Minimum forest cover required for sustainable water flow regulation of a watershed: a case study in Jambi Province, Indonesia."

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Abstract

In many tropical regions, the rapid expansion of monoculture plantations has led to a sharp decline in forest cover, potentially degrading the ability of watersheds to regulate water flow. Therefore, regional planners need to determine the minimum proportion of forest cover that is required to support adequate ecosystem services in these watersheds. However, to date, there has been little research on this issue, particularly in tropical areas where monoculture plantations are expanding at an alarming rate. Therefore, in this study, we investigated the influence of forest cover and oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*) plantations on the partitioning of rainfall into direct runoff and subsurface flow in a humid, tropical watershed in Jambi Province, Indonesia. To do this, we simulated ~~a~~ streamflow with a calibrated Soil and Water Assessment Tool (SWAT) model and observed several watersheds to derive the direct runoff coefficient (C) and baseflow index (BFI). The model had a satisfactory performance, with Nash–Sutcliffe efficiency values of 0.80–0.88 (calibration) and 0.80–0.85 (validation), and percent bias values of −2.9 to 1.2 (calibration) and 7.0–11.9 (validation). We found that the percentage of forest cover in a watershed was significantly negatively correlated with C and significantly positively correlated with BFI, whereas the rubber and oil palm plantation cover showed the opposite pattern. Our findings also suggested that at least 30 % of the forest cover was required in the study area for sustainable ecosystem services. This study provides new adjusted crop parameter values for

monoculture plantations, particularly those that control surface runoff and baseflow processes, and also describes the quantitative association between forest cover and flow indicators in a watershed, which will help regional planners in determining the minimum proportion of forest and the maximum proportion of plantation to ensure that a watershed can provide adequate ecosystem services.

1 Introduction

In recent years, monoculture plantations ~~has~~ rapidly expanded in Southeast Asia, and the areas under oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*) plantations are expected to further increase (Fox et al., 2012; Van der Laan et al., 2016). In Indonesia, which is currently the largest palm oil producer worldwide, the oil palm plantation area increased from 0.7 million ha in 1990 to 11 million ha in 2015 (Ditjenbun, 2015; Tarigan et al., 2016), and a further 1–28 million ha are projected to be required for palm oil production in 2020–2050 (Wicke et al., 2011; Afriyanti et al., 2016). This rapid expansion of oil palm plantations has been partly triggered by an increased demand for biofuel production (Mukherjee and Sovacoo, 2014). In addition, rubber plantations, which are also prevalent in Southeast Asia (Ziegler et al., 2009), currently cover 3.5 million ha of land in Indonesia (Ditjenbun, 2015).

Although oil palm is of economic value to farmers and the local regions in which it is grown, it has received environmental and social criticism, often being held responsible for deforestation (Wicke et al., 2011; Vijay et al., 2016; Gatto et al., 2017), biodiversity loss

(Fitzherbert et al., 2008; Koh and Wilcove, 2008; Wilcove and Koh, 2010; Carlson et al., 2012; Krashevska et al., 2015), decreased soil carbon stocks (Guillaume et al., 2015, 2016; Pransiska et al., 2016), and increased greenhouse gas emissions (Allen et al., 2015; Hassler et al., 2017). Similarly, rubber plantations have environmental impacts such as reducing the soil infiltration capacity, accelerating soil erosion, increasing stream sediment loads (Ziegler et al., 2009; Tarigan et al., 2016), and decreasing soil carbon stocks (Ziegler et al., 2011). Furthermore, the conversion of tropical rainforest into oil palm and rubber plantations affects the local hydrological cycle by increasing transpiration (Ziegler et al., 2009; Sterling et al., 2012; Röll et al., 2015; Hardanto et al., 2017), increasing evapotranspiration (ET) (Meijide et al., 2017), decreasing infiltration (Banabas et al., 2008; Tarigan et al., 2016), increasing the flooding frequency (Tarigan, 2016), and decreasing low flow levels (Yusop et al., 2007; Adnan and Atkinson, 2011; Comte et al., 2012; Merten et al., 2016). The~~se~~ climatic impacts that occur ~~owing~~ to land use change are expected to be stronger under maritime conditions, such as those in Indonesia, than under continental conditions because 40 % of the global tropical latent heating of the upper troposphere occurs over the maritime continent (Van der Molen et al., 2006).

The forests in Jambi Province, Indonesia have been largely transformed into plantations (Drescher et al., 2016), resulting in inhabitants experiencing water shortages during the dry season and a dramatic increase in flooding frequency during the wet season (Merten et al., 2016; Tarigan, 2016) because plantations promote higher levels of direct runoff than forested lands (Bruijnzeel, 1989, 2004; Tarigan et al., 2016; Dislich et al., 2017). However, this negative impact of plantation expansion could be minimized by maintaining an adequate proportion of forested land as a watershed, which raises the question, what is the minimum proportion of forest cover that is required in a watershed to support adequate water flow regulation?

The water flow regulation function of watersheds represents their ability to retain rain water and is one of the most important soil hydrological processes in tropical regions where rainfall is highly seasonal (Lele, 2009). Functional water flow regulation by a watershed reduces flood peaks by moderating direct runoff~~s~~ (Le Maitre et al., 2014; Ellison et. al, 2017) via soil water infiltration through the soil surface and percolation through the soil profile. This vertical movement of water through the soil determines how much water flows as direct runoff~~s~~ and how much reaches the water table where it sustain~~s~~ as baseflow or groundwater (Hewlett and Hibbert, 1967; Bruijnzeel, 1990; Le Maitre et al., 2014; Tarigan et al., 2016). Forest vegetation provides organic matter and habitat for soil organisms, thereby facilitating higher levels of infiltration than other land uses (Hewlett and Hibbert, 1967).

A number of empirically based and process-based approaches can be used for assessing the impacts of expanding rubber and oil palm plantations on hydrological characteristics in the Southeast Asia region. Empirically based approaches use long-term historical data to correlate land use changes with corresponding streamflow data (Adnan and Atkinson, 2011; Rientjes et al., 2011; Mwangi et al., 2016) or paired catchment studies (Bosch and Hewlett, 1982; Brown et al., 2005), whereas process-based approaches use physically based hydrological models in which the impact of land use changes is determined by varying the land use/cover settings (Khoi and Suetsugi, 2014; Guo et al., 2016; Zhang et al., 2016; Marhaento et al., 2017; Wangpimool et al., 2017). Process-based approaches have the drawback of requiring more data to be input and having high uncertainty in parameter estimation (Xu et al., 2014; Zhang et al., 2016). However, there is currently an absence of long-term historical data for Jambi Province, precluding the use of an empirically based approach.

