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Mitigation options for improving the ecosystem function of water flow regulation in a watershed with rapid expansion of oil palm plantations

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ABSTRACT

The impact of continuing rainforest transformation on hydrological functioning and other ecosystem functions in South East Asia remains uncertain. The vast majority of the local residents in our study area believe that the expansion of oil palm reduced the flow regulation function of a watershed causing more frequent flooding in the rainy season and water scarcity problems during the dry season. The research aimed to characterize surface runoff as an indicator of water flow regulation and simulate effectiveness of different mitigation options for surface runoff management in a watershed with rapid expansion of oil palm plantations. Our study started with plot experiments to characterize surface runoff used to adapt curve number (CN) values of the different land-use types required for SWAT modeling. Further, we carried out small watershed experiments to adapt the CN values of different mitigation options. The SWAT model performance was in satisfactory agreement with the Nash–Sutcliff efficiency values of 0.88 and 0.82 for calibration and validation, respectively. After successful model calibration and validation, we simulated the effectiveness of the following mitigation options: (a) frond pile management, and (b) frond pile management and silt pit treatment with a density of 20 units per ha. Both options were chosen for their simple construction enhancing their adoption and sustainable application. Frond pile management and the combination of frond pile and silt pit treatment reduced total surface runoff in a watershed scale from 151 mm to 141 mm (10%) and from 151 mm to 109 mm (31%), respectively. The mitigation options which were evaluated in this study were ecologically effective in regulating water flow through reduction of surface runoff. They were also economically viable, because the mitigation options increased the availability of water which can increase oil palm production while the implementation costs are low due to the simple design using frond leaves residues abundantly available onsite. Due to the fulfillment of at least two sustainability pillars, these mitigation options should be adopted as one evaluation criterion in the certification process carried out by Indonesian certification body for sustainable palm oil (ISPO). Further research is still needed to study optimal design criteria for mitigation options including their dimension, density and spatial distribution in a watershed.

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1. Introduction

Over the last decades, South East Asia has undergone dramatic land-use changes. Particularly the area under oil palm plantation has increased, often at the cost of forested land (Carlson et al., 2012; Gunarso et al., 2013; Carrasco et al., 2014; Margono et al., 2012; Tarigan et al., 2015). Oil palm is a highly profitable crop and the land devoted to this crop is likely to expand significantly in the humid tropical region in the future (Sayer et al., 2012; Carrasco et al., 2014). Indonesia, the world's biggest producer of oil palm has currently 8.5 million hectares of land under oil palm cultivation (Setiadi et al., 2011). The present plans of the Indonesian government entail 18 million hectares under oil palm cultivation by 2020 (Wicke et al., 2011; Setiadi et al., 2011).

The expansion of oil palm often is an important government program in these areas (Sayer et al., 2012). Apart from oil palm, another prevalent plantation crop in Indonesia is rubber, which covers 3.5 million hectares of land (Perkebunan, 2013).

In our study area, which is the Jambi Province of Sumatra (Indonesia), the transformation of land use from tropical lowland rainforest into agricultural systems such as rubber and oil palm plantations is happening at an accelerating rate. Under the ongoing process of rainforest transformation into agriculture plantations, the residents in our study region reported that they experienced more serious water shortage problems during the dry season (Merten et al., 2016; Tarigan and Sunarti, 2012) and increasing flooding frequency during the wet season (Tarigan, 2016). The water shortage problems are often associated with the decrease of infiltration due to the decrease of forest cover and increase of agriculture plantation in a watershed (Bruijnzeel, 1989, 2004).

The water flow regulation function is defined as the ability of a watershed to capture and store water from rain storms, reduce the direct runoff and flood peaks as well as release water more slowly so that flows are sustained into or through the dry season (Le Maitre et al., 2014; Hewlett and Hibbert, 1967). Water flow regulation refers to the amount, timing, and quality of water stored in and flowing through and out of an ecosystem (Millennium Ecosystem Assessment, 2005). The ability to store and release rain water is important because the amount of water that is available for people's use on a sustainable basis from water supply systems is directly related to the volume and evenness of the flows (McMahon et al., 2007). Bruijnzeel (1990) discusses the impacts of tropical forests on dry season flows and concludes that the infiltration properties of the forest are critical in terms of how the available water is partitioned between the runoff and base flow.

