Sustainability of Water Quality and Ecology 8 (2016) 4–13

Contents lists available at ScienceDirect

Sustainability of Water Quality and Ecology

journal homepage: www.elsevier.com/locate/swaqe

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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ARTICLE INFO

Article history:
Received 28 February 2016
Received in revised form 8 May 2016
Accepted 14 May 2016
Available online 18 May 2016

Keywords:
Expansion of oil palm plantation
Mitigation option
Surface runoff management
SWAT model

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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http://dx.doi.org/10.1016/j.swaqe.2016.05.001
2212-6139/

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