P is the soil management factor (dimensionless).

2.2.3.1. Rainfall erosivity factor (*R*)

Daily precipitation data were obtained from the Batutegi Dam station for the periods 1998–2010 and 2013–2016 (DGOMWRMS, 2017) and used to calculate R using the Bols equation (Bols, 1978). This equation was developed from precipitation data for Indonesia spanning a period of 38 years. The Bols equation is expressed as:

$$R_m = 6.119(Rain)^{1.21} \times (Days)^{-0.47} \times (MaxP)^{0.53} \tag{2}$$

where R_m is the monthly erosivity factor, *Rain* is the total monthly rainfall (cm), *Days* is the number of rainfall days in a particular month, and *MaxP* is the maximum rainfall in a particular month (cm).

2.2.3.2. Soil erodibility factor (*K*)

K reflects the sensitivity of soil characteristics to erosion. In this study, *K* was calculated from the following equation (Renard et al., 1997; Wischmeier and Smith, 1978):

$$100K = (2.71 \times M^{1.14}(10^{-4})(12 - OM) + 3.25(s - 2) + 2.5(p - 3))/7.59 \tag{3}$$

where *M* is (percentage of very fine sand + silt) × (100 − percent clay), *OM* is the percentage of organic matter, *s* is the soil structure code, and *p* is the soil permeability code. The soil properties for the study area were obtained from ICALRD (2016) and primary sampling.

2.2.3.3. Topographic factor (*LS*)

LS consists of the slope-length factor (*L*) and the slope steepness factor (*S*) and represents topographic impacts on the soil erosion rate. Several methods have been suggested to estimate *LS* (Mitasova, et al, 1996; Moore and Wilson, 1992; Wischmeier and Smith, 1978). In this study, *LS* was estimated using the System for Automated Geoscientific Analyses (SAGA), which uses the digital elevation model from the NASA Shuttle Radar Topography Mission (spatial resolution = 30 m). *LS* was calculated based on the equation provided by Desmet and Govers (1996):

$$L_{i,j} = \frac{(A_{i,j-in} + D^2)^{m+1} - A_{i.j-in}^{m+1}}{D^{m+2} * X_{i,j}^{m} \times 22.13^{m}} \tag{4}$$

where $L_{i,j}$ is the slope length factor for the grid cell with coordinates (i,j), $A_{i,j-in}$ is the contributing area at the inlet of the grid cell with coordinates (i,j) (m^2), D is the grid cell size (m), m is the slope length exponent, $X_{i,j}$ is $\sin \alpha_{i,j} + cos\ \alpha_{i,j}$ ($\alpha_{i,j}$ is the aspect direction for the grid cell with coordinates (i,j)). Further,

$$m = \frac{\beta}{(\beta + 1)} \tag{5}$$

$$\beta = \frac{\frac{\sin \Theta}{0.0896}}{3 * \sin\Theta^{0.8} + 0.56} \tag{6}$$

where β is the ratio of rill erosion to interrill erosion and Θ is the angle of the slope (degrees).

Calculation of *LS* was limited to a slope of 50% or 26.6°. Liu et al. (2000) stated that the slope length exponent did not increase for slope steepness ranging from 40–60%. A previous study limited the slope gradient to 50% during calculation of *LS* to determine soil erosion in Europe (Panagos et al., 2015).

2.2.3.4. Crop and Management factor (*CP*)

The *CP* value combines two factors found in equation (1): crop (*C*) and management (*P*) factors. The *C* factor represents the influence of cover crop type and the *P* factor represents the influence of soil management practices. For some land use categories, such as agroforestry and shade coffee, *C* and *P* values were hard to distinguish separately because these land uses combine both elements simultaneously. Thus, a conjoined *CP* value was employed for this study. *CP* values range between 0 and 1, with 0 indicating good vegetation ground cover and a well-protected soil surface and 1 indicating no vegetation cover and no soil management practices. Values close to 0 indicate good crop and soil conservation practices, which could reduce the rate and influence the direction of runoff and subsequently decrease soil erosion. Forests and young coffee were considered to have *P* factor values of 1 because no soil conservation practices were implemented for these land-use types in the target watersheds.

In this study, the assigned *CP* value was 0.001 for forest areas and 0.005 for agroforestry coffee, which was based on the value for forests with low litter (Hamer, 1980). As forests and agroforests have similar above-ground vegetation coverage, soil erosion rates are not significantly different between these land-use types (Kusumandari and Mitchell, 1997). The assigned *CP* values for young coffee and shade coffee were 0.3 and 0.1, respectively, based on a report from Roose (1976). Young coffee has less canopy and ground vegetation development than shade coffee, while shade coffee has better coverage because of the inclusion of shade trees. The assigned *CP* values for stream channels in the Sekampung Hulu and Sangharus watersheds were 0.

2.2.3.5. Impacts of BMPs

Continuous soil erosion contributes to soil degradation, which reduces land productivity. The application of BMPs can potentially decrease soil erosion in the study area. In particular, BMPs can reduce nonpoint source pollution from coffee plantations. The following simulation scenarios were developed in this study to understand the implications of BMPs:

(1) Converting shade coffee and young coffee to agroforestry coffee.

(2) Converting young coffee to shade coffee with subsequent application of cover crop to shade coffee. The P value of cover crop was obtained from Roose (1976) (Table 2.1).

(3) Converting young coffee to shade coffee with subsequent application of contour cropping to shade coffee. The contour system was divided into slopes of 0–8%, 8–20%, and > 20% according to the *P* values obtained from Hamer (1980) (Table 2.1).

Table 2.1 Soil management factor (*P*) values.

Conservation Practice	*P* factor value
Cover crop	0.1[a]
Contour cropping, slope gradient 0–8%	0.5[b]
Contour cropping, slope gradient 8–20%	0.75[b]
Contour cropping, slope gradient > 20%	0.9[b]
None	1[b]

[a]Roose (1976)
[b]Hamer (1980)

In all scenarios, the conditions for forests and agroforestry coffee were not changed because these land-use types were well-managed. Therefore, the simulations were only applied to shade coffee and young coffee areas. In scenarios 2 and 3, young coffee was converted to shade coffee, and subsequently all shade coffee areas were simulated with soil conservation techniques. Besides that, there was control scenario that simulate young coffee growths become shade coffee.

The agroforestry system scenario was applied in this study because the original land use was forest. Because the agroforestry system has multistory trees, providing nearly the same conditions as forest, applying this scenario could conserve ecosystems and support farmers' economic circumstances. Scenarios converting young coffee to shade coffee were also applied because these land uses were dominant in both watersheds. Subsequent applications of cover crops and contour cropping were simulated to achieve increased protection with respect to runoff and soil erosion.

2.2.3.6. Application of GIS techniques

Soil erosion was predicted by overlaying raster layers for the *R*, *K*, *LS*, and *CP* factors in ArcGIS 10.4.1. All layers were divided into 30 m grids and all maps were characterized by the WGS 1984 UTM zone 48S projection. Subsequently, soil erosion values were calculated in the raster module.

2.2.4. Statistical analyses

The statistical analyses for water samples collected from the two rivers were conducted using SPSS software (Version 17.0). Descriptive data analysis included reporting of means and standard errors. The Mann-Whitney U Test was conducted to determine statistically significant differences in the TSS values of the Sekampung Hulu and Sangharus Rivers. A significance value lower than 0.05 indicates significant differences in the water quality of the two rivers at the 95% confidence interval.

2.3. Results

2.3.1. Water quality

The Sekampung Hulu River displayed higher TSS concentrations in contrast to the Sangharus River (Table 2.2). The maximum TSS concentrations in the Sekampung Hulu and Sangharus Rivers were 813 mg L^{-1} (March 26, 2016) and 146 mg L^{-1} (Nov 20, 2016), respectively, while the minimum concentrations were 36 mg L^{-1} (April 23, 2016) and 16 mg L^{-1} (April 23, 2016), respectively. Further, as indicated in Table 2.2, the mean and standard error of TSS concentrations in Sekampung Hulu and Sangharus Rivers were 228 ± 87.5 and 69.3 ± 15.2, respectively. Statistical analysis indicated that the mean TSS concentration for the Sekampung Hulu River was significantly higher than that for the Sangharus River.

Table 2.2 Concentrations of total suspended solids (TSS) in the Sekampung Hulu and Sangharus rivers.

Date	TSS Concentration (mg L^{-1})	
	Sangharus River	Sekampung Hulu River
3/26/2016*	80	813
4/10/2016*	71	144
4/23/2016*	16	36
5/8/2016*	31	196
10/23/2016	62	89
11/6/2016	38	80
11/20/2016	146	220
12/4/2016	110	246

*source: Somura et al. (2019)

2.3.2. Erosion assessment

2.3.2.1. Rainfall erosivity factor (*R*)

Rainfall erosivity is one of the climatic factors influencing hydrological properties within a watershed. Daily precipitation data were provided by the Batutegi Dam station for a period of 17 years and were utilized to estimate *R*. The estimated *R* value for both Sekampung Hulu and Sangharus watersheds was 1433.5.

2.3.2.2. Soil erodibility factor (*K*)

The *K* factor is affected by the diversity of soil types and their parameters. Therefore, the *K* factor map was extracted from the soil type map (ICALRD, 2016). The Sekampung Hulu watershed indicated seven values for *K* ranging from 0.0007–0.0341, of which the most prevalent *K* value was 0.0341, accounting for 30.6% of the area. Similarly, the *K* value for the Sangharus watershed comprised four values, of which 0.0103 was the most prevalent with a coverage of 43.5%. The distribution of *K* is presented in Figure 2.4a and Table 2.3.

Table 2.3 Soil types and soil erodibility.

Soil Type	Soil Erodibility Factor (*K*)
Typic Dystrudepts	0.0341
Typic Endoaquepts	0.0263
Typic Kanhapludults	0.0177
Typic Hapludox	0.0250
Andic Dystrudepts	0.0103
Typic Hapludands	0.0013
Typic Udivitrands	0.0007

2.3.2.3. Topographic factor (*LS*)

The distribution of *LS* was determined using SAGA software and is presented in Fig. 2.4b. The *LS* values ranged between 0–9.7. The *LS* ranges 0–2, 2–5, 5–7, and 7–9.7 corresponded to 38.3%, 39.2%, 12.2%, and 10.3% of the total Sekampung Hulu watershed area, respectively, and 36.9%, 45.8%, 10.4%, and 6.9% of the total Sangharus watershed area, respectively. These results indicate that the percent area corresponding to *LS* value greater than seven was higher for the Sekampung Hulu watershed than the Sangharus watershed, thus indicating higher potential erosion rates.

2.3.2.4. Crop and management factor (*CP*)

Vegetation cover and land management affect soil erosion rates, as represented by *CP*. The distribution of *CP* was derived from the land use map (Figure 2.4c). The dominant *CP* value for both watersheds was 0.1, corresponding to 34.3% and 66.3% of the total area for the Sekampung Hulu and Sangharus watersheds, respectively.

2.3.2.5. Erosion

The results indicate that erosion rates for both watersheds ranged from 0–142 Mg ha^{-1} year^{-1}. Average soil erosion rates in the Sekampung Hulu and Sangharus watersheds were 12.5 Mg ha^{-1} year^{-1} and 5.6 Mg ha^{-1} year^{-1}, respectively, while the standard deviations were 26.4 and

12.3, respectively. The spatial distribution of erosion is presented in Figure 2.4d. Erosion rates greater than 10 Mg ha^{-1} year^{-1} corresponded to 21.8% and 15.5% of the total area for Sekampung Hulu and Sangharus watersheds, respectively. These results indicate potential soil degradation in the study area.

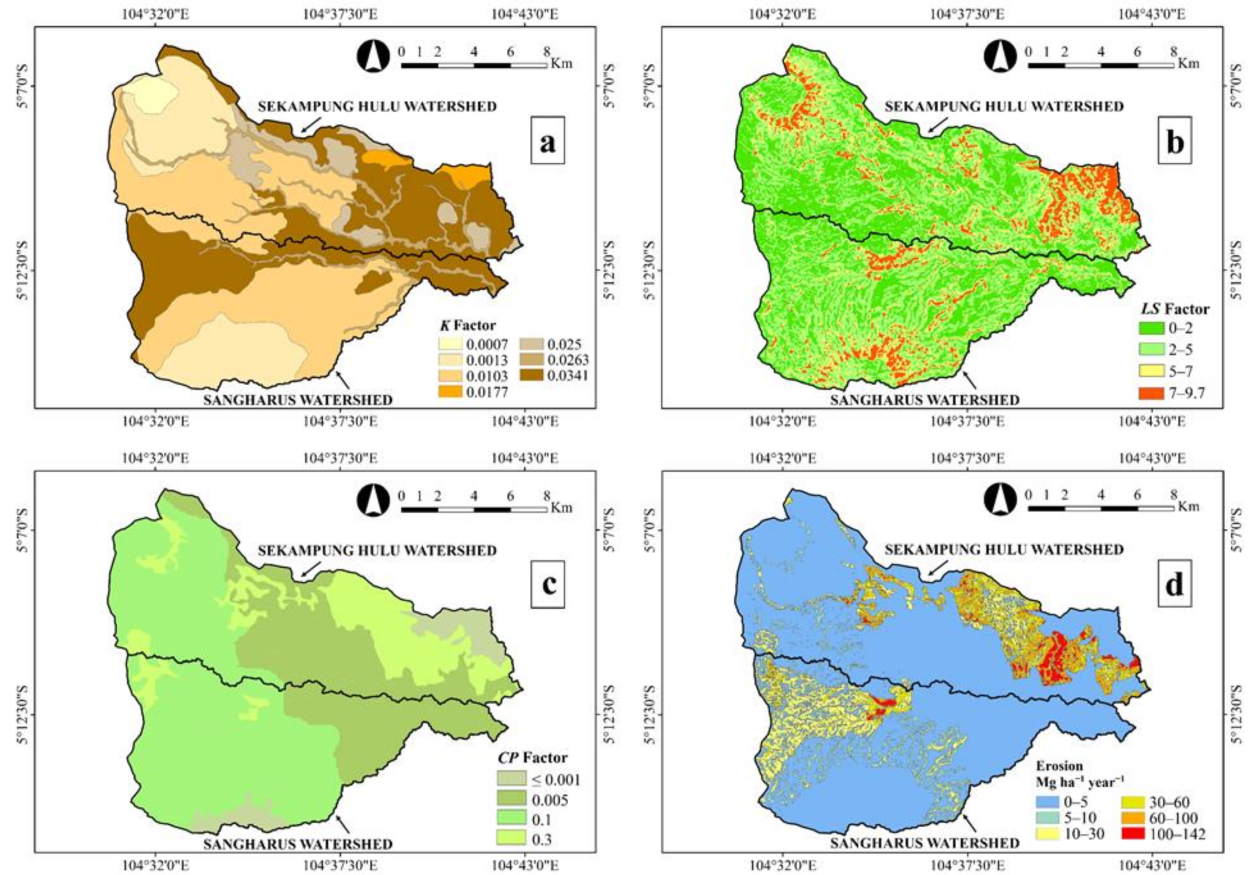

Figure 2.4. Distribution maps for: (a) Soil erodibility factor (*K*), (b) Topographic factor (*LS*), (c) Crop and Management factor (*CP*), and (d) Soil erosion.