The objective of the research was to characterize surface runoff as an indicator of flow regulation for different land-use types and simulate the effectiveness of different mitigation options using a SWAT model for surface runoff management in a watershed with rapid expansion of oil palm plantations. SWAT models quantify the water balance of a watershed on a daily basis, which can be used for the assessment of ecosystem services such as freshwater for agricultural uses, instream flows, flood risk and other water resource infrastructure. Simulation of management strategies can be performed without excessive investment of time or money (Arnold et al., 2012a; Neitsch et al., 2011; Volk et al., 2009). The SWAT modeling approach is one of the most widely used and scientifically accepted tools to assess the streamflow in a watershed (Gassman et al., 2007). SWAT models were recommended by Vigerstol and Aukema (2011) in order to evaluate the hydrological ecosystem service of a watershed. Two mitigation options were chosen due to the availability of materials onsite (plantation wastes such as frond leaves) and the simple structure (silt pit) for their implementation, enhancing the sustainability of farmers' adoption of the mitigation options. Mulch made of plantation wastes such as empty fruit bunches or palm fronds stacked across slopes all help to slow runoff, increase infiltration, and increase groundwater recharge (Fairhurst, 1996; Banabas et al., 2008). Silt pits can be built to trap surface runoff and prevent it from entering streams (Comte et al., 2012). Our study started with plot-level and small watershed-level experiments to characterize surface runoff for different land-use types and determine curve number (CN) values required for the subsequent SWAT modeling.

2. Material and methods

2.1. Study area

The study was carried out in the Merangin Tembesi watershed (2°17′25″S, 102°23′21″E), Jambi Province of Sumatra, Indonesia (Fig. 1a). The area is one of the hotspots of Indonesia's recent oil palm boom. The climate is tropical humid with an average temperature of 27 °C and rainfall of 2100–2700 mm year^{-1} or 120–250 mm month^{-1}. The rainy season lasts from October until March. Severe flooding usually occurs in January and February. A dry season with less than 100 mm monthly precipitation occurs from June to September. Soil types in the research region are mainly Acrisols (Allen et al., 2015).

The watershed modeling was carried out in the Merangin Tembesi watershed (1,345,268 ha, Fig. 1b). The plot and small watershed experiments were conducted around the Bungku village situated inside the Merangin Tembesi watershed. We selected the location due to the notable expansion of oil palm plantations and significant increase of water-related problems in the study area (Merten et al., 2016; Tarigan and Sunarti, 2012).

2.2. Watershed modeling

Watershed modeling was carried out using the SWAT model version 2012 (Arnold et al., 2012a). The SWAT model is a continuous model, i.e. a long-term yield model. The model was developed to predict the impact of land management

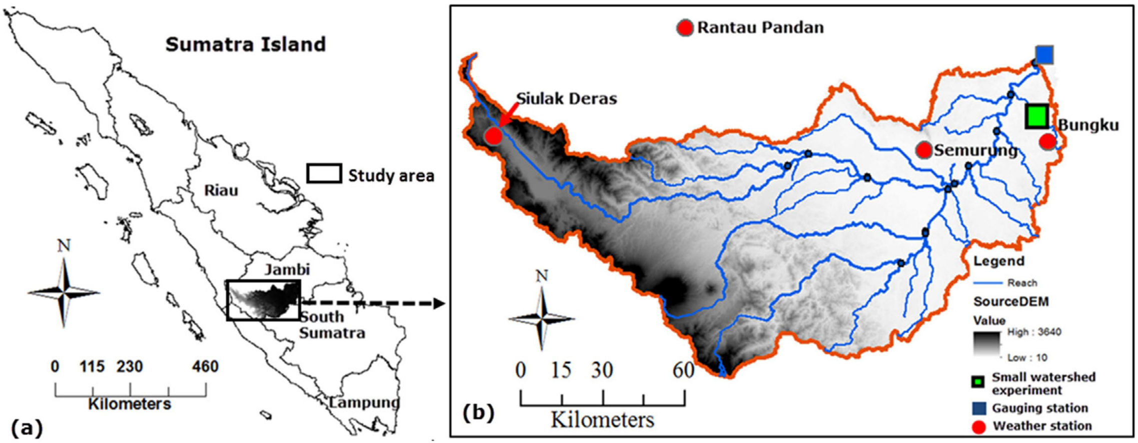

Fig. 1. (a) Study area in Jambi Province of Indonesia and (b) Merangin Tembesi watershed and the location of weather stations, gauging station and small watershed experiment.

practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soil, land use and management conditions over long periods of time. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. During the modeling process, a watershed is partitioned into a number of sub-watersheds to accommodate spatial heterogeneity of input parameters. Model input data sources for the watershed modeling include soil, land use, weather, and streamflow data (Table 1). The watershed modeling was based on a land-use map of the Merangin Tembesi watershed, using the map of planned oil palm expansion that was derived from concession permits obtained from the local government plantation office in Jambi Province (Fig. 2).

