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Impact of the Intensive Forest Management System on Runoff and Erosion Characteristics

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2013

TABLE OF CONTENTS

Chapter I
INTRODUCTION

Chapter II
SITE DESCRIPTIONS AND INTENSIVE FOREST MANAGEMENT SYSTEM

Chapter III
ESTIMATING RUNOFF USING HYDROMETEOROLOGY WATER BALANCE METHOD

Chapter IV
RUNOFF GENERATION FOLLOWING DIFFERENT DISTURBANCES OF SOIL HYDRAULIC PROPERTIES

Chapter V
RUNOFF AND SOIL EROSION CHARACTERISTICS IN DIFFERENT RECOVERY PERIODS OF THE INTENSIVE FOREST MANAGEMENT SYSTEM

Chapter VI

RUNOFF AND SUSPENDED SEDIMENT YIELD CHARACTERISTICS DURING DIFFERENT OPERATIONAL STAGES OF THE INTENSIVE FOREST MANAGEMENT SYSTEM

Chapter VII

CONCLUSIONS AND RECOMMENDATIONS

Chapter I

INTRODUCTION

1.1 Background

1.1.1 World tropical forest

Forests currently cover approximately 4 billion hectares, or 31% of Earth's land surface (FAO, 2010). Of this, the area of forest categorized by the Food and Agriculture Organization of the United Nations (FAO, 2010) as "primary forest" amounts to approximately 887 million hectares. By the mid-twentieth century, many countries had recognized that forests should be managed to produce services other than timber. Laws were enacted mandating multiple uses of forests including recreation, wildlife conservation, and water protection, in addition to traditional timber harvesting. Forests are also increasingly valued for soil protection, watershed management, protection against erosion and avalanches, and provision of biodiversity.

Almost all of the world's closed tropical forests are found in just 65 countries and cover approximately 1.66 billion hectares (Blaser *et al.*, 2011). The tropics are defined as the region centered on the equator, lying between latitudes of 23°30' N and 23°30' S, where the sun reaches a point directly overhead at least once during the solar year. From a climatological point of view, the tropical climate is defined as a non-arid climate with all 12 months having mean temperatures above 18ºC (McKnight and Hess, 2000). The flux of solar energy within this region is high because the incoming sunlight is projected at a 90° angle to the Earth's surface. This high solar energy flux results in a high rate of water evaporation over the tropical oceans and high rates of evapotranspiration over tropical land surfaces (Thomas and Baltzer, 2002). Within tropical regions, areas with relatively high precipitation harbor humid tropical forests, which possess higher levels of biological diversity and ecosystem productivity than other areas on Earth (e.g., Whitmore, 1984; Wilson, 1988).

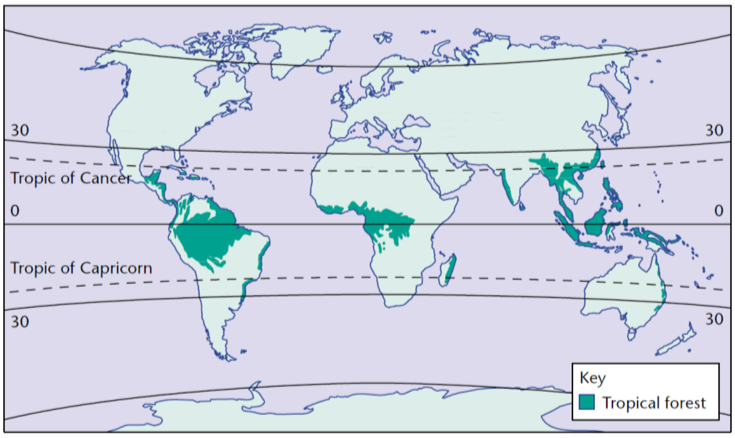

Figure 1.1 Global distribution of tropical forests (Thomas and Baltzer, 2002)

The function of tropical forests can be productive (timber, fiber, fuel wood, and non-timber forest products); environmental (climate regulation, carbon sequestration and storage, biodiversity preservation, and soil and water conservation); and social (providing subsistence or spiritual and cultural values for local populations and cultures) (Montagnini and Jordan, 2005). The roles of tropical forests in the provision of ecosystem services, such as catchment protection, biodiversity conservation, and carbon sequestration, are increasingly being recognized. Markets to facilitate payments for such services have been created in a number of countries and internationally. In recent years, the concept of “reduced emissions from deforestation and forest degradation” (REDD), which was only nascent in debates on tropical forests in 2005, has evolved to REDD+. REDD+ is part of a broader development agenda that specifically addresses the role of tropical forests in climate-change mitigation and adaptation. The term has been defined in the framework of the climate-change negotiations of the United Nations Framework Convention on Climate Change (UNFCCC) as “policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries" (UNFCCC, 2007). Since 2008, REDD+ has developed as a major new policy tool in tropical forest management and has the potential to provide substantial new and additional funding for the sustainable management of tropical forests (Blaser *et al.*, 2011). Thus, it is now generally recognized that tropical forests are important at both local and global scales. At local scales, tropical forests moderate climate and resources, whereas as regional and global levels, such forests influence climate patterns and biological diversity (e.g., Whitmore, 1984; Bruijnzeel, 1990; Eltahir & Bras, 1996; Blaser *et al.*, 2011).

1.1.2 Forest degradation

Forest degradation is a serious environmental, social, and economic problem. Forest degradation involves changes that negatively affect the characteristics of a forest such that the value and production of its goods and services decline. Such change is caused by disturbance (although not all disturbances cause degradation), which may vary in extent, severity, quality, origin, and frequency. Disturbance may be natural (e.g., that caused by fire, storm, or drought), human-induced (e.g., through harvesting, road construction, shifting cultivation, hunting, or grazing), or a combination of the two. Human-induced disturbance may be intentional (direct), such as that caused by logging or grazing, or unintentional (indirect), such as that caused by the spread of an invasive alien species (FAO, 2009).

Today, many tropical forests around the world are being managed unsustainably, generally because of the intensity of timber harvesting and the lack of adequate techniques to preserve sustainability. For example, insufficient measures may be in place to preserve ecosystem structure and function, and to ensure the ability of forests to regenerate desirable tree species. However, many management systems have been designed to avoid damage to the forest structure and to maintain forests. Natural forest management has been defined as "controlled and regulated harvesting, combined with silvicultural and protective measures, to sustain or increase the commercial value of future stands, all relying on natural regeneration of native species" (Schmidt, 1991). Sustainable forest management (SFM) is the management of natural forests so as to minimize the problems associated with timber extraction. SFM aims to maintain the productivity of forests for timber and other human needs, through the preservation of soil fertility and hydrological stability (Montagnini and Jordan, 2005).

One of the common forms of land-use change in humid tropical regions is the clearance of ground vegetation in association with timber harvesting, agricultural cultivation, mining, residential, and recreational development (Bruijnzeel & Critchley, 1994; Fox *et al.*, 1995). The presence of soil erosion in forests is a prime indicator of forest degradation. Soil erosion can have major impacts on a range of forest services: it reduces water quality, pollutes watersheds with nutrients and sediments, and is an indicator and cause of reduced soil fertility (potentially, therefore, reducing forest productivity). In an extreme form, soil erosion can also restrict access to the forest and hinder the extraction of products such as timber (FAO, 2011). Land-surface modification that involves the removal of vegetation cover severely alters near-surface hydrologic processes and accelerates surface erosion (e.g., Lal, 1990), potentially resulting in a variety of on- and off-site consequences such as reduced site productivity, the degradation of downstream water/habitat quality, and changes in channel morphology (Lyons & Beschta, 1983; Campbell & Doeg, 1989; Iwata *et al.*, 2003).

Among landscape features, roads are considered to have a substantial influence on hydrological processes and sediment export in managed mountainous forests in the tropics (Bruijnzeel & Critchley, 1994; Ziegler & Giambelluca, 1997; Ziegler *et al.*, 2000; Sidle *et al.*, 2004). Furthermore, roads tend to lead to the further encroachment of human influences into pristine forest areas, putting increasing demands on land and resources (Myers, 1994; Fox *et al.*, 1995).

There is also an increasing recognition that headwater ecosystems are ecologically unique within riverine landscapes and play important roles as sources of water, solutes, organic matter, and sediment, with potentially far-reaching influences on ecosystem processes downstream (Gomi *et al.*, 2002; Lowe & Likens, 2005). Thus, appropriate land management practices must be developed to conserve the unique and crucial processes of headwater ecosystems. However, there still exists a large gap in our understanding of which catchment processes maintain ecosystem integrity and are integral for land-use planning in tropical regions (Bruijnzeel, 1993; Gomi *et al.*, 2002).

One of the most common approaches in the study of hydrology and nutrient export, and in evaluating the response of natural systems to various human activities within headwater areas, is catchment outlet monitoring with a paired-catchment design (Brown *et al*., 2005). Investigations using such study designs have advanced our knowledge of catchment hydrology and nutrient budgets in relatively undisturbed systems, and have elucidated the response and recovery of catchment processes to various levels and types of human activities in temperate regions (e.g., Beschta, 1978; Grant & Wolff, 1991; Jones and Grant, 1996; Brown *et al*., 2005). Similar approaches are becoming increasingly common in tropical environments, providing better understandings of undisturbed forested ecosystems as well as managed forests. The results are generally consistent with those from temperate regions, including findings of the altered export of sediments, solutes, and hydrological fluxes following catchment disturbance (e.g., Abdulhadi *et al.*, 1981; Bosh and Hewlett, 1982; Douglas *et al.*, 1992; Van Der Plas and Bruijnzeel, 1993; Baharudin and Abdul Rahim, 1994; Grip *et al.*, 1994; Malmer & Grip, 1994; Stednick, 1996; Fujieda *et al.*, 1997; Williams & Melack, 1997; Watson *et al.*, 2001; Chappell *et al.*, 2004; Brown *et al.*, 2005; Ziegler *et al.*, 2006; Chaves *et al.*, 2008; Zimmermann, 2012).

1.1.3 Indonesian tropical forest

Estimates of the area of forests in Indonesia, including plantation forests, range from 94.4 million hectares to 98.5 million hectares (FAO, 2010). Mixed hill forests account for about 65% of the natural forests and are the most important for timber production. However, loss of forest has occurred at a rapid rate during the last 40 years, with the FAO (2010) estimating that forest cover declined by 3.42 million hectares between 2005 and 2010 and by 24.1 million hectares between 1990 and 2010.

Indonesian cutting systems have changed over the years. The first cutting system, termed the Indonesian Selective Cutting (or Tebang Pilih Indonesia, TPI), was introduced in 1972. The TPI system then evolved into the Indonesia Selective Cutting and Planting System (Tabang Pilih dan Tanam Indonesia, TPTI), which was first implemented in 1989. In the TPTI system, harvesting is allowed only for commercial trees species of a certain diameter, i.e., 50 cm for "full production forests" and 60 cm for "limited production forests." In addition, the length of cutting cycle is 35 years, which was designated based on the assumption that the diameter increment of commercial tree species is 1 cm per year and the volume increment is at least 1 m^3 ha^{-1} per year (Suhendang, 2002; Van Gardingen *et al.*, 2003). The TPTI system mandates replanting of the entire open forest area including the log-landing area, logging-road buffer, and ex-cutting area. Forest growth depends on the growth of natural regeneration. In the next harvesting periods, however, forest productivity has been found to decrease compared with the first harvesting period, and TPTI has been shown to be unsuccessful in restoring forest productivity in subsequent harvesting periods (Sianturi and Kanninen, 2005). In order to achieve SFM and sustained forest productivity, the Indonesian government has introduced a modified TPTI system, known as Selective Cutting and Intensive Line Planting (Tebang Pilih dan Tanam Jalur, TPTJ) or as the Intensive Forest Management System (IFMS), which was officially implemented as practice in 2002. The main activity of the IFMS is selective logging for timber harvesting and intensive rehabilitation with line planting to enrich the standing stock (Suryatmojo *et al*., 2011a). The IFMS system is a modified TPTI with focus on intensive rehabilitation after selective logging in order to increase the forest productivity in the next harvesting periods. Timber harvesting involves logging road construction, tree cutting, log skidding on skid trails, log hauling to log yards, and log or worker transportation. Intensive rehabilitation involves line clearing and intensive line planting. Although the IFMS can potentially increase forest productivity through intensive rehabilitation, the intensive line planting technique it uses increases the area of open forest compared with the TPTI system.

Vegetation cover change has a profound influence on the hydrological cycle. A reduction in vegetative cover from forest harvesting generally increases the average surface runoff volume and total water yield for a given area of land. In addition to the activities of timber harvesting described above, timber extraction involves the use of heavy machinery that can destroy the soil structure, thereby influencing water and nutrient cycling and accelerating soil erosion rates (Nussbaum and Hoe, 1996). The heavy machinery used in timber collection areas and on skidder roads has been shown to increase soil compaction by up to 40% compared to natural conditions (Nussbaum and Hoe, 1996; Nussbaum *et al.*, 1996). Furthermore, 10–30% of the soil surface may become bare due to logging roads, skidder tracks, and log landings (Bruijnzeel, 1992; Van Der Plas and Bruijnzeel, 1993). The use of heavy equipment tends to compact topsoil, setting in motion a negative spiral of reduced infiltrability and an increased frequency of overland flow and sheet erosion, thereby hindering the establishment of a new protective layer of vegetation and litter (Van Der Plas and Bruijnzeel, 1993). Different land-use practices also affect soil infiltration rates in different ways, depending on how they impact the intrinsic properties of a specific soil (Osuji *et al.*, 2010).

Forest cover reduction and surface soil disturbance increase changes in hydrologic response; in particular, they increase runoff and soil erosion. Several studies have investigated the rainfall–runoff–erosion cycle in Kalimantan, Indonesia (Standtmueller, 1990; Hartanto *et al.*, 2003; Ruslan and Manan, 1980; Suryatmojo *et al.*, 2011a). However, research concerning the hydrologic response to the IFMS in tropical Indonesian rainforests is still limited (Suryatmojo *et al.*, 2011b). Investigation is needed to clarify the hydrologic response of tropical rainforests managed using the IFMS.

When IFMS treatments are implemented in headwater areas, it is important to understand the heterogeneity of processes within a catchment, and thus, the vulnerability of different areas to land disturbance. It is also important to prioritize such areas for specific land development as needed. Currently, such knowledge is extremely scarce for tropical regions, hindering the formulation of guidelines that could promote more sustainable development. The present work attempts to extend our understanding in this regard.

1.2 Objectives of the research

In the context of the issues discussed above, this research addresses fundamental issues related to the implementation of the IFMS in terms of runoff and erosion in a tropical rainforest in Indonesia. The objectives of this study are as follows:

1. To investigate runoff characteristics in a tropical rainforest using a hydrometeorology water balance method. Water balance analysis was conducted in order to simulate hydrological processes and estimate runoff using a meteorological data series.
2. To investigate the runoff generation processes caused by IFMS-induced disturbances in soil hydraulic properties. Field experiments and laboratory analysis were conducted to determine related changes in infiltration capacity, soil compaction, and hydraulic conductivity. A numerical simulation model using saturated hydraulic conductivity was employed to generate the surface runoff.
3. To investigate the runoff and soil erosion characteristics in different recovery periods of the IFMS. For this, field experiments were conducted in small catchments to identify and compare recovery processes and vegetation regrowth following catchment disturbance in the form of runoff and soil erosion.
4. To investigate the runoff and suspended sediment yield characteristics of different operational stages of the IFMS. Field experiments were conducted in small paired catchments to identify and compare the runoff and suspended sediment yield following operational periods of the IFMS.

1.3 Thesis outline

The thesis is composed of seven chapters, designed to address the three objectives listed above. Synopses of each chapter follow:

Chapter 1 describes the status of tropical forests in Indonesia. Sustainable forest management is shown to be an important issue in anticipating threats to forest degradation, and changes in forest management systems of Indonesia are described. The problem statement and objectives of research are also presented.

Chapter 2 describes the study site, site plots, and catchment experiment sites within the study site, and describes the implementation of the IFMS.

Chapter 3 examines the water balance parameters needed to estimate runoff characteristics. The purpose of this study is to determine the status of the water balance in an Indonesian tropical rainforest and to estimate the monthly runoff.

Chapter 4 examines the variation in hydraulic properties of forest soils in terms of infiltration capacity, soil compaction, and soil hydraulic conductivity, in relation to different surface disturbances and estimates of runoff generation process. Surface runoff flow generation is numerically simulated using saturated hydraulic conductivity.

Chapter 5 examines the runoff and soil erosion in different recovery periods of the IFMS in small catchments. The purpose of this experiment was to investigate the impact of runoff and soil erosion characteristics in different recovery periods of the IFMS resulting from their respective forestry treatments.

Chapter 6 examines the runoff and suspended sediment yields in different operational stages of the IFMS in paired catchments. The purpose of this experiment was to determine the changes in runoff and suspended sediment yield during different operational periods of the IFMS using different rehabilitation techniques.

Chapter 7 provides the conclusions and future research perspectives.

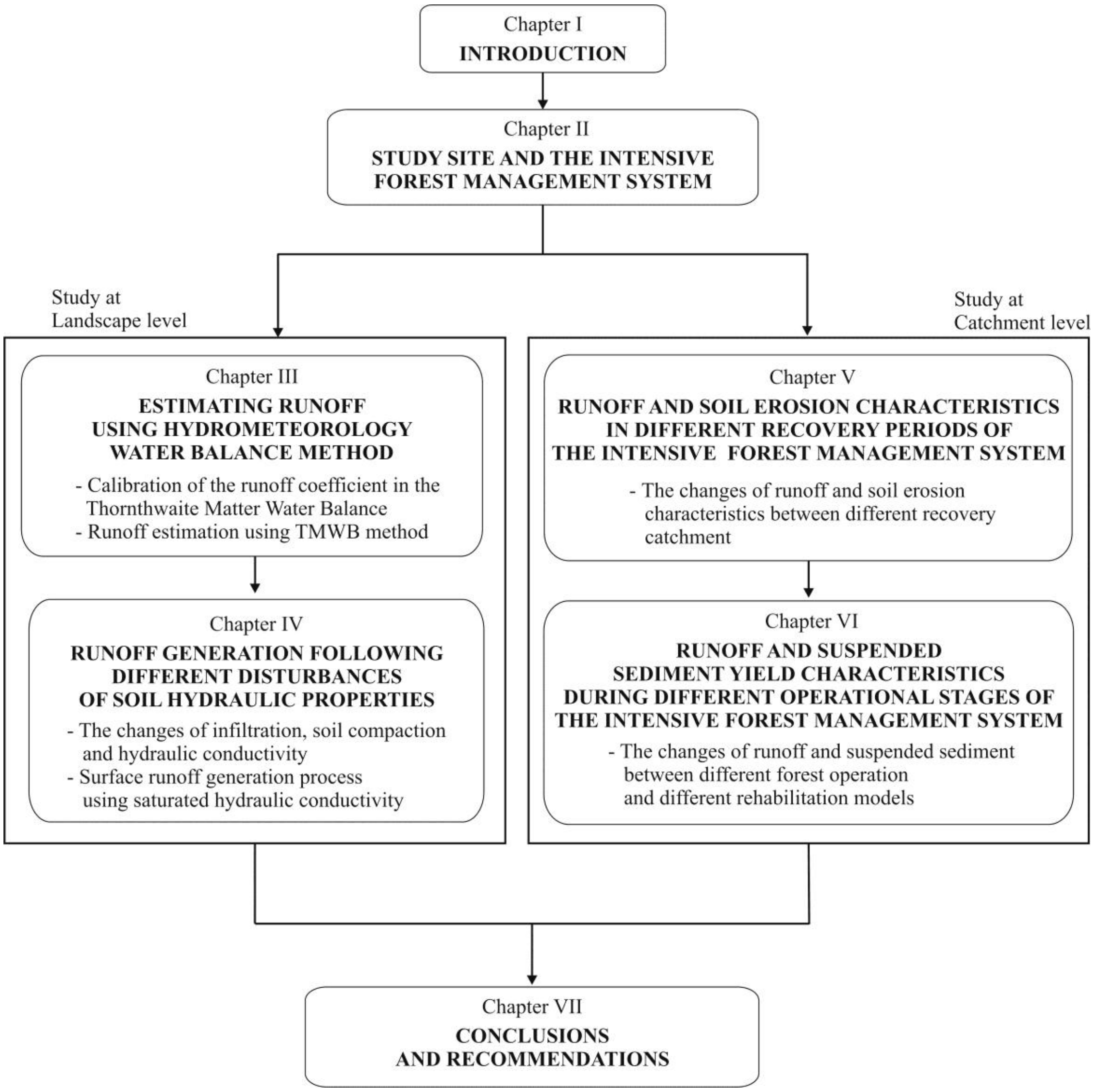

Figure 1.2 Structure of this study

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Chapter II

SITE DESCRIPTIONS AND INTENSIVE FOREST MANAGEMENT SYSTEM

2.1 Study site

All the work described in the following chapters was conducted in tropical rainforests at Bukit Baka Experimental Catchments, Central Kalimantan, Indonesia. The study site was located in the headwater region of the Katingan watershed, one of the largest in Central Kalimantan (Figure 2.1). The site is in the Sei Seruyan block of the Sari Bumi Kusuma (SBK) concession area, a private forest company (00º36’–01º10’S, 111º39’–112º25’E) located in the lowland part of Bukit Baka hills (Figure 2.2). This location is part of a high-biodiversity area known as the “Heart of Borneo.”

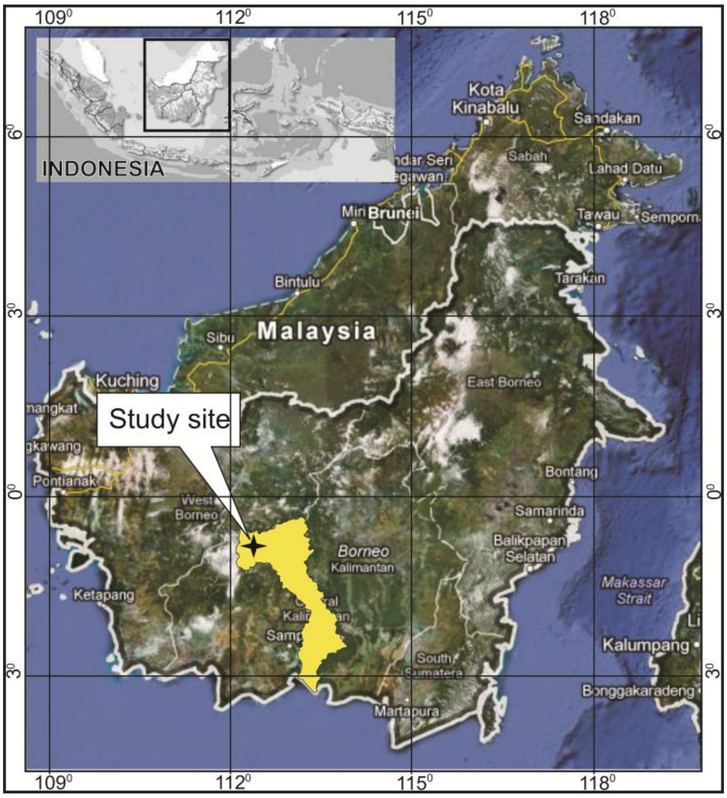


Figure 2.1 Study site in the headwater of Katingan watershed, Central Kalimantan.

The Katingan watershed has a total catchment area of 1,908,297 ha, and the length of the main river is 650 km. This location is approximately 400 km northwest of Palangka Raya, the provincial capital of Central Kalimantan, and approximately 500 km east of Pontianak, the provincial capital of West Kalimantan. The forest cover in this watershed includes 1,179,985 ha or 61.83% of the total area, most of which is found in the headwaters. This upstream catchment is a hilly region with altitudes from 150 to 1278 m above sea level (Figure 2.2).