Distributed hydrological models are useful for understanding the effects of land use changes on watershed flow regulation. Once such model is the Soil and Water Assessment Tool (SWAT) ecohydrological model (2012), which quantifies the water balance of a watershed on a daily basis (Neitsch et al., 2011) and has been recommended for evaluating the hydrological ecosystem services of a watershed (Vigerstol and Aukema, 2011). The SWAT model approach is one of the most widely used and scientifically accepted tools for assessing water management in a watershed (Gassman et al., 2007). Consequently, its popularity has also increased in Southeast Asia; Marhaento et al. (2017) recently used the SWAT model to analyze the impact of forest cover and agriculture land use on the runoff coefficient (C) and baseflow index (BFI) on Java Island, Indonesia and found that a decrease in forest cover from 48.7 % to 16.9 % and an increase in agriculture area from 39.2 % to 45.4 % increased C from 35.7 % to 44.6 % and decreased BFI from 40 % to 31.1 %. Meanwhile, Wangpimool et al. (2017) found that the expansion of rubber plantations in Thailand between 2002 and 2009 led to an annual reduction of approximately 3 % in the average water yield of the basin, whereas Babel et al. (2011) found that the expansion of oil palm plantations in Thailand increased nitrate loading (1.3 %–51.7 %) in the surface water based on SWAT simulations. Tarigan et al. (2016) also used the SWAT model to simulate the impact of soil and water conservation practices on low flow levels in oil palm-dominated watersheds in Jambi Province, Indonesia. This study aimed to quantify the minimum proportion of forest cover that is required to allow a watershed to provide adequate ecosystem services. We selected Jambi Province as our study area because of the rapid expansion of oil palm and rubber plantations in that area. The study findings provide new adjusted values for crop parameters of monoculture plantations, particularly those that control surface runoff and baseflow processes, and describe the quantitative association between forest cover and flow indicators in a watershed, which will help regional planners in determining the minimum proportion of forest that needs to be conserved to ensure that a watershed can provide adequate ecosystem services.

2 Methods

2.1 Study area

The study area ~~was~~ located in Jambi Province, Sumatra (1° 54′ 31.4″ S, 103° 16′ 7.9″ E, Fig. 1). There has been a rapid expansion of plantations in this area, particularly oil palm and rubber (Drescher et al., 2016). The area has a tropical humid climate, with an average temperature of 27 °C and an average rainfall of 2700 mm year^{-1}. The rainy season occurs from October to March. The area under oil palm plantation in the study area (Jambi Province) increased from 150 000 ha in 1996 to 600 000 ha in 2011, representing an almost 400 % increase (Setiadi et al., 2011), whereas the area under rubber plantation increased from 500 000 to 650 000 ha over the same period (Ditjenbun, 2015). In 2013, only 30 % of Jambi Province was covered with rainforest (mainly located in mountainous regions), with 55 % of the land having been converted into agricultural land, of which 10 % was degraded/fallow and will potentially be converted into monoculture plantations (Drescher et al., 2016).

The study area consists of two macro watersheds for the simulation of the C and BFI values with the SWAT model, namely Batanghari Hulu (BH; Fig. 1a) and Merangin Tembesi (MT; Fig. 1b) watersheds, which cover areas of 18 415 km^2 and 13 452 km^2, respectively. The dominant land uses in both watersheds are forest (BH, 50 %; MT, 30 %) and plantation (BH, 18 %; MT, 48 %). ~~Tropodult and Dystropept dominate soils in the study area with medium to heavy texture.~~

To ensure that the C and BFI values obtained from the macro watershed simulations (particularly those sub-watersheds that were dominated by oil palm or rubber) reflected the real observed values in the field, we carried out the direct C measurements in two small watersheds in the study area (Fig. 1c). These small watersheds were covered with 90 % oil palm and 80 % rubber plantations, respectively.

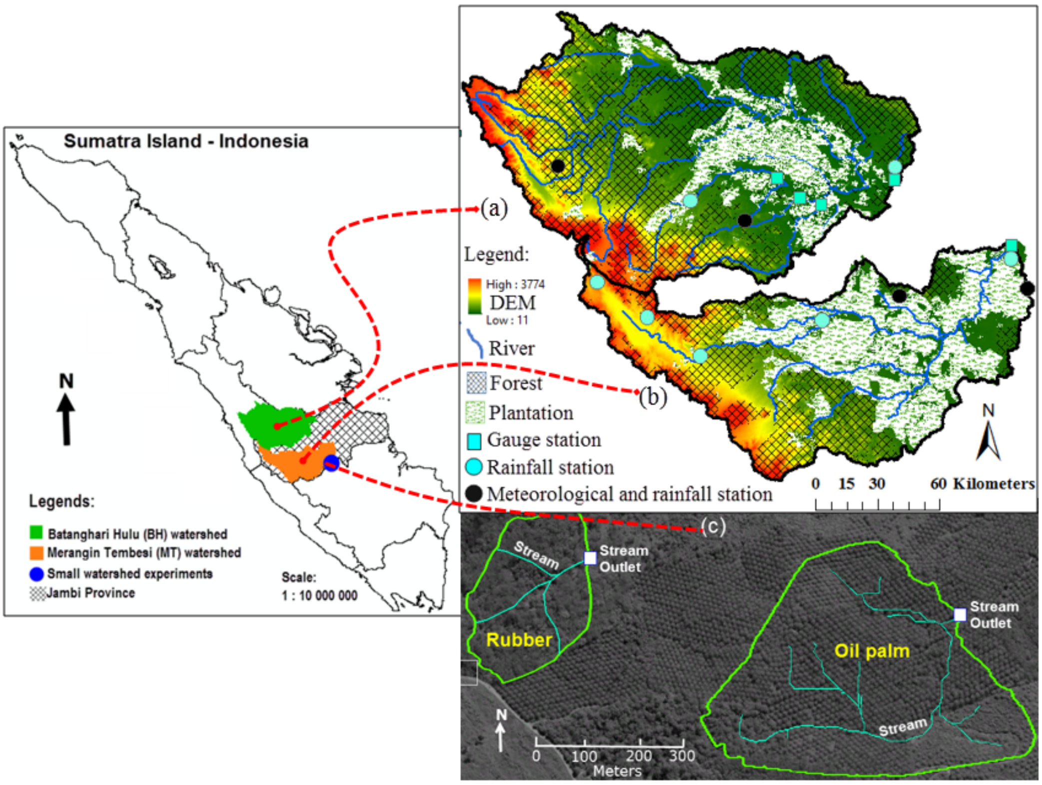

Figure 1. Locations of the (a, b) macro and (c) small watershed experiments in Jambi Province, Sumatra, Indonesia.