2.3.2.6. Simulation of BMPs

The simulation scenarios indicated that BMPs could effectively reduce soil erosion in the following order (from highest to lowest reduction): scenario 1 > scenario 2 > scenario 3 (Figure 2.5). Scenario 1 focused on conversion of shade and young coffee to agroforestry coffee, with resulting average erosion rates for the Sekampung Hulu and Sangharus watersheds of 0.4 ± 0.5 Mg ha^{-1} $year^{-1}$ and 0.3 ± 0.4 Mg ha^{-1} $year^{-1}$, respectively. Under this scenario, conversion to agroforestry coffee effectively reduced soil erosion by 96.8% and 93.9% in the Sekampung Hulu and Sangharus watersheds, respectively.

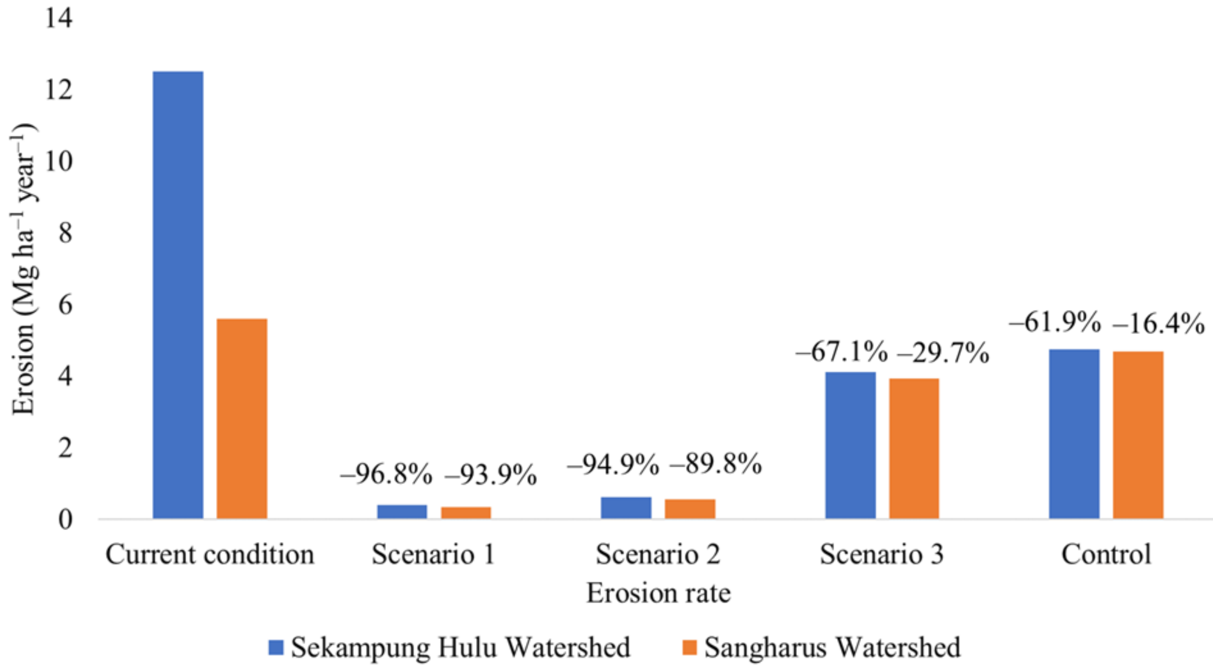

Figure 2.5 Impacts of best management practice simulation scenarios: application agroforestry (scenario 1), cover crops (scenario 2), and contour system (scenario 3) on soil erosion rate in the Sekampung Hulu and Sangharus watersheds.

Scenario 2 focused on conversion of young coffee to shade coffee with cover crop and resulted in an average soil erosion rate of 0.6 Mg ha^{-1} $year^{-1}$ for both watersheds (with standard deviations of 0.9 Mg ha^{-1} $year^{-1}$ and 0.7 Mg ha^{-1} $year^{-1}$ for the Sekampung Hulu and Sangharus watersheds, respectively). Under scenario 2, soil erosion reduced by 94.9% and 89.8% in the Sekampung Hulu and Sangharus watersheds, respectively. Scenario 3 was based on the application of contour cropping and resulted low reduction in soil erosion. This scenario resulted in an average erosion of 4.1 ± 7.8 Mg ha^{-1} $year^{-1}$ and 3.9 ± 6.6 Mg ha^{-1} $year^{-1}$ for the Sekampung Hulu and Sangharus watersheds, respectively. Under scenario 3, adoption of the contour system effectively reduced soil erosion by 67.1% and 29.7% in the Sekampung Hulu and Sangharus watersheds, respectively.

Control scenario was based on the simulation young coffee growths become shade coffee and resulted in the least reduction in soil erosion. This scenario resulted in an average erosion of 4.8 ± 8.8 Mg ha^{-1} $year^{-1}$and 4.7 ± 7.5 Mg ha^{-1} $year^{-1}$ for the Sekampung Hulu and Sangharus watersheds, respectively. Control scenario showed reducing of soil erosion by 61.9% and 16.4% in the Sekampung Hulu and Sangharus watersheds, respectively.

2.4. Discussion

The water quality analysis suggested that TSS concentrations in the Sekampung Hulu River were significantly higher than in the Sangharus River, indicating that the Sangharus River exhibited more optimal social forestry conditions. The USLE results indicated higher erosion in the Sekampung Hulu watershed, which agreed with the TSS trends obtained from water quality analysis.

A high soil erosion rate can be detrimental to environmental quality, especially if the erosion rate is greater than the tolerable soil loss. The definition of tolerable soil loss is the amount of soil erosion that does not lead to deterioration of soil functions, as long as soil erosion does not exceed soil formation rate (Verheijen et al., 2009). The parameters that influence tolerable soil loss are erosion rate, soil depth, social and economic scenario, evaluation of soil deterioration through soil depth change (Sparovek and Jong Van Lier, 1997), and lifetime soil use (Sparovek et al., 1997). The tolerable soil loss for Lampung is 10 Mg ha^{-1} $year^{-1}$ (Dariah et al., 2004). The average soil erosion values for the Sekampung Hulu and Sangharus watersheds as estimated by the USLE method were 12.5 Mg ha^{-1} year^{-1} and 5.6 Mg ha^{-1} year^{-1}, respectively. While 78.2% of the Sekampung Hulu watershed area had an erosion rate less than 10 Mg ha^{-1} year^{-1}, the soil erosion rates for the remaining area were greater than the tolerable soil loss. Similarly, 84.5% of the Sangharus watershed area had a soil erosion rate lower than 10 Mg ha^{-1} year^{-1}, while the remaining 15.5% of the area had erosion rates greater than the tolerable soil loss.

Verbist et al. (2010) studied soil erosion at the plot scale and concluded that the erosion rate in monoculture coffee plantations aged 3 to 5 years was 7–11 Mg ha^{-1} year^{-1}, while that for plantations older than six years was 4–6.3 Mg ha^{-1} year^{-1}. Afandi et al. (2002) concluded that the soil erosion rate in two-year-old coffee plantations was 22.7 Mg ha^{-1} year^{-1}. However, the erosion rate declined to 9.1 Mg ha^{-1} year^{-1} and 4.8 Mg ha^{-1} year^{-1} during the third and fourth years of growth, respectively. Widianto et al. (2004) studied soil loss in plots sized 10 m × 4 m with a slope of 30°. The results suggested that coffee trees experience high erosion in the first and second years of growth, that is, 33.6 Mg ha^{-1} year^{-1} and 37.2 Mg ha^{-1} year^{-1}, respectively. However, the erosion rate decreased for older coffee trees; the erosion rate in areas planted with seven-year-old coffee trees was 7.1 Mg ha^{-1} year^{-1} while that for areas with 10-year-old coffee trees was 6.8 Mg ha^{-1} year^{-1}. However, areas in the Sumberjaya, Lampung, planted with monoculture coffee trees younger than 3 years were found to have a lower soil erosion rate of 1.5 Mg ha^{-1} year^{-1} (Dariah et al., 2004).

Young coffee trees likely contribute to the higher soil erosion in the Sekampung Hulu watershed. According to Mr. Joni Ansonet (village head of Datar Lebuay), several local farmers planted coffee trees in the Wana Tani Lestari and Mandiri Lestari *HKm* areas of the Sekampung Hulu watershed from 2015–2016 (personal interview, 2019). The land-use type characterized by young coffee trees offers less coverage than agroforestry coffee and shade coffee. Further, the erosion rates in different areas were influenced by the age of the coffee trees. Therefore, soil loss due to erosion was higher in young coffee plantations (Widianto et al., 2004) due to less canopy cover and ground-layer vegetation. The conditions of land use cover can be seen in Figure 2.6; Figure 2.6d presents the poor surface cover conditions in coffee plantations less than one year old. Older coffee trees exhibited larger canopies consisting of leaves, branches, and stems that reduce the kinetic energy of rainfall. Subsequently, rainfall does not disperse soil aggregates in the top layer. Preti (2013) reported that slope stability depends on vegetation type and differences in their root characteristics and coverage.

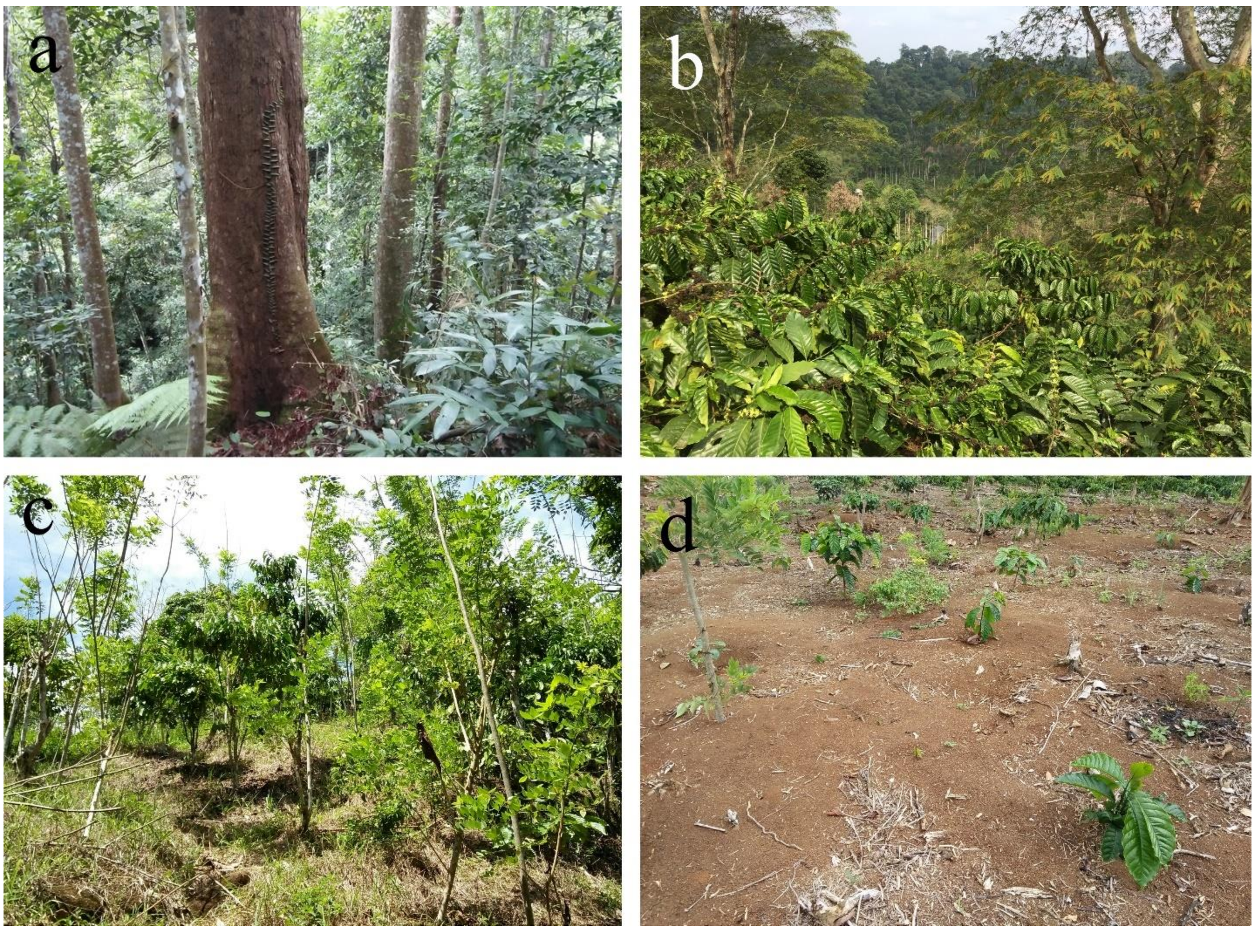

Figure 2.6 Land use cover: (a) forest, (b) agroforestry coffee, (c) shade coffee, and (d) young coffee.