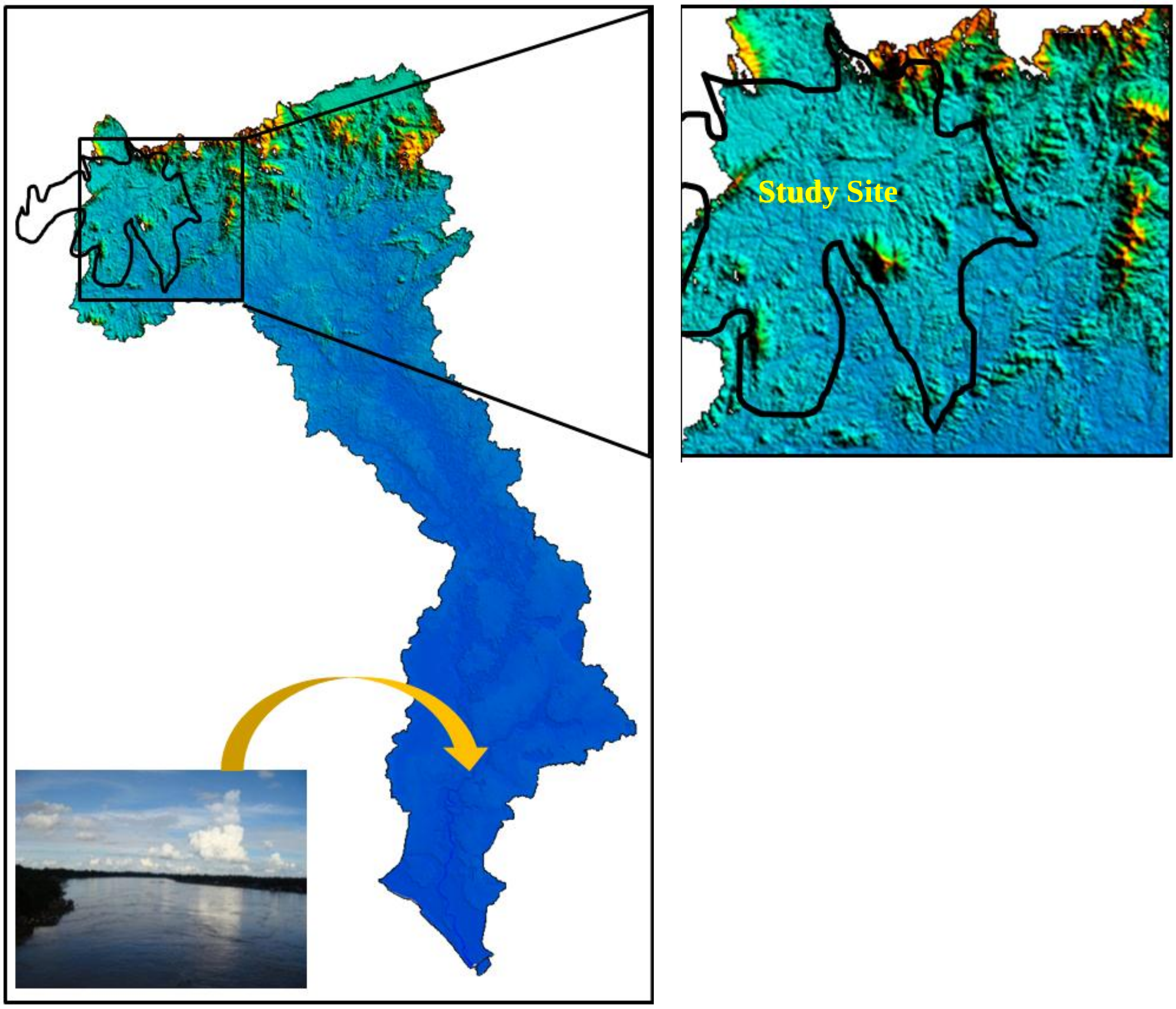


Figure 2.2 Study site at the Bukit Baka Experimental Catchments in the Sari Bumi Kusuma forest concession area (black-line border) located in the lowland part of Baka hills.

The mean annual rainfall from 2001 to 2012 was 3631 mm (Figure 2.4), with the highest average monthly precipitation (353 mm) occurring in November. The lowest average monthly precipitation (209 mm) was recorded in August (Figure 2.3). According to the forest climate classification system of Schmidt and Ferguson (1951), the area is a type A (very wet) tropical rainforest (monthly average rainfall > 100 mm). Since the location is between 5°N and 5°S, the study site is also classified as having an equatorial climate (Tan, 2008), which is generally characterized by high precipitation and high temperatures throughout the year.

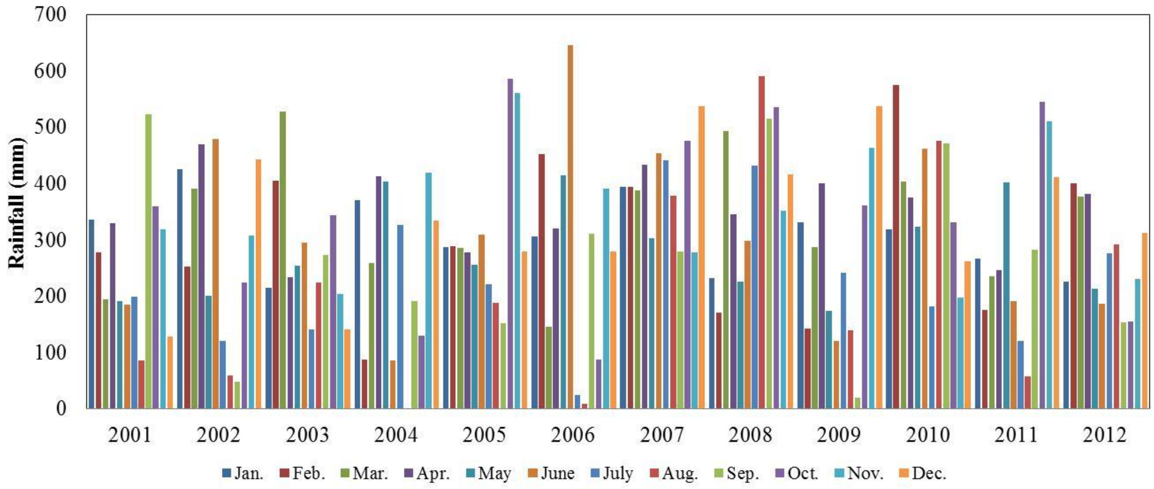


Figure 2.3 Monthly rainfall from 2001 to 2012.

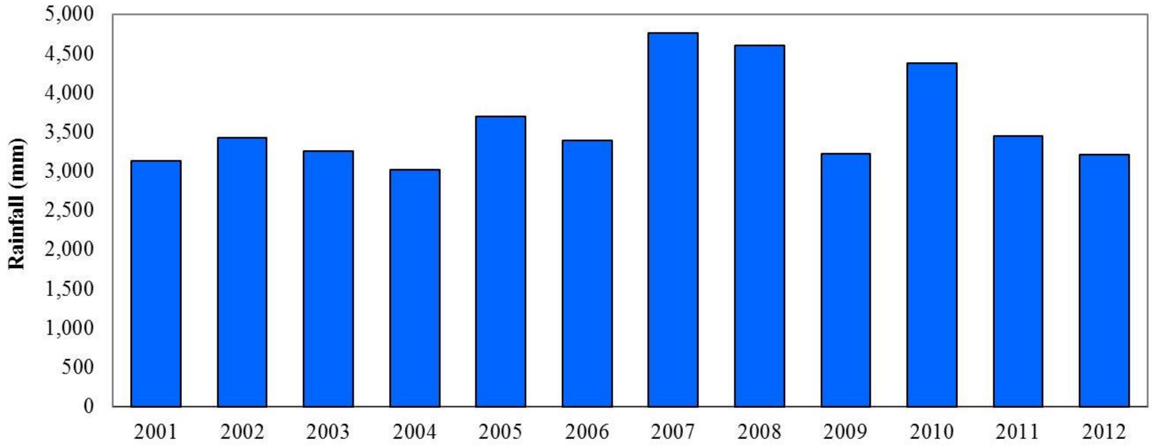


Figure 2.4 Annual rainfall from 2001 to 2012.

The number of rainy days varies from 95 to 112 days, and the mean temperature ranges from 30ºC to 33ºC at noon to between 22ºC and 28ºC at night. Average relative humidity ranges from 85% to 95% (Suryatmojo *et al.*, 2011). In terms of variation in temperature with increased elevation, the study site is categorized as a tropical lowland zone (Mohr, 1944).

Based on the map of Forest Type Classification, the study site is classified as being located in the tropical rainforest and is characterized as having similar forest vegetation to this classification in terms of structure and species distribution. Tropical rainforests exist in the constantly wet areas of humid tropics and are generally characterized by evergreen forms of vegetation (Tan, 2008). Tropical rainforests often form three distinctive layers of canopies. The highest canopy is formed by very tall trees, often from 40 to 60 m high, towering into the sky as rather isolated or widely spaced trees above the second layer of rainforest. The second layer is composed of 20–30-m-tall trees that grow closer together, yielding a dense canopy much like a roof. Below this second level, a third level exists, consisting of small young trees growing among a population of a variety of shrubs and other types of ground vegetation. The vegetation in Kalimatan is dominated by *Shorea* spp., *Eugenia* spp., *Eusideroxylon zwageri*, *Shorea laevis*, *Calophyllum inophyllum*, *Litsea firma*, *Anthocephalus chinensis*, *Macaranga hypoleuca*, *Durio lissocarpus*, and *Octomeles sumatrana*. The average number of trees in this natural forest is 228 per hectare (Suryatmojo *et al*., 2011).

Based on systematic geological map, the research site dominantly located in the geological type of Pinoh Metamorphics with muscovite-quartz schist, phyllite, slate, kornfels, and some metatuff and quartzite, as well as occasional andalusite, cordierite, and biotite, with rare deposits of silimanite and garnet. The soil in the region is classified as Ultisol and remains continuously moist (Widiyatno *et al*., 2010). This group of soils was previously called red–yellow podzolic soils. These red–yellow podzols appear to be more widely distributed in Indonesia and are a major soil in the lowland area of Kalimantan. Ultisols are derived from acid parent materials. In Kalimantan, the parent materials are also acidic in nature, but the difference is that they are not of recent volcanic origin. Granites, tertiary calcareous materials, shales, sandstone, and other tertiary sediments containing quartz can be found and contribute to formation of the red–yellow podzolic soils in Kalimantan (Supraptohardjo, 1961).

Ultisols are the most weathered type of soil in the region and show the ultimate effects of leaching. Ultisols are characterized as mineral soils with a B2 horizon containing 20% more clay than the upper B1 horizon.

2.2 Intensive Forest Management System (IFMS)

The IFMS is a new forest management system for tropical Indonesian forests that was officially implemented in 2002. The main activities are timber harvesting using a selective logging method and forest rehabilitation with intensive line planting. Timber harvesting involves logging road construction, tree cutting, log skidding on skid trails, log hauling to log yards, and transportation of logs.

In the IFMS phase of timber harvesting, several additional logging road system controls are imposed to minimize the impact of logging roads. This includes the alignment of logging roads along the contour and proper drainage for road surface runoff. Selective logging is carried out by the typical current commercial logging practices with cutting regimes of 40 cm diameter at breast height (DBH) for commercial dipterocarp and non-dipterocarp timber. A stricter cutting regime coupled with several additional selective logging controls is imposed to minimize the reduced impact logging on skid trails. This includes the alignment of skid trails along the contour, construction of cross-drains at 45–60° along the skid trails, and skid trail deactivation at the end of the skid trail line. Furthermore, no logging is allowed within a buffer area of at least 20 m on both sides of perennial streams.

Logging operations generally involve tree felling and bucking with chainsaws, upslope skidding of logs using crawler tractors, and the transportation of logs with logging trucks. Timber extraction using heavy machines destroys soil structure, which plays an important role in water and nutrient cycling, and accelerates soil erosion rates (Nussbaum and Hoe, 1996). Heavy machines in timber collection areas and on skidder roads increase soil compaction by up to 40% over natural conditions (Nussbaum and Hoe, 1996; Nussbaum *et al*., 1996), and 10%–30% of the soil surface may become bare due to logging roads, skidder tracks, and log landings (Bruijnzeel, 1992; Van Der Plas and Bruijnzeel, 1993). The damage to vegetation and soil caused by selective logging, logging roads, and skidder tractors are shown in Figures 2.5 and 2.6.

Figure 2.5 Selective cutting activities have left open areas due to tree felling and skidding using skidder tractors. High surface disturbance has further altered the hydrological process in the catchments.

The use of heavy equipment tends to compact topsoil, setting in motion a destructive cycle of reduced soil infiltrability and increased frequencies of overland flow and sheet erosion, thereby hindering the establishment of a new protective layer of vegetation and litter (Van Der Plas and Bruijnzeel, 1993). Different land-use practices affect soil infiltration rates in different ways depending on their effects on the intrinsic properties of the specific soil (Osuji *et al*., 2010).

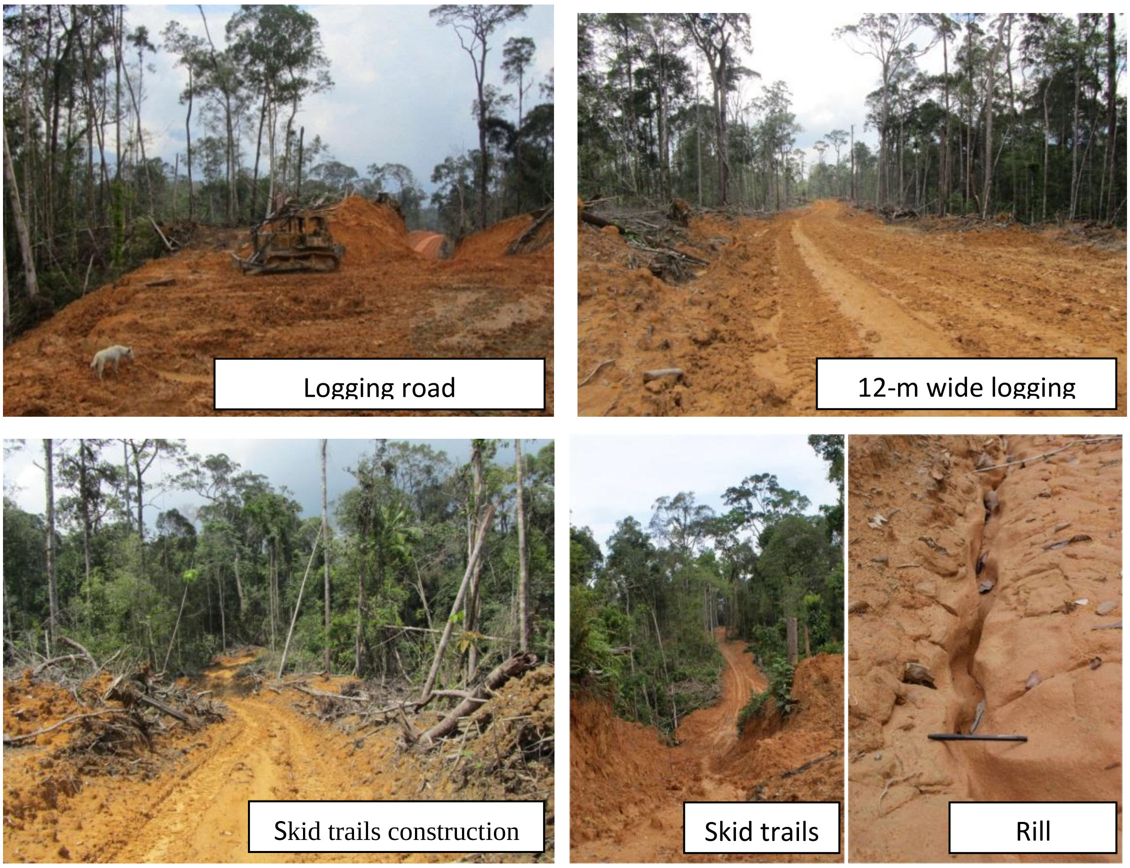


Figure 2.6 Soil destruction due to logging road and skid trail construction. Soil compaction potentially changes the hydraulic properties of forest soil and produces soil erosion.

The IFMS phase after selective logging is forest rehabilitation with intensive line planting. Intensive line planting involves line clearing and line rehabilitation. About 15%–20% of the forest area is a clear-cut line to enrich the standing stock using an intensive strip-line planting system (Figure 2.7). About 200 seeds per hectare are typically planted, and the expected standing stock at the end of rotation (30 years) is approximately 400 m^3 per hectare, assuming 160 trees per hectare with an average diameter of 50 cm (or 2.5 m^3 per tree; Na'iem and Faridah, 2006).

Selective logging and line clearing for intensive strip-line planting have increased the open area in forests and decreased forest canopy cover. Changes in forest canopy cover by the IFMS process are shown in Figure 2.8.

Figure 2.7 Land preparation processes for intensive line planting; it begins with determining the line direction (north–south or east–west), followed by manual land clearing and horizontal openings to prepare intensive planting.

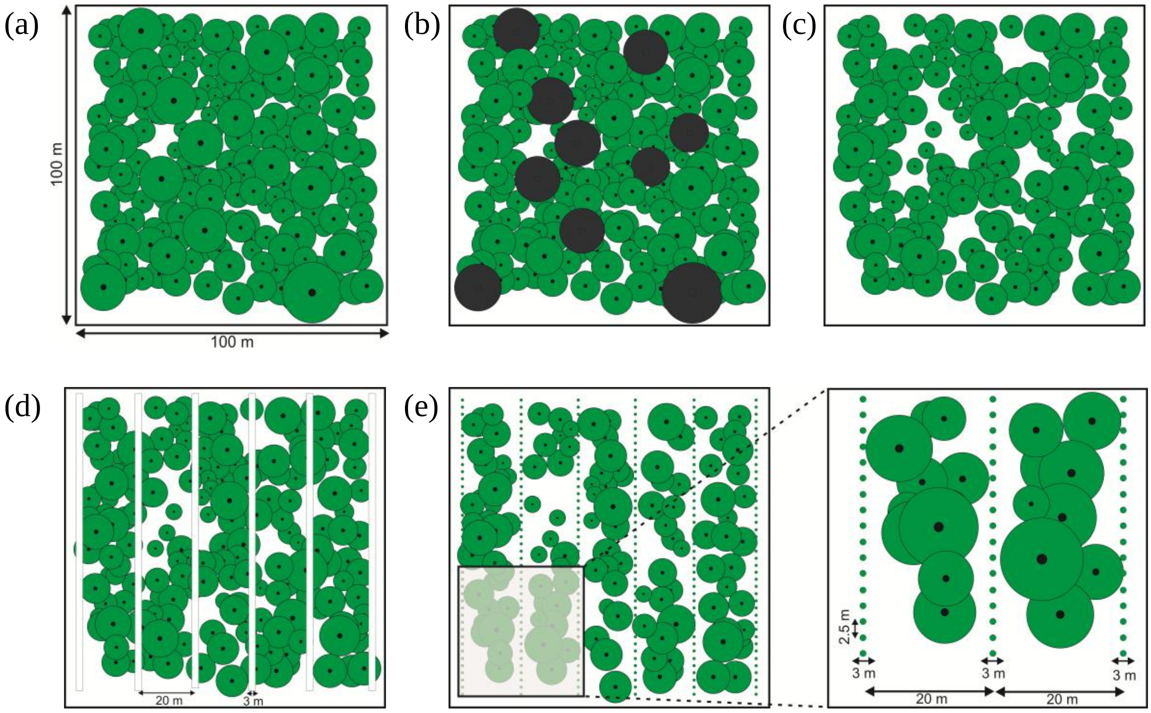


Figure 2.8 Changes in tree canopy cover due to the IFMS process: (a) natural forest, (b) trees selected for logging (denoted as black circle), (c) canopy cover after selective logging, (d) design of a clear-cutting line, and (e) canopy cover after the IFMS.

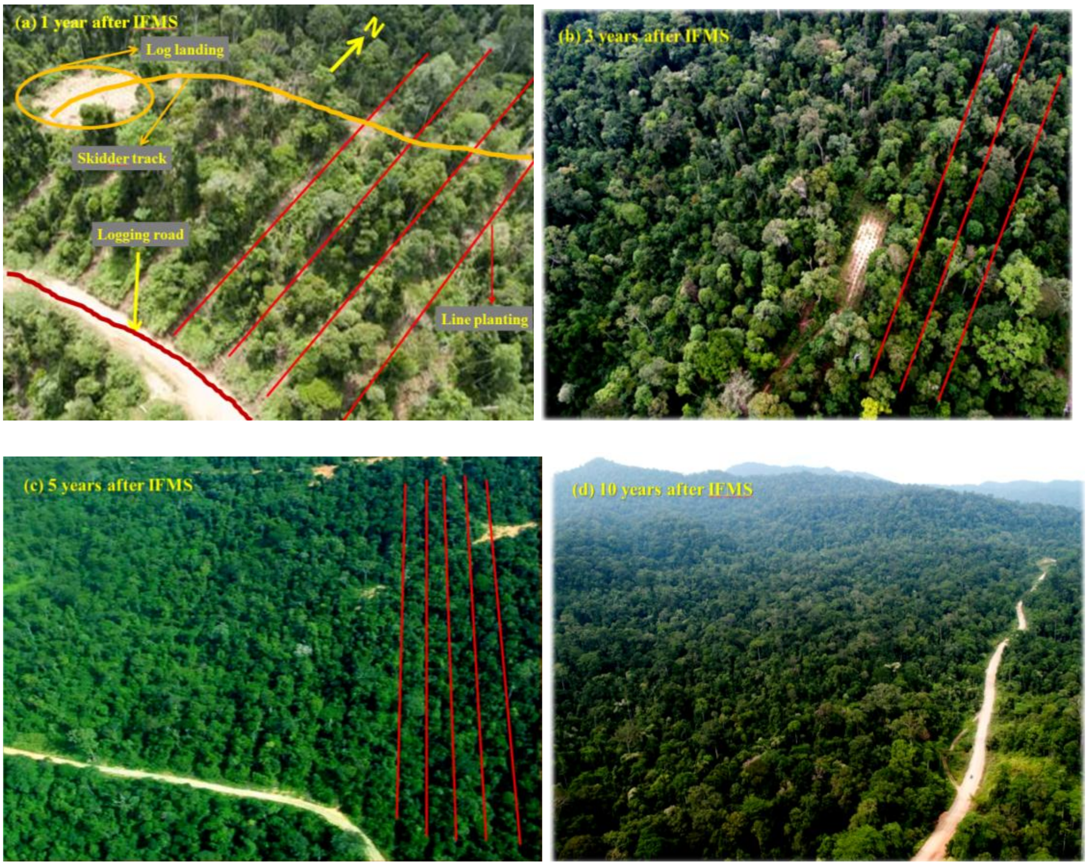


Figure 2.9 Canopy cover recovery after different periods following IFMS: (a) after 1 year, (b) after 3 years, (c) after 5 years, and (d) after 10 years (canopy cover has recovered to nearly natural conditions).

Figure 2.9 shows that after IFMS treatments, that the canopy has opened up dramatically in a large area, but that 10 years following IFMS treatment, the canopy cover seemed to recover to pretreatment levels. Land-use change in a catchment may lead to changes in its water balance. The response time of stream flow is generally determined by climate (mostly rainfall), vegetation characteristics, catchment properties, and vegetation management practices (Alice *et al*., 2005). The forest canopy serves as a barrier against precipitation reaching the ground. Selective logging activity using tractors has opened and destroyed approximately 4%–6% of the soil surface in the forested area by creating skid trails and a further 60%–75% by pulling logs using a tractor winch. Manual land clearing for intensive line planting has opened the canopy of approximately 15%–20% of the forested area in the study catchment.

To clarify the changes in vegetation structure due to IFMS activities, a permanent sample plot (PSP) was established for each IFMS period and in the virgin forest. PSP is a long term observation site of forest growth, for measuring diameter increment, volume increment and stand structure dynamics. PSP use 1 hectare square of forest area and located in the middle slope of each catchment. In the PSP, forest vegetation was measured using a nested cover quadrats method. Each type of vegetation measured at 25 subplots (total in 1 hectare). The subplot is classified into 4 types: 20 x 20 m for tree; 10 x 10 m for pole; 5 x 5 m for sapling; and 2 x 2 m for seedling. The tree canopy cover was calculated using a conversion equation from tree diameter to canopy area for each species (Tabel 2.1). To understand the changes in tree canopy cover, the vertical projection of the canopy in each PSP was determined as shown in Figures 2.10 and 2.11.

Table 2.1. Vegetation structure in the natural forest (virgin forest) and in the 10 different IFMS periods within the PSP area.