Oil palm and rubber are perennial crops that have a life cycle of 25 years. Both crops are planted in rows at planting distances of 8 and 4 m, respectively. In oil palm plantations, there are two types of paths between the planting rows: the harvest path, which is used to transport freshly harvested fruit bunches, and the so-called death path, which is used for piling pruned leaf fronds, which occupy approximately 2 m or one-quarter of this path. Both oil palm and rubber require very intensive harvesting activities, which occur twice per month for oil palm and almost daily for rubber; thus, soils along the harvest path and part of the death path are very compacted. The soils under oil palm and rubber plantations remain unploughed for the entire growing period. Weeds in the oil palm plantations are regularly eradicated using herbicides or mechanical equipment. Intensive inorganic fertilization (1000 kg ha^{-1} year^{-1}) also occurs, contributing to the degradation of the soil structure and fauna

2.2 SWAT model

The SWAT model is a continuous long-term yield model that was developed to simulate the impact of different land cover/management practices on streamflow in complex watersheds with varying soil, land use, and management conditions over long time periods. The major model components include weather, hydrology, soil temperature, soil properties, plant growth, nutrients, and land management (Neitsch et al., 2011; Arnold et al., 2012).

During the modeling process, ~~the~~ watershed is subdivided into several sub-watersheds, which are ~~themselves~~ further partitioned into hydrological response units (HRUs) that are defined by their topography, soil, and land use characteristics. The hydrological outputs of HRUs are calculated using the water balance equation and include total streamflow, surface flow and baseflow. These output components can then be used to calculate indicators of the water flow regulation functions of a watershed, namely C, which is the ratio of direct runoff to rainfall, and BFI, which is the proportion of baseflow in the streamflow.

Because the SWAT model was designed for temperate regions, adapting crop parameter inputs for use in tropical regions is necessary (Van Griensven et al., 2014). To avoid incorrect parameterization of sensitive values, we carried out field measurements for interception, infiltration, and surface runoff to adapt the parameter values, particularly those that control surface runoff and baseflow processes. We then performed SWAT model simulation in two study watersheds and conducted small watershed experiments to compare the observed C values with those obtained from simulations.

2.2.1 Model setup

Delineation of watersheds and their sub-watersheds in our study area was automatically performed by the SWAT model and was based on a digital elevation model (DEM) with a 30 m resolution. During this automatic delineation, we pre-defined 50 000 ha as a threshold for the minimum sub-watershed area, based on ~~which~~ the BH and MT watersheds ~~were subdivided~~ into 25 and 23 sub-watersheds, respectively.

Crop parameters

Oil palm plantations exhibit specific characteristics, particularly with respect to rainfall partitioning. These characteristics include high interception, high ET, low soil infiltration, high proportion of surface runoff, and absence of leaf litter, of which the first four can potentially reduce baseflow. Therefore, to consider these specific characteristics, we conducted field measurements and adjusted several crop parameters that are related to flow components, including canopy storage (CANMX), plant uptake compensation factor (EPCO), hydrologic soil group (HSG) and Soil Conservation Service (SCS) curve number (CN).

a) Interception

CANMX is the maximum amount of water that can be stored in the canopy and trunks of fully developed trees. Thus, an increase in this parameter reflects a reduction in the amount of rainfall that reaches the ground. In oil palms, rainfall is intercepted not only by leaves and branches but also by water reservoirs in leaf axils along the trunk. Therefore, we measured the water storage capacity of leaf axils along the trunks of four 10–12 year~~s~~ old oil palm trees with 10 replications per tree. We found that the leaf axils along the trunk can store up to 20 L or 8.4 mm of water (Table 1), which matches previous reports that the leaf axils along oil palm trunks have a high water storage capacity (Merten et al., 2016; Meijide et al., 2017).

Table 1. Water storage capacity of the leaf axils along the trunks of oil palm trees

Replicate	Water storage (mm)			
	Tree 1	Tree 2	Tree 3	Tree 4
1	14.2	10.8	4.4	6.2
2	10.6	10.2	4.2	5.9
3	9.4	10.5	5.9	7.9
4	8.1	10.4	5.4	7.4
5	8.8	11.5	3.8	9.8
6	9.4	10.9	6.0	8.0
7	9.3	10.6	5.9	7.5
8	10.1	11.0	5.2	7.3
9	8.9	11.2	4.7	10.5
10	9.5	11.3	4.9	7.2
Average = 8.4 mm				

We also measured the canopy interception by oil palm, rubber, agroforest, and forest canopies between November 2012 and February 2013. Rainfall interception was assessed by measuring throughfall and stemflow and subtracting these from the incident rainfall. In total, there were 30 rainfall events during this time, representing light-to-heavy rain. We found that oil palm plantations tended to exhibit higher levels of canopy interception (Fig. 2), with our estimates falling within the range of values that were previously reported for tropical forests in Southeast Asia (commonly 10 %–30 %; Kumagai et al., 2005; Dietz et al., 2006). These interception assessments were used to adjust the CANMX parameter of the SWAT model (Table 2).

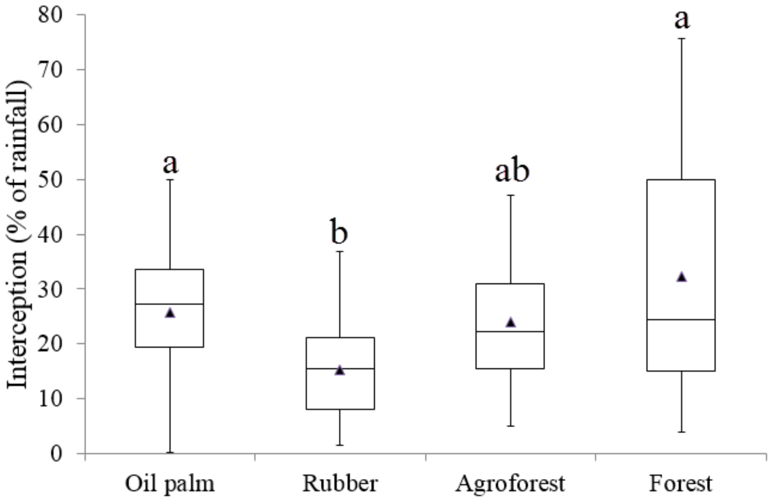

Figure 2. Canopy interception of rainfall under different land uses. Different letters indicate significant differences between the means (Bonferroni-corrected post hoc t-test based on ANOVA; $p < 0.05$).