Physical soil characteristics, such as macropores and permeability, also affect soil erosion rates (Dariah et al., 2003). The dominant soil type in Sekampung Hulu watershed was Typic Dystrudepts (30.6%), which had the highest *K* value of 0.0341 (Table 2.3), indicating vulnerability to soil erosion. Further, young coffee trees in this soil type constituted 11.3% of the total area for the Sekampung Hulu watershed. The dominant soil type in the Sangharus watershed was Andic Dystrudepts, which exhibited a lower *K* value of 0.0103. The lower K value of Andic Dystrudept compared to Typic Dystrudept is due to higher organic matter and permeability. Verbist et al. (2010) reported that the geological characteristics of lithology also influence the soil erosion rate.

Soil erosion rates are also affected by topography. High *LS* values ranging between 7–9.7 were estimated for 10.3% and 6.9% of the area for the Sekampung Hulu and Sangharus watersheds, respectively. Presence of young coffee trees in areas with high *LS* values resulted in high soil erosion rates. In addition, a high slope gradient indicated higher vulnerability to erosion (El Kateb et al., 2013). Therefore, erosion rates could be reduced by planting coffee on slope gradients less than 30%; however, slope gradients ranging between 50–70% could be considered optimal for agroforestry coffee characterized by good management practices (Sepulveda and Carrillo, 2015).

Analysis of BMP scenarios indicates that all scenarios could reduce soil erosion. Adoption of agroforestry can reduce soil erosion (Sepulveda and Carrillo, 2015) through a well-developed canopy system and supply of litter to the soil surface (Hairiah et al., 2006). Moreover, agroforestry can also decrease pest attacks (Pumarino et al., 2015) and increase carbon stock (De Beenhouwer et al., 2016). The simulation based on adoption of agroforestry indicated a reduction in soil erosion by 96.8% and 93.9% in the Sekampung Hulu and Sangharus watersheds, respectively.

The planting of cover crops (e.g. *Arachis pintoi, Calopogonium mucunoides, Peuraria javanica*) can reduce soil degradation by protecting the soil surface from rainfall, which can stimulate the breakdown of soil aggregates. The presence of cover crops in coffee plantations can decrease soil erosion by lowering runoff velocity. Therefore, the scenario based on cover crop adoption decreased soil erosion in the Sekampung Hulu and Sangharus watersheds by 94.9% and 89.8%, respectively. Cover crops can also increase the carbon stock of soils (Ladoni et al., 2016) and improve available soil water (Pires et al., 2017). Messiga et al. (2015) reported that a combination of cover crops and amendments could support biological, chemical, and physical soil properties.

The contour system of soil conservation is based on planting trees according to elevational contour lines. Simulation results indicated that the presence of a contour system could reduce soil erosion by 67.1% and 29.7% in the Sekampung Hulu and Sangharus watersheds, respectively. Further, implementation of a contour system could reduce runoff and soil erosion (Aflizar et al., 2010; Alegre and Rat, 1996; Shi et al., 2004), especially in sloped areas.

Control scenario that simulated young coffee growths become shade coffee without application BMP showed less effective compare with application BMP in reducing of soil erosion. The simulation of BMP scenarios indicated that the adoption of agroforestry and cover cropping would be more effective than the application of a contour system in reducing soil erosion. These results are in agreement with Xiong et al. (2018) who reported that biological techniques of soil conservation were more effective (up to 88%) than engineering techniques (like contour application) in reducing soil erosion.

Scenario 1 and 2 did not show big difference in reduction soil erosion. Concerning economic aspect, scenario 2 could give better income to farmers while supporting reduction of soil erosion. Farmers could have larger area of coffee plantation therefore it will improve their income.

In summary, adoption of agroforestry coffee is the most effective BMP for reducing soil erosion. However, with concern to economic aspects, the scenario 2 should be suggested to local farmers. Furthermore, it is crucial to raise awareness regarding the importance of this system, especially with respect to both income generation and environmental conservation, to encourage the adoption of cover crop among farmers.

2.5. Conclusions

The implementation of social forestry policies, such as community forests and partnership forests, in the Sekampung Hulu and Sangharus watersheds significantly altered land cover patterns. Consequently, this will influence water quality in the rivers. This study assessed water quality based on TSS concentrations in the two watersheds throughout 2016.

The Sekampung Hulu River was found to have significantly higher TSS concentrations than the Sangharus River during the study period. The higher TSS in the Sekampung Hulu River was aligned with the soil erosion assessment based on the USLE that indicated higher soil erosion in the Sekampung Hulu watershed than in the Sangharus watershed. The higher erosion in the Sekampung Hulu watershed was attributed to the higher presence of young coffee trees in the area. The area occupied by young coffee trees was higher in the Sekampung Hulu watershed because cultivation in the area was recently initiated by several new farmers. In the latest available Google Earth images of the study area from July 2017 (Google Earth, 2017), some places were observed to have even less vegetation, and the soil was visible. As three years have passed since this research was conducted, the conditions in the Sekampung Hulu watershed may have improved in some areas, because the canopy of young coffee trees and surface vegetation may now be more developed, as several other studies have indicated (Afandi et al., 2002; Iori et al., 2014; Widianto et al., 2004). However, it is also possible that farmers have planted new young coffee trees in other parts of the watersheds after securing permission to use the land. Thus, it is very important to disseminate the idea of BMPs to local farmers.

Adopting BMPs could minimize soil erosion that typically transports nutrients out of topsoil. Lack of nutrients in soil can reduce coffee growth and productivity, thereby reducing yield. Increasing coffee productivity is important because coffee provided the agricultural and forestry sector in Lampung province with a value of US $435,288,000 in 2014 (Statistics of Lampung Province, 2017a). Indonesia is now the fourth largest coffee producer in the world, after Brazil, Vietnam, and Colombia (International Coffee Organization, 2019). To maintain high coffee crop productivity in this area into the future, communicating with local farmers and suggesting simple techniques to conserve the environment are crucial for the sustainable maintenance of forest functions.

In this study, the adoption of agroforestry coffee systems, a relatively simple concept and set of techniques, was the most effective BMP scenario for reducing soil erosion. However, concerning to economic aspect, the adoption of cover crop was the better choice for farmers because they could have higher income through larger area of coffee plantation and also contribute in reducing soil erosion. The analyses of this study did not consider spatial and temporal land use planning for next several years in the watersheds, because of lack of data. As a next step, this information will be necessary to enter discussions with local farmers about young coffee tree planting.

Additionally, high soil erosion rates can increase sedimentation in reservoirs and subsequently reduce their storage capacities (Fu et al., 2008). The Batutegi Dam in the lower part of the studied watersheds is multipurpose, irrigating an agricultural area of 660 km^2 and contributing to hydroelectric power generation. Therefore, efficient land use management in the watersheds upstream is essential to reduce sediment discharge from the rivers (Mehri et al., 2018) and maximize dam functionality.

As a final word, the concept of "Social Forestry" is ideal to support local farmers and produce products in protected forests with strict rules. On the operational side, new techniques that combine multiple soil loss prevention methods were should provided, especially for areas with steep slope. This information could be useful for the government as well, to accelerate the improvement of watershed conditions and water quality.

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CHAPTER 3

Impact of human activities and natural processes on the seasonal variability of river water quality in two watersheds in Lampung, Indonesia

3.1. Introduction

Indonesia has an estimated population of more than 266 million (National Development Planning Agency et al., 2018) and thus its economic growth should be managed effectively to ensure secure access to food, housing, education, and health. Population growth increases land use demand for agriculture commodities (Angus et al., 2009) and results in forest exploitation, particularly impacting communities nearby forested areas. Of particular environmental concern is the illegal practice of forest conversion into agricultural land in forested areas that are easy to access. Such practices result in accelerated soil erosion from increased land exposure (Tadesse et al., 2017) and increased nutrient loss to rivers and streams (Zheng et al., 2005).

The Indonesian government issues regulations on social forestry to involve the local community in sustainable forest management. These regulations support local economic growth and provide equity for social welfare, and also maintains and protects forest ecosystem functions (Ministry of Environment and Forestry, 2016). The community forestry (*Hutan Kemasyarakatan, Hkm*) and forestry partnership (*Kemitraan Kehutanan, mitra*) regulations have been applied in Tanggamus Regency in Lampung province. The farmers in this regency predominantly plant coffee trees, as well as pepper, cacao, clove, and fruit trees (durian, avocado). Coffee is the largest export from the agricultural and forestry sector in Lampung province, with a value US $ 435,288,000 (Statistics of Lampung Province, 2017a) and a production of 131,501 ton (Statistics of Lampung Province, 2017b) in 2014. Furthermore, Indonesia is the fourth largest coffee producer after Brazil, Vietnam, and Colombia (International Coffee Organization, 2019).

Coffee plantation requires fertilization to maintain yield and quality. Eleven years ago, chemical fertilizers were not commonly applied in coffee plantations under the management of social forestry in the Tanggamus Regency (Banuwa, 2008). However, due to lowered soil nutrient availability following the conversion of forests to agricultural land (Neris et al., 2012), the application of some chemical fertilizers was necessary to increase productivity. In particular, the application of N-fertilizers has been found to increase coffee yield (Castro-Tanzi et al., 2012) and improve bean quality (Vinecky et al., 2017). Stream water in forested areas are typically higher in quality compared with rivers in other land use types (Kändler et al., 2017). Excessive fertilizer application can cause water quality degradation in rivers and/or reservoirs nearby agricultural land (Tian et al., 2019). It is therefore necessary to monitor the water quality in nearby rivers and reservoirs in order to determine the impacts of excessive fertilization as a result of social forestry practices.

The links between water quality and land use have been studied in a number of watersheds throughout the world (Bu et al., 2014; Lin et al., 2015; Meneses et al., 2015). A recent study conducted from March to July 2016 in the study area detected clear differences in water quality between the two adjacent watersheds and briefly analyzed relationship between land use and water quality (Somura et al., 2019). The study identified that Sangharus River had higher nitrate (NO_3) while Sekampung Hulu River had higher total suspended solids (TSS), aluminum, and iron. However, the seasonal patterns of river water quality have not yet been investigated in the area. Moreover, detailed analyses for understanding the reason for the differences in water quality between the watersheds have not been conducted. Seasonal climate variability plays an important role in water quality within ecosystems (Tuboi et al., 2018) as rainy and dry seasons can influence river water quality. The dry season has higher total solids (TS) and biochemical oxygen demand (BOD) because of low river discharges and increased industrial wastewater discharges, while in the rainy season a higher NO_3 concentration is detected because of high runoff that transports fertilizers (Mena-Rivera et al., 2017).

In this study, two adjacent watersheds were targeted, Sekampung Hulu and Sangharus, where forested land has been predominantly converted into coffee plantations under social forestry management. The Batutegi Dam is a water supply source for irrigation, drinking water, and nearby power plants, and is located downstream of the rivers in the study area. Therefore, the hydrological characteristics of the rivers can influence the reservoir function (Shivers et al., 2018). As social forestry concept has also been adopted in other areas in Indonesia, management of water quality environment under a social forestry system is essential to give information to stakeholders about the sustainable use of mountainous areas. This study aimed to determine the seasonal water quality characteristics through observations spanning one year and to identify the impacts of local fertilizer application on river water quality in the watersheds. In addition, the reasons why clear differences in water qualities were observed in the adjacent watersheds. Based on the results, recommendations could be suggested for effective water quality management in these watersheds.

3.2. Materials and Methods

3.2.1. Study Area

The study area is located in the Sekampung Hulu (5°5’38” S, 104°30’34” E) and Sangharus (5°15’58” S, 104°42’56” E) watersheds in Lampung province, Indonesia (Figure 3.1). The study area of the Sekampung Hulu watershed covers 141.3 km^2 consisting of social forestry (137.6 km^2) and private land (3.7 km^2). The study area of the Sangharus watershed covers 117.2 km^2, and also consists of social forestry (106.7 km^2) and private land (10.5 km^2). With regards to the local geology, the Sangharus watershed consist of 2% sandstones and tuff, 3.7% clay and sand deposits, 62.3% basaltic andesite tuff, and 32% pumice tuff. The Sekampung Hulu watershed consists of 7.2% clay and sand deposits, 1.9% granite, 2.9% schist, 57.8% basaltic andesite tuff, and 30.1% pumice tuff (Indonesian Center for Agricultural Land Resources Research and Development [ICALRD], 2016) (Figure 3.2A).

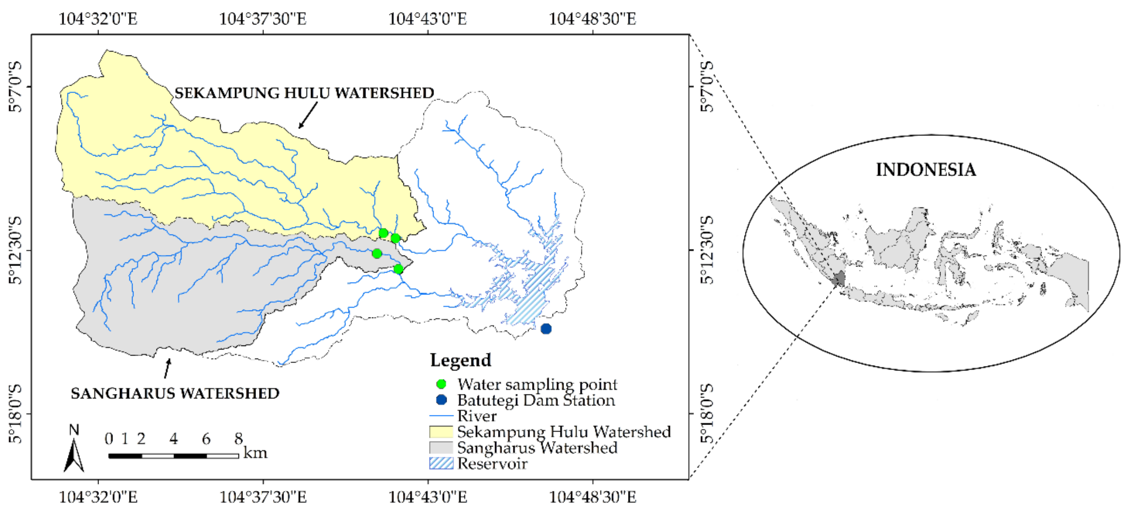

Figure 3.1 Map of study area showing the location of the Sekampung Hulu and Sangharus watersheds in Indonesia. The sampling locations are highlighted by the green circles.