Plot site*	Individual amount per-hectare (N/ha)			
(years after IFMS treatment)	Tree[a]	Pole[b*]	Sapling[c*]	Seedling[d*]
Virgin Forest	212	208	1,027	690
2008 (1-year)	113	152	3,226	18,433
2007 (2-year)	85	202	3,472	13,900
2006 (3-year)	153	363	1,888	10,700
2005 (4-year)	141	521	1,851	8,267
2004 (5-year)	163	349	1,931	13,900
2003 (6-year)	152	192	1,568	8,650
2002 (7-year)	150	209	1,648	13,400
2001 (8-year)	134	173	1,973	7,900
2000 (9-year)	150	208	2,245	9,333
1999 (10-year)	153	181	1,472	8,600

*Measurements conducted in 2010

[a] Tree is vegetation with diameter >20 cm (at 1.3 m above the land surface)

[b] Pole is vegetation with a 10–20 cm diameter

[c] Sapling is vegetation with a <10 cm diameter and >1.5 m height

[d] Seedling is vegetation with a height <1.5 m

[*] The number of poles, saplings and seedlings calculated from the extrapolated of 25 subplots.

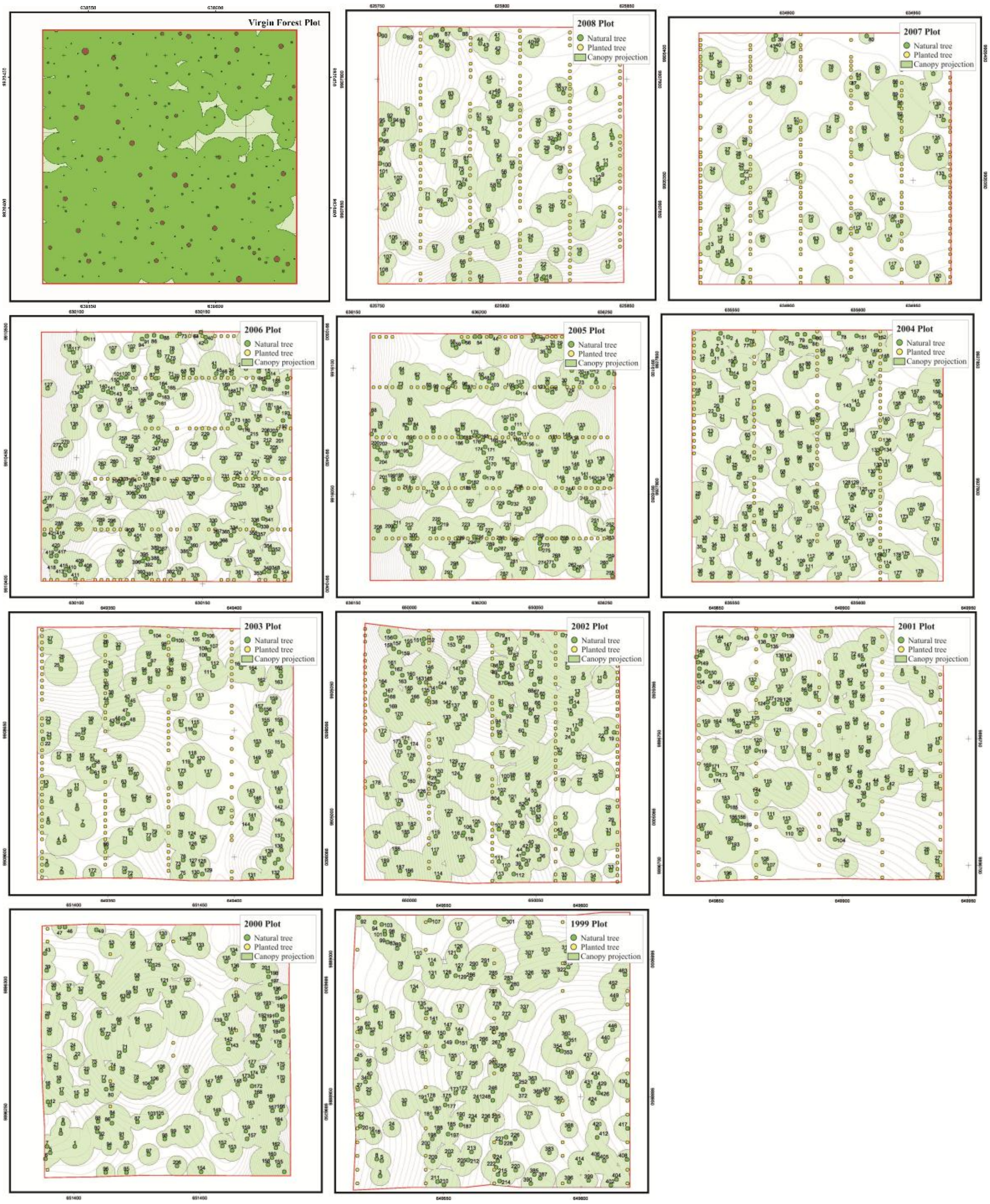


Figure 2.10 Horizontal projection of tree canopy cover density in the natural forest (virgin forest) and in the 10 different IFMS periods within the PSP area.

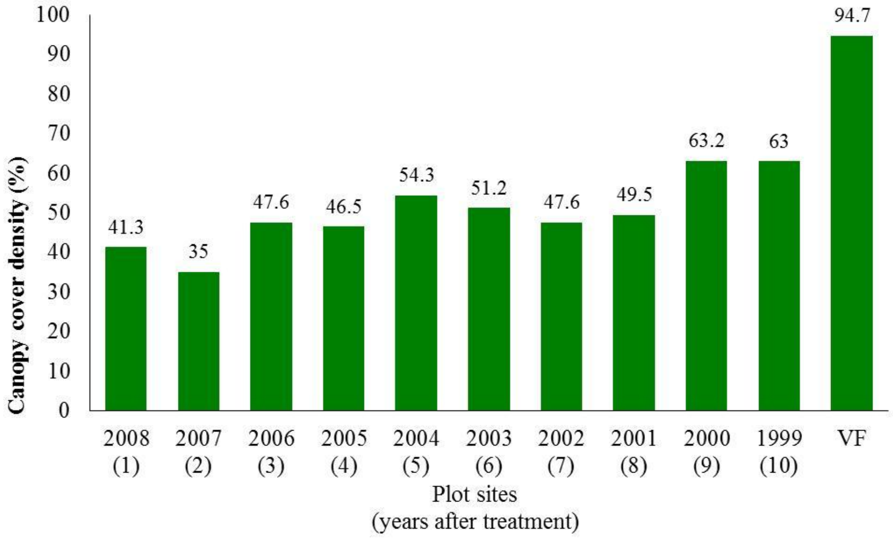


Figure 2.11 Average tree canopy cover density in the natural forest (VF) and in the 10 different IFMS periods within the PSP area.

These results indicated that selective logging and clear cutting lines in the IFMS have increased the canopy openness, potentially encouraging the growth of light-seeking understory vegetation.

2.3 Experiment sites

In the study site of the SBK concession area, several experimental sites were established to study the hydrologic responses to IFMS. Eleven experimental plots were established to represent the different periods of IFMS to investigate the changes in soil hydraulic properties located inside the PSP area (Figure 2.12).

Three catchment experiments were conducted for the long-term monitoring of catchment hydrology and sediment export based on outlet measurements to evaluate catchment hydrological responses and sediment budgets in different IFMS periods.

Three paired catchment experiments were used to monitor the catchment hydrology responses for each period of IFMS treatments, and determine the difference in responses between standard IFMS and modified IFMS. All experimental sites were scattered across the study site as shown in Figure 2.12.

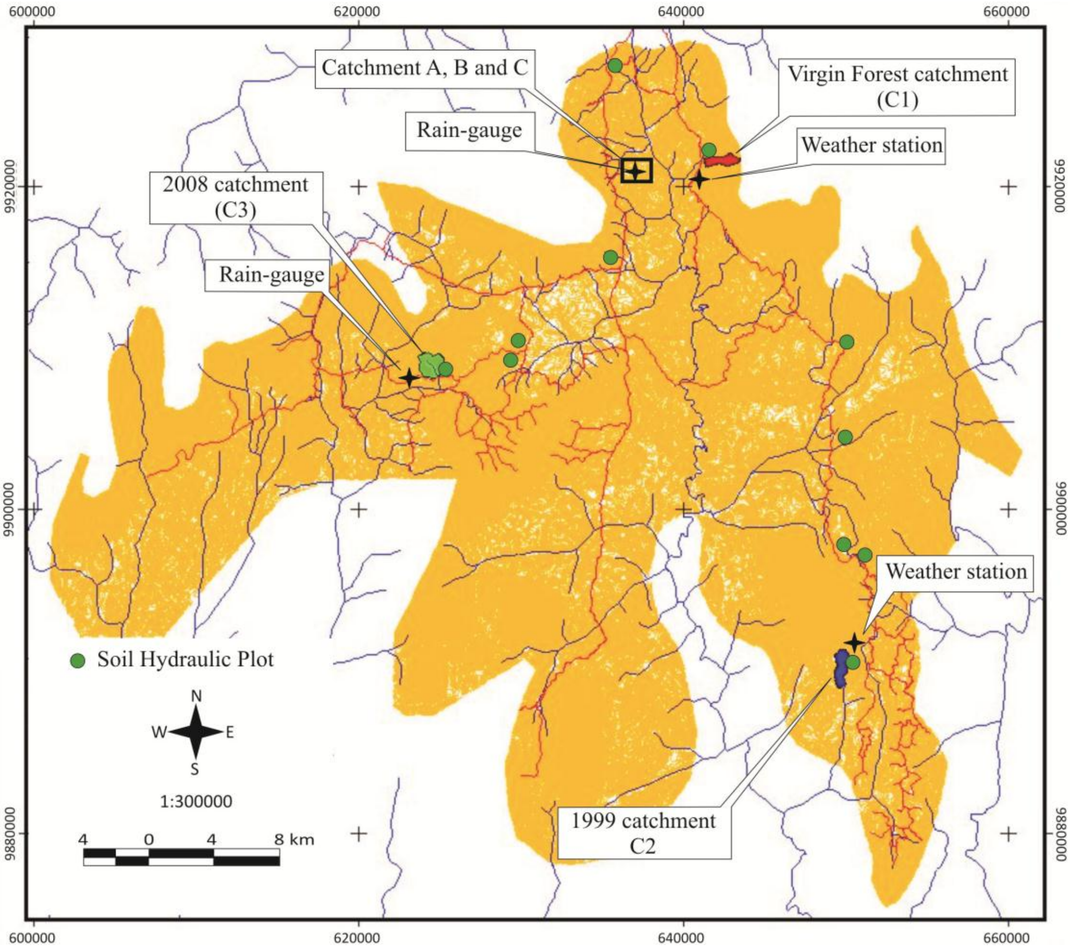


Figure 2.12 Location of the experimental sites in the study site, including 11 experimental plots for soil hydraulic properties, 3 catchment experiments to monitor hydrological response during different IFMS periods (C1, C2 and C3), and 3 catchment experiments to monitor hydrological responses to different IFMA types and phases (catchment A, B, and C).

2.3.1 Experimental plots for soil hydraulic properties

Field investigations were conducted in the 11 plot experiments in virgin forest plots and the 10 different IFMS periods within the PSP area. Field measurements of infiltration were made using a portable double-ring infiltrometer. At each test site, the infiltrometer was employed at four locations in triplicate based on differences of topography (Figure 2.13). A 100-cm^3 undisturbed soil core sample was used to measure the saturated hydraulic conductivity via laboratory analysis.

Figure 2.13 Infiltration test and preparing soil sample test for saturated hydraulic conductivity.

2.3.2 Catchment experiments for runoff and soil erosion during different recovery periods of the IFMS

The field catchment experiment was conducted in in an undisturbed forest (natural forest) as a control plot and two small catchments that had been rehabilitated at different times using intensive line planting (treated catchments). The treated catchments were forest that had been selectively logged and intensively line planted in 1999, and a forest that had been selectively logged and intensively line planted in 2008. Hereafter, these catchments are referred to as the “C1,” the “C2” and the “C3,” respectively (Figure 2.12).

2.3.2.1 Description of the virgin forest catchment (C1)

C1 was located on the lower slope of the Bukit Baka hills protected area. The virgin forest catchment has an area of 110 ha, a catchment slope of 11.36%, and 2 km of main river length (Figure 2.14). The soil depth ranged from 1.5 to 2 m with a 10–15-cm layer of organic topsoil. High canopy cover density reduced the sunlight reaching the forest floor. Therefore, the growth of understory vegetation was very slow due to reduced sunlight exposure from canopy tree shading (Figure 2.15).

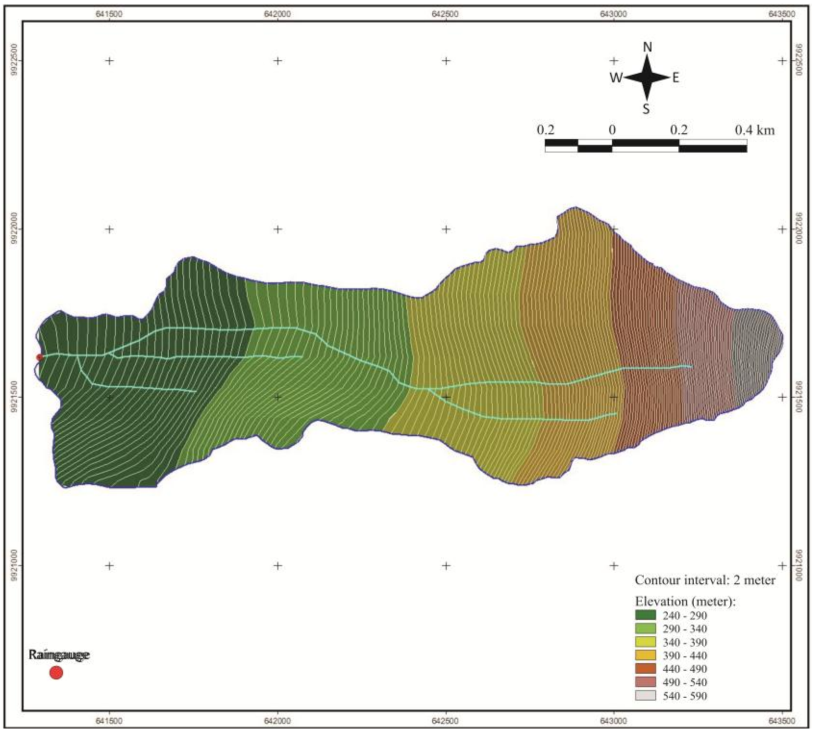


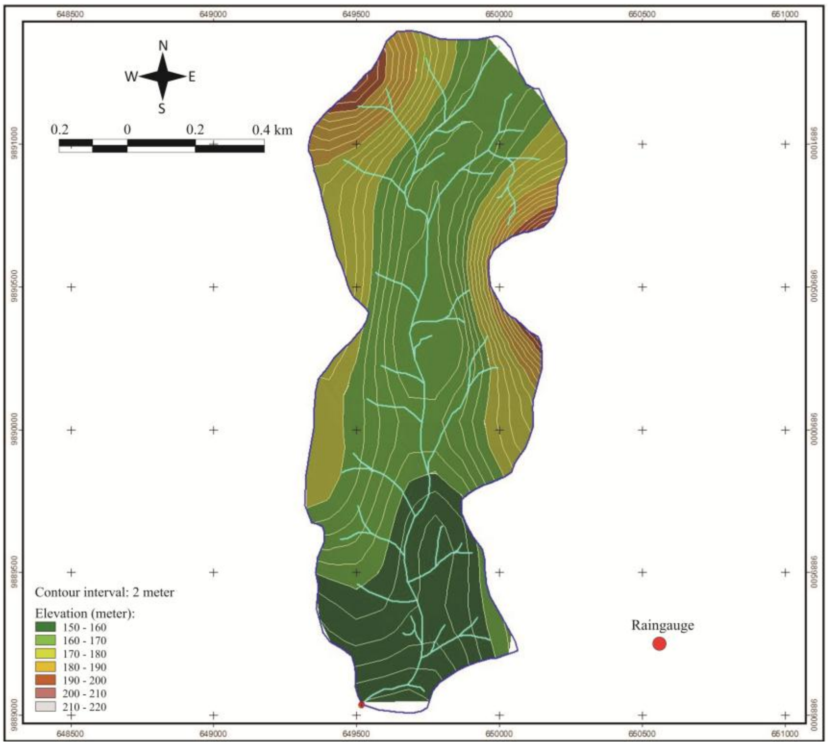
Figure 2.14 Contour map of the C1

Figure 2.15 Canopy cover, forest floor and vertical soil layer (0-150 cm) in the C1

A 2.5-m-wide flume weir was established in the catchment outlet to monitor and measure both runoff and sediment. A weather station was established near the catchment outlet (Figure 2.16).

Figure 2.16 Flume weir in the C1 outlet and the weather station.

2.3.2.2 Description of the 1999 catchment (C2)



2.17 Contour map of the C2

C2 was located on the lowland portion of the Bukit Baka hills, 42 km south of the virgin forest catchment (Figure 2.12). The C2 area was 149 ha in size with a catchment slope of 5.49% and 2.4 km of main river length. The strip-line intensive planting was established in 1999. The canopy cover profile, forest floor condition, and 10-year-old line-planted trees in the C2 are shown in Figure 2.18.

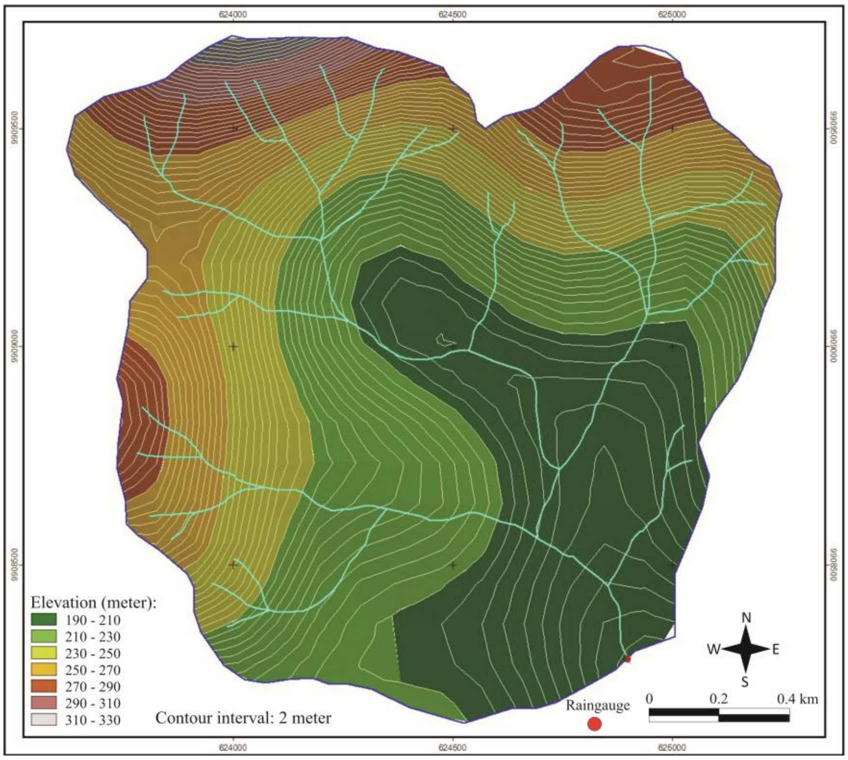
Figure 2.18 Canopy cover, forest floor and 10-years old *Shorea leprosula* at the line planted area in the C2.

A 2.5-m-wide flume weir was established in the catchment outlet to monitor and measure the runoff and sediment, and a weather station was established near the catchment outlet (Figure 2.19).

Figure 2.19 Flume weir in the C2 outlet and the weather station.

2.3.2.3 Description of the 2008 catchment (C3)

C3 was located on the lowland portion of the Bukit Baka hills, 35 km southwest of the C1 (Figure 2.12). The total drainage area of the C3 was 191 ha with a catchment slope of 5.1% and 2.1 km of main river length (Figure 2.20). The canopy cover profile, forest floor condition, and 1-year-old line-planted trees are shown in Figure 2.21.



2.20 Contour map of the C3

Figure 2.21 Canopy cover, forest floor and 1-year old *Shorea macrophyla* at the line planted area.

A 2.5-m-wide flume weir was built in the catchment outlet to monitor and measure the runoff and sediment, and a rain gauge was established near the catchment outlet (Figure 2.22).

Figure 2.22 Flume weir in the C3 outlet and the rain-gauge.

2.3.3 Catchment experiment for hydrological response monitoring during different operational stages of the IFMS

This field experiment was conducted in three, small, paired catchments with similar physical characteristics (Table 2.2). Catchment A, B, and C represent the control, standard IFMS, and modified IFMS, respectively (Figures 2.23 and 2.24). The IFMS phases of logging roads, selective logging, and intensive line planting were implemented in catchments B and C.

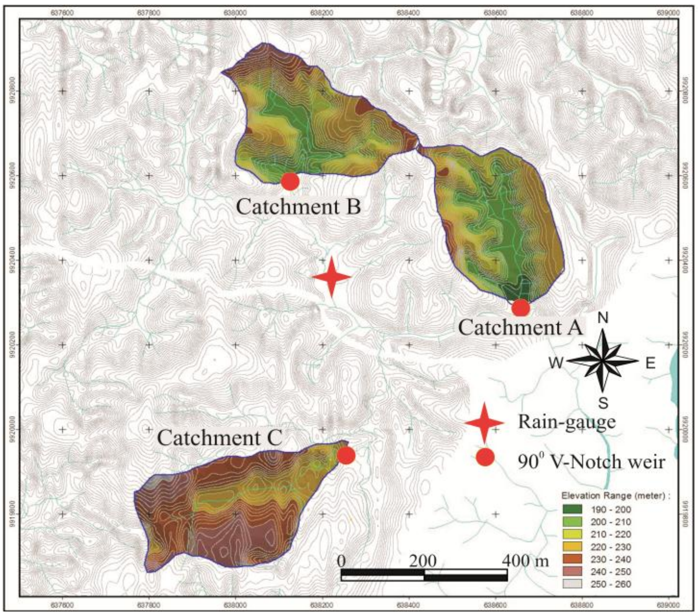


Figure 2.23 Three paired catchment experiments.

Standard IFMS is a harvesting and rehabilitation system with selective logging and intensive strip-line planting. In the standard IFMS, the intensive strip-line planting is used in a north–south or east–west planting direction. Modified IFMS uses the same method of harvesting system as the standard IFMS, but is modified in terms of the rehabilitation technique. Specifically, strip-line planting is exchanged for contour-line planting. This method is used to reduce the surface runoff and soil erosion with consideration for site-specific topography.