In this study, the SWAT model aimed to simulate the effectiveness of different mitigation options in reducing surface runoff from oil palm plantations at the watershed scale. The SWAT model provides some built-in operations that can be used to simulate different surface runoff managements including terraces, strip cropping, contouring, grassed waterways, filter strips, and conservation tillage. We assumed that the characteristics of planned mitigation option using frond pile management in oil palm plantation resembled the strip cropping available as built-in operation in the SWAT model. In the modeling processes the watershed was sub-divided into smaller sub-watersheds. Delineation of the watershed and their sub-watersheds was carried out automatically by the SWAT model and was based on a digital elevation model (DEM) with a 30-m resolution. During the automatic delineation we pre-defined an area of 10.000 ha as a threshold for a minimum sub-watershed area. Based on this threshold, the watershed in our study area was sub-divided into 23 sub-watersheds. After sub-watershed delineation, the SWAT model simulated the flow components (surface runoff) that were used to calculate the runoff coefficient (C).

2.3. SWAT parameters

One important parameter of the SWAT model related to surface runoff modeling is the runoff curve number (also known as SCS curve number, hereafter called CN (short for curve number), Abbaspour et al., 2007; Arnold et al., 2012b). The CN

Table 1
Model input data sources for the watershed modeling.

Data type	Scale/resolution	Source data	description/properties
Topography	30 m	SRTM	Digital Elevation Model with 30 m pixel resolution
Soils	1:250,000	LREP	Soil hydraulic conductivity, bulk density, available water content and texture were resampled in the field
Land use	1:100,000	BAPPEDA (Regional planning office) and DISBUN (Agricultural Plantation office)	Land-use map year 2010
Weather	4 stations (daily rainfall, temperature, wind speed and relative humidity)	BMG office (Meteorology and geophysics board)	Station location: Rantau Pandan, Semurung, Bungku and Siulak Deras
Streamflow	daily discharge data	BBWS (Ministry for Public work)	Data from 1996 until 2012

Abbreviations: SRTM (Shuttle Radar Topography Mission), BAPPEDA (Badan Perencana Pembangunan Daerah), DISBUN (Dinas Perkebunan), BMG (Badan Meteorologi Geofisika), BBWS (Balai Besar Wilayah Sungai).

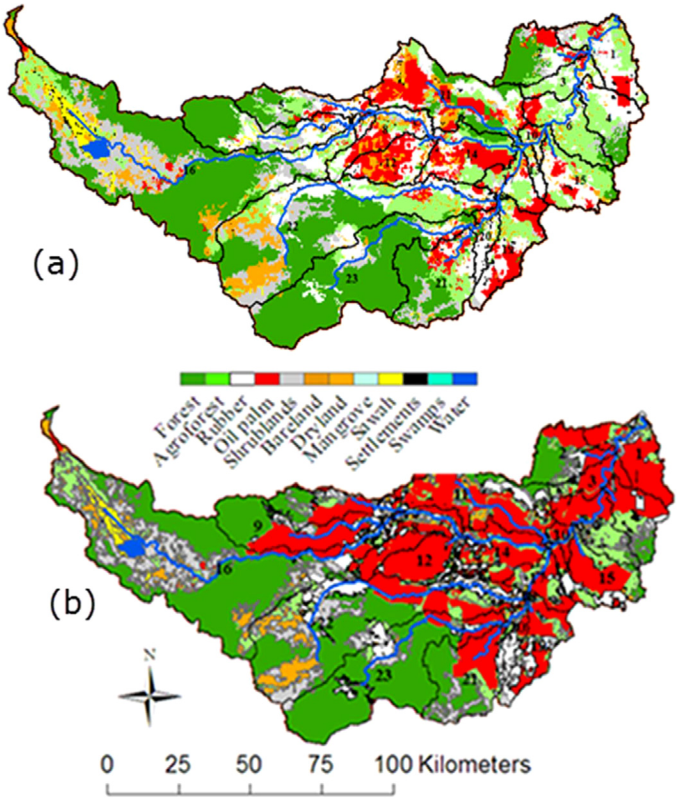

Fig. 2. Merangin Tembesi watershed: (a) land-use map of 2010; (b) planned expansion of oil palm plantation based on concession permits.

value determines the proportion of rainfall which becomes surface runoff. Its value ranges from 0 to 100. The greater the CN value the higher the proportion of surface runoff from a particular rainfall event. The greater the proportion of surface runoff in a particular rainfall event, the less favorable the water flow regulation will be. The CN value is differentiated into Hydrologic Soil Groups (HSG) A, B, C, and D (see Table 2), which is primarily a function of soil infiltration for particular antecedent soil water conditions (Natural Resources Conservation Service, 2009). CN values of soils with high, moderate, slow, and very slow infiltration rates are placed into the HSG A, B, C, and D group, respectively. We also measured infiltration rate in the study area using a double-ring infiltrometer to adjust HSG for different land-use types.