b) ET

Actual ET was determined by measuring the daily depletion of soil moisture content at a distance of 2 m from the trunks of oil palm trees. Soil moisture measurements were made on consecutive no rain days over the 16-day period from 25 July, 2012 to 10 August, 2012. On an average, soil moisture decreased by 6 % (vol) over this period, which is equivalent to 72 mm or 4.5 mm day^{-1} and is relatively high compared with the average land use in the study area. Similarly, Meijide et al. (2017) also reported a yearly oil palm ET of 1216 mm (4.7 mm day^{-1}) using Edy covariance measurements in the study area. This ET rate is similar to or even higher than ET rates for forests in Southeast Asia (Kumagai et al., 2005), despite oil palm having a much lower stand density and biomass per hectare. Therefore, we accordingly adjusted EPCO, which is related to ET (Table 2).

c) Infiltration and surface runoff

One important parameter of the SWAT model that is related to surface runoff is CN (Arnold et al., 2012), which determines the proportion of rainfall that becomes surface runoff (range, 0–100, with a higher value reflecting a higher level of surface runoff). The CN value is grouped into four HSGs (i.e., A, B, C, and D) according to the soil infiltration capacity. To adjust the CN value, we measured soil infiltration and surface runoff in each land use type (i.e., oil palm, rubber, agroforest, and forest) using a double-ring infiltrometer and multidivisor runoff collectors mounted at the lower end of each plot, respectively. The infiltration rate in different land-use types increases in the following order: oil palm harvest path (3 cm h^{-1}) < oil palm circle (3 cm h^{-1}) < rubber harvest path (7 cm h^{-1}) < between rubber trees (7.8 cm h^{-1}) < forest (47 cm h^{-1}). The infiltration in the oil palm, rubber plantations were markedly lower than those at the forest. Low infiltration rate in the oil palm is associated with the soil compaction due to the intensive harvest activities.

For all HRUs with oil palm and rubber land uses, we selected HSG category D (Table 2) owing to its high surface runoff and low infiltration rate. We assumed that CN values of the forest and agroforest were similar to those of the evergreen and mixed forest, respectively, in the SWAT crop database.

d) Litter fall

In the oil palm plantations, ~~we hardly found any litter~~ outside the frond piles. Litter fall in oil palm plantations does not naturally occur, but leaves are cut during fruit harvest and piled up in a frond pile, which occupies only 12 % of the entire oil palm plantation area. Consequently, the ground surface of oil palm plantations is ~~mostly clean~~ without litter, leading to higher surface runoff~~s~~. There was also ~~hardly any~~ understory vegetation (grasses) because herbicides were routinely sprayed. The absence of the litter fall affected Manning's "n" value for overland flow (OV_N).

Table 2. Adapted crop parameter inputs for the study area

SWAT parameter	Definition	Oil palm	Rubber	Agroforest	Forest
CANMX (mm)	Maximum trunk storage	8.4	0	0	0
	Maximum canopy storage	4.7	2.7	4.3	5.8
HYDGRP	Hydrologic soil group	D	D	B	C
CN2	Curve number	83	83	65	45
SOL_BD (g cm^{-3})	Soil bulk density	1.2–1.3	1.2–1.3	1	0.9
EPCO	Plant uptake compensation factor	1	1	1	1
OV_N	Manning's "n" value for overland flow	0.07	0.14	0.4	0.5
SOL_K (mm h^{-1})	Saturated hydraulic conductivity	30	78	400	470
SOL_AWC (mm mm^{-1})	Available water capacity	0.1	0.1	0.2	0.2
BLAI (m^{2} m^{-2})	Maximum potential leaf area index	3.6[a]	2.6	5	5

CHTMX (m)	Maximum canopy height	12	13	14	20
T_BASE	Base temperature	20	20	20	20
T_OPT	Optimal temperature	28	28	30	30

[a] Fan et al., 2015

e) Baseflow

The baseflow recession constant (ALPHA_BF) was calculated by plotting the daily streamflow hydrograph on semi-log paper and determining the average values from several individual rainfall events. Several previous studies have shown that ALPHA-BF ranges from 0.9 to 0.95 in Indonesia.

General input data

The SWAT model ~~required additional input data~~ to the crop parameters described above, such as the climate, topography, soil type, and land use for each sub-watershed (Table 3).

Table 3. Model input data sources

Data type	Resolution	Description	Source[a]
Topography	30 m	DEM with a resolution of 30 m per pixel	LAPAN
Soil	1:250 000	Soil hydraulic conductivity, bulk density, available water content, and texture were resampled in the field	Soil Research Institute, Ministry of Agriculture
Land use	1:100 000	Land use map with intensive ground check	Regional Planning office (BAPPEDA)
Rainfall and climate	Daily	Rainfall and meteorological stations at Rantau Pandan, Siulak Deras, Muara Hemat, Padang Aro, Depati Parbo,	BMG office and CRC990

		Bangko Bungo, Pematang Kabau, and Bungku	
Streamflow	Daily discharge data	Stations at Muara Tembesi, Air Gemuruh, Batang Tabir, Batang Pelepat, and Muara Kilis	Ministry of Public Works (BBWS)

[a] LAPAN, National Aeronautics and Space Agency (*Lembaga Antarikasa dan Penerbangan Nasional*); BAPPEDA, Regional Planning Agency (*Badan Perencanaan Daerah*); BMG, Meteorology and Geophysics Agency (*Badan Meteorologi dan Geofisika*); CRC990, Collaborative Research Centre 990; BBWS, Catchment Regional Agency (*Balai Besar Wilayah Sungai*).

DEM with a resolution of 30 m per pixel was obtained from the National Aeronautics and Space Agency, rainfall and climate data were sourced from the Meteorology and Geophysics Agency, and streamflow data were provided by the Ministry of Public Works. All these data are freely available for research purposes on official request to the corresponding institutions. The streamflow time series and rainfall records for the small catchments and the resampled soil hydraulic conductivity, bulk density, available water content, and texture data have been deposited by the first author at Bogor Agricultural University and in the EFForTS Database (https://efforts-is.uni-goettingen.de). The land use and soil map for the study area was obtained from Jambi Province Regional Planning and Agricultural Plantation offices (Ditjenbun, 2015).

2.2.2 Model validation and calibration

Prior to model calibration and validation, we performed a sensitivity analysis, particularly for the parameters that control surface runoff and baseflow using a previously reported procedure (Moriasi et al. 2012; Van Griensven et al., 2006; Arnold et al., 2012). The sensitivity analysis was performed using the SWAT Calibration and Uncertainty Procedure (SWAT-CUP) package, which is an interface for auto-calibration that was specifically developed for SWAT and which links any calibration/uncertainty or sensitivity program to SWAT (Abbaspour, 2015).