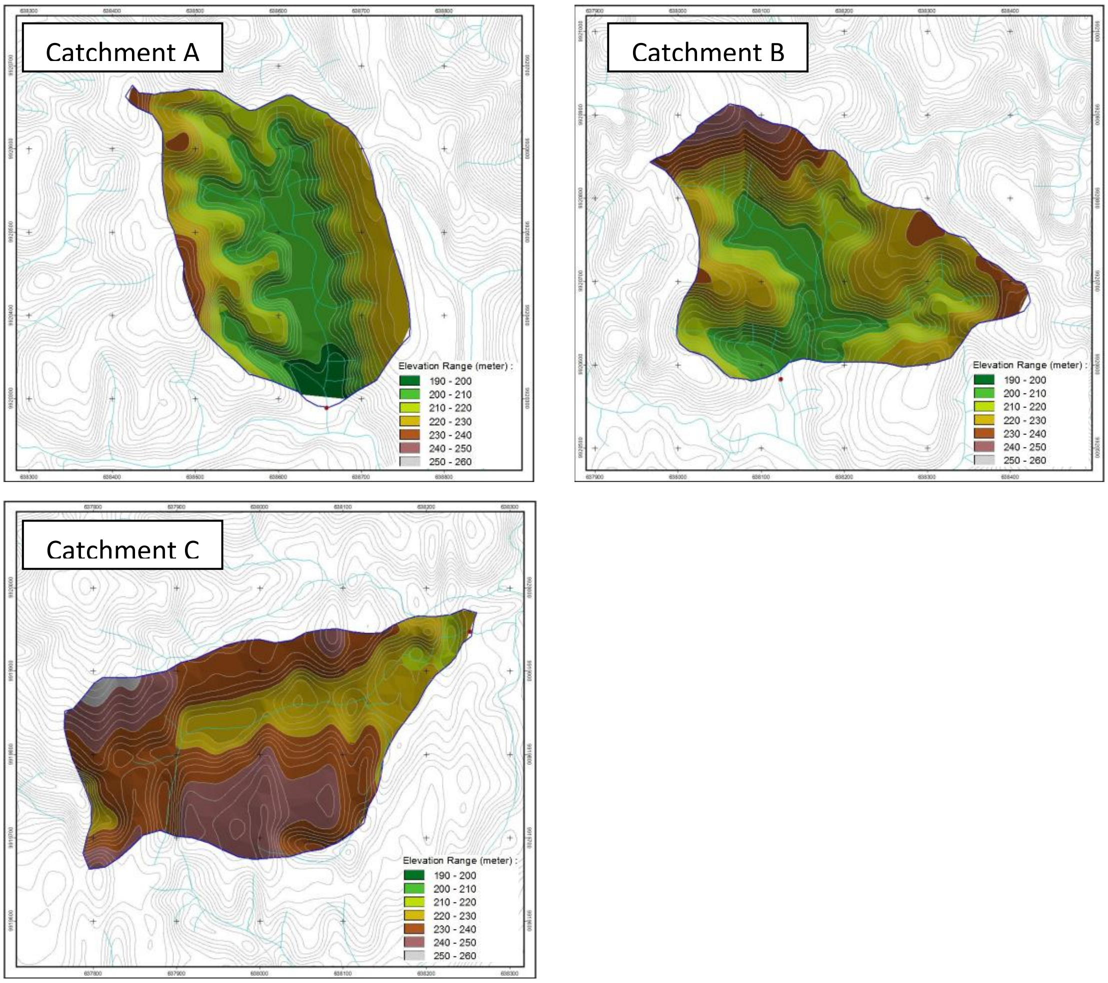


Figure 2.24 Contour maps of catchments A, B, and C.

Table 2.2 Physical catchment characteristics of the three-paired catchment experiments.

Physical characteristics	Catchment A	Catchment B	Catchment C
Drainage area (km^2)	0.087	0.087	0.094
Catchment circularity[a]	0.57	0.80	0.34
Catchment slope (%)	30.9	32.5	22.4
Drainage density (km/km^2)	17.84	15.66	15.28
Main river length (km)	0.47	0.38	0.52

[a] $Rf = \frac{A}{L^2}$ A = catchment area; L = length of the catchment

To determine the hydrologic responses of the three catchments to IFMS, automatic tipping-bucket rain gauges were installed near the three catchments. A 90° V-notch weir and a water-level logger were also installed at each catchment outlet (Figure 2.25).

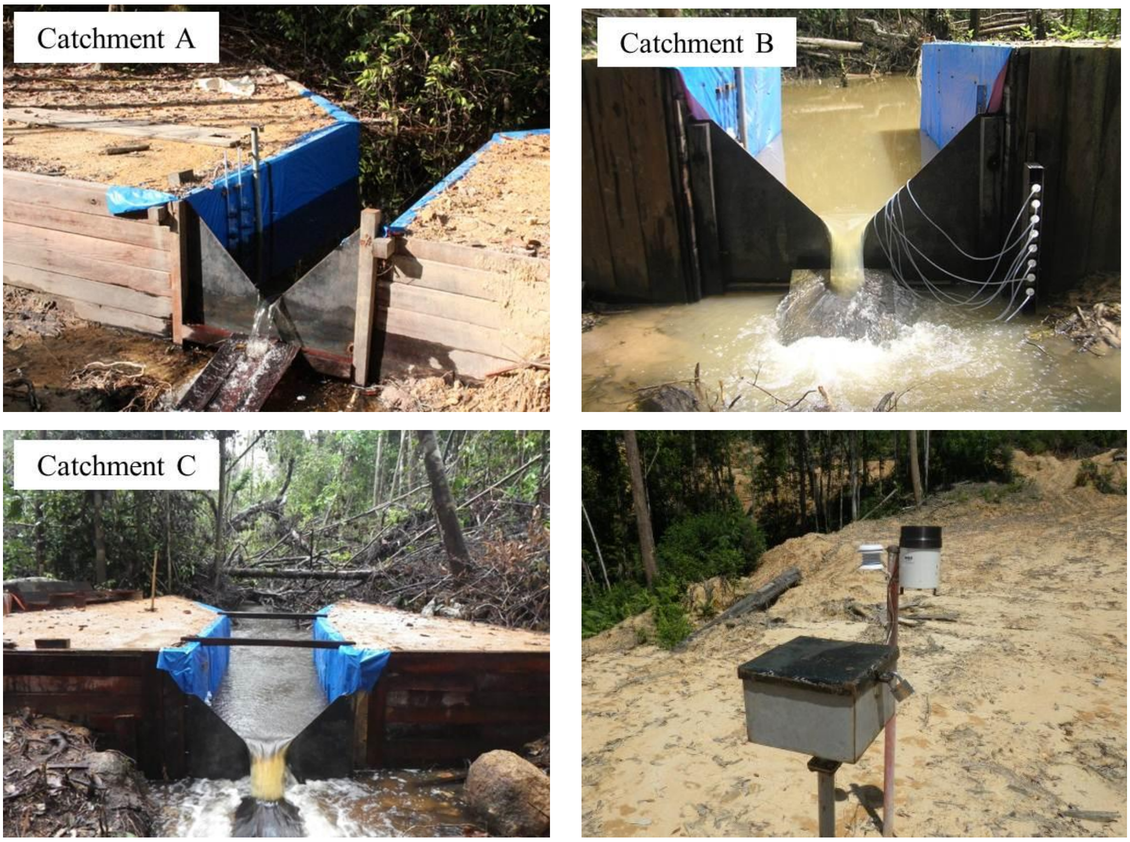


Figure 2.25 The 90° V-notch weir installed at the outlet of catchment A, B and C, and the rain-gauge.

The suspended sediment was measured using a rising stage suspended sampler installed in the 90° V-notch weir. A rising stage suspended sampler works on the siphon principle and consists of a number of bottles arranged on top of each other in a frame. Each bottle is fitted with two-hole stopper, one hole for sample inlet and one for air exhaust (Gordon *et al*., 1992) as shown in Figure 2.26.

Figure 2.26 Rising stage suspended sampler installed at the outlet of catchments A, B, and C.

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Chapter III

ESTIMATING RUNOFF USING THE HYDROMETEOROLOGY WATER BALANCE METHOD

Abstract

The water balance is an essential aspect in understanding hydrological response. Changes in the hydrological cycle affect the water balance and runoff. Understanding the water balance status in the forested area is important for managing water resources and anticipating potential disturbance caused by the implementation of a particular forest management system. This study was conducted in a natural tropical rain forest of Central Kalimantan, Indonesia. The objective of this study was to examine the water balance in the tropical rain forest using a Thornthwaite–Mather Water Balance (TMWB) model and to estimate runoff volume. The TMWB model calculates the water balance based on long-term average monthly precipitation, potential evapotranspiration, and combined latitudes, soil properties, and vegetation characteristics. The results found a good agreement between the predicted and observed monthly streamflows. This method assumed that 50% of the surplus water is actually available as streamflow in any given month, and the rest become detention water to supply soil moisture and ground water. It is also assumed that 50% of detention water is available as streamflow in the next month. During the investigation period, evapotranspiration ranged from 81 to 151 mm m^{-1} (mean = 109.8 mm m^{-1}). Annual evapotranspiration ranged from 1246 to 1519 mm (31.9%–41.2% of the rainfall). Annual runoff ranged from 1242 to 2244 mm (39.9%–54.6% of the annual rainfall), and 13.5%–18.1% of the rainfall was retained in the catchment as detention water and stored as soil moisture and as groundwater supply. The results suggested that in the forested area, a strong relationship exists among rainfall, evapotranspiration, and runoff production. Reductions in canopy cover, increases in surface disturbance, and overall land-use changes potentially impact the water balance, especially in terms of evapotranspiration and infiltration processes, which increase runoff and reduce catchment detention water.

3.1 Introduction

Tropical rain forests are among the most important biomes because of their high levels of primary productivity, and water and energy exchange with the atmosphere. Tropical rain forests are also a major source of global land surface evaporation (Choudhury *et al.*, 1998) and have profound influences on global and regional climates, as well as on hydrological cycles (e.g., Lean and Warrilow, 1989; Nobre *et al.*, 1991; Noguchi *et al.*, 2004; Kumagai *et al.*, 2005). Evapotranspiration in tropical rain forests is an important hydrological subject not only with regard to water resources and water availability for irrigation at the local level, but in terms of regional and global-scale water cycle studies (Noguchi *et al*., 2004). In the humid tropics, climate change may drastically alter hydrological regimes, in addition to the altered rainfall patterns and land cover transformations occurring mainly as a result of forest conversion (Bruijnzeel, 1996). Consequently, such anthropogenic alterations may further accelerate global climate changes.

However, the water balance of Southeast Asian tropical rain forests is largely uncertain, and field studies on the exchange of water between Southeast Asian tropical rain forests and the atmosphere have been poorly documented compared with studies performed in Amazonian tropical rain forests (Kumagai *et al*., 2005). To understand hydrological responses to catchment changes, determining the water balance and related variables is essential. The main components of the water budget in terms of runoff and evapotranspiration (E_t) always use indicators for analyzing watershed conditions and describing watershed ecosystem functions. The water balance, as calculated for a single soil profile or for an entire watershed, refers to the balance between incoming water by precipitation and outgoing water from evapotranspiration, groundwater recharge, and streamflow. Several possible methods to calculate water balance have been developed, but these depend on available baseline data such as meteorology, vegetation structure, soil water characteristics, and stream gauge data in the catchment, as well as several physical characteristics.

Thornthwaite (1948) proposed an empirical method to estimate evapotranspiration from mean temperature data. The method was modified by Thornthwaite and Mather (1955) to make it more applicable to a wide range of soils and vegetation. The Thornthwaite and Mather (1955) procedure calculates the water balance for the root zone. The technique has been successfully applied to water balances for whole watersheds and in calculations of recharge to groundwater (Thornthwaite and Mather, 1957; Alley, 1984; Peranginangin *et al*., 2004). In applying the TMWB procedure for a watershed, not all water leaving the root zone is immediately available for streamflow. Therefore, monthly streamflow is not well predicted, unless a certain portion of the runoff is carried over from 1 month to the next. The TMWB assumes that 50% of the surplus water is actually available as streamflow in any month.

The TMWB model offers a method to predict the hydrological processes of an entire watershed; in particular, it estimates evapotranspiration, water detention, water deficit, surplus water available for runoff, and runoff itself. This simple model is a useful tool for examining the transport of water and other materials in the scales of time and space that are of interest to geochemists and ecologists by combining several data for meteorology, physical factors, and vegetation characteristics.

The TMWB method has been generally accepted, particulary for water balances with dominant vegetation cover in the catchment. This technique uses long-term average monthly rainfall and average potential evapotranspiration, along with combined latitude and soil and vegetation characteristics. The last two factors are combined in the water-holding capacity (WHC) of the root zone. The method is applicable in those areas that are poorly monitored and can predict seasonal trends in rainfall, evapotranspiration, surplus or deficit in soil moisture, and runoff potential.

The objective of this chapter is to determine the status of the water balance in an Indonesian tropical rain forest using a TMWB model and to estimate monthly runoff. Understanding the water balance status in tropical rain forests under natural conditions is crucial to the effective management of water resources in these managed forests.

3.2 Methods

This study was conducted in a tropical rain forest in the Sei Seruyan block of Sari Bumi Kusuma (SBK) company concession area, a private forest in Central Kalimantan, Indonesia. The study site was located in the headwater region of the Katingan watershed, one of the largest in Central Kalimantan. The method uses air temperature as an index of the energy available for evapotranspiration, assuming that air temperature is correlated with the integrated effects of net radiation and additional controls such as evapotranspiration and that available energy is shared in fixed proportions between heating the atmosphere and evapotranspiration. Thornthwaite and Mather (1957) assumed that 50% of the surplus water is actually available as streamflow in any given month. For a small watershed in New Jersey, 75% of the total runoff was assumed to be carried over to the next month, and good agreement was found between the predicted and observed monthly streamflows (Mather, 1981; Steenhuis and Van der Molen, 1986).

This method has been tested using measured runoff in the Rio Macho basin in Costa Rica, and the results indicated that this method can be satisfactorily applied to estimate mean monthly streamflow (Calvo, 1986). The TMWB method is useful for description, classification, management, and research (Black, 1996).

The empirical equation developed by Thornthwaite, which relates the evaporation to mean air temperature is

$$PE = 16\left(10\frac{T}{I}\right)^{a}, \tag{1}$$

where PE is the monthly potential evapotranspiration, T is the monthly mean air temperature (°C); I is a heat index for the station, which is the sum of 12 monthly heat indices i given by $i = (T/5)^{1.514}$, and a is a cubic function of I.

This method of computing the monthly water balance was revised and sumarized by Thornthwaite and Mather (1957). To determine the water balance at a site, the following specific information is necessary:

(a) latitude,
(b) mean monthly air temperature,
(c) monthly precipitation,
(d) runoff conversion coefficient,
(e) information of the WHC for soil at the depth for which the balance is to be computed.

Temporally varying inputs are monthly rainfall (P) and potential evapotranspiration (PE_t) in millimeters. Field soil moisture capacity (FSMC) varies as a function of soil texture and plant rooting depth (estimated from general information on vegetation type), which are used for calculating the water storage (ST). Accumulated potential water loss (APWL) is the sum of negative values from the difference $P – PE_t$, accumulated from 1 month to the next over a 1-year period. Soil moisture has a maximum value equal to ST. The moisture status of the soils depends on the APWL, which is calculated by two different methods depending on whether the potential evaporation is greater than or less than the cumulative precipitation (Steenhuis and Van der Molen, 1986).

For months when the potential evapotranspiration is in excess of the precipitation, the APWL is incrementally calculated from the differences in potential evapotranspiration $(\sum PE_t)$ and precipitation $(\sum P)$,

$$APWL_t = APWL_{t-\Delta t} + (\sum PE_t - \sum P) \tag{2}$$

where $APWL_t$ is the accumulated potential water loss at time t (mm), $APWL_{t-\Delta t}$ is the accumulated potential water loss at time $t - \Delta t$ (i.e., previous month; mm), $\sum PE_t$ is cummulative evapotranspiration over time period Δt (mm), and $\sum P$ is the cumulative precipitation over the time period Δt (mm).

The relationship between APWL and the amount of water stored in the root zone is expressed as

$$ST_t = ST_f \left[\exp\left(\frac{-APWL_t}{ST_f} \right) \right] \tag{3}$$

where ST_t is the available water stored in the root zone at time t (mm) and ST_f is the available water storage at field capacity in the root zone (mm).

Months when potential evaporation is less than the precipitation (P), the storage in the soil is calculated as the difference between the potential evapotranspiration and measured precipitation:

$$ST_t = ST_{t-\Delta t} + (-\sum P - \sum PE_t) \tag{4}$$

If the storage ST_t at time t is higher than field capacity, then the percolation ($Rech_t$) is simply calculated as

$$Rech_t = ST_t - ST_{t-\Delta t} + \sum P - \sum PE_t \tag{5}$$

and the APWL is set equal to zero. If, on the other hand, the moisture content in the root zone does not reach field capacity, then the APWL can be found by combining equations (3) and (4), and no percolation will occur in this situation:

$$APWL_t = -ST_t \ln\left[\frac{\left(ST_{t-\Delta t} + \Sigma P - \Sigma PE_t\right)}{ST_f} \right] \tag{6}$$

Temporally varying inputs are monthly precipitation (P) and potential evapotranspiration (PE_t) in millimeters. FSMC varies as a function of soil texture and plant rooting depth (estimated from general information on vegetation type). APWL is the sum of negative values from the difference $P – PE_t$, accumulated from 1 month to the next. Soil moisture, the available water stored in the root zone (ST), has a maximum value equal to FSMC and decreases as a function of APWL according to equation (2). From these data, one calculates the actual evapotranspiration (AE_t).

The above information and calculation are used to derive total water available for runoff (TARO) as surplus water. Runoff (RO) is total flow with some detention to account for temporary storage, i.e., the surplus soil moisture. For a particular month, RO is some fraction ($k < 1$) of TARO for that month, as calibrated for the system. Water detention (DET) is detention water for the groundwater supply. The DET is equal to the remaining portion of TARO and represents temporary water storage as surface ponding, a raised groundwater table, and oversaturation of the soil. Thornthwaite and Mather (1955, 1957) suggested that for large watersheds, k should be about 0.5 and should increase for smaller watersheds, steep topography, and shallow soils.

3.3 Results and Discussion

3.3.1 Meteorological data

Meteorological data used were from three manual raingauges measured since 2001 and one unit automatic weather station installed in 2009. The available rain gauges provide an adequate coverage of elevation and topography. Monthly rainfall and average temperature are shown in Table 3.1 and the annual rainfall is given in Figure 3.1.

Table 3.1 Monthly rainfall and average temperature

	Monthly rainfall (mm)													Temp.
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Avg.	(ºC)
Jan.	337	426	215	371	287	307	395	232	332	318	267	226	310	28.75
Feb.	279	252	406	88	289	453	395	171	143	575	176	401	302	28.50
Mar.	195	391	528	259	286	145	388	494	288	404	236	377	332	28.68
Apr.	331	469	235	413	278	321	433	346	400	376	247	383	353	28.62
May	191	200	255	404	256	414	303	226	175	323	402	214	280	28.79
June	185	480	295	86	310	646	454	298	120	463	192	188	310	28.18
July	200	120	141	326	222	26	442	432	242	182	120	277	228	28.29
Aug.	87	60	225	0	188	9	379	592	140	477	58	292	209	28.86
Sep.	524	48	274	191	153	311	279	516	20	471	283	154	269	28.61
Oct.	360	225	344	131	586	87	477	535	362	332	546	156	345	28.46
Nov.	320	308	204	420	561	391	278	352	463	198	510	231	353	28.51
Dec.	129	443	141	335	280	280	538	416	538	263	411	313	341	28.74
Total	3,136	3,424	3,263	3,024	3,694	3,390	4,762	4,610	3,223	4,383	3,451	3,212	3,631	

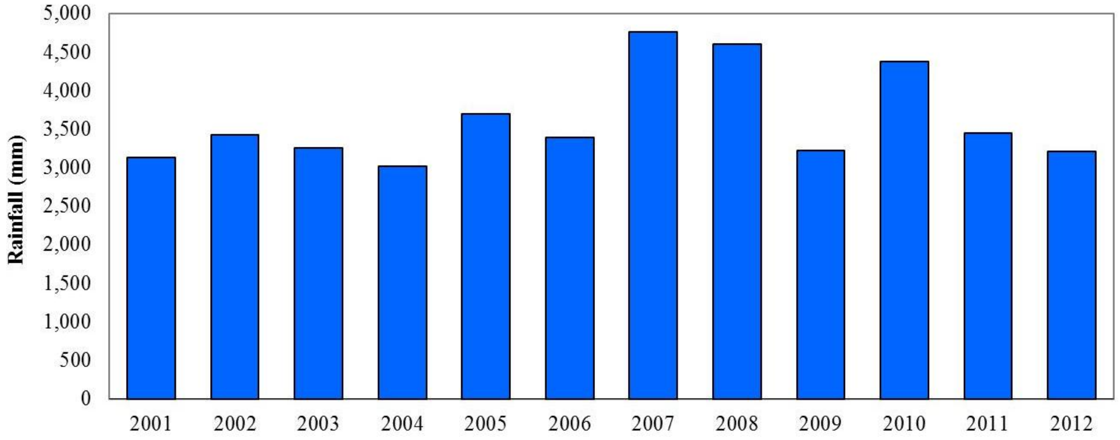

Figure 3.1 Annual rainfall from 2001 to 2012.

According to the forest climate classification system of Schmidt and Ferguson (1951), the area is type A (very wet) tropical rain forest (monthly average rainfall > 100 mm). The mean annual rainfall from 2001 to 2012 was 3631 mm, with the highest average monthly precipitation (353 mm) occurring in November and the lowest average monthly precipitation (209 mm) occurring in August (Table 3.1). The number of rainy days varies from 95 to 112 days, and the mean annual temperature is 30ºC–33ºC at noon and 22ºC–28ºC at night.

The FSMC is described as the WHC that varies as a function of soil texture and plant rooting depth (estimated from general information on vegetation type from the SBK company concession area). The estimated soil depth within the watershed was between 200 and 300 cm. Soil texture was dominated by clay loam and the available water was 250 mm/month. The root zone depth average was 1.60 m. A combination of available water and root zone depth produced a WHC of 400 mm.

3.3.2 Calibration of the runoff coefficient in water balance

The TMWB model requires only one calibration parameter, which can be termed the runoff coefficient (*k*), used to estimate monthly runoff (RO) and detention water (DET). Streamflow measured at the natural forest catchment in 2011 was used to calibrate between runoff observed with the stream gauge and the runoff calculated using the TMWB method. Calculated TMWB values in 2011 is shown in Table 3.2.

Table 3.2 Average TMWB monthly water balance for the upper Katingan watershed

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
P	267.4	176.2	236.4	247.5	401.9	192.1	120.4	58.4	283.4	546.0	510.3	411.2	3451.3
PEt	111.6	114.8	109.0	109.2	109.5	103.9	111.8	105.9	107.4	109.6	102.9	100.7	
APWL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-47.5	0.0	0.0	0.0	0.0	
ST	400.0	400.0	400.0	400.0	400.0	400.0	400.0	355.2	400.0	400.0	400.0	400.0	
AEt	111.6	114.8	109.0	109.2	109.5	103.9	111.8	103.2	107.4	109.6	102.9	100.7	1293.6
DEF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	
TARO	155.8	61.4	127.4	138.3	292.4	88.2	8.7	0.0	131.2	436.4	407.4	310.6	2157.7
RO	93.35	69.63	79.06	100.99	180.76	117.19	26.39	2.17	65.60	251.01	312.82	257.13	1556.1
DET	77.90	30.68	63.72	69.13	146.19	44.10	4.34	0.00	65.60	218.21	203.71	155.28	

Note: all values are prorated per unit area and expressed as millimeters of water flux.

Runoff resulted in the values shown in Table 3.2 and then calibrated to observed runoff from stream gauge in the natural forest in the study site. Several calibration values of *k* were analyzed to find the highest coefficient correlation. The highest correlation coefficient of 0.82 was found for a *k* value of 0.5. The calibration results are shown in Figure 3.2.

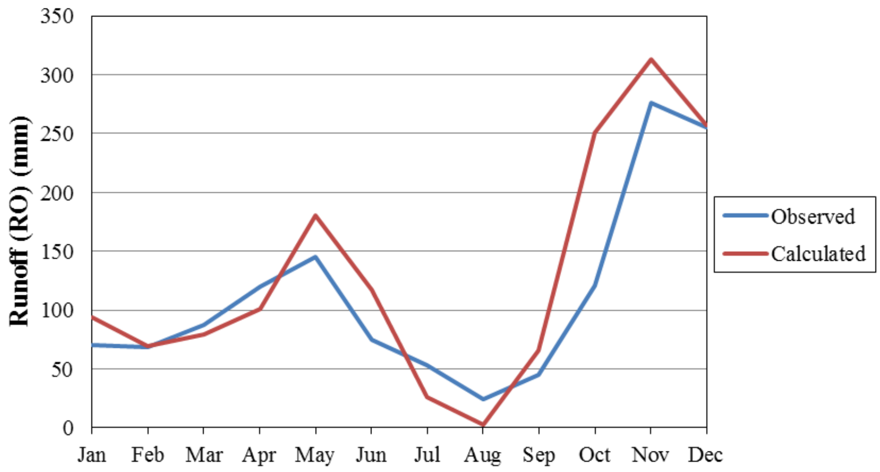

Figure 3.2 Calibration results from observed and calculated monthly RO.