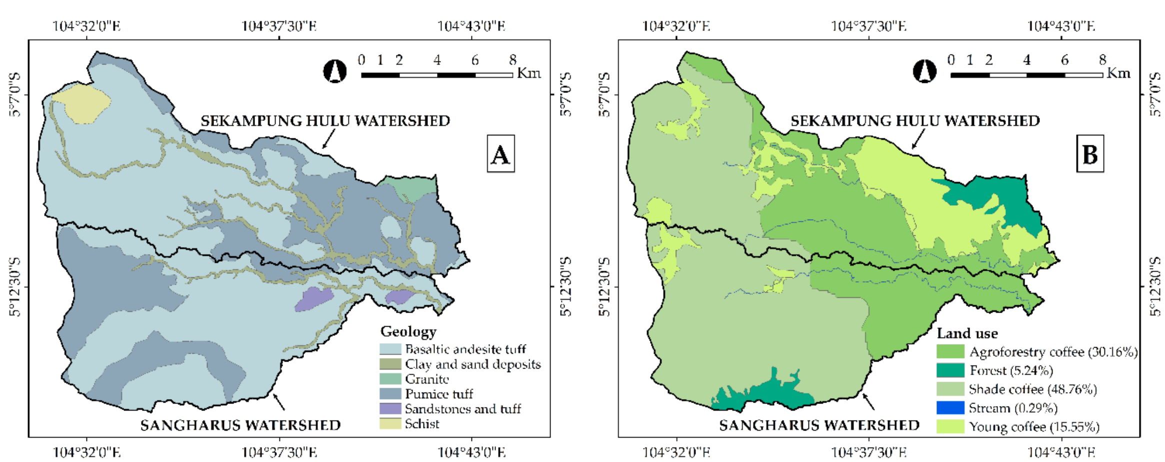

Figure 3.2 (A) Geology and (B) Land use of the Sekampung Hulu and Sangharus watersheds.

The watershed topographies are characterized by mountain ranges and hills at elevations ranging between 282 to 1767 m above sea level. The total annual precipitation in 2016 was 1294 mm (Directorate General of Operation and Maintenance Water Resources Mesuji Sekampung [DGOMWRMS], 2017). The precipitation data for the study period (2016) and the 17-year precipitation mean are illustrated in Figure 3.3. The study region is defined as climate type Af (rainfall in the driest month at least 60 mm) based on the Koppen classification (Banuwa, 2008). The study region is located in the tropics and therefore experiences rainy and dry seasons. In 2016, the dry season in the Tanggamus Regency occurred between June–August, while the rainy season occurred between January–May and September–December (Tim Katam Balitklimat, 2019).

Based on field observations and land use data analyses (National Land Agency, 2017), (Figure 3.2B), the watersheds were predominantly covered by coffee trees. Commercial trees such as pepper, cacao, clove, rubber, durian, and avocado were also identified. In addition, timber tree species of high economic value, such as mahogany (*Swietenia mahagoni)* and sonokeling trees (*Dalbergia latifolia)* were found. The land area in the Sekampung Hulu watershed consists of 33.9% agroforestry coffee, 34.3% shade coffee, 25.7% young coffee, 5.8% forests, and 0.3% rivers. The land area in the Sangharus watershed consists of 25.6% agroforestry coffee, 66.3% shade coffee, 3.3% young coffee, 4.6% forests, and 0.2% rivers. The land use of young coffee involves coffee plantation in early growth and has less coverage condition. Shade coffee refers to coffee plantations with shade trees such as *Gliricidia sepium, Paraserianthes falcataria,* and others. Agroforestry coffee is multistory system that consists of coffee plantation with more than 5 other tree species.

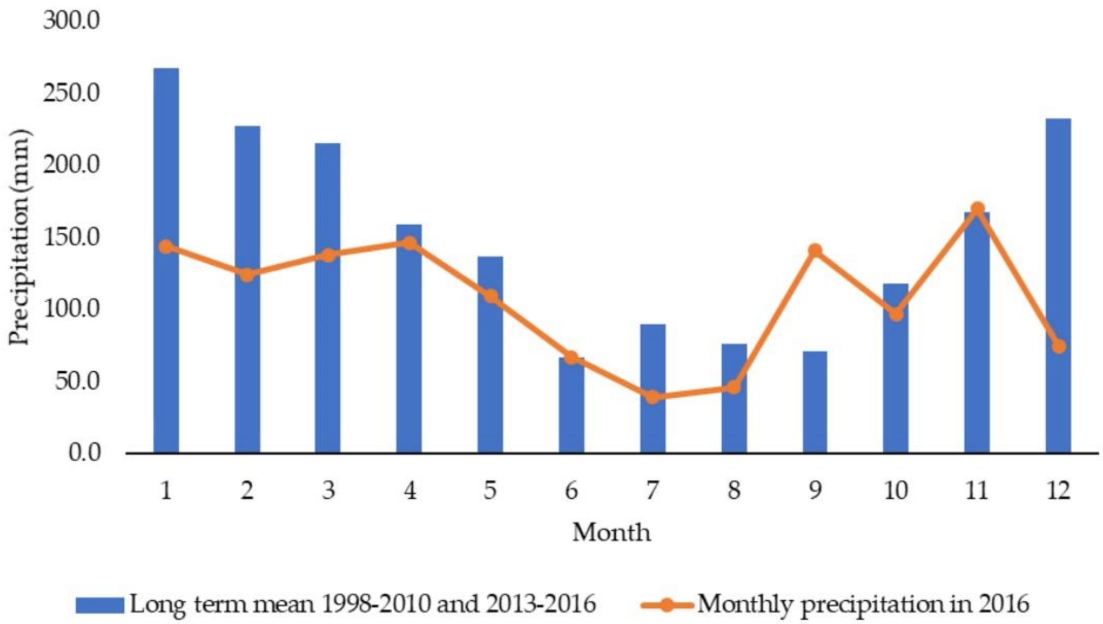

Figure 3.3 Long-term 17-year mean precipitation (bars) and monthly precipitation for 2016 (line), source from station Batutegi Dam, Directorate General of Operation and Maintenance Water Resources Mesuji Sekampung ([DGOMWRMS], 2017).

3.2.2. Water Sampling and Analyses

The water sampling sites in the Sekampung Hulu and Sangharus Rivers were located downstream of the watersheds because of ease of accessibility (Figure 3.1). Water samples were collected in 23rd October, 6th and 20th November, and 4th December, 2016. To determine the water quality characteristics for the entire year, water quality data collected in 26th March, 10th and 23rd April, 8th May, and 17th July, 2016 were compared from a previous study (Somura et al., 2019). Water sampling from a previous study had the same locations as this study sampling sites. Water quality parameters were analyzed, including calcium, potassium, magnesium, sodium, chloride (Cl), NO_3, phosphate (PO_4), sulfate (SO_4), Al, Fe, silicon, water temperature, electric conductivity (EC), dissolved oxygen (DO), and pH. Through the analyses, the circumstances of water quality in the area can be understood and use the information to consider the effects of human activities and natural processes on water quality characteristics. Water quality information can also support recommendations to handle water quality issues in the study area.

All samples were taken composite at a depth approximately 20 – 30 cm below the water surface in each vertical. At each sampling site, the water samples were collected of 250 mL in bottle. Then, water samples were stored in cool box with ice gel when transported to the laboratory. Water temperature, EC, DO, and pH were measured on site using a Horiba multi-parameter water quality meter (U-53G, Horiba, Kyoto, Japan), a DO meter (Hanna Instruments HI 9142, Woonsocket, United States), and a bench pH meter (Hanna Instruments HI 2550, Woonsocket, RI, US), respectively.

Other parameters were analyzed according to the available methods and equipment in the laboratory. All water samples were filtered by a 0.20 μm cellulose acetate membrane filter (Advantec Dismic- 25CS, Japan) before analyses process. Ca, K, Mg, Na, Cl, NO_3, PO_4, and SO_4 were measured by ion chromatography (Dionex ICS-1600, Sunnyvale, CA, US) and Al, Fe, and Si were analyzed by inductively coupled plasma atomic emission spectroscopy (ICPE-9000, Shimadzu, Kyoto, Japan).

3.2.3. Survey of local fertilizer application

Information regarding fertilizer application in the Sekampung Hulu and Sangharus watersheds was conducted via a questionnaire to local farmers because no statistical information related to this aspect was available in the area. In addition, there are many advantages to understanding the local manner of farming activities through direct communication because chemicals contained in fertilizers are a key parameter determining water quality characteristics. The questions were framed to obtain information regarding the amount of fertilizer applied, kinds of fertilizers applied, and the schedule of fertilizer application. Each watershed contains a habitat of approximately 2,500 farmers. A number of 93 farmers in each watershed was surveyed based on the total number of farmers, a confidence level of 95%, and a margin of error of 10%. The respondents were categorized as farmers of private land tenure, farmers of *HKm*, and farmers of *mitra*. The dominant crop in the study area is coffee. Area size of farmers' fields ranges 0.25–6 ha with the predominant size being 1–2 ha.

The social forestry farmers selected in the Sekampung Hulu watershed for the survey were grouped as follows: *HKm* Sinar Harapan, *HKm* Wana Tani Lestari, *Hkm* Mandiri Lestari, *HKm* Bina Wanajaya 1, and *HKm* Bina Wanajaya 2. The farmers in the Sangharus watershed were grouped as follows: private land tenure, *Hkm* Sidodadi, *HKm* Trisno Wana Jaya, *HKm* Karya Tani Mandiri, *HKm* Sinar Harapan, and *mitra* Sumber Rejeki. As *Hkm* Sinar Harapan is located both in the Sekampung Hulu and Sangharus watersheds, the respondents were surveyed for both watersheds.

3.2.4. Statistical Analysis

The water quality data and fertilizer application survey were statistically evaluated. The application of an independent samples t-test or a Mann-Whitney U-test were conducted based on normality distributions. These statistical analyses were performed to determine the significant difference of water quality in the two rivers and fertilizer application amount in the two watersheds. The application of a one sample t-test can determine the seasonal variability of water quality. The one sample t-test was conducted to compare a single data observation in the dry season with that of the mean sample in the rainy season in order to determine the significant differences. Statistical analyses were conducted using Statistical Product and Service Solutions (SPSS) 17.0 software (SPSS Inc, 2008). SPSS is user friendly and widely used throughout the world.

3.2.5. Uncertainties and shortcomings of the study

Water samples were not collected every month at the target sites. Thus, sampling numbers of stream water may not be sufficient to show the level of water concentrations in the watersheds, though differences in water quality characteristics can be understood through this study. Besides this, as the sampling was conducted only downstream because of low accessibility to the mountainous streams, and no observations were conducted along the rivers from middle to upper streams, this research is not able to discuss any trends in water concentrations along the rivers from upstream to downstream in the watersheds.

In addition, the characteristics of seasonal variability of water quality are affected by the climate condition of El Niño or La Niña. Normally, the dry season in the study area is from June to September, but in 2016, the season was shorter, and was from June to August (Figure 3.3). Moreover, the application of fertilizer may vary across years depending on farmers' preference for applying fertilizer and their financial conditions. Thus, climate variability and farmers' decisions will also affect stream water quality.

To collect information on fertilizer application, the survey was conducted in such places as farmers' homes, fields, and pathways. Hence, accurate location of all respondents' land tenure was difficult to identify on the map. This means it is difficult to understand the exact location of farmland to which amounts of fertilizer are being applied. Increasing the number of respondents and surveys to all farming groups will provide more detailed information. Accumulation of knowledge through long-term observation of water qualities and local surveys should be conducted in future for a comprehensive understanding of water quality circumstances in the watersheds.

3.3. Results

3.3.1. Water Sampling

Results from statistical analyses data showed that Ca, K, Mg, Na, Si, Cl, NO_3, PO_4, and SO_4 concentrations were significantly higher in the Sangharus River relative to the Sekampung Hulu River (Table 3.1). By contrast, Fe concentrations were significantly higher in the Sekampung Hulu River (0.53 ± 0.19 mg L^{-1}) relative to the Sangharus River (0.27 ± 0.22 mg L^{-1}). Al, DO, EC, pH, and water temperature showed no significant difference between the two rivers.

Seasonal patterns of Ca, K, Mg, Na, Si, Cl, and PO_4 concentrations were significantly higher in the dry season (July) for both rivers (Figure 3.4, Table 3.2) relative to the rainy season. NO_3 concentrations were lower in the dry season for both rivers with concentrations of 0.23 mg L^{-1} in Sekampung Hulu River and 0.58 mg L^{-1} in Sangharus River. SO_4 concentrations in the Sangharus River were higher in the dry season (7.66 mg L^{-1}) but showed no significant difference in concentration between the rainy (1.16 mg L^{-1}) and dry seasons (0.97 mg L^{-1}) in the Sekampung Hulu River. Similarly, the results showed no significant difference in the seasonal patterns of Al and Fe concentrations in both rivers. The pH and EC were lower in the dry season for both rivers. The pH value in dry season in Sekampung Hulu River and Sangharus River were 6.01 and 6.37, respectively, and EC concentrations in dry season in Sekampung Hulu River and Sangharus River were 5.20 mS cm^{-1} and 12.60 mS cm^{-1}, respectively. DO was higher in the dry season for both rivers with concentrations of 7.29 mg L^{-1} in Sekampung Hulu River and 6.73 mg L^{-1} in Sangharus River. Water temperature in the Sangharus River was higher during the rainy season (28.38 °C), while the water temperature in the Sekampung Hulu River showed no significant difference between the two seasons (27.31°C in dry season and 28.35°C in rainy season).