Following the sensitivity analysis, we calibrated the SWAT model using the Latin hypercube sampling approach of the SWAT-CUP software. We first determined parameter ranges based on the minimum and maximum values allowed in SWAT. We then performed calibration and validation of the SWAT model by comparing the simulated monthly streamflows with observed data at the Muara Kilis and Muara Tembesi gauging stations from 2007 to 2009 for calibration and 2012 to 2014 for validation. Moriasi et al. (2012) recommended the use of three quantitative statistics for model evaluation: the Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data. In this study, we used NSE and PBIAS to evaluate the model performance. NSE is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared with the measured data variance (“information”)

(Nash and Sutcliffe, 1970). PBIAS measures the average tendency of simulated data to be larger or smaller than that of observational data (Gupta et al., 1999), with an optimum value of zero and lower values that indicate better simulations. Positive values of PBIAS indicate model underestimation, whereas negative values indicate model overestimation.

2.3 Simulated C and BFI values and the proportion of land use types in a watershed

The output of the validated SWAT model consisting of flow components for each sub-watershed was used to calculate indicators of the water flow regulation functions of a watershed, namely C, which is the ratio of direct runoff to rainfall, and BFI, which is the proportion of baseflow in the streamflow. To analyze the association between the C and BFI values and the proportion of each land-use type in a watershed, we derived data vectors from the BH and MT watersheds. Each of these vectors corresponded to the percentage of land use types, C and BFI in each of the 25 sub-watersheds from the BH watershed and 23 sub-watersheds from the MT watershed (Fig. 3a and b; Table 4).

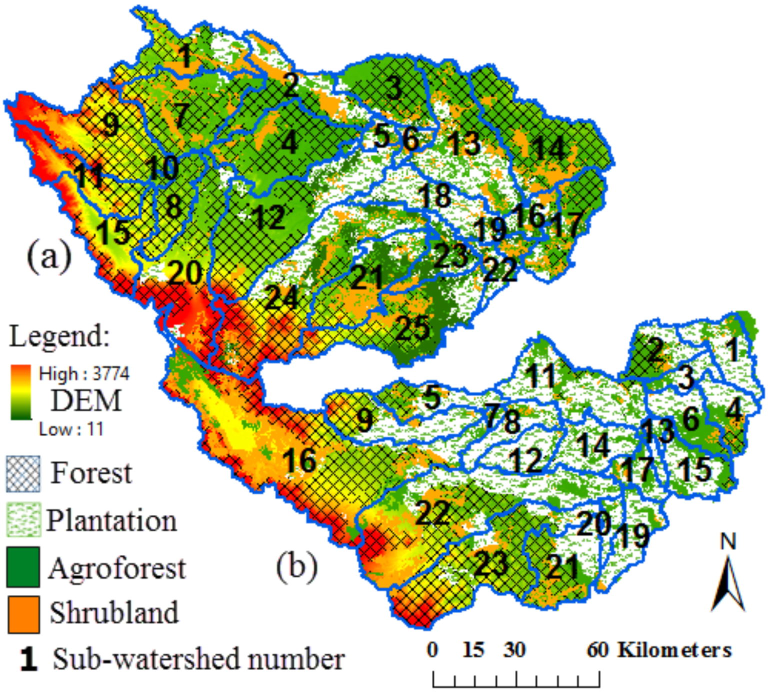

Figure 3. Land use types and sub-watershed number of the (a) BH and (b) MT watersheds.

Table 4. The percentage of land use types, C and BFI in each sub-watershed within the BH and MT watersheds

Sub-wat. nr.	Percentage of land use types					C	BFI
	F	AF	RP	OP	S		
				BH watershed			
1	56	0	17	0	26	0.21	0.71
2	46	0	26	0	26	0.27	0.63
3	90	0	0	0	0	0.00	0.99
4	76	0	0	0	0	0.18	0.75
5	16	0	67	0	17	0.40	0.32
6	0	0	67	0	34	0.41	0.23
7	68	0	0	0	19	0.17	0.76
8	100	0	0	0	0	0.01	0.98
9	80	0	0	0	0	0.15	0.79
11	55	0	0	0	0	0.31	0.57
12	61	0	23	0	0	0.23	0.62
13	30	0	41	0	18	0.32	0.42
14	84	0	0	0	16	0.04	0.91
15	49	0	0	0	0	0.31	0.58
24	66	5	25	5	0	0.14	0.76
25	44	32	0	7	17	0.04	0.93
				MT watershed			
1	0	13	0	85	0	0.59	0.11
2	56	0	0	44	0	0.36	0.45
3	0	16	0	82	0	0.58	0.13
4	21	20	12	48	0	0.45	0.32
5	32	0	19	38	12	0.40	0.29
6	0	46	0	52	0	0.43	0.37
8	0	0	15	86	0	0.54	0.01
9	48	0	0	53	0	0.59	0.11
10	0	0	0	96	0	0.34	0.37
11	0	0	19	69	0	0.67	0.00
12	0	0	13	88	0	0.66	0.01
14	0	0	20	80	0	0.54	0.01

16	0	20	39	0	24	0.36	0.35	15	0	27	14	57	0	0.65	0.01
17	59	0	0	0	24	0.16	0.71	16	70	0	0	0	31	0.53	0.22
18	0	0	82	19	0	0.48	0.03	17	0	28	11	57	0	0.28	0.65
19	19	30	0	0	52	0.13	0.75	19	0	12	31	57	0	0.53	0.23
20	69	0	0	0	0	0.22	0.69	20	0	0	63	37	0	0.60	0.10
21	45	24	0	0	32	0.08	0.87	21	48	0	0	36	16	0.65	0.01
22	0	26	16	58	0	0.35	0.28	22	36	0	17	17	16	0.32	0.42
23	0	48	33	0	20	0.23	0.61	23	100	0	0	0	0	0.40	0.32

Sub-wat. nr, sub-watershed number (see Fig. 3a and b); F, forest; AF, agroforest; RP, rubber plantation; OP, oil palm; S, shrubland.

2.4 Measured C values

We carried out the direct C measurements from two small watersheds (Fig. 1c) between 2013 and 2015 using rectangular weirs and water recorders for comparison with simulated C values. The land use~~s~~ in the small watersheds ~~are~~ similar to the proportions found in several of the sub-watersheds shown in Table 4 (e.g., BH 18, MT 1, MT 8, MT 10, MT 11, MT 12, MT 14, and MT 20). The direct runoff components of the hydrographs were separated using the straight-line method described by Blume et al. (2007), following which C was calculated. We did not calculate BFI values along with C values in the small watershed experiments because BFI calculation requires hydrograph records over a longer period.