Figure 3.2 shows the agreement between observed and calculated runoff (RO) for the upper Katingan catchment. The assumption was made that 50% of the total water available for runoff (TARO) or surplus water in the present month will become runoff and the rest will become detention water (50% of the detention water will flow out in the next month). The calculated water balance underestimated runoff during the dry season and overestimated runoff during the rainy season compared to the perennial stream in the observed natural catchment. These errors resulted because surface soil moisture storage (ST) did not remain constant over these periods.

3.3.3 Long-term monthly water balance from 2001 to 2012.

Using the fitted coefficient *k*, the TMWB value for the headwater region of the Katingan watershed was calculated for the 2001–2012 period. The calculated water balance is shown in Table 3.3 and Figure 3.3.

Table 3.3 Annual water balance from 2001 to 2012

	Annual Water Balance (mm)											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
P	3136.4	3424.0	3262.6	3024.3	3694.3	3390.0	4761.9	4609.8	3109.1	4354.4	3451.3	3211.7
AEt	1366.8	1407.0	1519.2	1217.4	1296.3	1246.7	1314.8	1270.2	1426.7	1421.3	1296.3	1314.8
TARO	1769.6	2017.1	1743.4	1806.9	2398.0	2143.4	3447.1	3339.7	1682.4	2933.1	2155.0	1897.0
RO	1351.9	1436.4	1366.2	1306.1	1796.0	1606.3	2505.3	2516.9	1242.7	2244.1	1556.1	1347.4
DET	442.4	504.3	435.9	451.7	599.5	535.8	861.8	834.9	420.6	733.3	538.7	474.2

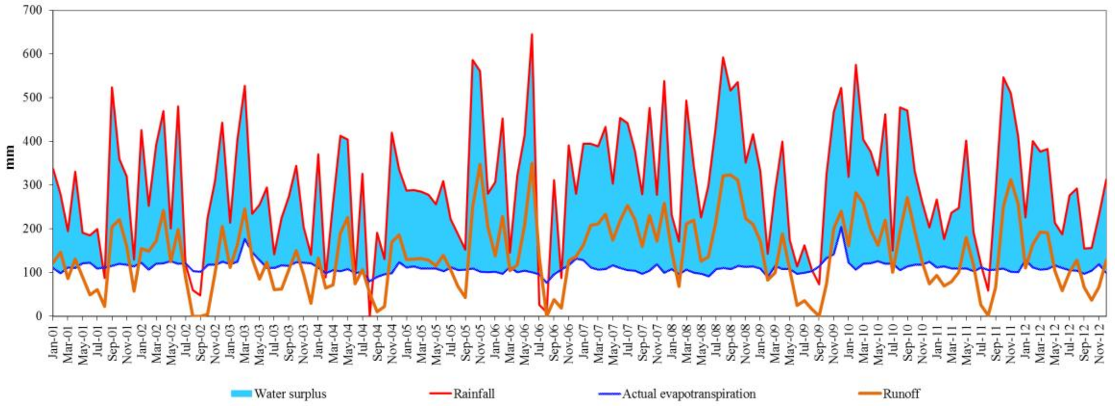

Figure 3.3 Time series of the long-term monthly water balance from 2001 to 2012.

Figure 3.3 shows the average water balance at the study site from 2001 to 2012, illustrating expected relationships among rainfall (P), evapotranspiration (AE_t), and runoff (RO). It shows that runoff occurs throughout the years with minimum runoff taking place mainly from July to September, and the maximum runoff occurring from November to January. The dry season is dominated by high potential evapotranspiration (PE_t), which draws surface soil moisture storage (ST) down so that from July to September, the runoff is at a minimum near zero. Water surplus is defined as total water available for runoff (TARO). This water surplus then used to produce both runoff (RO) and detention water (DET).

Even though the study site was classified as a tropical rain forest climate, a dynamic variation in the rainfall–runoff response still occurred throughout the years. The dry season took place largely from June to October, while the rainy season occurred predominantly from November to May with two peaks in rainfall amount at the beginning and end of the rainy season. Transitions between the dry and rainy seasons were so sharp that soil moisture storage (ST) was a significant factor in total water available for runoff (TARO). The reduced ST caused the TARO to be utilized for ST first, with the remaining being used as runoff.

Annual rainfall varied in the period from 2001 to 2012, the lowest rainfall occurred in 2004, and the highest was in 2007. To understand the water balance dynamics of the lowest and highest annual rainfall, the calculated water balance is shown for 2004 in Table 3.4 and Figure 3.4, and the calculated water balance for 2007 is shown in Table 3.5 and Figure 3.5.

Table 3.4 Calculated water balance in 2004

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total	% of P
P	371.2	88.3	258.7	413.2	403.9	86.4	326.3	0.0	190.9	130.6	419.7	335.1	3024.3	
PEt	111.8	98.9	105.6	103.6	107.8	99.7	100.8	90.6	90.1	95.9	98.8	123.7		
APWL	0.0	-10.6	0.0	0.0	0.0	-13.3	0.0	-90.6	0.0	0.0	0.0	0.0		
ST	400.0	389.5	400.0	400.0	400.0	386.9	400.0	319.0	400.0	400.0	400.0	400.0		
AEt	111.8	98.8	105.6	103.6	107.8	99.5	100.8	81.0	90.1	95.9	98.8	123.7	1217.4	40.3
DEF	0.0	0.1	0.0	0.0	0.0	0.2	0.0	9.5	0.0	0.0	0.0	0.0		
TARO	259.4	0.0	142.7	309.6	296.1	0.0	212.4	0.0	19.7	34.7	320.8	211.4	1806.9	59.7
RO	133.5	64.8	71.3	190.5	225.5	74.0	106.2	53.1	9.9	22.3	169.1	185.9		
DET	64.8	0.0	35.7	77.4	74.0	0.0	53.1	0.0	4.9	8.7	80.2	52.8		

In 2004, 3024 mm of rainfall (P) was used for the evapotranspiration (AE_t) of 1217 mm or 40.3% of the rainfall. Fewer rainfall events in 2004 influenced higher AE_t. Runoff (RO) was 1306 mm or 43.2% of the rainfall. In this low rainfall input, only 903 mm infiltrated and recharged the groundwater. Detention water (DET) did not occur in February, June, and August because no water was available for runoff (TARO) or to supply detention. All rainfall in February and June were used to fill soil moisture storage (ST). The RO that occurred in February, June, and August was supplied from the previous month's rainfall.

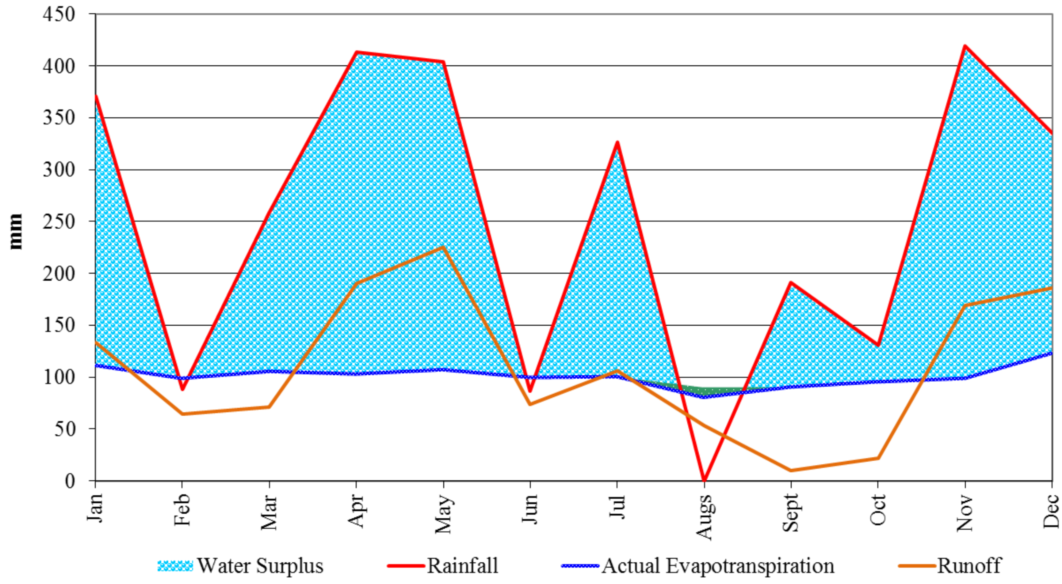

Figure 3.4 Monthly water balances in 2004.

The water balance investigation in 2004 illustrated that low deficit water (when the actual evapotranspiration is higher than input rainfall) occurred in February, June, and August (Figure 3.4). Deficit input water in August caused deficit soil moisture to be used in evapotranspiration (marked with a green area). During the dry season period from July to September, the RO decreased. Even though 190 mm rainfall occurred in September, this rainfall was used to fill the deficit soil moisture in August; therefore, the RO was still low at 9.9 mm. RO in October began increase after the soil moisture reached saturated conditions.

Table 3.5 Calculated water balance in 2007

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total	% of P
P	395.2	394.7	388.4	433.2	303.2	454.3	442.2	379.0	279.3	476.5	277.6	538.2	4761.9	
PEt	128.7	111.7	107.5	108.0	116.8	110.3	106.5	104.2	97.8	104.8	118.8	99.7		
APWL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
ST	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0		
AEt	128.7	111.7	107.5	108.0	116.8	110.3	106.5	104.2	97.8	104.8	118.8	99.7	1314.8	27.6
DEF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
TARO	266.6	283.1	280.9	325.2	186.5	344.0	335.7	274.7	181.5	371.7	158.8	438.5	3447.1	72.4
RO	162.9	208.2	211.2	232.8	174.5	218.6	253.8	221.3	159.5	231.2	172.3	259.0		
DET	66.6	70.8	70.2	81.3	46.6	86.0	83.9	68.7	45.4	92.9	39.7	109.6		

In 2007, 4761 mm of rainfall was used for the actual evapotranspiration of 1314 mm or 27.6% of the rainfall. Runoff was 2505 mm or 52.6% of the total rainfall. In this high rainfall period, soil moisture storage (ST), stable under saturated conditions, caused increased runoff due to direct runoff in the stream channel.

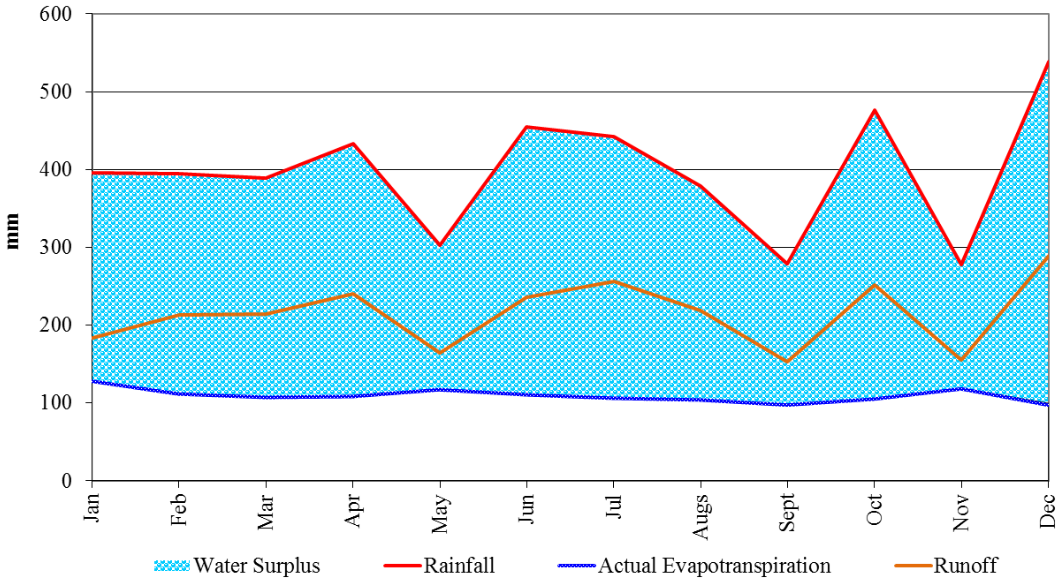

Figure 3.5 Graphic of the water balance in 2007.

Rainfall occurred every month in 2007; therefore, the soil moisture may have always been under a saturated condition (Figure 3.5), ensuring persistent monthly runoff. A comparison of the ratio of rainfall to evapotranspiration (P:AE_t) between the low annual rainfall in 2004 and the high annual rainfall in 2007 showed that evapotranspiration was higher in the 2004 (1217 mm, 40.3% of the rainfall) than 2007 (1314 mm, 27.6% of the rainfall). During 2004, rainfall occurred on 123 days, while in 2007 rainfall occurred on 202 days. This indicates that in years of low annual rainfall, sunlight may reach the forest canopy at much higher intensity and trigger higher photosynthesis rates, leading to an increase the evapotranspiration amount.

3.3.4 Monthly evapotranspiration

During the monitoring period from 2001 to 2012, the variation data from monthly rainfall and calculated evapotranspiration (AE_t) were used to determine the water balance characteristics at the study site. Variations in the monthly rainfall amount also influenced the variation in evapotranspiration as shown in Figure 3.6.

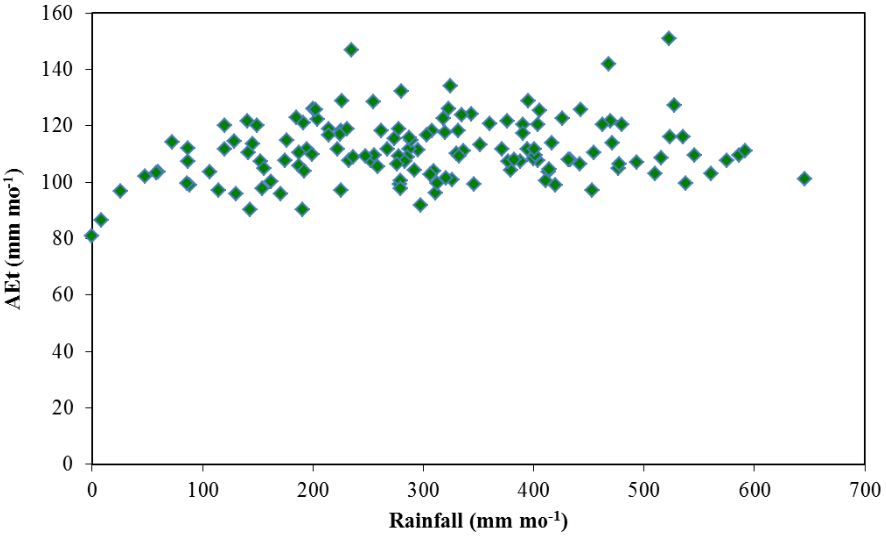

Figure 3.6 Evapotranspiration from various monthly rainfalls.

Figure 3.6 shows that the monthly evapotranspiration for a 12-year period ranged from 81 to 151 mm m^{-1} (mean = 109.8 mm m^{-1}). Annual evapotranspiration ranged from 1246 to 1519 mm (27.5%–46.5% of the rainfall). Annual evapotranspiration was similar to that found in a previous study in Bukit Tarek, Malaysia, which found that evapotranspiration ranged from 1243 to 1605 mm (Noguchi *et al.*, 2004). Evapotranspiration, measured using a 80-m-tall canopy crane in Lambir Hills National Park, Sarawak Malaysia, resulted in an annual evapotranspiration (sum of evaporation and interception) of 1545 mm, accounting for approximately 72% of the total rainfall (Kumagai *et al*., 2005).

3.3.5 Monthly runoff

Interannual and monthly variations in rainfall were used to directly examine the relationship between rainfall and runoff. Figure 3.6 shows a linear relationship between monthly rainfall and runoff for the upper Katingan watershed (r^2 = 0.8), with a runoff intercept at 30.7 mm month^{-1} of rainfall. The runoff intercept represents the P below which the regression predicts that runoff would not occur.

Calculated runoff is not strictly surface runoff, but includes water removal for use outside the watershed as well as subsurface flow and groundwater flow. In the water balance concept, it is instructive to consider how antroppogenic activity may alter the natural water flow. There are two aspects of altered flow. The first is the reduction in total flow by water removal from the system. The second is the alteration of the shape of the natural hydrograph by water capture during periods of high natural flow and release during periods of low or no natural flow (Fischer *et al*., 1996).

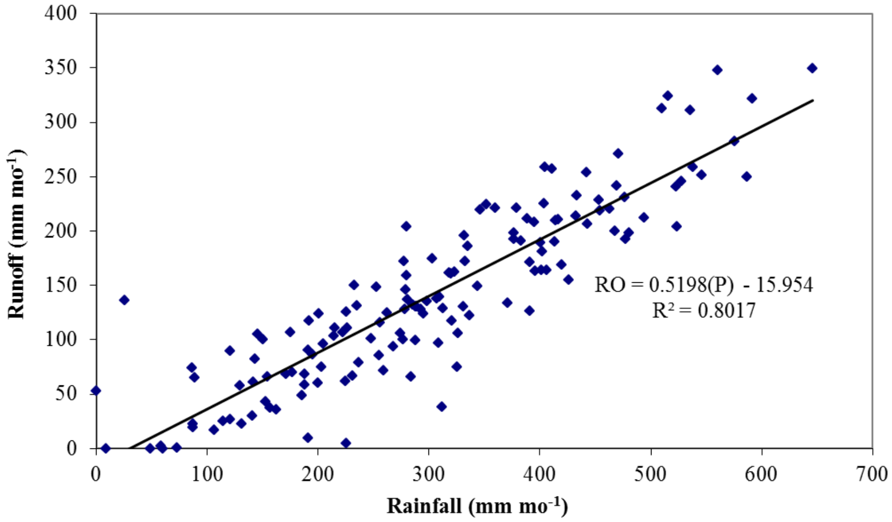

Figure 3.6 Correlation between monthly rainfall and runoff.

Runoff represents approximately 60% of the precipitation in the moist portions of the tropics (Lewis *et al*., 1995; Lewis, 2008). At the study site, annual runoff ranged from 1242 to 2244 mm or 39.9% to 54.6% of the annual rainfall. Detention water to supply soil moisture and groundwater ranged from 13.5% to 18.1% of the annual rainfall.

Runoff in the study site varied temporally. The results from the TMWB model provided estimates of runoff over the past 12 years. Even with only 1 year of a calibration record, this model provided seemingly realistic estimates of seasonal and monthly variations in runoff based on a simple conceptual model of well-understood physical factors, especially in vegetation characteristics.

3.4 Conclusions

The results found a good agreement between the predicted and observed monthly streamflows. This method assumed that 50% of the surplus water is actually available as streamflow in any given month, and the rest become detention water to supply soil moisture and ground water. It is also assumed that 50% of detention water is available as streamflow in the next month. During the investigation period, evapotranspiration ranged from 81 to 151 mm m^{-1} (mean = 109.8 mm m^{-1}), the annual evapotranspiration ranged from 1246 to 1519 mm (31.9%–41.2% of the rainfall), and annual runoff ranged from 1242 to 2244 mm (39.9%–54.6% of the rainfall). A total of 13.5%–18.1% of rainfall was detained in the catchment as detention water and stored as soil moisture or groundwater supply.

The overall results of calculations using the the TMWB method indicated that the water balance status and estimated runoff are not experiencing the problems leading to water deficit under natural tropical forest conditions. These results suggest that in the forested area, a strong relationship exists among rainfall, evapotranspiration, and runoff production. Surface disturbance, land-use changes, and reductions in canopy cover potentially impact the water balance—in particular, they influence evapotranspiration and infiltration processes that increase runoff and reduce detention.

The implementation of a forest management system such as that described here potentially changes the hydrologic cycle. To understand these hydrological changes, we need detailed within-catchment experimental observations to quantify and predict hydrologic responses under a forest management system.

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Chapter IV

RUNOFF GENERATION FOLLOWING DIFFERENT DISTURBANCES OF SOIL HYDRAULIC PROPERTIES

Abstract

The implementation of tropical forest management has led to changes in forest structure and increased surface disturbances due to logging activities. Different forest treatments are suspected to affect soil hydraulic properties in different ways. We investigated the impact of an intensive forest management system (IFMS) on soil hydraulic properties including infiltration characteristics, soil compaction, and hydraulic conductivity, as well as the generation of surface runoff. Soil hydraulic properties were measured for four types of surface disturbances (line planting, cleared area, logged area, and skidder tracks) between different periods of operation of an IFMS. The fundamental activities associated with mechanized selective logging and intensive line planting reduced soil hydraulic properties, including infiltration characteristics, soil compaction, and hydraulic conductivity within the near-surface soil profile. Ground-based harvesting using a skidder tractor significantly increased the rate of soil compaction, which influenced the infiltration capacity and K_s. Recent forest operations significantly disturbed the soil surface (via compaction and topsoil/subsoil mixing) and produced large variation in the near-surface values of K_s. Surface K_s values were lower on skidder tracks than other disturbed surface types. Reductions in surface K_s to a depth of 0.2 m may increase the frequency of surface runoff flow, particularly during large seasonal storms. The changes in surface K_s are evidence that forest disturbances have altered the surface hydrological pathways, thereby creating an opportunity for surface runoff flow to be generated on disturbed sites. Concurrent with succession to forested land cover, an increase in infiltrability reduces the propensity to generate surface runoff flow. The estimated recovery time for near-surface K_s on the non-skidder tracks was 10–15 years, while in the skidder tracks it was more than 20 years.

4.1 Introduction

In forested areas, the movement of water between the atmosphere and soil plays an important role in the storage capacity of the land. Hydrologic processes in a forested catchment start with rainfall interception by forest vegetation. Forest canopies serve as a barrier against precipitation reaching the ground. A portion of the precipitation is inevitably intercepted by the canopy (canopy interception). Some flows along braches and stems (stemflow) until it reaches the ground, some drips from the foliage and branches or passes through canopy openings to the ground (throughfall), and some is further intercepted by the forest floor (litter interception). Hydrologic processes continue once water enters the soil and becomes groundwater through the infiltration process. When rainfall rates exceed the infiltration capacity, surface runoff or ponding of water on the soil surface occurs and can potentially cause soil erosion.

Evidence worldwide suggests that changes in interception loss, evapotranspiration, infiltration, and stormflow pathways caused by various degrees of forest conversion can alter the timing and magnitude of direct runoff and baseflow for an unpredictable period of time (Bruijnzeel, 1990, Beschta *et al*., 2000, Bruijnzeel, 2004, Ziegler *et al*., 2006). Some studies have investigated changes in hydrological variables within the soil profile that may have implications for the partitioning and movement of subsurface stormflow (Van der Plas and Bruijnzeel, 1993, Malmer, 1996, Noguchi *et al*., 1997, Ziegler *et al*., 2004, Zimmermann *et al*., 2006). An understanding of the spatial variability of soil hydraulic properties is important to accurately determine the subsurface flux of water (Hendrayanto *et al*., 1999) and its variation following disturbances of surface soil (Malmer and Grip, 1990, Van Der Plas and Bruijnzeel, 1993, Noguchi *et al*., 1997, Williamson and Neilsen, 2000, Ziegler *et al*., 2006, Ziegler *et al*., 2007, Osuji *et al*., 2010). Infiltration is the movement of water from the atmosphere to the soil across some definable but intangible interface (Black, 1991). Different land use practices affect the infiltration rate (IR) in different ways, depending on their effects on the intrinsic properties of the soil (Osuji *et al*., 2010). Water movement into and through soil profiles is affected by a variety of factors, which reflect the surface and subsurface conditions and flow characteristics. Surface conditions such as the type of vegetation cover, land management practices, roughness, crusting, cracking, slope, and chemistry have a significant impact on surface ponding, surface runoff velocity, and the ability of the water to enter the soil. Conditions underground that affect soil water movement can include soil texture, structure, organic matter content, depth, compaction, amount of voids, layering, water content, groundwater table, and the root system. These factors affect the soil’s water-holding capacity and the ability of water to move (Chang, 2006). Forest vegetation with its characteristic canopy architecture has a significant role in rainfall infiltration processes. In forested hillslopes, soil water has been observed to increase rapidly and gently in the region downslope from tree stems, especially at points close to the tree stems (Liang *et al.*, 2007).