Table 3.1 Statistical parameters of water quality concentrations in the Sekampung Hulu and Sangharus Rivers.

Parameters	River	Mean ± SD	*P* value
Al (mg L^{-1}) [1]	Sangharus	0.43 ± 0.48	0.052
	Sekampung Hulu	0.93 ± 0.52	
Ca (mg L^{-1}) [1]	Sangharus	5.91 ± 1.48	0.000***
	Sekampung Hulu	2.16 ± 0.71	
Cl (mg L^{-1}) [1]	Sangharus	1.12 ± 0.05	0.000***
	Sekampung Hulu	0.91 ± 0.08	
DO (mg L^{-1}) [2]	Sangharus	5.84 ± 0.47	0.965
	Sekampung Hulu	6.08 ± 0.97	
EC (mS cm^{-1}) [1]	Sangharus	43.44 ± 24.75	0.078
	Sekampung Hulu	26.12 ± 9.90	
Fe (mg L^{-1}) [1]	Sangharus	0.27 ± 0.22	0.015*
	Sekampung Hulu	0.53 ± 0.19	
K (mg L^{-1}) [1]	Sangharus	1.96 ± 0.34	0.001**
	Sekampung Hulu	1.36 ± 0.29	
Mg (mg L^{-1}) [1]	Sangharus	2.16 ± 0.63	0.000***
	Sekampung Hulu	0.65 ± 0.24	
Na (mg L^{-1}) [1]	Sangharus	6.63 ± 1.55	0.000***
	Sekampung Hulu	3.40 ± 0.46	
NO_3 (mg L^{-1}) [1]	Sangharus	1.08 ± 0.25	0.000***
	Sekampung Hulu	0.58 ± 0.21	
pH [1]	Sangharus	7.99 ± 0.98	0.368
	Sekampung Hulu	7.60 ± 0.82	
PO_4 (mg L^{-1}) [2]	Sangharus	0.18 ± 0.11	0.003**
	Sekampung Hulu	0.04 ± 0.05	
Si (mg L^{-1}) [1]	Sangharus	26.71 ± 4.83	0.000***
	Sekampung Hulu	15.21 ± 2.15	
SO_4 (mg L^{-1}) [2]	Sangharus	4.72 ± 1.46	0.000***
	Sekampung Hulu	1.14 ± 0.33	
Water Temperature (°C) [2]	Sangharus	28.13 ± 1.99	0.965
	Sekampung Hulu	28.23 ± 1.79	

* Significant *p* value 0.05, ** significant *p* value 0.01, *** significant *p* value 0.001, SD = standard deviation, [1] = independent samples t-test, [2] = Mann-Whitney U-test. Legend: Cl, chloride; DO, dissolved oxygen; EC, electric conductivity; NO_3, nitrate; PO_4, phosphate; SO_4, sulfate.

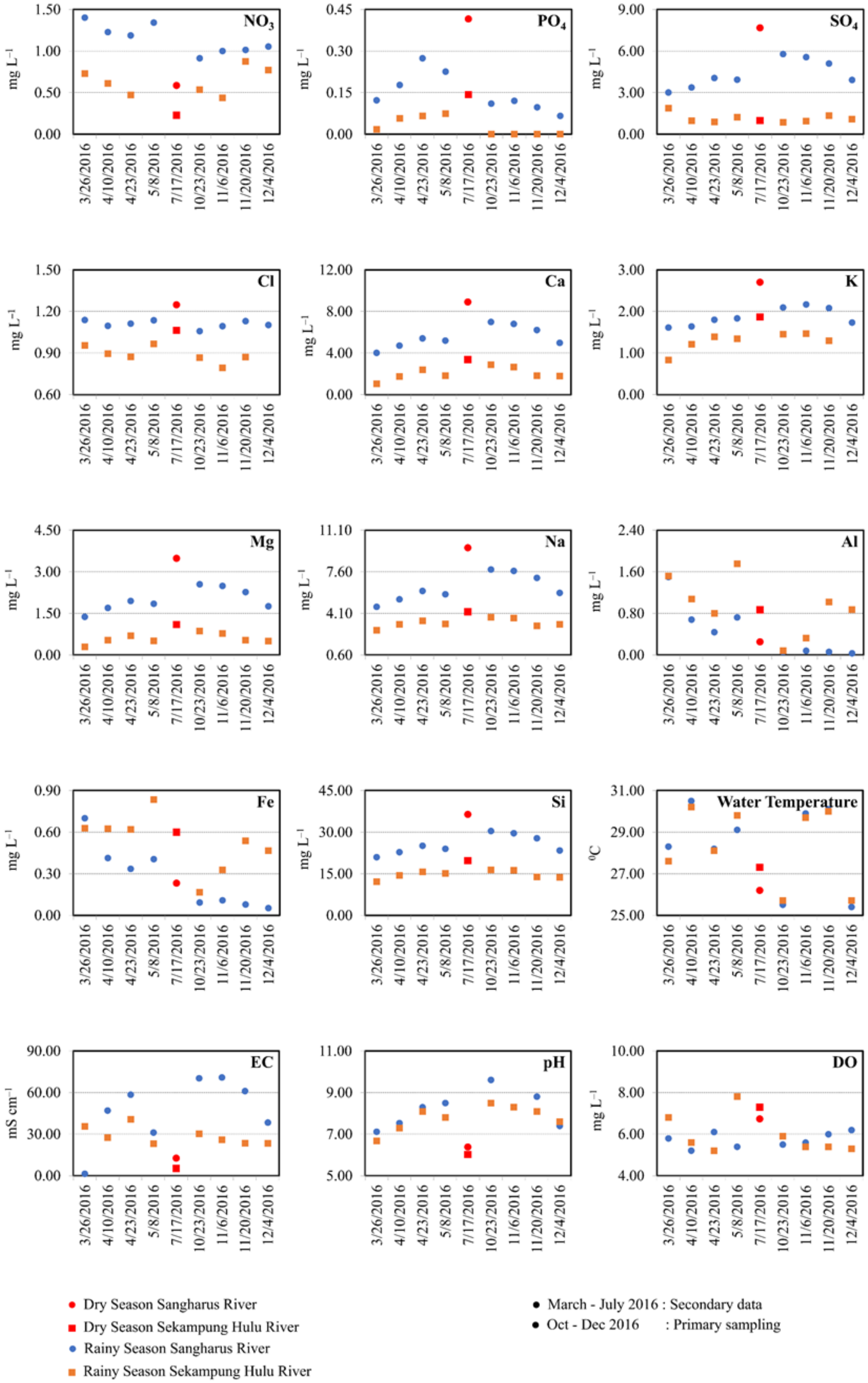

Figure 3.4 Water quality comparisons between the Sekampung Hulu and Sangharus Rivers.

Table 3.2 Seasonal patterns of water quality concentration between the rainy and dry seasons.

Parameters	River	Mean ± SD in rainy season	Concentration in dry season	*P* value
Al (mg L^{-1})	Sangharus	0.45 ± 0.51	0.25	0.311
	Sekampung Hulu	0.93 ± 0.56	0.87	0.761
Ca (mg L^{-1})	Sangharus	5.53 ± 1.04	8.89	0.000***
	Sekampung Hulu	2.01 ± 0.59	3.35	0.000***
Cl (mg L^{-1})	Sangharus	1.11 ± 0.03	1.25	0.000***
	Sekampung Hulu	0.89 ± 0.06	1.06	0.000***
DO (mg L^{-1})	Sangharus	5.73 ± 0.36	6.73	0.000***
	Sekampung Hulu	5.93 ± 0.91	7.29	0.004**
EC (mS cm^{-1})	Sangharus	47.30 ± 23.39	12.60	0.004**
	Sekampung Hulu	28.74 ± 6.46	5.20	0.000***
Fe (mg L^{-1})	Sangharus	0.27 ± 0.23	0.23	0.614
	Sekampung Hulu	0.52 ± 0.21	0.60	0.336
K (mg L^{-1})	Sangharus	1.87 ± 0.22	2.70	0.000***
	Sekampung Hulu	1.28 ± 0.22	1.87	0.000***
Mg (mg L^{-1})	Sangharus	1.99 ± 0.41	3.48	0.000***
	Sekampung Hulu	0.59 ± 0.18	1.10	0.000***
Na (mg L^{-1})	Sangharus	6.26 ± 1.14	9.62	0.000***
	Sekampung Hulu	3.30 ± 0.36	4.22	0.000***
NO_3 (mg L^{-1})	Sangharus	1.14 ± 0.17	0.58	0.000***
	Sekampung Hulu	0.64 ± 0.16	0.23	0.001**
pH	Sangharus	8.19 ± 0.82	6.37	0.000***
	Sekampung Hulu	7.80 ± 0.60	6.01	0.000***
PO_4 (mg L^{-1})	Sangharus	0.15 ± 0.07	0.42	0.000***
	Sekampung Hulu	0.03 ± 0.03	0.14	0.000***
Si (mg L^{-1})	Sangharus	25.50 ± 3.41	36.40	0.000***
	Sekampung Hulu	14.65 ± 1.44	19.70	0.000***
SO_4 (mg L^{-1})	Sangharus	4.35 ± 1.02	7.66	0.000***
	Sekampung Hulu	1.16 ± 0.34	0.97	0.156
Water Temperature (°C)	Sangharus	28.38 ± 1.98	26.20	0.017*
	Sekampung Hulu	28.35 ± 1.88	27.31	0.162

*Significant *p* value 0.05, **Significant *p* value 0.01, ***Significant *p* value 0.001

3.3.2. Fertilizer Application

Fertilizers used by farmers in each watershed are summarized in Table 3.3 based on the questionnaire survey. In the Sekampung Hulu and Sangharus watersheds, farmers applied inorganic fertilizers such as urea (N 46%), phonska fertilizer (N 15%, P_2O_5 15%, K_2O 15%, S 10%), mutiara fertilizer (N 16%, P_2O_5 16%, K_2O 16%, MgO 0.5%, CaO 6%), and triple super phosphate (TSP) fertilizer (P_2O_5 45%, Ca 15%). Furthermore, farmers in the Sekampung Hulu watershed also applied super phosphate (super *fosfat* or SP-36) (P_2O_5 36%, S 5%), ammonium sulfate (*amonium sulfat* or ZA) (N 21%, S 24%), and KCl (K_2O 60%) fertilizers.

Table 3.3 Types and number of fertilizers applied in the watersheds.

Fertilizer	Fertilizer use by number of respondents	
	Sangharus Watershed	Sekampung Hulu Watershed
Urea	63	62
Phonska	44	54
Mutiara	7	8
TSP	1	3
SP-36	0	5
ZA	0	2
KCl	0	1

Legend: TSP, triple super phosphate; SP-36, super phosphate (super *fosfat);* ZA, ammonium sulfate (*amonium sulfat*).

Based on the survey, it was determined that urea application was significantly higher in the Sangharus watershed (166.8 kg ha^{-1}) relative to the Sekampung Hulu watershed (120.3 kg ha^{-1}), as noted in Table 3.4. By contrast, the application of mutiara and phonska fertilizers showed no significant difference in both watersheds. TSP, SP-36, ZA, and KCl fertilizers in the Sangharus watershed were not detected in the independent samples t-test and The Mann-Whitney U-test due to their small number or complete absence in the dataset.

Table 3.4. Urea, mutiara, and phonska applications in Sangharus and Sekampung Hulu watersheds.

Fertilizer	Watershed	Application rate Mean ± SD (kg ha^{-1})	*P* value
Urea	Sangharus	166.8 ± 131.8	0.002*
	Sekampung Hulu	120.3 ± 122.1	
Mutiara	Sangharus	94.7 ± 140.9	0.908
	Sekampung Hulu	48.9 ± 38.5	
Phonska	Sangharus	122.1 ± 80.9	0.21
	Sekampung Hulu	109.3 ± 82.6	

* Significant *p* value 0.01. All the tests were conducted by Mann-Whitney U-test.

The annual schedule of fertilizer application had varied between the farmers (Figure 3.5). The recommendation for minimum fertilizer application is twice a year at the beginning and end of the rainy season (Ministry of Agriculture, 2014). However, most farmers applied fertilizers once a year rather than twice a year. Altering the timings at which fertilizers are applied can have large impacts on stream water quality. Fertilizers applied in the middle of the rainy season are likely to degrade water quality, while splitting fertilizer application between the beginning and end of the rainy season is beneficial, as coffee trees have a longer duration to absorb nutrients. Furthermore, precipitation at the beginning and end of the rainy seasons is typically lower in intensity compared to that in the middle of the rainy season, allowing for lower fertilizer concentrations in surface runoff.

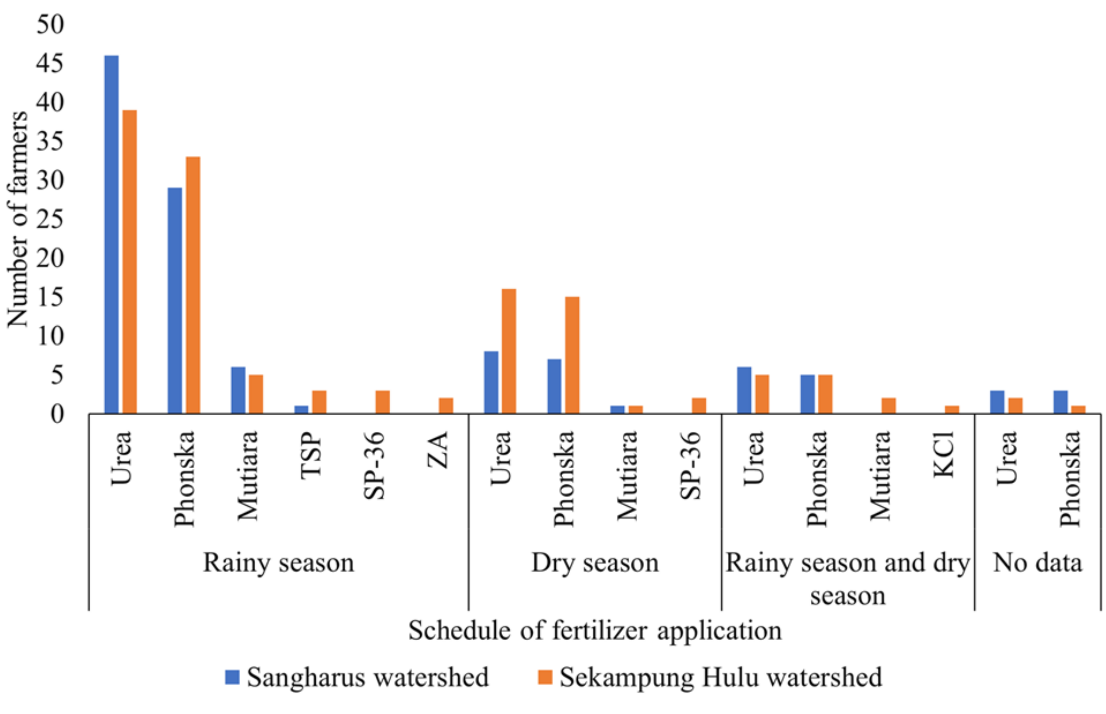

Figure 3.5 Seasonal schedule of fertilizer application in the Sangharus and Sekampung Hulu watersheds based on the number of farmers.