After identifying appropriate HSG for a particular soil and a land–use type, there are two references to determine the CN value for a certain crop: (1) the SWAT crop database and (b) the Technical Release 55 of the Conservation Engineering Division of the United States Department of Agriculture (USDA, 1986). The CN value is already available for various crops in the SWAT model database. Since the land-use types, such as oil palm and rubber plantations, in the study area are relatively region-specific, we carried out plot and small watershed experiments to adapt the CN values of the existing references. In this research, adaptation of the CN value was required threefold: (a) the CN values for different land-use types in the watershed, and (b) the CN value for frond pile management, and (c) the CN value for the combination of frond pile management and silt pit treatment.

2.3.1. Adaptation of CN values for different land-use types

The plot experiment was carried out to determine the order of magnitude of CN values of different land-use types in the study area. We measured surface runoff in five land-use types along a rainforest transformation gradient, i.e. secondary rainforest, agroforest, shrubland, rubber and oil palm plantations. Overland flow was measured in each plot by using the runoff collectors mounted at the lower end of each plot. Eight plots, each 8 m × 12 m, were established as follows: (a) two plots in 14-year-old (14y-OP) and 8-year-old (8y-OP) oil palm plantation, respectively, (b) two plots in 8-year-old rubber monoculture (RP), (c) two plots in shrubland (SL), (d) one plot in agroforest (AF), and (e) one plot in secondary forest (SF). All plots have similar soil characteristics and slope steepness. The texture of the soil was dominantly clay loam.

2.3.2. Adaptation of CN values for mitigation options

From 2013 until 2015 we conducted experiments in the small watershed, which is 14.2 ha in size (Fig. 1b). The aim of the experiments was to adapt the CN values for the studied mitigation options. The watershed was dominated by oil palm trees (9%) aged from 10 to 14 years. The upper part of the watershed area (10%) was covered by secondary forest.

The row distance and the planting distance in a row are normally 8–9 m in oil palm plantations. The spaces between planting rows in oil palm function either as harvest or as inactive (dead) path. The soil of the harvest paths can become very compacted because farmers use them as a way to transport the oil palm fruit bunches or to carry fertilizers and they are rarely cultivated. Meanwhile, the inactive (dead) paths are used to stack old frond leaves. When the frond leaves are arranged properly in a dead path, they function as mulch and potentially reduce surface runoff from the upper slope. In this experiment we asked the farmer to stack the frond leaves such that they covered as much as possible of the soil surface on the dead path in the small watershed. We measured streamflow without mitigation treatments (November 2013–March 2014), after frond pile treatment (April 2014–December 2014), and after a further treatment combining frond pile and silt pit construction (January 2015–December 2015). Silt pits were constructed to collect and store surface runoff. The collected water infiltrated through the bottom into deeper soil layers. The length, width and depth of individual silt pits were 3 m, 0.5 m, and 0.5 m, respectively. The pits were constructed across flow paths with a density of 20 silt pits per ha.

We recorded the streamflow from the small watershed before and after the respective treatment using a rectangular weir and a HOBO automatic water level recorder and then calculated the runoff coefficient values. The surface runoff components of the streamflow were separated by using the straight line method (Blume et al., 2007). After a hydrograph separation, we calculated the runoff coefficient C, which is the ratio of surface runoff to rainfall (Blume et al., 2007).

2.4. Model calibration and validation

The outputs of the SWAT model included surface runoff, groundwater discharge and total streamflow. The SWAT model was calibrated using a SWAT-CUP described in Abbaspour (2012). SWAT-CUP is an interface for auto-calibration that was developed for the SWAT software. The interface links a calibration/uncertainty and sensitivity procedures to SWAT. In SWAT-CUP, users can manually adjust parameter values and ranges iteratively between autocalibration runs. Parameter sensitivity analysis helps to focus the calibration and uncertainty analysis and is used to provide statistics for goodness-of-fit.