Land conversion and timber extraction are likely to alter the biodiversity and hydrologic responses of forested areas. In tropical Indonesia, rainforests are managed by an intensive forest management system (IFMS). The IFMS has promoted selective logging for timber harvesting and intensive line planting to enrich the standing stock. Timber extraction using heavy machines destroys the soil structure, which affects water and nutrient cycling, and accelerates soil erosion rates (Malmer and Grip, 1990, Van Der Plas and Bruijnzeel, 1993, Nussbaum and Hoe, 1996). Heavy machines in timber collection areas and on skidder roads can increase soil compaction by up to 40% of natural conditions (Nussbaum and Hoe, 1996, Nussbaum *et al.*, 1996), and 10–30% of the soil surface may be denuded due to logging roads, skidder tracks, and log landings (Bruijnzeel, 1992, Van Der Plas and Bruijnzeel, 1993). The use of heavy equipment tends to compact the topsoil, setting in motion a negative spiral of reduced infiltrability and an increased frequency of surface runoff flow and sheet erosion, thereby hindering the establishment of a new protective layer of vegetation and litter (Van Der Plas and Bruijnzeel, 1993).

In addition, selective logging and intensive line planting systems are suspected to dramatically impact soil properties. The loss of forest cover following harvesting reduces the interception of raindrops (increasing drop impact energy and soil detachment) and evapotranspiration (increasing the amount of water available for infiltration) and increases the amount of water stored in the soil. Therefore, soil moisture capacity is reached with less rainfall, and any excess can produce surface runoff and increase peak-flow and stream-flow volumes.

The implementation of the IFMS has reduced the forest canopy cover, destroyed the surface soil, changed the hydraulic conductivity, and increased direct runoff and soil erosion. Soil compaction has been considered the principal form of damage associated with logging, restricting root growth and reducing productivity (Williamson and Neilsen, 2000). Logging roads and skid trails in particular can alter the hydrologic response and serve as sediment sources and transport pathways on cleared land (Bruijnzeel and Critchley, 1994, Ziegler and Giambelluca, 1997, Wemple *et al.*, 2001, Chappell *et al.*, 2004, Ziegler *et al.*, 2006). Many studies have indicated that vegetation cover and forest disturbances from logging are the principal cause of hydrological differences between catchments (Abdulhadi 1981, Liu *et al*., 2006, Zang *et al*., 1999, Zhao *et al*., 2009, Mapa, 1999, Malmer and Grip, 1990, Harden and Scruggs, 2003, Peng Li *et al*., 2004, Van Der Plas and Bruijnzeel, 1993, Osuji *et al*., 2010, Ilsteds *et al*., 2007, Murugayah, *et al*., 2009). One of the most common outcomes is an increase in runoff, with proportional increases that vary between catchments. Data from rainfall-simulation experiments and saturated hydraulic conductivity (K_s) measurements in a disturbed upland watershed in northern Thailand have convincingly shown that the various land cover types within the fragmented landscape differ in their ability to infiltrate rainwater (Ziegler and Giambelluca, 1997; Ziegler *et al*., 2000).

Different forest treatments within the IFMS are believed to affect soil hydraulic properties in different ways. When the forest soil receives a certain treatment, there is an accompanying change in the intrinsic properties of the soil and this alters the hydrological balance of the soil. The impact of secondary forest on the hydrological cycle has yet to receive the same attention as primary forest and agricultural ecosystems. This is particularly true with regard to the effects of forest regrowth on soil hydrology. This chapter investigated the impact of the IFMS on soil hydraulic properties including infiltration characteristics, soil compaction, and hydraulic conductivity, as well as the generation of surface runoff using saturated hydraulic conductivity.

4.2 Methods

4.2.1 Infiltration capacity and soil compaction

Field observations of soil hydraulic properties were conducted on 11 plots, including 1 virgin forest plot and 10 plots at different operational periods of the IFMS (Figure 2.12). The IR or infiltrability tends to be high during the early stages of ponded infiltration when the pressure gradient dominates over gravitational force, but gradually decreases to a constant rate when gravitation is the only force acting on the water; this is called the steady-state infiltrability (Hillel, 1980 in Malmer and Grip, 1990). The maximum rate at which water can enter the soil surface is termed the infiltration capacity (f_m). The infiltration capacity diminishes over time in response to several factors that affect the downward movement of the wetting front (Brooks *et al*., 2003).

Soil compaction is a form of physical degradation resulting in the densification and distortion of the soil, which reduces biological activity, porosity, and permeability, strength is increased and soil structure partly destroyed (EC-JRC, 2010). Soil compaction can be defined as the increase in soil bulk density with a corresponding decrease in the void ratio. It can reduce the water infiltration capacity and increase the erosion risk by accelerating runoff. The relative amount of compaction can be expressed in terms of bulk density, porosity, infiltration capacity, or penetrometer resistance.

In the present study, field measurements of infiltration were made using a portable double-ring infiltrometer. The inner ring was 13 cm in diameter and 24 cm high, while the outer ring was 30 cm in diameter and 15 cm high. A total of 123 infiltrometer tests were performed in the 10 plots from the first year until 10 years after forest treatments began and in the 1 undisturbed forest (virgin forest) plot. In each plot, the infiltrometer test was performed at four locations with three repetitions based on differences in topography: a line-planted area, cleared area, logged area, and an area with skidder tracks, as shown in Figure 4.1. These test sites were selected using a random sampling method. The tests were conducted after a minimum of 2 days without rainfall. Measurements in the line-planted, cleared, and logged areas were conducted in July 2010; in the area with skidder tracks, they were conducted in September 2011.

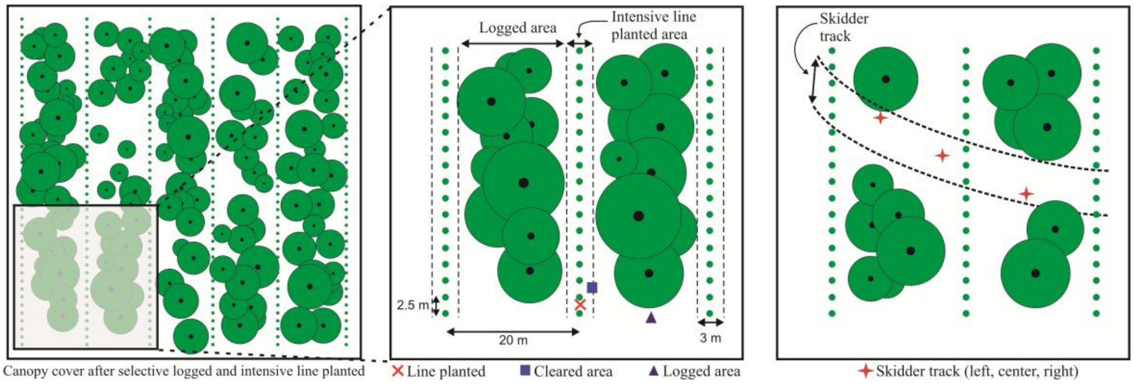


Figure 4.1 Infiltrometer test sites in line-planted, cleared, logged, and skidder-track areas.

Each infiltrometer was driven 10 cm into the ground by hammering a wooden platform placed on top of the device. Great care was taken to minimize soil disturbance within the inner ring. Water was added to both rings, but measurements were made only in the inner ring. The outer ring provided a buffer that reduced boundary effects caused by the cylinder and by lateral flow at the bottom of the ring. A plastic sheet was placed in the inner ring. The outer ring was filled with water to 5 cm and the water level was maintained. The inner ring was filled with water to give a pounding depth of 5 cm for the constant head of water at the skidder track, and of 10 cm for all other sites. The plastic sheet was removed and the level of water was recorded continuously every 10 min at the skidder track and every 15 min at all other sites. Cumulative infiltration and elapsed time were recorded over a 3–4 h period to ensure that steady-state infiltrability had been attained. The infiltrability (*IR*) was calculated from the cumulative infiltration as a function of time.

Using Horton's infiltration model, the infiltration capacity (f_m; in mm h^{-1}) at time t (h) can be described by:

$$fm = fc + \left(fo - fc\right) e^{-kt} \tag{1}$$

where f_o is initial infiltration capacity (mm h^{-1}), f_c is final equilibrium infiltration capacity (approaching constant) (mm h^{-1}), and k is a recession constant or the decreasing *IR* (mm h^{-1}).

The total infiltration F (mm) was calculated by:

$$F = \int_{o}^{t} fm \; dt = t\,(fc) + \left(\frac{fo - fc}{-k}\right)\left(e^{-kt} - 1\right) \tag{2}$$

The constant k was calculated by rearranging Eq. 1:

$$k = \left[\ln\left(fo - fc\right) - \ln\left(f - fc\right)\right] / t \tag{3}$$

The dry bulk density of soil was measured using undisturbed soil core samples and soil structure and texture were measured using disturbed soil samples. The sampling sites were the same as those for infiltration measurements (11 plots). Undisturbed soil samples were taken using thin-walled samplers (volume: 100 cm^3, inner diameter: 5 cm, height: 5.1 cm). The sharpened edge of the sampler was inserted vertically into 0–10 cm of the soil profile in each plot. During the process of insertion, roots and organic material were carefully severed from the soil layer around the sampler. Bulk density was measured as the mass of the 100 cm^3 core samples after drying for 24 h at 105°C. Particle density was measured using the pycnometer method, and total porosity was calculated as 1 – (bulk density/particle density). Soil structure and texture were determined by qualitative analysis in the laboratory.

4.2.2 Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_s) is a key property of the flowpaths of almost all modes of streamflow (Elsenbeer, 2001, Ziegler *et al*., 2004). This parameter was estimated from infiltration measurements taken in each plot, using the falling-head method (Jury et al., 1991).

$$K_s = \frac{L}{t_1} \ln\left(\frac{b_0 + L}{b_1 + L}\right) \tag{4}$$

where b_0 is ponded water in the soil column at t=0, b_1 is the height of ponded water at t, and L is the length of the soil column. An additional 32 undisturbed soil samples were collected from the plots. Sampling points at the skidder track plots were selected at locations aged 1–12 years after forest treatments began and eight soil core samples were taken from the virgin forest plot at soil depths of 0–10, 10–20, 20–30, 30–40, 40–50, 90–100, 120–130, and 150 cm.

In the laboratory, water retention test using pressure plate was used to measure the volumetric water content, θ. Undisturbed soil core samples were placed on an aluminum tray and were slowly saturated by adding water from the bottom over a 24 h period. Soil water retention curves were measured using the pressure plate method (Jury *et al*., 1991) for matric pressure heads (ψ) of -5, -10, -30, -60, -100, -150, -200, and -500 cm. After measuring the water content at ψ = -500 cm, the soil samples were resaturated from the bottom over a 24 h period.

Then the K_s of each sample was measured using the falling head method (Klute & Dirksen, 1986). The observed hydraulic data sets were analyzed using physical-based models for soil water retention and hydraulic conductivity functions using the lognormal distribution (LN) model (Kosugi, 1996). The LN model is effective for analyzing hydraulic properties and soil water movements in connection with the soil pore-size distribution (Kosugi, 1997a, b, c). Based on this model, water retention and hydraulic conductivity can be expressed as:

$$Se = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} = Q\left(\frac{\ln(\psi / \psi_m)}{\sigma}\right) \tag{5}$$

where S_e is the effective saturation; θ_s and θ_r are the saturated water content and residual water content, respectively; K_s is the saturated hydraulic conductivity; ψ_m is the matric potential head at an S_e of 0.5, which is related to the median pore radius by the capillary pressure function; σ (dimensionless) is the standard deviation of the log-transformed pore radius and represents the width of the pore radius distribution; and Q denotes the complementary normal distribution function (Kosugi, 1996).

The relationship between hydraulic conductivity K and ψ (Kosugi, 1996) was derived by substituting Eq. (5) into the pore structure model proposed by Mualem (1976):

$$K(\psi)=K_s\left\{Q\left[\frac{\ln(\psi/\psi_m)}{\sigma}\right]\right\}^{0.5}\left\{Q\left[\frac{\ln(\psi/\psi_m)}{\sigma}+\sigma\right]\right\}^{2} \tag{6}$$

Equations (5) and (6) produce adequate descriptions of the measured hydraulic properties of various field soils (Kosugi, 1997a,b,c, 2001). The LN model was used to obtain the best fit to the observed data sets. The best fit was achieved by minimizing the residual sum of squares (RSS) between the computed and measured θ and K values. To fit the water retention model to the observed water retention $\theta(\psi)$ curves, ψ_m and σ of the LN model were optimized by minimizing the RSS. θ_s was fixed at a maximum measured θ value for each soil.

A two-dimensional saturated soil water flow simulation using the Fortran program was applied to generate surface runoff from different periods of IFMS. Several parameters were set up for different periods of forest operation and different types of forest treatment. The main parameters of canopy cover, net rainfall, and K_s were used in simulations.

4.3. Results and Discussion

4.3.1 Infiltration capacity

IR curves against time four each of the four different sampling locations in the 11 plots are shown in Figure 4.2.

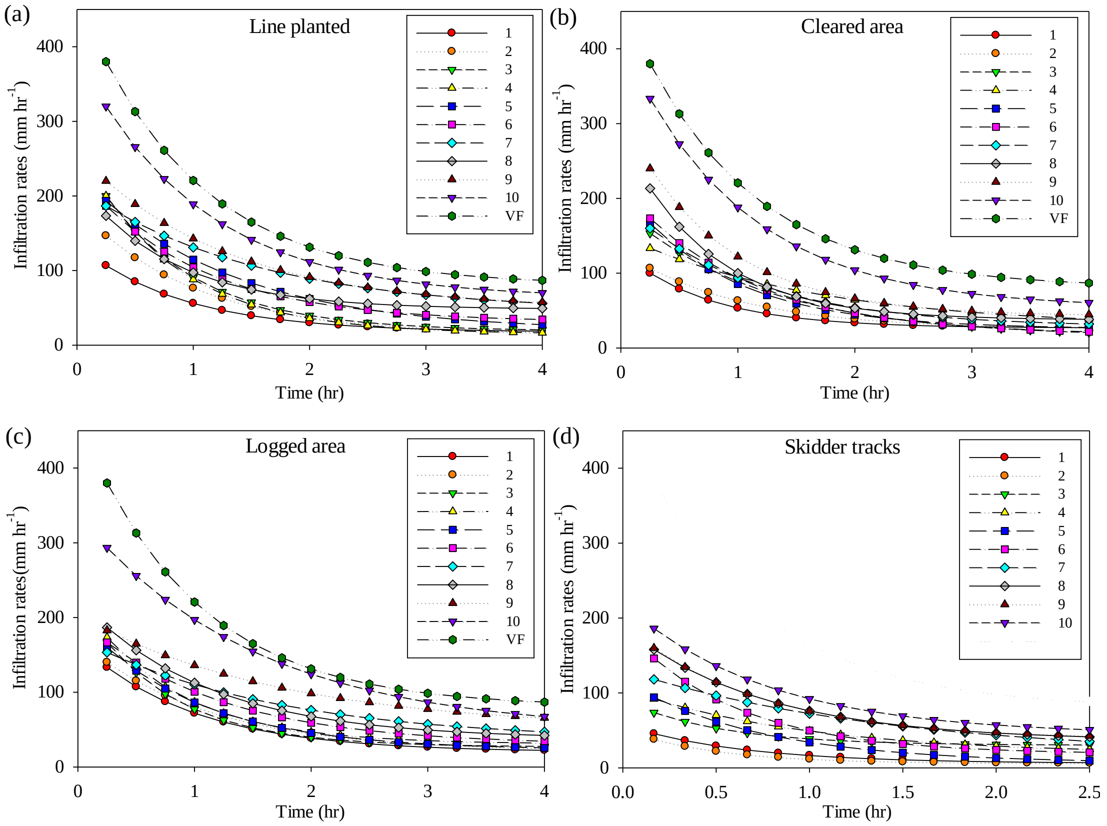


Figure 4.2 Calculated infiltration rates against time in 11 plots (numbers in the legend indicate the time [years] after IFMS treatment).

Selective logging and intensive line planting decreased IR especially at the beginning of the test. The steady state rate occurred over the range of 2.5–3.5 h. The virgin forest had the highest IR both at the beginning of the test (392 mm h^{-1}) and once it reached a steady state (80 mm h^{-1}); those in the line-planted, cleared, logged, and skidder-track areas were 360 and 64, 360 and 40, 260 and 40, and 240 and 36 mm h^{-1}, respectively. At the site 10 years after forest operations began the IR was substantially decreased both at the beginning of the test and at the steady state rate. The ranges of IR between the beginning of the test and the steady state after one year in the line-planted, cleared, logged, and skidder-track areas were 100 to 24 mm h^{-1}, 100 to 20 mm h^{-1}, 120 to 12 mm h^{-1} and 42 to 6 mm h^{-1}, respectively.

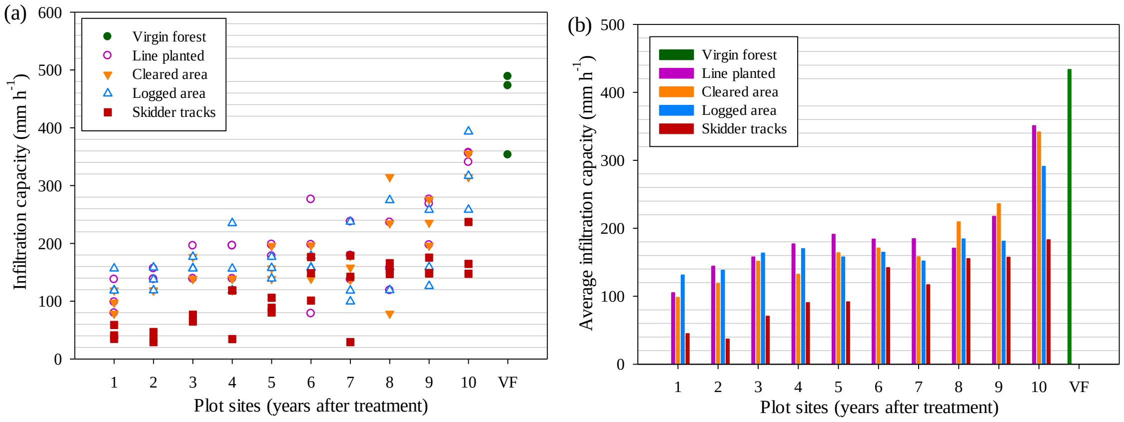


Figure 4.3 Infiltration capacity (*f_m*) of the 11 plots. (a) Data measurement distributions. (b) Average infiltration.

Figure 4.3 shows the average infiltration capacity (f_m) of each plot. The f_m of the line-planted, cleared, and logged areas were slightly different. That of the skidder tracks was lower than all other sites. Manual land clearing in the intensive line-planted area contributed to the soil compaction that reduced the f_m. In the logged area, the ground was affected by logs being pulled by the skidder tractor, which slightly lowered the f_m at the beginning of the test compared to the intensively line-planted area. The impact of mechanized logging significantly reduced the f_m curve from the beginning of the test until the steady state rate was achieved.

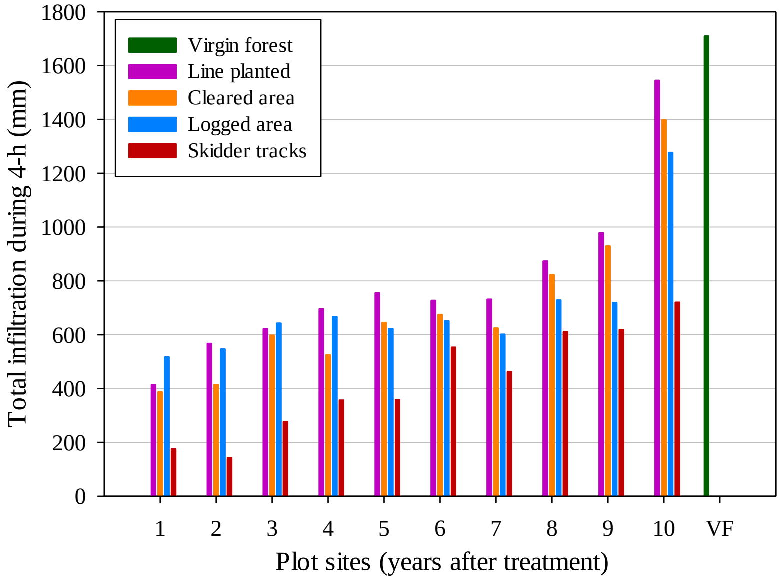


Figure 4.4 Total infiltration (*F*) during a 4 h period in each plot.

Total infiltration (*F*) in the virgin forest during a 4 h period was 1,709 mm. The *F* for the line-planted, cleared, and logged areas in 10-year-old sites was similar to that of the virgin forest, but dramatically different from that of the skidder-track area. The lowest *F* value of 2.4 mm was recorded at the skidder tracks after 2 years. Compared to virgin forest, the F values at the 1-year-old site were 57%, 72%, and 91% lower in the line planted, logged, and skidder track areas, respectively.

Activities that compact or alter the soil surface, such as driving tractors and pulling logs over the ground, can reduce the infiltration capacity of the soil. The direct impact of raindrops can also have an impact. Water infiltration depends largely on the pores present in the soil. Forest soils contain many macro-pores through which large quantities of water can move into the soil. Some macro-pores result from structural pores and cracks in the soil. The volume of these pores and their continuity determines the flow of water into the soil. Soil organic matter and soil texture are two important factors that determine soil *IR*. Organic matter helps to improve soil aggregation, which allows rapid water movement into the soil. The ages of trees are correlated with litter production. Forest litter layers physically protect the soil surface from extreme temperature and moisture, the impacts of raindrops, and erosion forces, improving *IRs*. Older trees tend to produce more litter, which contributes to the build-up of organic matter. Through the decomposition process, both litter quality and quantity influence the build-up of organic matter in the soil. Soil with a higher organic matter content will have a higher *IR* (Lado *et al*., 2004). In this study, the organic matter content in the site dating to 1999 was the highest and was close to that of the virgin forest because of the higher canopy density and decomposition rate of the litter.

Total water infiltration (Figure 4.4) varied according to the duration of IFMS operation, increasing from the 1-year-old site to the 10-year-old site, at which point it was similar to that of the virgin forest. This was because, when water is supplied to an initially dry soil, the suction gradient across the soil surface becomes very high, which results in a high *IR*. As the wetting front moves downward, the suction gradient across the soil profile decreases, which limits the *IR* of water into the soil surface. After a long time, the *IR* approaches zero. The decrease in *IR* may also be caused by the dispersion of soil aggregates, or slaking, as well as soil compaction and surface sealing or clogging of the soil pores (Iistedt *et al*., 2007). Pores in the soil become clogged when the soil pores are saturated with water. Pores in forest soils are always related to the trees in that particular forest. Depending on the age of the tree, the tree roots create pores and enlarge the existing pores as they grow. The standing trees in the 10-year-old site were bigger than those at the other sites. Their larger roots would have created larger pores, leading to rapid water movement. Therefore, it can be concluded that forest rehabilitation would recover the infiltration capacity of degraded areas. We estimate that infiltration capacity would recover to the level of a virgin forest in less than 15 years in the line-planted, cleared, and logged areas but after 20 years in the skidder track area, if allowed to recover.

4.3.2 Soil compaction

In general, at all test sites, soil bulk density increased after logging, with the largest difference observed in the skidder tracks (Figure 4.5). Selective logging using skid trails and tractor winches has opened and destroyed the soil surface over approximately 4–6% and 60–75% of the forested area, respectively. Manual land clearing for intensive line-planting has opened approximately 15–20% of the forested area. Tractor movement has significantly increased the soil compaction and reduced the infiltration capacity, especially along skid trails.

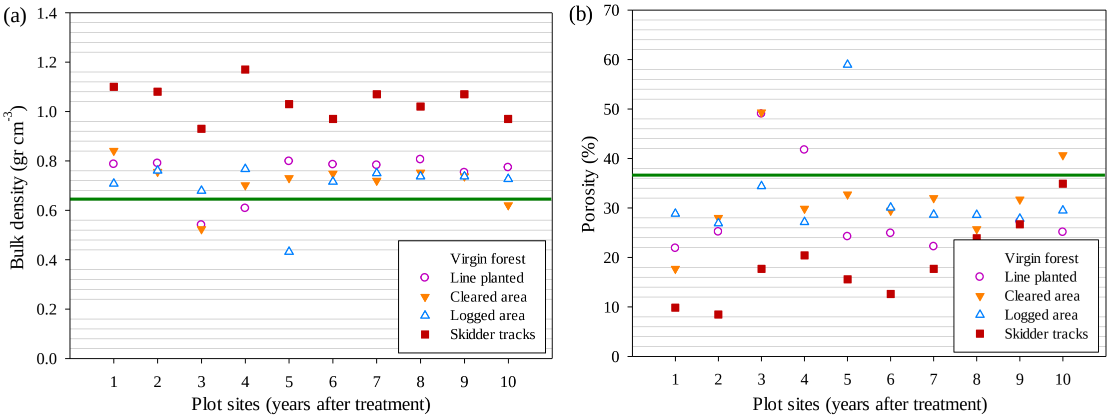


Figure 4.5 Physical characteristics of the soil: (a) bulk density; (b) porosity.