3 Results and Discussion

3.1 Measured C values

The average C value was based on nine individual rainfall events during the field experiment. The observed C values that were measured during two small watershed experiments was 0.59

(Table 5). This value was comparable with the averaged simulated values of 0.60 for sub-watersheds with comparable proportions of land use type with those of the small watershed experiment (Table 6).

Table 5. Observed C values obtained from field experiments in two small watersheds that were dominated by plantation cover

Event Nr.	Rainfall (cm h^{-1})	Rainfall volume (m^3)		Runoff (m^3)		C	
		Small wat. 1	Small wat. 2	Small wat. 1	Small wat. 2	Small wat.1	Small wat. 2
1	6.0	8960	3136	4500	1320	0.50	0.42
2	3.0	5180	1813	2625	840	0.51	0.46
3	1.4	4095	1433	3000	810	0.73	0.57
4	0.6	1456	509.6	1080	255	0.74	0.50
5	10.7	14923	5223	11250	3900	0.75	0.75
6	3.1	6006	2102	4050	1020	0.67	0.49
7	2.3	8188	2885	6150	1584	0.75	0.55
8	2.2	4416	1465	2400	780	0.54	0.53
9	9.6	8916	3121	5400	1650	0.61	0.53
Average						0.65	0.53
Total						0.59	

Table 6. Simulated C values for the sub-watersheds used in the SWAT simulation (Table 4) that had similar percentages of plantation cover to the two small watersheds used in the field experiments

Sub-watershed code (see Table 4)[a]	Percentage of plantation cover		C
	Oil palm	Rubber	
BH-18	82	19	0.49
MT-1	85	0	0.59
MT-8	86	15	0.54
MT-10	96	0	0.67
MT-11	69	19	0.67
MT-12	88	13	0.54
MT-14	80	20	0.65
MT-20	37	63	0.65
Average			0.60

[a] Sub-watersheds were selected that had >80 % plantation (oil palm and rubber) cover, allowing a comparison to be made with the small watersheds used in the field experiment

3.2 SWAT model performance

The sensitive parameters that were included in the calibration of the SWAT model are ranked in Table 7. Some of these parameters play an important role in controlling the initial abstraction of rainfall (e.g., CANMX), rainfall partitioning into surface runoff (e.g., CN2 and OV_N), and vertical movement of water through the soil (e.g., SOL_BD, SOL_K, and SOL_AWC).

Table 7. Sensitivity rank, initial and final values of the calibration parameters that were used in the study for the BH and MT watersheds

Parameter	Description	Sensitivity rank	Initial value range	Best-fit values	
			BH and MT	BH	MT
ALPHA_BF	Baseflow recession constant	1	0.0 to 1.0	0.94	0.91
CN2	SCS runoff curve number for moisture condition II	2	−0.2 to 0.2 (V)[a]	0.14	0.12
GW_DELAY	Groundwater delay time (days)	3	30 to 450	62.5	57.2
CANMX	Maximum canopy storage (mm)	4	−0.2 to 1.0 (V)[a]	0.95	0.76
SOL_BD	Soil bulk density	5	−0.5 to 0.6 (V)[a]	0.46	0.47
GWQMN	Water depth in a shallow aquifer for a return flow (mm H_2O)	6	0.0 to 2.0	0.99	0.95
SOL_K	Saturated hydraulic conductivity (mm h^{-1})	7	−0.8 to 0.8 (V)[a]	0.71	0.62
CH_N2	Manning's "n" value for the main channel	8	0.0 to 0.3	0.05	0.15
SOL_AWC	Available water capacity of the soil (mm H_2O/mm soil)	9	−0.2 to 0.4 (V)[a]	0.09	0.04
OV_N	Manning's "n" value for overland	10	−0.2 to 1.0 (V)[a]	0.51	0.3

flow

[a] (V) = Variable depends on land use and soil, and so changes in calibration were expressed as a fraction.

A visual comparison of best-fit simulations and observed data is shown in Fig. 4. Overall, the model performance was satisfactory, with NSE values of 0.80–0.88 (calibration) and 0.84–0.85 (validation) and PBIAS values of −2.9 to 1.2 (calibration) and 7.0–11.9 (validation) for BH and MT watersheds, respectively.