3.4. Discussions

3.4.1. Fertilizer and land use effects on water quality characteristics

The concentration of NO_3 was significantly higher in the Sangharus River relative to the Sekampung Hulu River. This trend correlates with urea fertilizer application. Farmers apply nitrogen fertilizers to increase coffee bean quality (Vinecky et al., 2017). Farmers in the Sangharus watershed applied significantly higher amounts of urea fertilizer (166.8 kg ha^{-1}) relative to the Sekampung Hulu watershed (120.3 kg ha^{-1}). Higher concentrations of NO_3 and nitrogen in stream water of watersheds in Czech Republic, Germany, and China have been linked to fertilization in agricultural land (Bu et al., 2014; Kändler et al., 2017).

The application of phonska and mutiara fertilizers did not statistically vary between both watersheds (Table 3.4), but K, Ca, Mg, PO_4, and SO_4 were significantly higher in the Sangharus River relative to the Sekampung Hulu River (Table 3.1). However, the fertilizer doses of phonska and mutiara fertilizers in the Sangharus watershed (122.1 kg ha^{-1} and 94.7 kg ha^{-1}) was slightly higher than the Sekampung Hulu watershed (109.3 kg ha^{-1} and 48.9 kg ha^{-1}). Shade coffee agricultural fields in the Sangharus watershed covered 66.3% of the total land use, which was significantly higher than the Sekampung Hulu watershed (34.3%). As such, the agricultural fields in the Sangharus watershed required higher levels of fertilizer application to maintain agricultural fertility. Higher concentrations of SO_4 in agricultural lands have been associated with higher fertilizer application (Bahar et al., 2008). Mg concentrations have also been correlated with agriculture land use (Rothwell et al., 2010) due to fertilizer application.

3.4.2. Additional factors controlling stream water quality

Parent material can also influence water quality in the Sangharus River by increasing K, Ca, Mg, and Na concentrations. The concentrations of K, Ca, Mg, and Na could get influence from basic volcanic parent materials (Anda et al., 2015). As the Sangharus watershed predominantly consists of larger basaltic andesitic tuff, chemical weathering of this parent material can release higher amounts of K, Ca, Mg, and Na nutrients to the rivers in this watershed.

The concentration of Si in the Sangharus River varied from 20.9 to 36.4 mg L^{-1} compared to 12.1 to 19.7 mg L^{-1} in the Sekampung Hulu River, with peak concentrations in the dry season. Research in Java in Indonesia demonstrated higher Si availability in areas with parent material consisting of tuff and volcanic ash rather than clay sediment (Husnain et al., 2008). The parent material in the Sangharus watershed is dominated by 62.3% basaltic andesitic tuff relative to 57.8% basaltic andesitic tuff in the Sekampung Hulu watershed, which is likely a cause of the higher observed Si concentrations in the Sangharus River. Furthermore, pumice tuff—which is high in SiO_2 (Papadopoulos et al., 2008)—contributed 32% of the parent material in the Sangharus watershed, while the contribution of pumice tuff in the Sekampung Hulu watershed was 30.1%.

In this study, the Fe concentrations in the Sekampung Hulu River were significantly higher than those in the Sangharus River (Table 3.1). Al concentrations in both rivers were not significantly different but the concentrations were slightly higher in the Sekampung Hulu River. The soil pH in the Sekampung Hulu and Sangharus watersheds was found to be acidic, ranging 4.18–5.11 (Banuwa, 2008). Acidic soil influences the mobility of Al and Fe cations in soil. Al and Fe concentrations are derived from the weathering of parent material (J. Wang et al., 2017) and are higher in concentration in acidic relative to basaltic rocks (Anda et al., 2015). Higher Fe and Al in the Sekampung Hulu River compared to the Sangharus River is likely due to the watershed's lower basaltic content relative to the Sangharus watershed (Figure 3.2). Additionally, the higher Al and Fe concentrations also result from erosion (Chanpiwat and Sthiannopkao, 2014), which is supported by higher concentrations of total sediment solids in the Sekampung Hulu River relative to the Sangharus River (Somura et al., 2019).

Anthropogenic activities in the Sekampung Hulu and Sangharus watersheds also affect water quality because people use streams for washing, bathing, and toilet facilities. In addition, human population density influences NO_3 and Cl concentrations through the amount of human waste. Mayo et al. (2019) have stated that human waste could contribute to the NO_3 load in the river, while Cl concentrations in rivers could be influenced by human waste, fertilizer, livestock waste, and seawater aerosols (Kelly et al., 2012). In particular, treated wastewater has been found to influence Cl concentrations in stream water (Kelly et al., 2010). As sodium chloride (NaCl) is a significant food ingredient, chlorides tend to accumulate in stream water via human waste. Furthermore, there are no human waste treatment facilities in the two watersheds, and thus human waste is directly transferred to the rivers. The NO_3 and Cl concentrations are significantly higher in the Sangharus River compared to the Sekampung Hulu River, possibly due to the higher population in the Sangharus watershed relative to the Sekampung Hulu watershed as the Sangharus watershed has a larger area of private land. Furthermore, Cl concentrations in rivers are also influenced by precipitation derived from seawater aerosols, as regions closer to the ocean tend to have higher Cl concentrations in precipitation relative to mid-continental regions (National Atmospheric Deposition Program [NADP], 2015). The relative proximity of the Sangharus watershed to the sea (56 km) compared to the Sekampung Hulu watershed (72 km) might be the cause of the higher Cl concentrations in the Sangharus River.

3.4.3. Trends in seasonal water quality characteristics

The impact of agricultural land use on water quality can vary between the rainy and dry seasons (Shi et al., 2017; Yu et al, 2016). The concentration of NO_3 in stream water depends both on the amount of runoff and the rate of fertilizer application in agricultural land (Khan and Mohammad, 2014). The concentration of NO_3 is typically higher in the rainy seasons (Shi et al., 2017) due to increased runoff. Urea fertilizer application in both watersheds is predominantly scheduled during the rainy season, which further adds to the increased NO_3 concentrations in stream water (Figure 3.5). Because of less runoff, the concentration of NO_3 was lowest during the dry season in both the Sangharus and Sekampung Hulu Rivers at 0.58 and 0.23 mg L^{-1}, respectively, which is in agreement with previous research in Tanzania (Selemani et al., 2018). Further, lowered NO_3 concentration during the dry season influences biological activity and denitrification processes, which further reduces NO_3 concentrations (House et al., 2001).

The concentration of PO_4 in both rivers was significantly higher in the dry season (Figure 3.4, Table 3.2). This observation is also consistent with high phosphorus values reported during the dry season in Kenya (Mokaya et al., 2004). Higher PO_4 concentrations may be due to lower water discharge and therefore lower dilution of PO_4 during the dry season (Álvarez-cabria et al., 2016). In contrast, the dilution effect during the rainy season would reduce PO_4 concentrations. The dilution effect during the rainy season also influences the concentrations of K, Ca, Mg, Cl, Na, and Si, which were also lower in the rainy season relative to the dry season in both rivers.

SO_4 concentrations in the Sangharus River were also lower in the rainy season, likely caused by the dilution effect under high discharge. In contrast, SO_4 concentrations in the Sekampung Hulu River showed no significant difference between the rainy and dry seasons. The lack of variability in sulphate concentrations may be due to the larger variety of fertilizers applied in the Sekampung Hulu watershed (phonska, SP-36, and ZA), which include fertilizers containing sulfur. Thus, SO_4 concentrations during the rainy season are likely to become less diluted in the Sekampung Hulu River.

EC was higher during the rainy season, which was likely due to higher nitrate fertilizer application and increased runoff from agricultural land. Yakovlev et al. (2015) have showed a correlation between NO_3 concentration and EC. Similar observations in EC trends were also reported in a previous study (Shi et al., 2017) that showed that EC was higher in the rainy season compared to the dry season. Water temperature in the Sangharus River was lower in the dry season compared to the rainy season, possibly because of groundwater effects. Silva et al. (2011) have stated that the dry season has lower stream water temperature than the rainy season predominantly because of groundwater contributions.

It is likely that the lower water temperatures during the dry season in this study increased the DO levels in the stream water (Xu et al., 2019), as oxygen is more soluble in colder temperatures. Gandaseca et al. (2011) have stated that oxygen dissolves more easily in water with low temperatures compared to warm water. Lower water temperatures and higher DO concentrations were observed in the dry season in both the Sangharus and Sekampung Hulu Rivers. The pH was higher in the rainy season (8.19 in the Sangharus River and 7.80 in the Sekampung Hulu River) compared to that in the dry season (6.37 in the Sangharus River and 6.01 in the Sekampung Hulu River) and was likely influenced by increased pollution (such as detergent, fertilizer) from human activities in the study area under high discharge/runoff.

3.4.4. Water quality status and recommendations to improve water quality

The water quality parameter standards were available for pH, Cl, SO_4, Na, NO_3, Al, and Fe. There are guidelines for those parameters which if have concentration above recommendation level will cause health problem or aesthetics problem in drinking water. pH concentration in both rivers does not exceed maximum contaminant level. Usually, pH found in ranges 6.5-8.5 (United States Environmental Protection Agency [USEPA], 2009). Cl and SO_4 concentrations were below maximum contaminant level of 250 mg L^{-1} (USEPA, 2009). The Na concentration in both rivers are below the threshold value of 200 mg L^{-1} (WHO, 2017) which beyond that value will distract the taste.

The converting of NO_3 to NO_3-N resulted in 0.24 mg L^{-1} and 0.13 mg L^{-1} NO_3-N in the Sangharus River and the Sekampung Hulu River, respectively. These NO_3-N concentrations were below the United States Environmental Protection Agency (USEPA) national primary drinking water standard (USEPA, 2009) and the recommended level from the Ministry of Health of the Republic of Indonesia for sanitation hygiene of 10 mg L^{-1} (Ministry of Health Republic Indonesia, 2017). However, Fe concentrations of 0.53 mg L^{-1} in the Sekampung Hulu River exceeded the maximum national secondary USEPA level of 0.3 mg L^{-1} (USEPA, 2009). Furthermore, the Al concentrations in both the Sangharus and Sekampung Hulu Rivers were 0.43 mg L^{-1} and 0.93 mg L^{-1}, respectively, and exceeded the national secondary USEPA's maximum recommended Al level of 0.05–0.2 mg L^{-1}.

The adoption of soil conservation techniques could reduce contaminant flow to water streams, as Al and Fe concentrations are influenced by soil erosion (Chanpiwat & Sthiannopkao, 2014). The application of soil conservation practices such as cover cropping, contour cropping, terracing, and agroforestry could minimize soil erosion (Alegre and Rat, 1996; Langdale et al., 1991; Sepulveda and Carrillo, 2015; Sharda and Samra, 2002) in land use shade coffee and young coffee plantations. Furthermore, the application of soil conservation practices could also reduce nutrient transport to water streams. For example, riparian buffers have been found to increase nutrient retention in watersheds and minimize nutrient transport to rivers (Mayer et al., 2007). Therefore, the adoption of soil conservation practices in this study area is necessary to prevent nutrient loss to rivers and minimize metal contamination. Additionally, proper timing of fertilizer application for coffee trees should be considered because application in the middle of the rainy season had higher rainfall intensity, which can promote higher surface runoff. Splitting fertilizer in the beginning and end of the rainy seasons can minimize nutrient losses to stream water. Gildow et al. (2016) have stated that the timing of application of seasonal fertilizers reduces phosphorus load to water bodies. The optimal timing of N fertilizer application could reduce NO_3-N loss to stream water (Randall and Mulla, 2001). Timing of N fertilizer, if adjusted to the highest N requirements of the crop, that is, the stage before fruit filling, could decrease N application routines without a decline in the yields of coffee beans (Bruno et al., 2011). Implementation of effective land management policies on the watershed scale is necessary to prevent water quality degradation in the Batutegi Dam in order to improve water supply for irrigation and drinking water downstream.

3.5. Conclusions

The result of study has revealed seasonal water quality characteristics and possible reasons for the observed characteristics in adjacent two watersheds for the first time. Although the study sites were located close to each other, they showed different water quality characteristics. The human activities of fertilizer application and young coffee plantations, as well as the natural processes of geological characteristics, influenced the differences between the two watersheds. Based on the results, the Sangharus River contained higher amount of nutrients than the Sekampung Hulu River due to higher fertilizer application amounts in the watershed. Moreover, geological characteristics played an important role in the Sangharus River in determining its water quality characteristics because the watershed consisted of higher basaltic andesite tuff compared to the Sekampung Hulu watershed. Seasonal water quality measurements and questionnaire surveys to local farmers revealed that NO_3 concentrations in both watersheds were higher in the rainy season to correspond with the annual schedule and total amounts of fertilizer application in the watersheds. Despite the application of fertilizers, NO_3 levels remained below the recommended water quality standard. However, Al and Fe levels in stream water exceeded the recommended level for drinking water, which was likely due to soil erosion from improper land management in the Sekampung Hulu watershed.