The model outputs were validated against the streamflow data from the hydrological stations in the study area. The validation results were expressed as Nash–Sutcliff efficiency (Nash and Sutcliffe, 1970) and percent bias (PBIAS, Gupta et al., 1999). Percent bias measures the average tendency of the simulated data to be larger or smaller than the observations. The optimum value is zero, and low magnitude values indicate better simulations. Positive values of PBIAS indicate model underestimation and negative values indicate model overestimation. The daily streamflow data from the gauge at the outlet of the studied watershed were available for calibration for the period of 2007–2010. These streamflow data were split into two subsets for model calibration (2007–2009) and validation (2010).

3. Results and discussion

3.1. Relating field measurements to CN values

In this study, adaptation of the CN value was required threefold: (a) the CN values for region-specific land-use types related to oil palm and rubber plantations, (b) the CN value for frond pile management, and (c) the CN value for the combination of frond pile management and silt pit treatment.

3.1.1. CN values for region-specific land-use types

The results of the plot experiment on surface runoff were used to adapt the CN value to better represent the conditions in the study area. The plot experiments showed that the average surface runoff at the oil palm and rubber plantations were markedly higher than those in the shrubland, agroforest and secondary forest (Fig. 3). Based on the plot experiment results, the following rules were used to adapt CN values for region-specific land-use types in the study area: (a) the CN values of different land-use types were based on the ascending order of the C values (Fig. 3), i.e. SF < AF < SL < RP < OP, (b) the CN values for oil palm and rubber plantations should be distinctly higher than those of shrubland, agroforestry and secondary forest, and (c) if neither reference provides the CN value of a particular land use, then its value will be obtained by averaging the closest neighboring land-use types based on Fig. 3. When the SWAT crop database was used as reference to determine the CN values of these land-use types, the values of different land-use types were not distinct (Table 2). Distinct CN values were obtained when the SCS Engineering method (USDA, 1986) was used as reference to determine CN values for oil palm and rubber plantations. Therefore, we used the SCS Engineering method as reference for determining the CN values for oil palm and rubber plantation. The CN values for shrubland and secondary forest were referenced from the SWAT crop database. Neither SWAT crop database nor USDA (1986) contained a CN value for agroforest. Since the C value of agroforest lies between shrubland and agroforest (Fig. 3), the CN value for agroforest was determined by averaging the CN values of shrubland and secondary forest.

Data on soil infiltration rate is required to determine the HSG for a particular land-use type. Based on our field measurement using a double-ring infiltrometer, infiltration rates in the study area can be divided into two categories: high infiltration rates (>30 cm h^{-1}) were found under frond piles of the oil palm plantations and in a forest (Fig. 4), while a low infiltration rates (<10 cm h^{-1}) were found under agricultural plantations (oil palm and rubber). In an ascending order the observed infiltration rates were as follows: oil palm (3 cm h^{-1}) < rubber trees (7.8 cm h^{-1}) < frond piles (30 cm h^{-1}) (<forest

Table 2
Adapted CN values for region-specific land-use types and mitigation options in the study area.

Land use/mitigation option		Hydrologic soil group			
		A	B	C	D
Oil palm	CN value based on SWAT crop database	45	66	77	83
	CN value based on USDA (1986)	67	78	85	89
	Adapted CN value	67	78	85	89
Rubber plantation	CN value based on SWAT crop database	45	66	77	83
	CN value based on USDA (1986)	67	78	85	89
	Adapted CN value	67	78	85	89
Shrubland	CN value based on SWAT crop database (Range-Brush)	39	61	74	80
	CN value based on USDA (1986)	30	48	65	73
	Adapted CN value	39	61	74	80
Agroforest	CN value based on SWAT crop database	n.a.	n.a.	n.a.	n.a.
	CN value based on USDA (1986)	n.a.	n.a.	n.a.	n.a.
	Adapted CN value	35	58	72	79
Secondary Forest	CN value based on SWAT crop database (Forest-Mixed)	36	60	73	79
	USDA (1986)	30	55	70	77
	Adapted CN value	30	55	70	77
Frond pile	CN value based on SWAT crop database	n.a.	n.a.	n.a.	n.a.
	CN value based on USDA (1986)	n.a.	n.a.	n.a.	n.a.
	Adapted CN value	63	73	79	83
Frond pile + silt pit	CN value based on SWAT crop database	n.a.	n.a.	n.a.	n.a.
	CN value based on USDA (1986)	n.a.	n.a.	n.a.	n.a.
	Adapted CN value	57	66	72	76