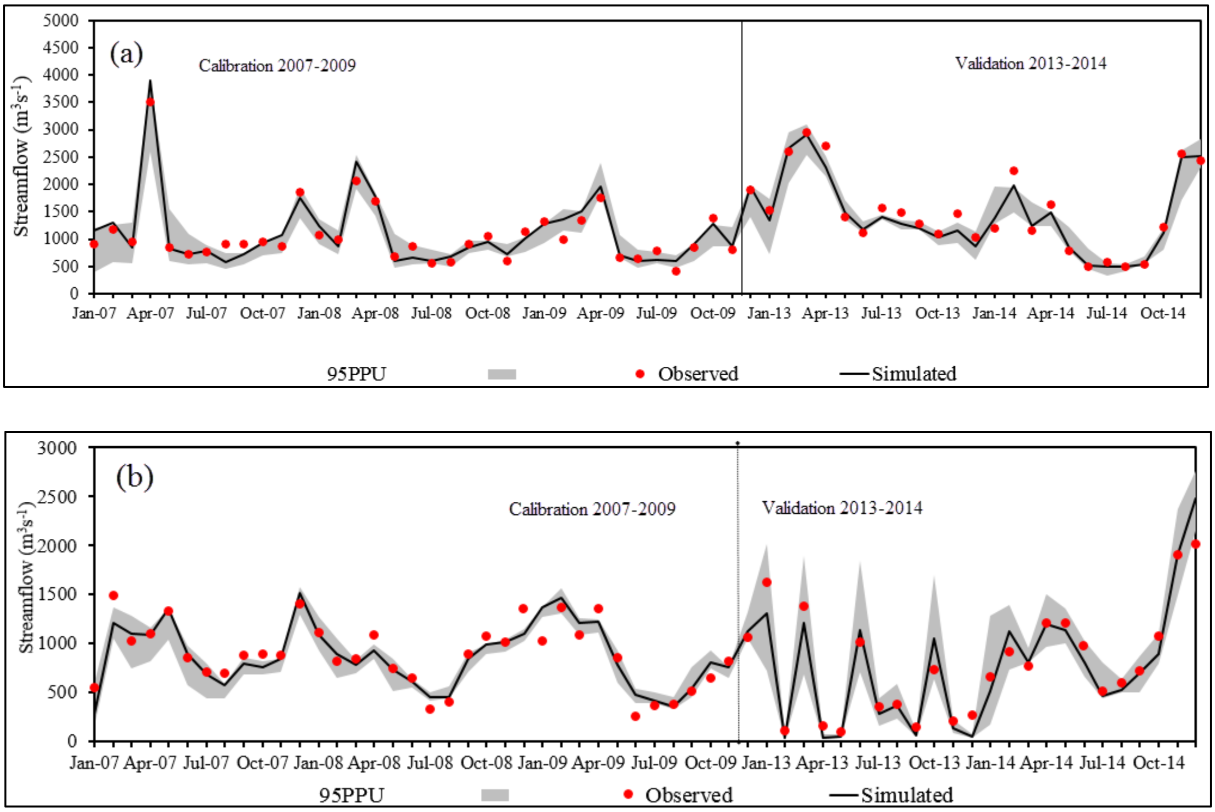

Figure 4. Observed vs. simulated streamflow and 95 % uncertainty interval (95PPU; see Abbaspour, 2015) with P factors of 0.83 and 0.76 and R factors of 0.65 and 0.69 for the (a) BH and (b) MT watersheds, respectively (defined as simulations with NSE > 0.5).

3.3 Simulated C and BFI values and the proportion of land use types in a watershed

The proportion of a particular land use type in a sub-watershed was significantly correlated with C and BFI values obtained from 48 data vectors (Table 4). C values significantly decreased as the percentage of forest cover increased (R^2 = 0.73; $p < 0.05$; Fig. 5a) and significantly increased as the percentage of plantation cover increased (R^2 = 0.74; $p < 0.05$; Fig. 5b). Low infiltration capacity in oil palm and rubber plantations was the reason for higher C values in the sub-watersheds with high proportions of ~~the~~ plantation land use. There were no significant associations between C values and any of the other land use types such as shrubland (Fig. 5c), agroforest (Fig. 5d), and dryland farming (data not shown). Some sub-watersheds had low C values despite having low levels of forest cover (e.g., BH 19). This can be explained by the fact that BH 19 had no oil palm or rubber plantations ~~and had 52 % of~~ shrubland, which will have helped in reducing the C value. Furthermore, some watersheds had 100 % forest cover but a low BFI value (e.g., MT 23). This is the only sub-watershed in the MT watershed to have a high proportion of steeper slopes (76 % of the sub-watershed), which will increase C and decrease BFI. Among the 48 sub-watersheds we considered, only two had these slope characteristics.

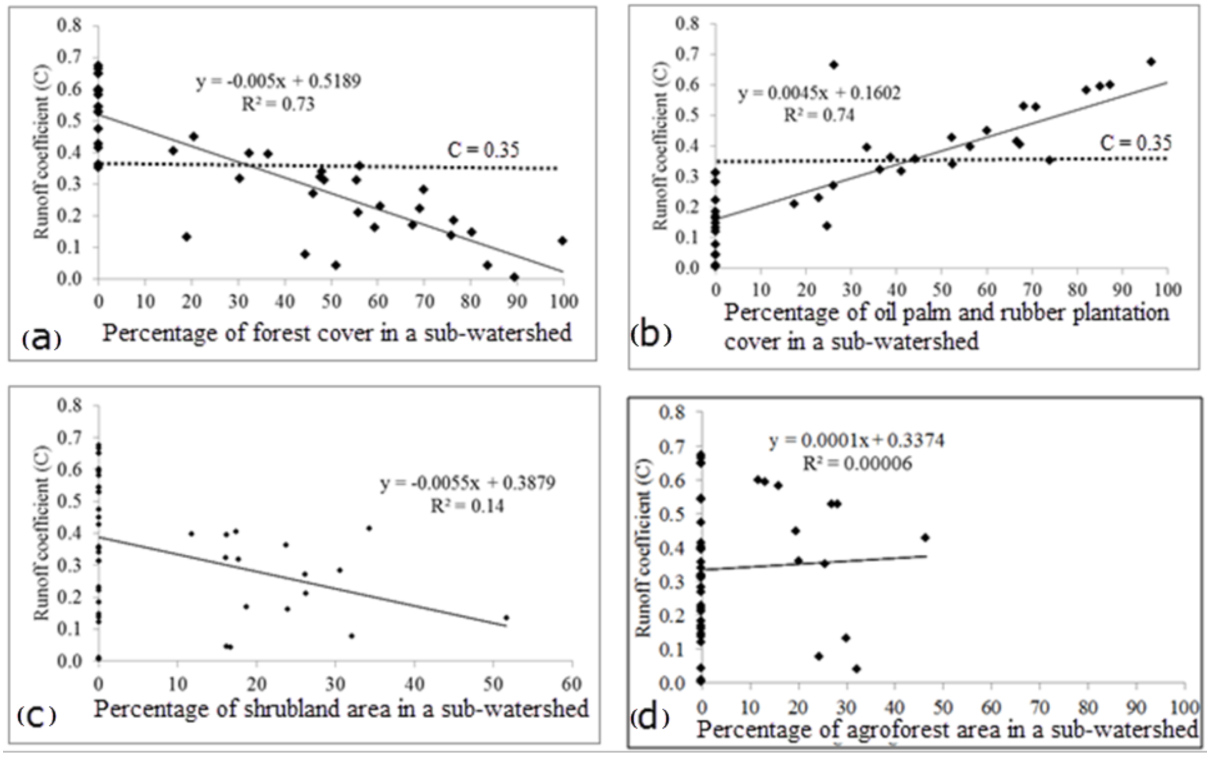

Figure 5. Association between simulated C values and the percentage of each land use type in a particular sub-watershed. Dotted lines indicate the maximum acceptable C value according to the Ministry of Forestry Decree (2013).

The Ministry of Forestry of Indonesia considers C values of <0.35 to be adequate for supporting the required ecosystem services of Indonesian watersheds (Ministry of Forestry Decree, 2013). Based on our findings, ~~at least~~ 30 % ~~of the~~ forest cover~~s~~ (Fig. 5a) and ~~no more~~ than 40 % ~~of the~~ plantation cover (Fig. 5b) are required in ~~the~~ sub-watershed to achieve the ~~required~~ C value.