To protect the environment from the adverse effects of soil erosion and nutrient loss, soil conservation practices should be implemented in the study area such as cover cropping, contour cropping, terracing, and agroforestry. Agroforestry practices in coffee plantations have already been applied in several sites; however, the practice of planting young coffee plantations needs to be implemented for effective soil conservation practices. Moreover, application of soil conservation practices in shade coffee plantations can provide more environmental benefits to reduce surface runoff.

Policy makers are required to develop regulations for a sound water environment based on the different characteristics of the two watersheds. The policies should consider background reasons to determine water quality characteristics in the area. In addition, farmers are recommended to adopt soil conservation practices to prevent sustainable land from experiencing reducing nutrient loss and erosion.

This study was conducted for only a year, with missing information for a five-month duration. A one-year period of research is too short to investigate all aspects of a water environment. Thus, long-term research on water quality should be conducted to understand comprehensive aspects of water characteristics across dry and wet years. In addition, studies on water quality in the upper and middle watersheds were not conducted due to low accessibility. To determine effective management strategies, further studies on the upper and middle reaches of the watersheds are necessary for a holistic view of the watershed water chemistry characteristics. In addition, the number of respondents in the questionnaire survey was minimal according to the total number of famers in the study area. To increase the accuracy of the information regarding the schedule and the amount of fertilizer applied, the number of respondents in questionnaire survey needs to be higher.

In recent years, new technology of artificial intelligence (AI) and machine learning tools have begun to be used for water quality forecasts (Alizadeh et al., 2017; Alizadeh et al., 2018; Olyaie et al., 2015; Shamshirband et al., 2019; W. C. Wang et al., 2014). These tools are very robust; however, for obtaining good results, it is very important to accumulate local information for a water quality database. By conducting this kind of research in ungauged and poorly gauged watersheds continuously, AI and machine learning based analyses can be conducted to implement water resources management, protect fresh water resources, and develop future conservation plans regarding these watersheds.

3.6. References

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CHAPTER 4

Summary in English

The growing population in Indonesia influences land demand for agriculture that accelerates converting land uses from forest to agricultural land. This situation provides issues in soil erosion and water quality degradation. It is important to protect forest from deforestation and forest degradation, as forest has function supporting biodiversity (flora and fauna), determining hydrological characteristics, and support life for communities. Local communities surrounding forest area have strong bonding with forest as they depend on forest resources for living. Utilization of forest area by local communities often rise conflict of forest tenure. Local communities that live surrounding forest area have potential on forest management to ensure forest functions. Therefore, forest management policy for giving legal access to local communities is a solution to use forest resources in order to support economic growth and reduce conflicts with consideration in maintaining forest functions.

Social forestry is the system of forest management that empowers local communities by giving legal access to forest resources. This policy gives equity to local communities for increasing prosperity and economic development, for balancing the relationship between environment and dynamic social culture, and for maintaining sustainable forest function. Besides that, legal access to forest tenure can reduce deforestation and improve rehabilitation. In Tanggamus Regency, Lampung, Indonesia, coffee plantation is predominant land use and cultivated by smallholder in social forestry area. Coffee cultivation becomes one of the important sources to support economic growth. Local community around forest in Tanggamus Regency area has legal access to use forest in order to increase their livelihoods and welfare through community forest and forestry partnership programs, where they have to maintain forest function.

The first study assessed the water quality of Sekampung Hulu and Sangharus Rivers in Lampung, Indonesia, based on their total suspended solids (TSS) concentrations. Subsequently, the extent of soil erosion in the two watersheds was determined and best management practices (BMPs) were recommended for the study area. Water sampling was conducted in 2016 to estimate TSS levels in the two watersheds. Additionally, the Universal Soil Loss Equation (USLE) was integrated with an ArcGIS model to evaluate soil erosion in the watersheds. The results indicate that TSS concentrations in the Sekampung Hulu and Sangharus Rivers ranged from 36–813 mg L^{-1} and 16–146 mg L^{-1}, respectively. The mean and standard error of TSS concentrations in Sekampung Hulu and Sangharus Rivers were 228 ± 87.5 and 69.3 ± 15.2, respectively. Statistical analysis indicated that the mean TSS concentration for the Sekampung Hulu River was significantly higher than that for the Sangharus River. Further, the average soil erosion rates in the Sekampung Hulu and Sangharus watersheds were 12.5 Mg ha^{-1} $year^{-1}$ and 5.6 Mg ha^{-1} $year^{-1}$, respectively. Erosion rates greater than the tolerable soil loss rate in Indonesia (Dariah et al., 2004), 10 Mg ha^{-1} $year^{-1}$, corresponded to 21.8% and 15.5% of the total area for Sekampung Hulu and Sangharus watersheds, respectively. The results indicated that young coffee trees increased soil erosion rates, especially in areas characterized by vulnerable soil. The USLE results concurred with the TSS analysis and indicated higher erosion rates for the Sekampung Hulu watershed than the Sangharus watershed. The simulation scenarios of BMPs were developed in this study to know the potential reduction of soil erosion. The simulation scenarios adopting agroforestry or cover crops could reduce soil erosion more than 90%. While the contour system was found less effective. Concerning about economic aspect, the adoption of cover crop was the better choice for farmers because they could keep the area of coffee trees.

The subsequent study identified seasonal water quality characteristics in two adjacent mountainous rivers (Sangharus and Sekampung Hulu Rivers) in Lampung, Indonesia, and determined the impacts of fertilizer application on river chemistry as a result of social forestry management. Water chemistry was measured in 2016 covering 15 parameters, including calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), chloride (Cl), nitrate (NO_3), phosphate (PO_4), sulfate (SO_4), aluminum (Al), iron (Fe), silicon (Si), water temperature, electric conductivity (EC), dissolved oxygen (DO), and pH. A farmers' questionnaire survey to obtain information on fertilizer application was conducted in study area. The water quality results indicated that Ca, K, Mg, Na, Si, Cl, and PO_4 concentrations were significantly higher in the dry season for both rivers relative to the rainy season. It was probably due to lower water discharge and therefore lower dilution during the dry season. The seasonal patterns of Al and Fe concentrations in both rivers showed no significant difference. While EC and NO_3 were higher in the rainy season, likely linked to the dominant timing of urea fertilizer application during the rainy season. Based on the survey, it was determined that urea application was significantly higher in the Sangharus watershed (166.8 kg ha^{-1}) relative to the Sekampung Hulu watershed (120.3 kg ha^{-1}), which possibly attributed to the higher NO_3 levels in Sangharus river. Moreover, geological characteristics also probably played an important role in water characteristics. Sangharus watershed consisted of wider basaltic andesite tuff area compared to the Sekampung Hulu watershed. The weathering of this rock could release higher levels of K, Ca, Mg, and Na to the river and partly contributed to the water quality formation. Based on the water quality analysis, Al and Fe concentrations were higher than the recommended level for drinking water of USEPA, which was likely due to elevated soil erosion attributed to improper land management. Therefore, it is necessary to adopt effective land management practices such as cover cropping and agroforestry.

Finally, the results of this study exhibited important insights for sustainable land management in the study area. Despite the two adjacent watersheds, we found that the water quality environment showed statistically significant and completely different characteristics. That is, it was found that one watershed had a high concentration of nutrients such as nitrogen and phosphorus, and the other watershed had a high TSS concentration. Although the concept of social forestry is very useful, there was a gap between farmers and land management. Therefore, in the future, it is necessary to conduct surveys involving not only farmers but also the government and to lead to sustainable watershed management.

Summary in Japanese

インドネシア・ランプン州の社会林業が支配的な流域における

土壌侵食と季節的な水質特性の評価

インドネシアでは人口増加によって農業に対する土地需要が増加し，森林から農地への転換が促進されている．これにより，土壌侵食や水質悪化の問題が引き起こされる．森林には動植物の多様性を維持し，水を貯えゆっくりと流出させる機能，そして周辺住民の生活をサポートする機能を有するため，森林を破壊や劣化から保護することが重要と言える．森林地域周辺住民の生活は，森林資源に大きく依存しているため，森林資源の利用や管理において対立を引き起こすこともある．しかし，森林周辺の地域住民は森林の機能を守るための管理プログラムを実行できる可能性があることから，地域住民に対して合法的に森林資源利用を許可し，それと同時に，森林機能の維持管理を義務化する森林管理政策が必要となってきた．

Social Forestry（社会林業）は森林資源への合法的なアクセスを提供することにより，地域社会に管理権限を付与する森林管理システムである．この政策は地域住民の繁栄と経済発展を促し，環境と社会文化との関係を維持し，持続可能な森林機能の利活用を可能にする．加えて，このシステムは無法な森林伐採を減らし，森林資源の回復を促すことができる．インドネシア，スマトラ島，ランプン州にあるタンガマス県の山間部では，コーヒー農園が主要な土地利用である．社会林業地域においても小規模オーナーらによってコーヒーが栽培されている．コーヒー栽培はこの地域の経済成長を支える重要項目の一つになっている．タンガマス県の森林周辺地域住民は，彼らの生活と福祉を向上させるために社会林業や林業パートナーシッププログラムを通じて森林機能の維持管理を行いながら合法的に森林資源を活用する事ができる．

研究論文1では，インドネシア，ランプン州の山間部に位置するSekampung Hulu川とSangharus川の水質特性を，総浮遊物質（Total suspended solids: TSS）濃度に基づいて評価した．隣接する 2 流域において TSS 濃度の明確な違いを明らかにし，その理由を解析すると共に，調査流域に最適な管理方法（Best Management Practices: BMPs）を提案した．TSS の挙動把握のため，2016 年を対象にサンプリングを行った．また，流域の土壌侵食量を評価するため，土壌侵食モデル（Universal Soil Loss Equation: USLE）と ArcGIS を用いた．水質分析の結果，Sekampung Hulu 川と Sangharus 川における TSS 濃度はそれぞれ，36～813 mg L^{-1}，16～146 mg L^{-1}であり，その平均値と標準誤差はそれぞれ，228±87.5 mg L^{-1}，69.3±15.2 mgL^{-1}であった．統計解析の結果，Sekampung Hulu 川の TSS 濃度平均値は Sangharus 川のそれと比べて有意に高かった．加えて，USLE によって計算された平均土壌侵食量は，Sekampung Hulu 川で，12.5 Mg/ha/年，Sangharus 川で 5.6 Mg/ha/年と推定された．インドネシアで定められた許容侵食量 10 Mg/ha/年を超える土壌侵食エリアは Sekampung Hulu 川流域で 21.8%，Sangharus 川流域で 15.5%を占めていた．土壌侵食量は，脆弱な土壌が優先する地域において，樹齢が若く，キャノピーや下草が発達していない斜面からの寄与が大きかった．次に，BMPs のシナリオとして 3 種類設定し解析を進めた結果，アグロフォレストリーあるいは被覆作物(Cover crop)の適用により 90%以上，土壌侵食を減少させる事ができた．経済的な側面を考慮すると，コーヒーの木の面積を維持できる被覆作物の適用が農家にとって良いと考えられた．

研究論文 2 では，Sekampung Hulu 川と Sangharus 川の季節的な水質変動特性を評価した．対象項目は，Ca，K，Mg，sNa，Cl，NO_3，PO_4，SO_4，Al，Fe，Si，water temperature，electric conductivity（EC），dissolved oxygen（DO），pH の 15 項目とした．水質分析に加えて，農民への聞き取り調査から，施肥の量，タイミング，種類に関する情報を入手した．水質分析の結果から，雨期と比べて乾期の方が，両流域とも Ca，K，Mg，Na，Si，Cl，PO_4 濃度が高くなる傾向が把握された．これは乾期の流量低下によって希釈効果が働かず濃度が高くなったと考えられた．水質項目 Al と Fe には乾期と雨期との間に明確な濃度差は検出されなかった．一方で，EC や NO_3 は雨期に濃度が高く，施肥のタイミングと関係していると考えられた．両流域とも Urea（尿素）が多く使用されており，Sekampung Hulu 川流域（120.3 kg ha^{-1}）より Sangharus 川流域（166.8 kg ha^{-1}）の方が，統計的に有意に使用量が多いことが把握された．さらに地質学的特性が水質形成に対して重要な役割を占めていると考えられた．Sangharus 川は Sekampung Hulu 川より玄武岩質安山岩質凝灰岩の割合が高い．従って風化作用により，より多くの K，Ca，Mg，Na などが河川に供給され，それが水質形成に一定の役割を占めていると考えられた．水質分析の結果より，Sekampung Hulu 川においては Fe 濃度がアメリカ合衆国環境保護庁の定める二次飲用水基準より高いことが把握された．また Al 濃度については両流域とも二次飲用水基準濃度を超えていた．これは不適切な土地管理による土壌侵食の増加によるものと考えられたことから，被覆作物やアグロフォレストリーなどの適用による効果的な土地管理が必要と考えられた．

最後に，本研究成果は，対象地域の持続可能な土地管理に関して重要な知見を示した．隣接する 2 流域にも関わらず，水質環境が統計的有意に，全く異なる特徴を示すことを発見した．すなわち，一方の流域は窒素やリンなどの栄養塩濃度が高く，他方の流域では TSS 濃度の高い事が把握された．社会林業のコンセプトは非常に有益だが，農民による土地管理との間にギャップがある事が把握されたことから，今後，農民だけではなく行政も巻き込んで調査を進め，持続可能な流域管理に繋げる必要があると考えられた．