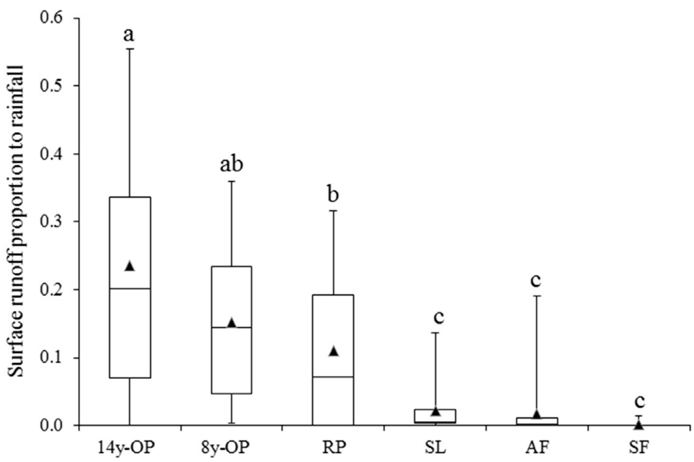

Fig. 3. Surface runoff of different land-use types in the study area: (a) 14-year-old oil palm plantations (14y-OP) and 8-year-old (8y-OP), (b) rubber monoculture (RP), (c) shrubland (SL), (d) agroforest (AF), and (e) secondary forest (SF). The different letters indicate significant differences among averages according to a Bonferroni-corrected posthoc *t*-test based on an ANOVA ($p < 0.05$).

(47 cm h^{-1}). Based on this measurement, land use under oil palm was categorized into HSG D and the CN value for oil palm was 89. This value is higher than the existing CN value found in SWAT crop data base (83).

It is well known that CN values are the most sensitive parameter in hydrological modeling including SWAT. Our findings corroborate that methods to determine the CN values should be tested to identify appropriate and realistic CN values for region-specific land-use types.

3.1.2. CN value for mitigation options

The ecosystem function of water flow regulation in a watershed is improved when the proportion of surface runoff in a particular rainfall event decreases and baseflow increases. Mitigation treatments in this study showed a reduction of the surface runoff proportion in a particular rainfall event. As an example, a single rainfall event before treatment (Jan 8, 2014) and after treatment (Jan 14, 2015) showed that the streamflow after treatment had lower peak discharge compared to that before treatment, implying lower surface runoff after treatment and higher baseflow compared to that before treatment (Fig. 5a). To calculate the percentage of surface runoff reduction, we selected eight pairs of surface runoff events before and after each

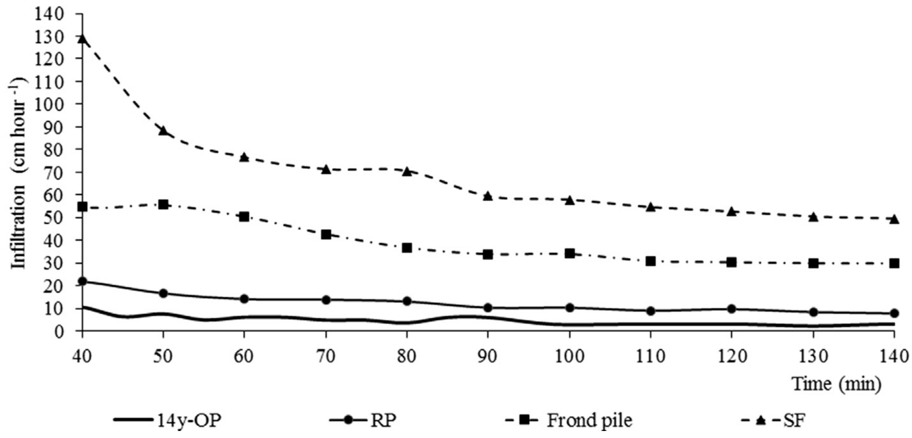

Fig. 4. Infiltration rate in oil palm aged 14 years (14y-OP), rubber plantation (RP), frond pile, and secondary forest (SF).