The soil structure at the 11 sites was dominated by angular blocky material and the soil texture was dominated by silty clays, which contained 40% or more clay and 40% or more silt (Table 4.2).

Table 4.1 Soil structure and soil texture

Test sites	Soil structure	Soil texture
1-year	Sub angular blocky	Silty clay
2-year	Angular blocky	Silty clay
3-year	Angular blocky	Silty clay
4-year	Sub angular blocky	Silty clay
5-year	Sub angular blocky	Silty clay loam
6-year	Angular blocky	Silty clay
7-year	Angular blocky	Silty clay
8-year	Angular blocky	Silty clay
9-year	Angular blocky	Silty clay
10-year	Sub angular blocky	Silty clay
Virgin forest	Angular blocky	Silty clay

The soil bulk density in the virgin forest was 0.636 g cm^{-3}. Selective logging and intensive line planting have increased the soil bulk densities in comparison to virgin forest. After timber was logged on the 1-year-old site, the soil bulk densities of the line-planted, cleared, logged, and skidder-track areas were 0.786, 0.841, 0.708, and 1.1 g cm^{-3}, respectively. Manual land clearing in the line-planted and cleared areas increased soil bulk density by 23–32%, whereas in the logged area by 11% and in the skidder tracks of mechanized logging increased by 73%.

In the 10-year-old site, the soil bulk densities of the line-planted, cleared, logged, and skidder-track areas were 0.773, 0.621, 0.727, and 0.97 g cm^{-3}, respectively. The values in the line-planted, cleared, and logged areas recovered to levels similar to that of virgin forest, but that for skidder-track areas was still 52% larger than that in virgin forest.

4.3.3 Soil hydraulic conductivity

Ground-based harvesting using a skidder tractor changes the soil hydraulic properties of forest soil. It decreases infiltration characteristics including *IR* (Figure 4.2), infiltration capacity (Figure 4.3), and F (Figure 4.5). Soil compaction due to their use also increases the dry bulk density and decreases soil porosity (Figure 4.5). Volumetric water content and hydraulic conductivity were analyzed to assess recovery across different forest management periods. Figure 4.6 shows water retention $\theta(\psi)$ curves for a skidder track area over 0–12 years after treatment.

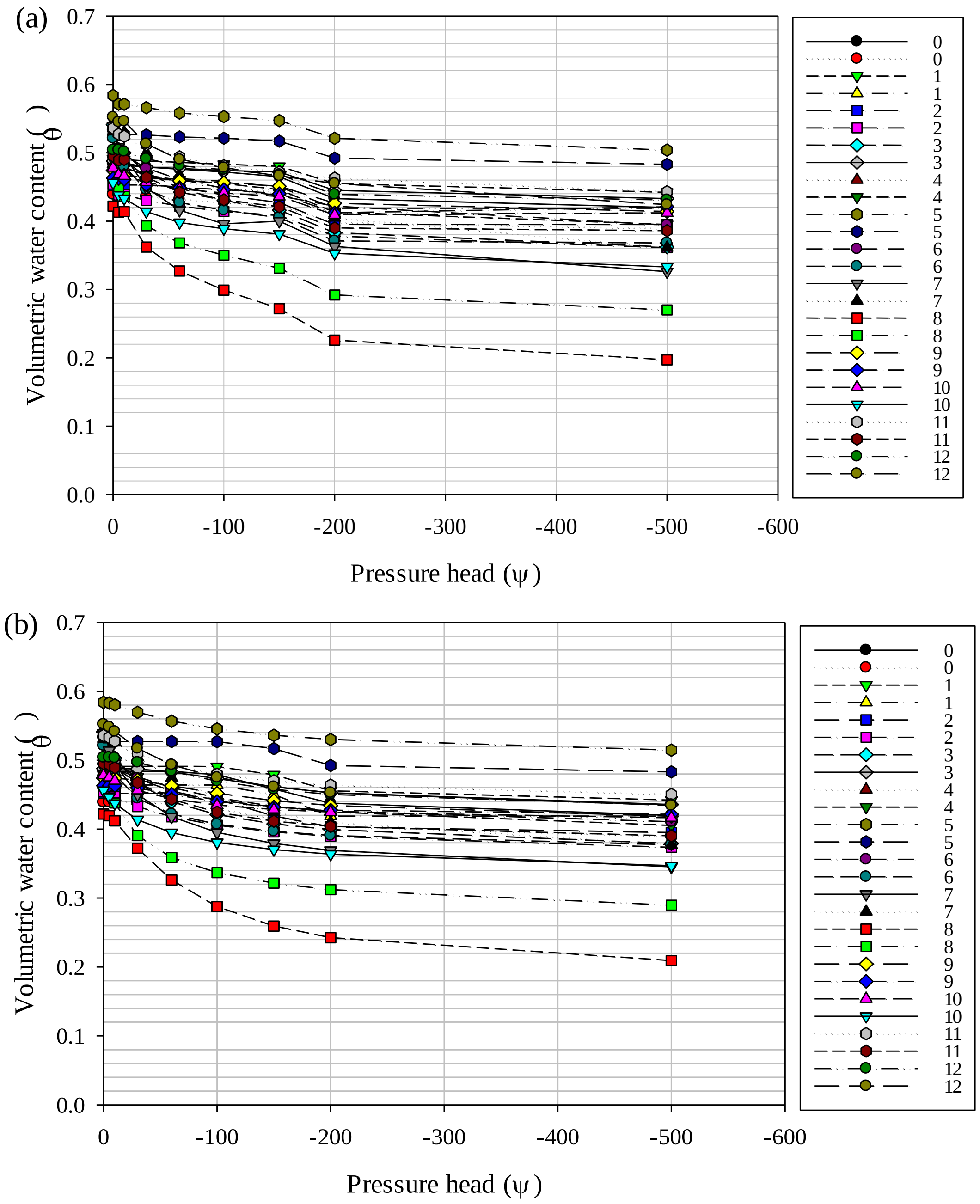


Figure 4.6 Water retention $\theta(\psi)$ curves for a skidder track area 0–12 years after IFMS treatment. (a) Observed $\theta(\psi)$. (b) Estimated $\theta(\psi)$.

No large differences were found between observed $\theta(\psi)$ and estimated $\theta(\psi)$. Water retention curves showed large changes in the range of $0 > \psi > -60$ cm. The greatest changes tended to occur in the 8-year-old site, indicating a lower soil moisture content and higher soil compaction at that site. The different θ values in the skidder track may be associated with different levels of soil compaction caused by different volumes of tractor traffic.

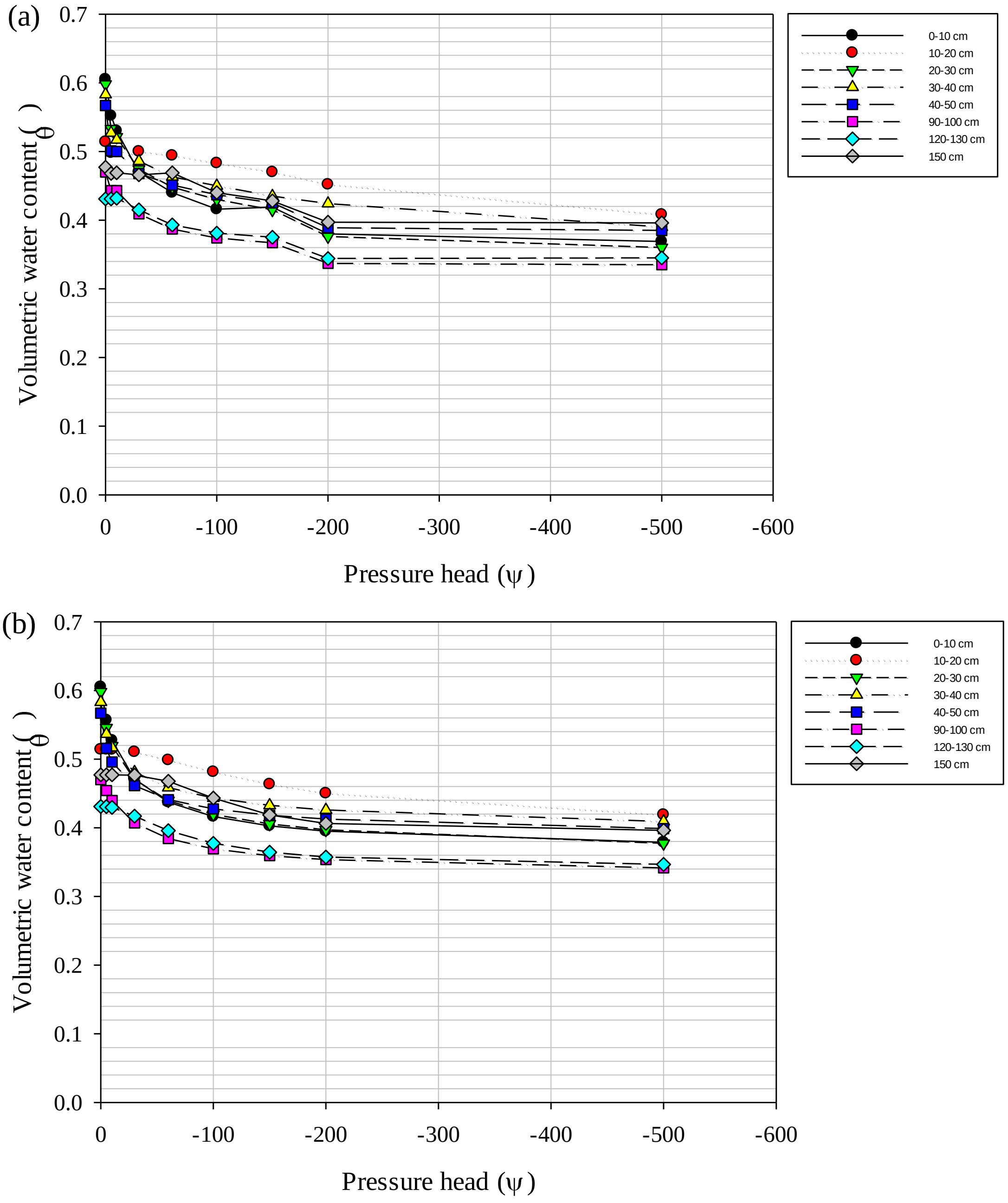


Figure 4.7 Water retention $\theta(\psi)$ curves in the virgin forest at different soil depths. (a) Observed $\theta(\psi)$. (b) Estimated $\theta(\psi)$.

Water retention curves in the virgin forest (Figure 4.7) showed large changes in the range of $0 > \psi > -30$ cm, indicating the existence of soil macropores. The curves for surface soils (0–50 cm deep) tended to show greater changes than subsurface soils (50–150 cm deep). In surface soil, there was intensive root growth that increased the number of macropores and the porosity.

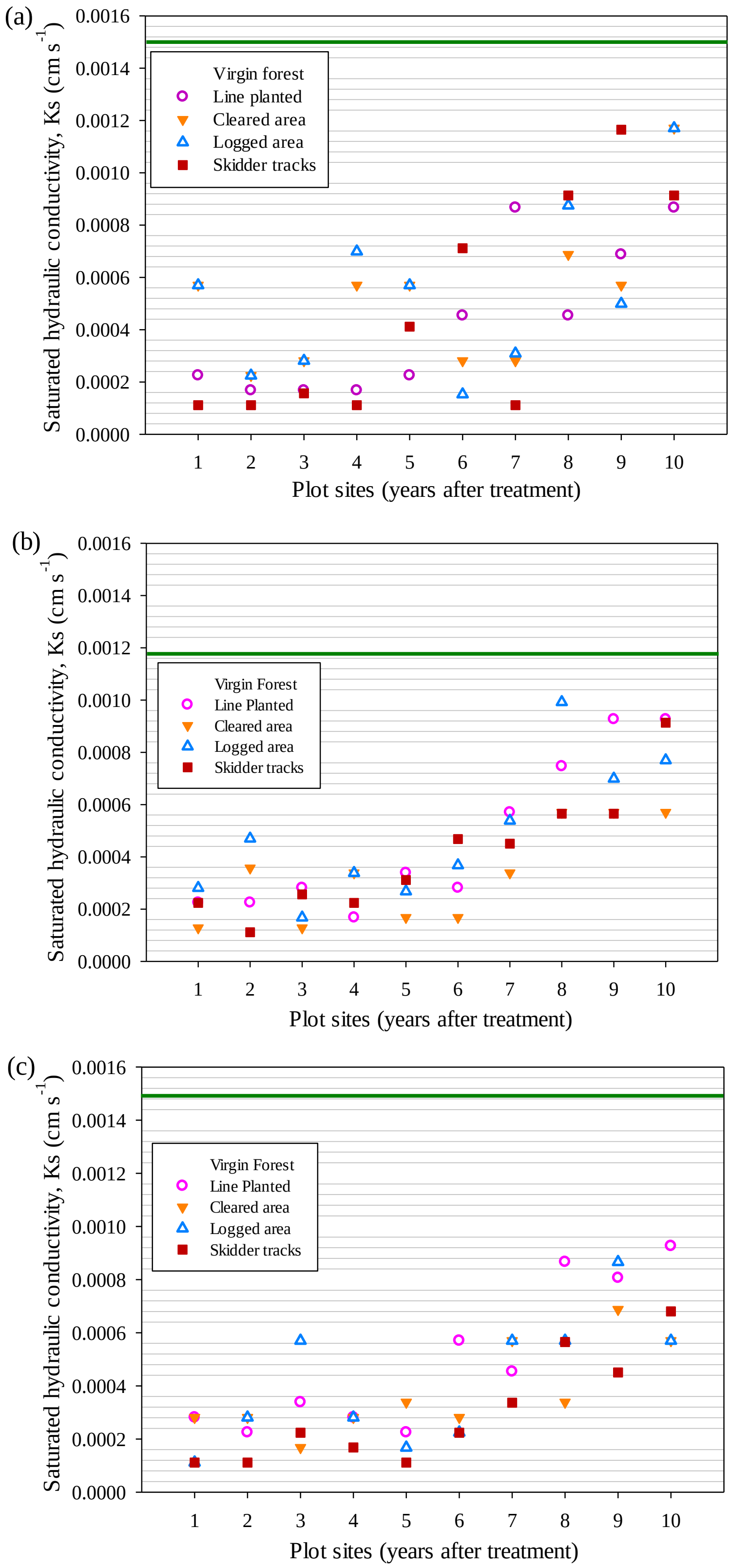


Figure 4.8 Saturated hydraulic conductivity (K_s) at all 11 plots, calculated from infiltration measurements taken in each area. (a) Upper slope. (b) Middle Slope. (c) Lower slope.

The saturated hydraulic conductivity (K_s) at different slope locations tended to increase according to site age, i.e., from the 1-year-old site to the 10-year-old site (Figure 4.8). Values were higher at upper slopes than in the middle and at lower slopes. Those in skidder tracks were lower than at other test sites especially in 7- to 10-year-old sites. The recovery of K_s tended to take longer in skidder tracks than in other areas. In 6- to 10-year-old sites, no large differences in K_s values were found between test plots. These results indicate that soil hydraulic conductivity needs at least 15 years of recovery time to reach the K_s levels of a virgin forest.

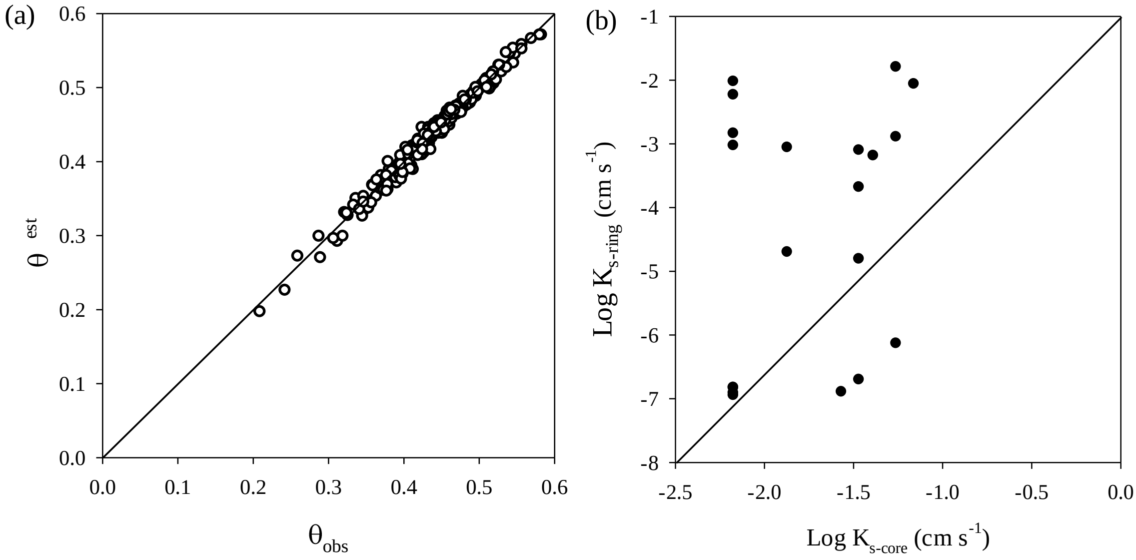


Figure 4.9 (a) Relationship between observed (θ_{obs}) and estimated (θ_{est}) water content. (b) Relationship between K_s measured using ring infiltrometer tests ($K_{s\text{-ring}}$) and soil core samples ($K_{s\text{-core}}$).

Figure 4.9a shows the relationship between observed and estimated θ using the LN model. There was good correspondence between observed and estimated values (data fall closely around 1:1 line), indicating that the retention model (Eq. 5) can adequately express the observed water retention curves. Figure 4.9b shows the relationship between K_s measured from the ring infiltrometer test ($K_{s\text{-ring}}$) and soil core samples ($K_{s\text{-core}}$). The data are widely scattered, which indicates that the results from the infiltrometer tests did not adequately correspond to the K_s values from soil core samples. This may be due to several factors, such as the different locations, sample size, time period, and the different number of samples. Direct measurements of K_s (either in the laboratory using soil core samples previously taken from the field, or directly in the field without removing a soil sample) are preferred to indirect methods (derived from soil textural characteristics).

Field methods provide data that better represent the reality of water flow in natural conditions.

4.3.4 Saturated hydraulic conductivity to generate surface runoff

Measurements of saturated hydraulic conductivity (K_s) following the various surface disturbances were used to assess the influence of forest fragmentation on the near-surface hydrologic response. Forest fragmentation results in a mosaic of surfaces with distinct infiltration characteristics. Water discharge in a forested catchment includes vertical drainage in surface soil and downslope drainage in subsurface soil (Figure 4.10).

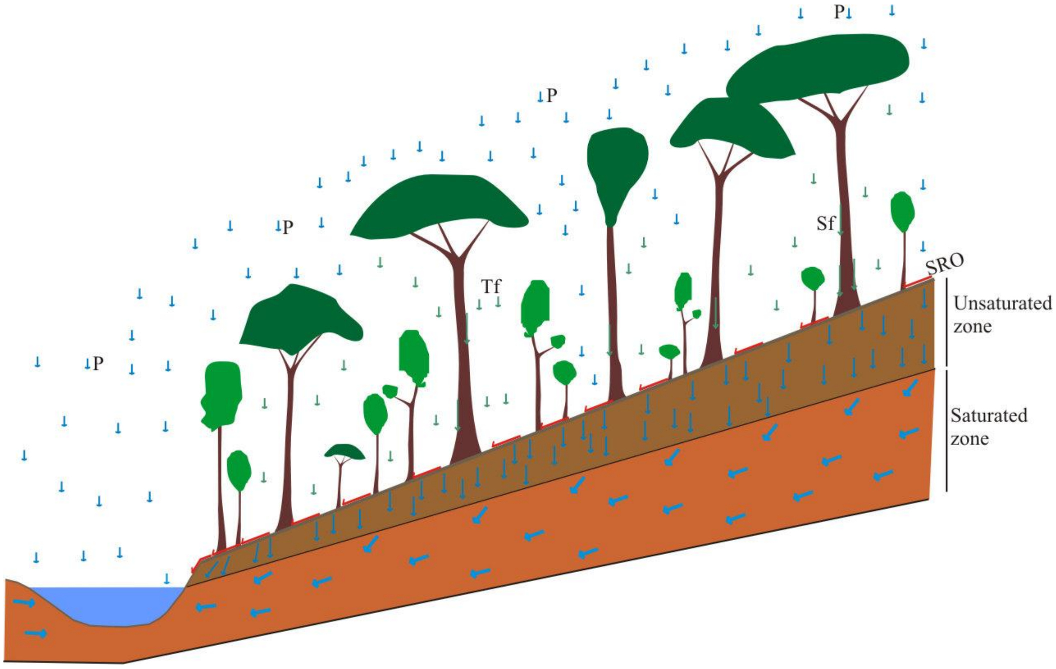


Figure 4.10 The process of water discharge in a forested catchment.

In vertical drainage, rainfall is supplied to the soil surface and infiltrates the soil profile unless the rainfall intensity is greater than the soil permeability. The water moves vertically in surface soil (unsaturated zone) and discharges at the bottom of the soil profile. Vertical drainage is considered an input into subsurface soil (saturated zone).

Different degrees of canopy cover lead to different levels of canopy interception. In the present study, canopy cover density between plots was measured from a 1 ha permanent sample plot (PSP). Each plot was established with three sets of PSPs. The average canopy cover density between plots is shown in Figure 4.11.

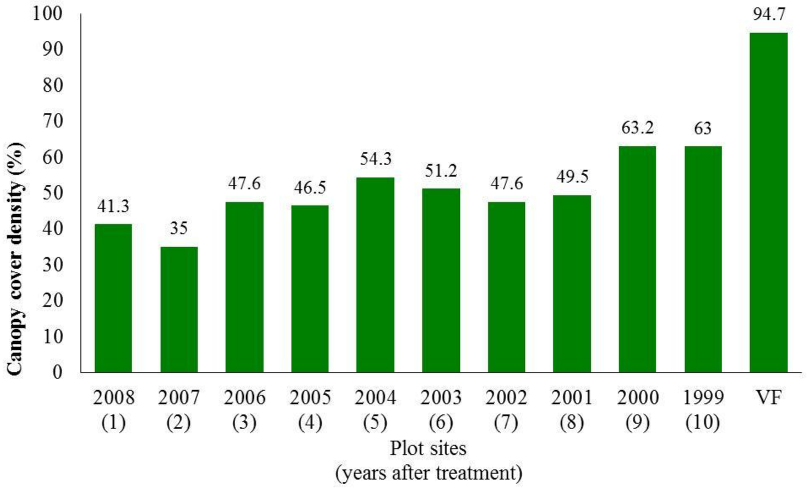


Figure 4.11 Average canopy cover density measured in permanent sample plots at different sites. The data were assumed to represent a logged area.

Canopy cover density influences the net rainfall that reaches the forest floor. To determine the variation in net rainfall between plots under the different treatments (line-planted, cleared, logged, and skidder-tracked areas), an assumption was developed as shown in Figure 4.12.

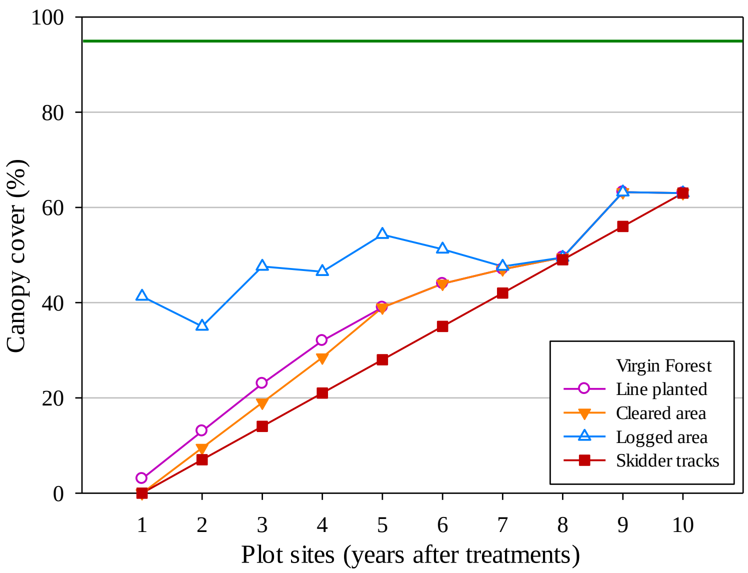


Figure 4.11 Canopy cover in the plot sites at different forestry treatments.