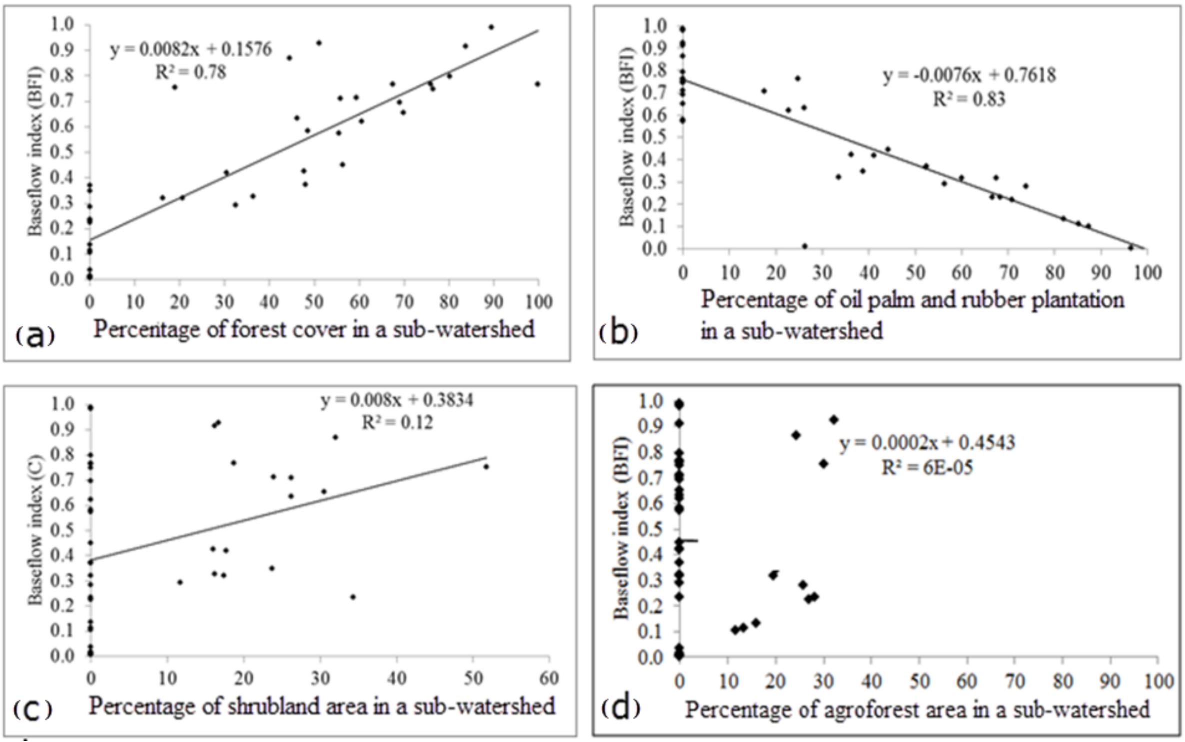

Figure 6. Association between simulated BFI values and the percentage of each land use type in a ~~particular~~ sub-watershed.

BFI values significantly increased as the percentage of forest cover increased (R^2 = 0.78; p < 0.05; Fig. 6a) and significantly decreased as the percentage of plantation cover increased (R^2 = 0.83; p < 0.05; Fig. 6b). BFI was not significantly related to any other land use types such as shrubland (Fig. 6c), agroforest (Fig. 6d), and dryland farming (data not shown).

According to Neitsch et al. (2009), the SWAT model consider~~ed~~ only shallow groundwater in ~~the~~ stream flow simulation. Therefore, we expected that ~~the~~ SWAT ~~model~~ underestimated ~~the simulated~~ BFI value in our study area. To improve the performance of the

SWAT model for deep groundwater flow (low flow) simulation, Pfannerstill et al. (2014) modified groundwater module by splitting the active groundwater storage into a fast and a slow contributing aquifer. ~~The result of this modification leads to better prediction of low flow.~~

3.4 Application of the research findings

The conversion of tropical rainforest into oil palm and rubber plantations affects the local hydrological cycle by increasing ET, decreasing infiltration, decreasing low flow levels, and increasing flooding frequency. In Jambi Province, Indonesia, forested areas have been largely transformed into plantations, resulting in inhabitants experiencing water shortages during the dry season and dramatic increases in flooding frequency during the wet season. One way in which this problem could be mitigated is by maintaining an adequate proportion of forested and plantation areas in a particular watershed, but this raises the question about what is the minimum percentage of forest area and the maximum proportion of plantation area in a watershed that will allow the maintenance of adequate water flow regulation. This study is the first to describe the quantitative association between forest and plantation areas and the flow indicators C and BFI; this understanding is required by spatial planners if they are to balance the ecology and socioeconomic functions of a landscape with the rapid expansion of plantation crops. In addition, our study provides data regarding how SWAT input parameters related to tropical plantations such as oil palm and rubber should be adjusted, particularly those that play an important role in controlling rainfall initial abstraction (e.g., CANMX), rainfall partitioning into surface runoffs (e.g., CN2, OV_N), and vertical movement of water through (e.g., SOL_BD, SOL_K, and SOL_AWC).

4 Summary

We found that ALPHA_BF, CN2, GW_DELAY, CANMX, SOL_BD, GWQMN, SOL_K, CH_N2, SOL_AWC, and OV_N were sensitive parameters in our model, some of which play an important role in controlling the initial abstraction of rainfall (e.g., CANMX), rainfall partitioning into surface runoff (e.g., CN2, OV_N), and vertical movement of water through the soil (e.g., SOL_BD, SOL_K, and SOL_AWC).

Overall, the SWAT model performance was ~~satisfactory~~, with NSE values of 0.80–0.88 (calibration) and 0.80–0.85 (validation) and PBIAS values of −2.9 to 1.2 (calibration) and 7.0–11.9 (validation). We found that the percentage of forest cover in a watershed was significantly negatively correlated with C and positively correlated with BFI, whereas the percentage of rubber and oil palm plantation cover showed the opposite pattern. Finally, our findings suggest that a watershed should contain at least 30 % forest cover and a maximum of 40 % plantation cover for maintaining sustainable water flow regulation ecosystem services.

The quantitative association between forest cover and flow indicators, which was derived in this study, will help regional planners in determining the minimum proportion of forest cover that needs to be maintained to ensure effective water flow regulation in a watershed.

5. Data availability

The land use data are freely available for research purposes upon official request to the corresponding institutions: the Digital Elevation Model with a resolution of 30 m per pixel can be obtained from the National Aeronautics and Space Agency; the rainfall and climate data can be obtained from the Meteorology and Geophysics Agency; the streamflow data of the six macro watersheds can be obtained from the Ministry of Public Works; and the land use data can be obtained from the Regional Planning office. The streamflow time series and rainfall records for the small catchments and data for the resampled soil hydraulic conductivity, bulk density, available water content and texture have been deposited by the first author at Bogor Agricultural University and in the EFForTS Database (https://efforts-is.uni-goettingen.de).

Acknowledgments

This study was performed in the framework of the joint Indonesian-German research project EFForTS-CRC 990 (http://www.uni-goettingen.de/crc990) and was funded by the Directorate General of Higher Education (DIKTI), Indonesia.

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