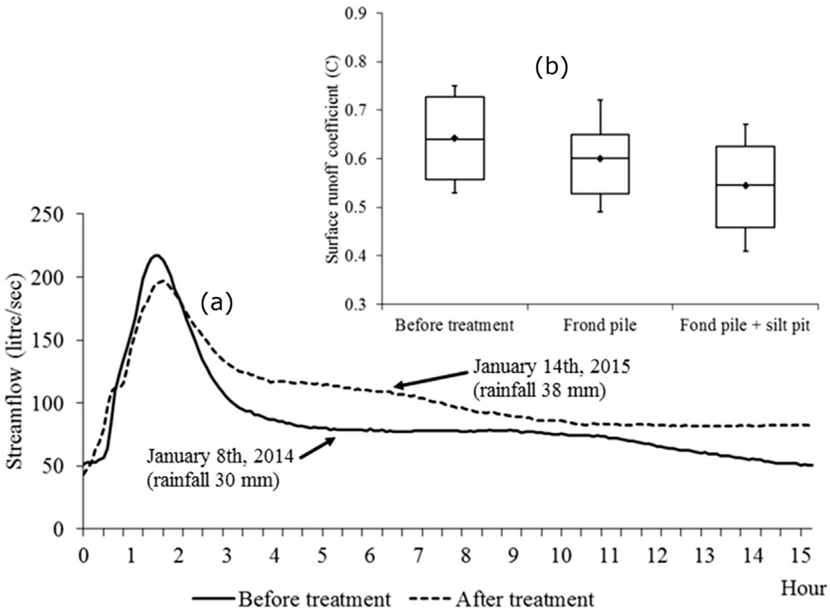

Fig. 5. (a) Example of streamflow pattern before treatment (Jan 8, 2014) and after combined treatment (Jan 14, 2015); (b) reduction of surface runoff coefficient (C) values after treatment with the respective mitigation options.

treatment, calculated and averaged the surface runoff coefficient (C) values. The C values decreased from 0.64 to 0.60 and 0.55 as the result of frond pile management and combination of frond pile management-silt pit treatment representing 6.7% and 15%, reduction of the C values respectively (Fig. 5b).

The CN values for frond pile mitigation were obtained by multiplying the percentage of C reduction (6.7%) with the CN value without mitigation measures which were 67, 78, 85, and 89, obtaining 63, 73, 79 and 83, respectively (Table 2). The CN values for the combination of frond pile-silt pit were obtained by multiplying the percentage of C reduction (15%) with the CN value without mitigation measures which were 67, 78, 85, and 89, obtaining 57, 66, 72 and 76, respectively (Table 2).

Our findings showed that the small watershed experiment was necessary for determining the realistic CN values for location-specific mitigation options such as frond piles and silt pits.

3.2. SWAT Model calibration and validation

The model input parameters that were used for the calibration process and their fitted values after calibration are shown in Table 3.

Table 3
The SWAT calibration parameters including the initial and best fit values.

Parameter	Description (units)	Initial value	Best fit value
CN2	SCS runoff curve number for moisture condition II	Variable[a]	−0.0045
ALPHA_BF	Baseflow recession constant	0.97	0.985
GW_DELAY	Groundwater delay time (days)	70	11.8
GWQMN	Water depth in a shallow aquifer for return flow (mm H_2O)	9.8	4.15
CH_N2	Manning's "n" value for the main channel	0.018	0.045
CH_K2	Hydraulic conductivity in the main channel alluvium (mm h^{-1})	0.02	79.5
SOL_AWC	Available water capacity of the soil (mm H_2O/mm soil)	Variable[a]	0.65
SOL_K	Saturated hydraulic conductivity (mm h^{-1})	Variable[a]	0.578
SOL_BD	Soil bulk density (g cc^{-3})	Variable[a]	−0.088
SLSUBBSN	Sub-watershed slope length (m)	100	79.25

[a] Variable depending on land use and soil, changes in calibration were therefore expressed as fraction.

Overall, the model performance was in satisfactory agreement with Nash–Sutcliff efficiency values of 0.88 and 0.82, and with the PBIAS −2.4 and 12 for calibration and validation respectively. Percent bias indicated that the model overestimated during calibration and underestimated during validation. The optimum value is zero, where low magnitude values indicate better simulations.

3.3. Simulation of mitigation options

In our simulation of mitigation options for improving the ecosystem function of water flow regulation in the Merangin Tembesi watershed, frond pile management and the combination of frond pile and silt pit treatment reduced the yearly average surface runoff from 151 mm to 141 mm (10%) and from 151 mm to 109 mm (31%) respectively (Fig. 6). Based on the Ministry of Forestry Decree (2014), the acceptable value for C is less than 0.35 (represented as solid line in Fig. 6). During the dry season (May–October), the combination of frond pile and silt pit treatment reduced the C value to levels approaching the acceptable level of C value. But during the rainy season (November–April), it only fell to 50% of the acceptable level. One consequence of high surface runoff during the rainy season is the occurrence of flooding. This is illustrated by the fact that the frequency of flooding in the study area increased significantly in the last ten years (Tarigan, 2016).

Our study showed that simple mitigation options such as frond leaves and silt pits can reduce the problem of water flow regulation associated with oil palm expansion. Further research is needed to determine the optimal design and the dimension of silt pits in order to effectively reduce surface runoff during rainy season.