APPENDICES

Appendix 1

Monthly rainfall

Year	Monthly rainfall (cm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1998	34.01	25.14	42.67	19.55	24.15	10.78	13.05	10.57	6.47	13.68	16.72	21.66
1999	35.05	25.93	14.66	7.61	9.34	2.65	10.79	7.09	6.77	37.83	37.83	25.93
2000	28.97	20.96	16.76	26.20	4.65	7.36	15.22	3.89	3.07	24.96	25.89	29.68
2001	21.73	32.02	20.30	19.27	20.78	5.67	8.78	3.92	15.57	15.57	24.66	17.23
2002	33.58	12.42	45.15	20.98	11.07	4.65	17.56	1.11	3.90	1.63	8.69	23.67
2003	12.22	32.99	20.40	13.90	20.83	5.66	3.49	7.89	15.01	5.58	17.81	20.51
2004	46.48	25.46	21.74	8.78	11.02	8.67	12.91	11.67	11.75	4.40	22.66	47.39
2005	45.22	32.95	38.06	17.21	13.23	15.10	12.60	10.45	16.40	16.60	11.99	4.37
2006	21.96	22.56	23.09	27.71	15.43	1.22	3.65			1.75	6.78	30.45
2007	33.92	27.70	18.60	16.62	24.83	12.43	12.10	10.15		8.30	0.95	22.70
2008	18.55	12.48	17.01	15.27	1.45	4.80	0.90	11.32	10.46	14.33	15.96	42.07
2009	21.29	30.40	26.76	27.83	17.70	4.44	4.43	6.68	1.10	12.78	8.55	16.48
2010	25.45	36.03	18.13	11.48	14.06	10.01	18.57	23.28	11.95	19.97	51.21	43.58
2013	26.20	14.61	14.17	8.48	10.81	3.75	8.07	1.93	3.14	6.44	3.86	15.26
2014	11.81	6.91	5.81	7.55	11.46	2.71	4.54	11.71	0.22	5.60	9.14	18.12
2015	24.37	14.94	8.30	7.53	11.30	7.12	2.37	2.39	0.40	0.75	5.40	8.46
2016	14.37	12.40	13.79	14.64	10.92	6.67	3.89	4.58	14.06	9.66	16.98	7.44

source: station Batutegi Dam, Directorate General of Operation and Maintenance Water Resources Mesuji Sekampung ([DGOMWRMS], 2017)

Number of rainfall days in a month

Year	Number of rainfall days in month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1998	21	15	21	16	15	9	9	12	10	10	16	13
1999	23	20	14	8	7	3	8	9	8	19	19	20
2000	17	18	13	15	5	9	12	7	4	10	20	20
2001	13	16	14	10	12	5	9	3	16	16	15	18
2002	16	13	15	15	9	4	5	2	1	3	8	14
2003	12	22	14	11	9	5	6	5	8	9	13	18
2004	22	20	16	10	10	8	9	4	8	3	11	20
2005	25	17	19	11	11	12	9	13	9	12	13	7
2006	19	13	15	10	14	1	6			1	7	15
2007	15	11	10	12	11	8	6	4		6	2	14
2008	12	12	10	13	4	2	3	17	9	21	18	30
2009	22	18	15	17	9	5	3	7	1	16	17	15
2010	20	20	17	8	14	13	12	16	17	16	14	16
2013	25	12	14	12	14	7	16	5	4	7	4	16
2014	20	12	7	10	14	8	10	12	3	10	19	20
2015	23	20	13	13	13	8	4	3	1	2	14	17
2016	15	17	22	19	11	8	9	10	13	17	21	18

source: station Batutegi Dam, Directorate General of Operation and Maintenance Water Resources Mesuji Sekampung ([DGOMWRMS], 2017)

Maximum rainfall in a month

Year	Maximum rainfall in a month (cm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1998	6.61	7.01	7.05	3.00	8.27	3.95	4.33	2.22	1.20	3.95	3.45	7.35
1999	4.00	3.30	3.02	3.09	3.84	2.25	4.66	2.48	2.67	6.80	6.80	6.91
2000	6.40	4.50	4.33	7.51	1.52	2.75	3.60	1.50	1.37	4.95	4.44	4.57
2001	3.64	5.66	5.56	6.66	6.11	3.38	2.70	3.35	3.82	3.82	4.23	4.22
2002	5.43	2.06	9.05	2.71	4.56	3.07	7.83	0.56	3.90	1.14	2.26	4.77
2003	3.34	6.05	3.48	5.55	6.02	1.84	1.21	3.05	6.12	3.25	5.55	4.01
2004	5.88	4.24	6.23	2.64	3.39	3.33	3.15	7.84	4.06	2.82	6.82	5.95
2005	5.86	8.63	6.88	5.32	2.92	4.01	3.71	3.02	7.01	3.85	2.12	1.30
2006	2.92	4.28	4.00	7.00	4.10	1.22	1.36			1.75	4.25	8.15
2007	10.01	10.00	4.50	5.00	7.65	6.90	3.33	6.65		4.00	0.53	7.70
2008	5.35	3.50	3.15	2.90	0.54	3.30	0.50	1.94	4.60	2.11	3.02	4.34
2009	2.40	5.35	4.03	8.02	9.50	1.50	3.66	2.85	1.10	2.00	2.36	5.05
2010	3.85	4.94	6.85	3.44	2.65	2.13	7.07	6.11	3.03	7.02	10.04	10.03
2013	2.09	3.40	2.43	2.35	2.87	1.37	2.15	0.67	1.09	1.81	2.01	2.64
2014	2.22	2.39	3.53	1.55	2.06	0.93	1.43	4.63	0.13	1.71	1.48	2.81
2015	3.51	2.45	1.44	2.46	3.21	4.92	1.62	1.84	0.40	0.55	1.49	1.55
2016	4.00	2.86	2.97	4.17	4.34	2.71	1.40	1.32	4.58	1.60	2.50	2.70

source: station Batutegi Dam, Directorate General of Operation and Maintenance Water Resources Mesuji Sekampung ([DGOMWRMS], 2017)

Rainfall Erosivity Factor (*R* Factor)

Year	*Rm*											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1998	283.91	238.01	386.51	108.62	247.47	80.14	106.03	50.37	21.87	101.75	96.81	217.97
1999	216.19	144.78	81.93	48.80	74.70	18.25	92.56	37.72	39.20	343.62	343.62	214.20
2000	253.86	138.61	120.74	259.51	23.02	41.68	101.16	15.73	14.64	237.40	169.12	202.60
2001	150.78	276.25	167.86	203.16	195.17	44.70	51.10	36.19	93.74	93.74	177.91	105.69
2002	286.25	56.67	553.45	115.55	89.30	37.11	273.99	3.69	65.33	7.07	48.54	186.38
2003	74.54	255.46	131.73	118.78	222.32	32.32	13.23	63.14	159.45	32.58	148.22	127.01
2004	380.98	161.73	181.93	48.06	72.23	59.45	88.41	185.72	95.39	37.99	239.33	410.46
2005	346.41	347.58	348.30	150.40	79.61	106.09	93.63	56.32	180.46	116.44	55.14	16.78
2006	113.68	171.92	159.50	323.72	102.49	8.65	14.37			16.20	53.50	325.07
2007	413.05	373.79	158.12	133.93	284.11	135.25	101.86	143.76		71.14	2.97	228.37
2008	158.56	78.39	117.47	87.23	3.61	55.50	2.23	43.26	83.77	54.47	80.68	248.49
2009	92.12	238.24	191.42	272.55	232.50	21.62	43.98	42.51	7.22	52.38	34.17	120.00
2010	153.59	266.95	149.26	84.94	72.67	44.45	184.04	195.61	58.50	174.89	703.46	543.21
2013	103.63	93.41	70.07	39.76	55.16	14.34	31.21	5.15	13.33	31.97	23.67	75.21
2014	45.31	31.32	40.22	30.19	49.66	7.40	15.63	84.17	0.20	22.16	27.46	86.18
2015	129.95	63.45	28.78	33.95	63.94	57.61	11.70	14.48	1.24	2.27	16.83	27.00
2016	89.85	59.30	60.98	84.06	77.87	38.81	13.47	15.14	100.57	32.24	73.18	30.19
Rm Average	193.69	176.23	173.43	126.07	114.46	47.26	72.86	62.06	62.33	84.02	134.98	186.17
R total (MJ mm ha^{-1} h^{-1} $year^{-1}$)												1433.53

Appendix 2

Soil properties for calculated soil erodibility factor (*K* factor)

Soil Type	Soil Texture			C organic (%)	Organic matter (%)	Structure Code	Permeability Code	*K* factor
	Sand	Silt	Clay					
Typic Dystrudepts[1]	13	58	29	3.09	5.31	3	4	0.0341
Typic Endoaquepts[1]	6	37	57	2.01	3.47	4	5	0.0263
Typic Kanhapludults[1]	33	32	35	3.64	6.28	3	3	0.0177
Typic Hapludox[1]	39	18	43	1.47	2.53	4	4	0.0250
Andic Dystrudepts[2]	32	17	51	3.57	6.15	3	3	0.0103
Typic Hapludands[1]	14.5	51.5	34	7.50	12.93	3	3	0.0013
Typic Udivitrands[1]	57	32	11	7.50	12.93	1	2	0.0007

Source: [1] ICALRD (2016), [2] primary sampling

Structure code

Structure class	Structure class code
Very fine granular	1
Fine granular	2
Med or coarse granular	3
Blocky, platy, or massive	4

Source: U.S. Department of Agriculture, Natural Resources Conservation Service (2017)

Permeability code

Profile permeability class code	Permeability class of 1951	Saturated hydraulic conductivity range μm sec^{-1}	Saturated hydraulic conductivity classes 1993
6	Very slow	<30	Very low or mod. low
5	Slow	0.30 to <1.20	Moderate low
4	Slow or moderate	1.20 to <4.80	Moderate high
3	Moderate	4.80 to < 15.00	Moderate high or high
2	Moderate or rapid	15.00 to < 30.00	High
1	Rapid	≥ 30.00	High or very high

Source: U.S. Department of Agriculture, Natural Resources Conservation Service (2017)

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U.S. Department of Agriculture, Natural Resources Conservation Service. (2017). *National Soil Survey Handbook, Title 430*. United States Department of Agriculture.

Appendix 3

Water sampling concentration

Parameters	River	Concentration								
		3/26/2016	4/10/2016	4/23/2016	5/8/2016	7/17/2016	10/23/2016	11/6/2016	11/20/2016	12/4/2016
Al (mg L^{-1})	Sangharus	1.50	0.68	0.44	0.72	0.25	0.06	0.08	0.06	0.03
	Sekampung Hulu	1.52	1.08	0.80	1.76	0.87	0.08	0.33	1.02	0.87
Ca (mg L^{-1})	Sangharus	4.01	4.72	5.41	5.18	8.89	6.98	6.79	6.20	4.97
	Sekampung Hulu	1.03	1.73	2.38	1.80	3.35	2.86	2.65	1.82	1.79
Cl (mg L^{-1})	Sangharus	1.14	1.10	1.11	1.14	1.25	1.06	1.09	1.13	1.10
	Sekampung Hulu	0.96	0.90	0.87	0.96	1.06	0.87	0.79	0.87	
DO (mg L^{-1})	Sangharus	5.80	5.20	6.10	5.40	6.73	5.50	5.60	6.00	6.20
	Sekampung Hulu	6.80	5.60	5.20	7.80	7.29	5.90	5.40	5.40	5.30
EC (mS cm^{-1})	Sangharus	1.50	47.10	58.40	31.10	12.60	70.20	70.80	61.00	38.30
	Sekampung Hulu	35.60	27.46	40.70	23.05	5.20	30.40	25.87	23.55	23.26
Fe (mg L^{-1})	Sangharus	0.70	0.41	0.34	0.41	0.23	0.09	0.11	0.08	0.05
	Sekampung Hulu	0.63	0.62	0.62	0.83	0.60	0.17	0.33	0.54	0.47
K (mg L^{-1})	Sangharus	1.61	1.64	1.80	1.83	2.70	2.09	2.16	2.08	1.73
	Sekampung Hulu	0.83	1.21	1.39	1.34	1.87	1.45	1.46	1.30	
Mg (mg L^{-1})	Sangharus	1.37	1.70	1.95	1.85	3.48	2.55	2.49	2.27	1.75
	Sekampung Hulu	0.30	0.54	0.69	0.52	1.10	0.86	0.78	0.54	0.51
Na (mg L^{-1})	Sangharus	4.67	5.30	6.00	5.71	9.62	7.79	7.69	7.08	5.82
	Sekampung Hulu	2.69	3.18	3.50	3.24	4.22	3.79	3.72	3.08	3.18
NO_3 (mg L^{-1})	Sangharus	1.40	1.23	1.19	1.34	0.58	0.91	1.00	1.01	1.06
	Sekampung Hulu	0.73	0.61	0.47		0.23	0.54	0.44	0.88	0.78
pH	Sangharus	7.1	7.5	8.3	8.5	6.4	9.6	8.3	8.8	7.4
	Sekampung Hulu	6.7	7.3	8.1	7.8	6.0	8.5	8.3	8.1	7.6
PO_4 (mg L^{-1})	Sangharus	0.12	0.18	0.27	0.23	0.42	0.11	0.12	0.10	0.07
	Sekampung Hulu	0.02	0.06	0.07	0.07	0.14	0.00	0.00	0.00	0.00
Si (mg L^{-1})	Sangharus	20.9	22.8	25.1	24	36.4	30.4	29.6	27.8	23.4
	Sekampung Hulu	12.1	14.4	15.6	15.1	19.7	16.3	16.2	13.8	13.7
SO_4 (mg L^{-1})	Sangharus	3.01	3.39	4.05	3.95	7.66	5.78	5.57	5.11	3.92
	Sekampung Hulu	1.90	1.00	0.88	1.24	0.97	0.87	0.96	1.36	1.09
Water Temperature (°C)	Sangharus	28.30	30.50	28.20	29.10	26.20	25.50	29.90	30.10	25.40
	Sekampung Hulu	27.60	30.20	28.10	29.80	27.31	25.70	29.70	30.00	25.70

March – July 2016: secondary data (Somura et al. 2019), Oct – Dec 2016: primary sampling

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Assessment of soil erosion in social forest-dominated watersheds in Lampung, Indonesia. Rahmah Dewi Yustika, Hiroaki Somura, Slamet Budi Yuwono, Bustanul Arifin, Hanung Ismono, and Tsugiyuki Masunaga. *Environmental Monitoring and Assessment*, *191*:726 (15 pages), https://doi.org/10.1007/s10661-019-7890-5

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