The results that we found in this study including the surface runoff coefficient (C) of different land-use types and mitigation options obtained from plot and small watershed experiments are relatively site specific. The absolute values can change when the soil types are different from those at the study area. But the ascending order of C values in different land-use types will remain the same. The effectiveness of frond piles and silt pits in reducing surface runoff reached 31% in our study, using a density of 20 silt pits per ha at the watershed scale. This effectiveness can change from one watershed to another depending on whether silt pits are constructed across flow paths or not.

Similar simulations using SWAT model were carried out by Widiyaliza (2015) in Batang Tabir watershed (neighboring watershed of our study area). The simulation showed that the mitigation option using silt pits with a density of 30 silt pits

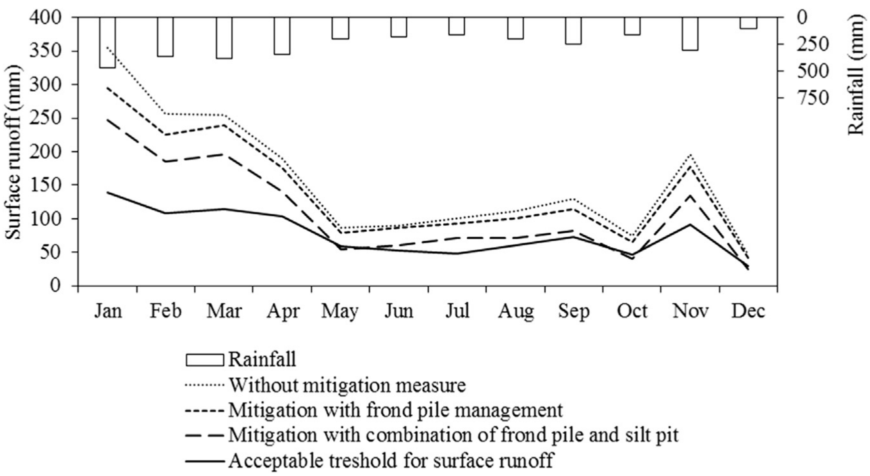

Fig. 6. Surface runoff in the Merangin Tembesi watershed before and after mitigation measures.

per ha reduced the C value to 22.9%, which was lower than that found in our study (31%). One reason for lower reduction of C value in this study was that the CN values were not adapted to region-specific crops resulting in lower Nash–Sutcliff efficiency (0.6) compared to that in our study (0.82).

3.4. Sustainability issues

The main sustainability issue in the study area is the harmonization of agricultural and environmental goals by maintaining long term ecosystem functioning while increasing productivity. With few exceptions, conversion of forest to oil palm plantations has reduced ecosystem functioning compared to forests (Dislich et al., 2015). The greatest impacts of forest conversion have been observed on water regulation and supply, gas regulation and habitat functions. Food and raw material production is the only function that increases in oil palm plantations (Merten et al., 2016; Dislich et al., 2015). Therefore, current practices of oil palm industries in Indonesia may not be sustainable, especially from the water ecosystem function point of view. The negative impacts of oil palm plantations on water ecosystem functions can be reduced through improved plantation management practices (Yusoff and Hansen, 2007; Comte et al., 2012; Schrier-Uijl et al., 2013). Some management practices have been introduced in oil palm plantations (Comte et al., 2012), but most of those practices have not been implemented widely by smallholder farmers. According to Dumanski and Peiretti (2013), there are three pillars for sustainable implementation of management options by smallholder farmers: (a) ecologically effective, (b) economically viable, and (c) socially accepted. The mitigation options which were evaluated in this study were ecologically effective in regulating water flow through reduction of surface runoff. They were also economically viable, because the mitigation options increased the availability of water which can increase oil palm production while the implementation costs are low due to the simple design using frond leave residues abundantly available onsite. The mitigation option was implemented in inactive (dead) paths, minimizing the risk of reducing cultivated area and disturbing harvest transport activity. Due to the fulfillment of at least two sustainability pillars, these mitigation options should be adopted as one evaluation criterion in the certification process carried out by Indonesian certification body for sustainable palm oil (ISPO).

4. Conclusions

Based on our plot and small watershed experiments, the expansion of oil palm plantations reduced the water flow regulation function of a watershed reflected by increasing surface runoff. The SWAT model was able to simulate flow regulation at the watershed scale with rapid expansion of agricultural plantations with satisfactory performance. Frond pile management in combination with silt pit treatment improved the flow regulation function in a watershed with rapid expansion of oil palm plantations. Due to their ecological and economic sustainability, these mitigation options can potentially be adopted as one evaluation criterion in the certification process for sustainable water flow regulation in oil palm plantations. Further research is still needed to study optimal design criteria for mitigation options including their dimension, density and spatial distribution in a watershed.

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