Figure 4.11 was developed based on the PSP measurements and field observations. The canopy covers for line-planted, cleared, and skidder-tracked areas were assumed to be similar to those of logged areas in the 8- to 10-year-old sites. In the 5- to 7-year-old sites, canopy cover in cleared areas was assumed to be similar to that of line-planted areas. The data on the canopy cover of line-planted areas, when plotted on a graph, followed a curved line that was assumed to represent a vegetation growth curve. In 1- to 4-year-old sites, there were different canopy covers between line-planted and cleared areas, with line-planted areas having more canopy cover than cleared areas that had 1–4 years of succession. No vegetation planted at skidder tracks, so the canopy cover at skidder tracks affected from surrounding vegetation. Therefore, the canopy cover at skidder tracks in 1-to 10-year-old sites is assumed in straight line.

The soil hydraulic properties determined as described above were used to generate surface runoff (SRO) values (Table 4.2), based on the assumption that the surface soil disturbance from IFMS operations affected the K_s at 0–15 cm soil depth.

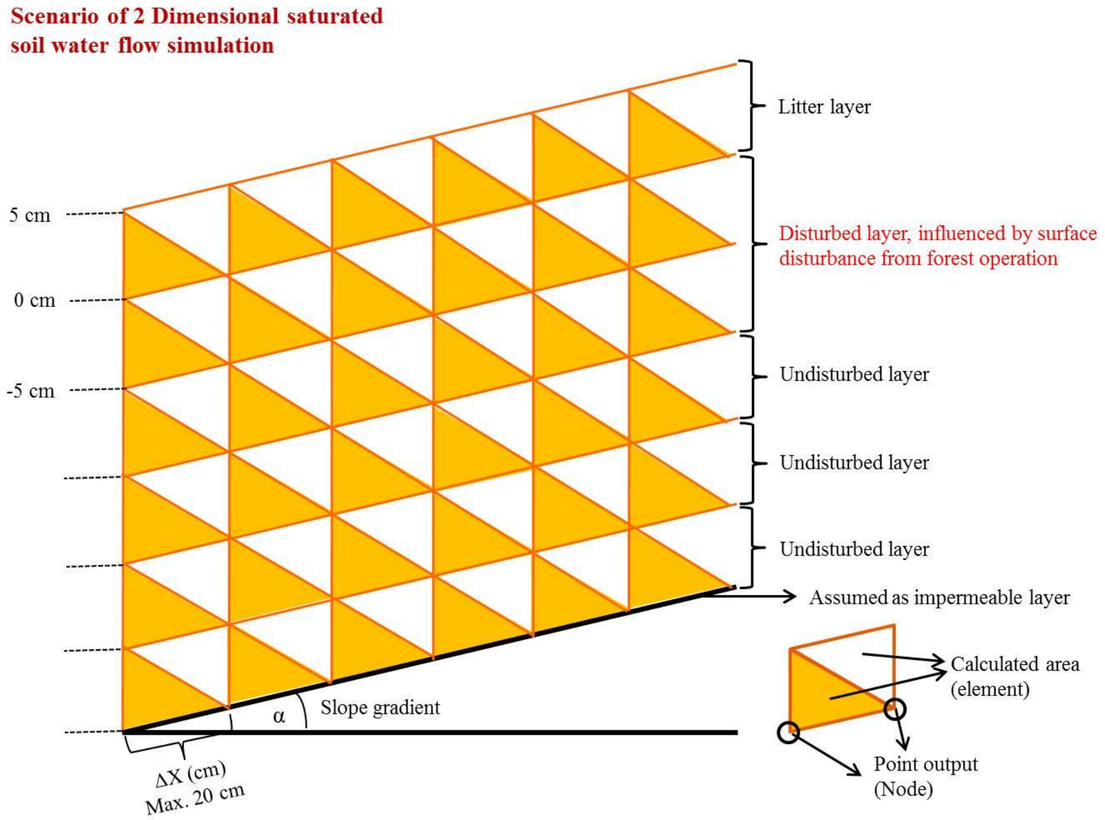


Figure 4.12 Scenario setting for surface runoff simulation.

Table 4.2 Observed soil hydraulic properties in different periods and test sites under IFMS treatment.

Test sites	Plot sites	K_s	Ψ_m	θ_r	σ	θ_e
Line planted	1-year	0.0002	-51.7840	0.3485	1.5910	0.1512
	2-year	0.0002	-53.3802	0.3515	1.5603	0.1482
	3-year	0.0003	-51.4185	0.3478	1.5982	0.1519
	4-year	0.0002	-53.5833	0.3519	1.5565	0.1479
	5-year	0.0003	-51.2237	0.3474	1.6020	0.1523
	6-year	0.0004	-47.0335	0.3389	1.6882	0.1608
	7-year	0.0006	-44.0213	0.3324	1.7551	0.1673
	8-year	0.0007	-43.3268	0.3308	1.7711	0.1689
	9-year	0.0008	-41.9226	0.3275	1.8044	0.1722
	10-year	0.0009	-41.0198	0.3254	1.8264	0.1743
cleared area	1-year	0.0004	-48.3744	0.3417	1.6598	0.1580
	2-year	0.0003	-49.0211	0.3430	1.6464	0.1567
	3-year	0.0002	-53.5833	0.3519	1.5565	0.1479
	4-year	0.0004	-47.8510	0.3406	1.6708	0.1591
	5-year	0.0003	-49.3260	0.3437	1.6401	0.1561
	6-year	0.0002	-51.9810	0.3488	1.5872	0.1509
	7-year	0.0004	-47.8510	0.3406	1.6708	0.1591
	8-year	0.0005	-45.3997	0.3354	1.7239	0.1643
	9-year	0.0006	-44.0285	0.3324	1.7549	0.1673
	10-year	0.0007	-42.6708	0.3293	1.7865	0.1704
Logged area	1-year	0.0002	-52.6517	0.3501	1.5742	0.1496
	2-year	0.0003	-49.8810	0.3448	1.6288	0.1549
	3-year	0.0003	-48.8732	0.3427	1.6494	0.1570
	4-year	0.0004	-47.0335	0.3389	1.6882	0.1608
	5-year	0.0003	-50.5322	0.3460	1.6157	0.1537
	6-year	0.0004	-47.6623	0.3403	1.6748	0.1595
	7-year	0.0005	-45.9036	0.3365	1.7128	0.1632
	8-year	0.0005	-45.1193	0.3348	1.7302	0.1649
	9-year	0.0007	-42.7485	0.3295	1.7847	0.1702
	10-year	0.0007	-43.4338	0.3311	1.7686	0.1687
skidder tracks	1-year	0.0001	-56.9932	0.3580	1.4942	0.1417
	2-year	0.0001	-59.3777	0.3620	1.4528	0.1377
	3-year	0.0004	-47.0833	0.3390	1.6871	0.1607
	4-year	0.0003	-51.2387	0.3474	1.6017	0.1523
	5-year	0.0001	-59.3777	0.3620	1.4528	0.1377
	6-year	0.0003	-51.2387	0.3474	1.6017	0.1523
	7-year	0.0003	-51.2491	0.3474	1.6015	0.1523
	8-year	0.0007	-43.3423	0.3308	1.7708	0.1689
	9-year	0.0007	-43.3331	0.3308	1.7710	0.1689
	10-year	0.0008	-41.6762	0.3270	1.8104	0.1727
Virgin forest	top soil	0.0012	-39.2047	0.3209	1.8721	0.1788
	20-30 cm	0.0006	-44.0910	0.3325	1.7535	0.1672
	30-40 cm	0.0005	-44.9986	0.3346	1.7329	0.1652
	40-50 cm	0.0006	-44.3201	0.3331	1.7482	0.1667
	90-100 cm	0.0008	-41.8066	0.3273	1.8072	0.1724

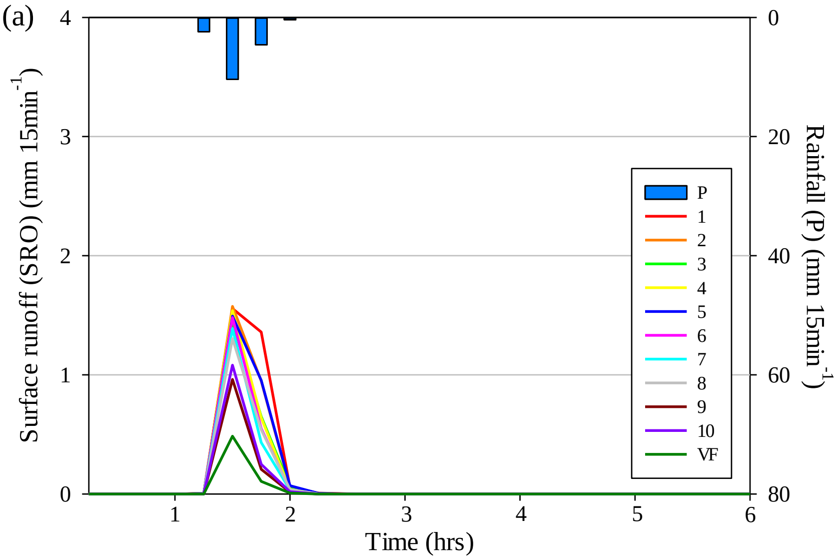
Table 4.2 shows all of the observed K_s values at different periods and test sites of IFMS treatment. The values were lower for all test sites than for the virgin forest, further confirming that surface soil disturbances reduce the K_s value. The soil hydraulic properties shown in Table 4.2 were used to estimate surface runoff flow.

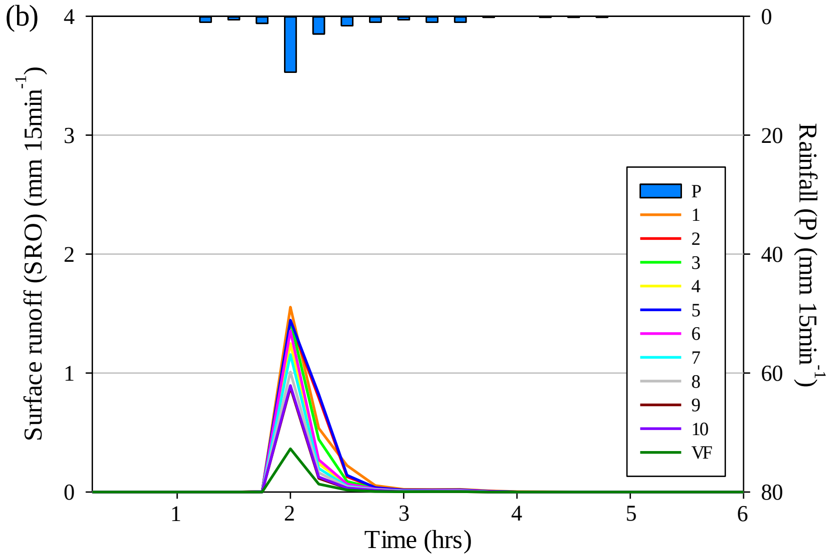
4.3.4.1 Surface runoff in different forest operation.

This simulation combined each treatment area as shown in Figure 4.13. The slope gradient was assumed to be 30°, as average slope gradient in the study sites.

Figure 4.13 Simulation scenario of surface runoff flow in different periods of forest operation.

Several rainfall events (17.8, 21.2, 27.2, 29.2, 37.6, 41.4, 53.4 and 66.6 mm) were used to generate the surface runoff hydrograph shown in Figure 4.14.




(b)
Surface runoff (SRO) (mm 15min^{-1})
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Rainfall (P) (mm 15min^{-1})
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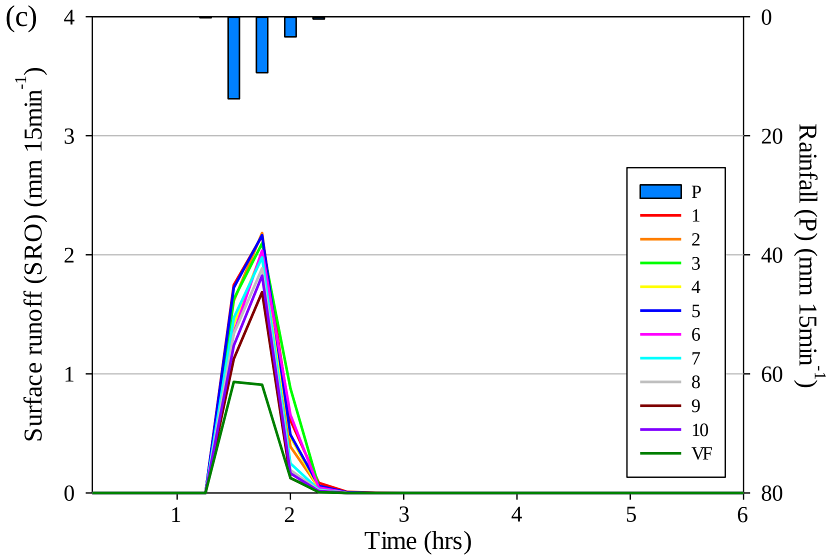
(c)
Surface runoff (SRO) (mm 15min^{-1})
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Rainfall (P) (mm 15min^{-1})
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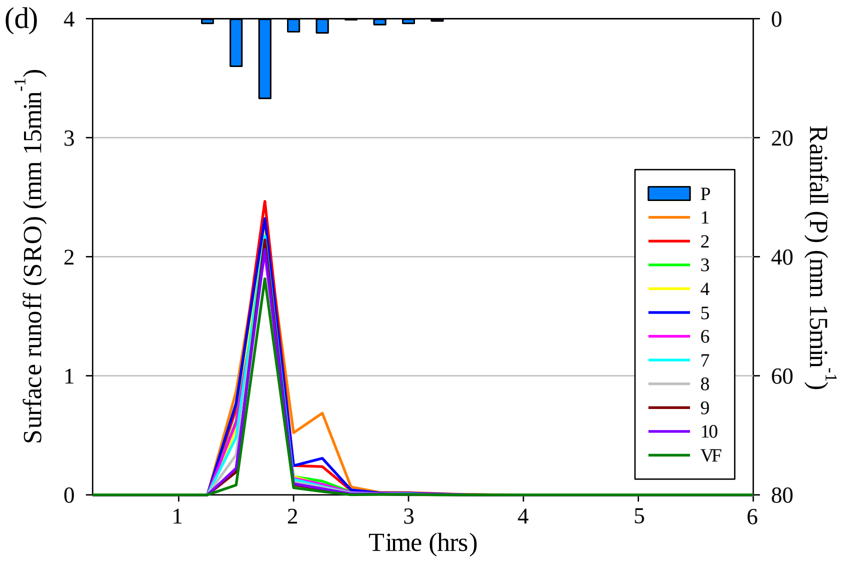
(d)
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Rainfall (P) (mm 15min^{-1})
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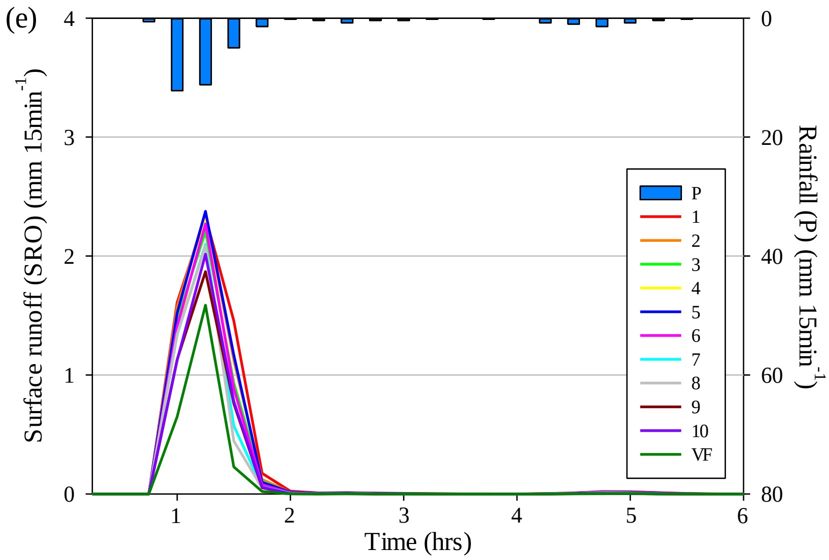
(e)
Surface runoff (SRO) (mm 15min^{-1})
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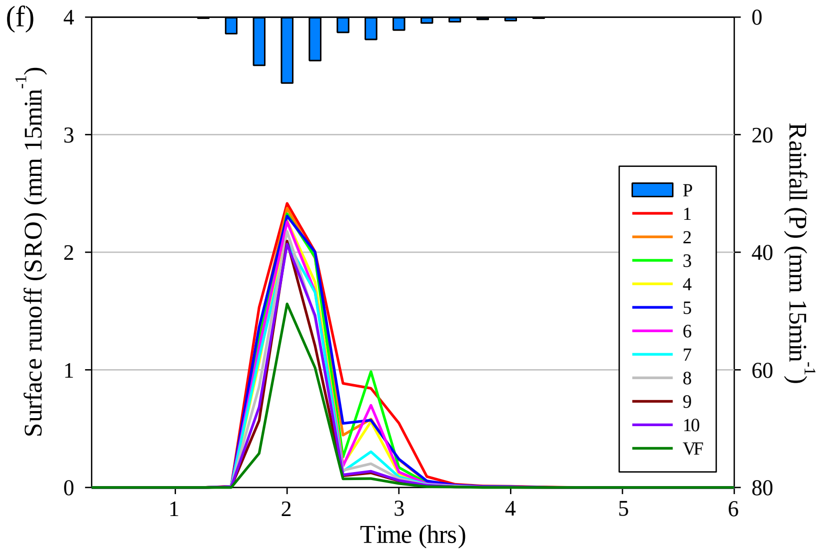
(f)
Surface runoff (SRO) (mm 15min^{-1})
Rainfall (P) (mm 15min^{-1})
Time (hrs)
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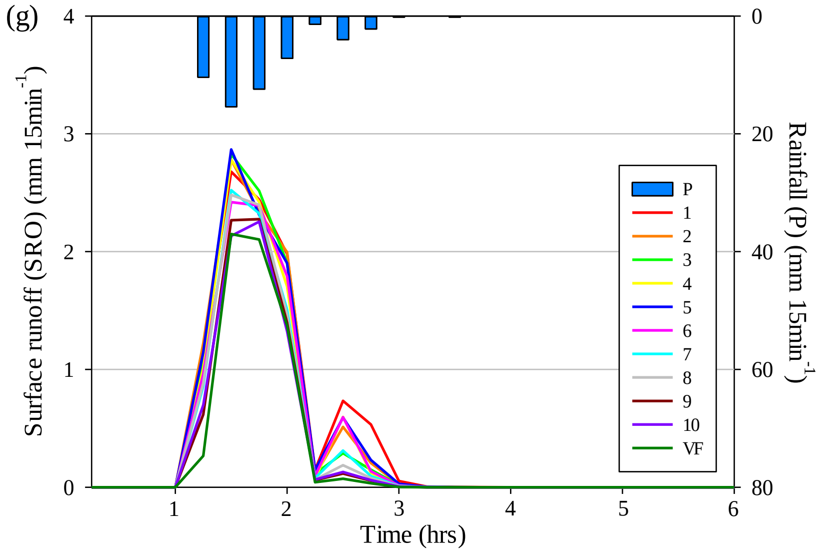
(g)
Surface runoff (SRO) (mm 15min^{-1})
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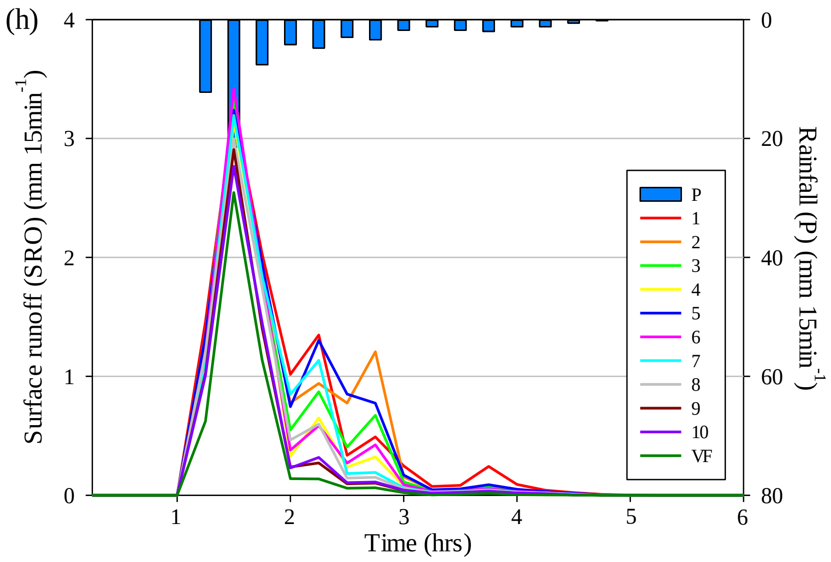


Figure 4.14 Surface runoff hydrograph generated from rainfall events of: (a) 17.8 mm, (b) 21.2 mm, (c) 27.2 mm, (d) 29.2 mm, (e) 37.6 mm, (f) 41.4 mm, (g) 53.4, and (h) 66.6 mm.

The SRO hydrograph indicated that there was a significant difference between plots during rainfall events (Figure 4.14). A dramatic difference was apparent between the virgin forest (VF) site and 1-year-old site. 10 years after logging operations were ceased and vegetation was allowed to recover, differences were still found in the hydrograph between the VF site and 10-year-old site. This indicates that surface disturbances at that site in the 10-year-old site still affected the hydraulic properties of the forest soil at the time of this study. Low peak rainfall intensity (Ip) produced a lower peak discharge (Qp) in the VF site that was significantly different than the hydrographs at the other sites (Figure 4.14a, b, c and f). Higher Ip produced a higher Qp in the VF site and tended to be similar to the other sites (Figure 4.14d, e, g and h).

Figure 4.15 shows the relationship between Ip and Qp, and Figure 4.16 shows the relationship between rainfall and total SRO.

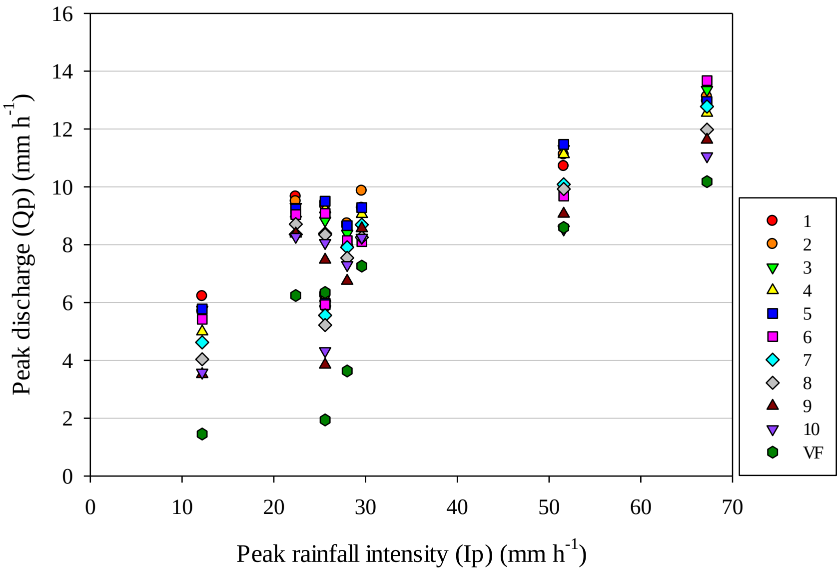


Figure 4.15 Relationship between peak rainfall intensity and peak discharge,

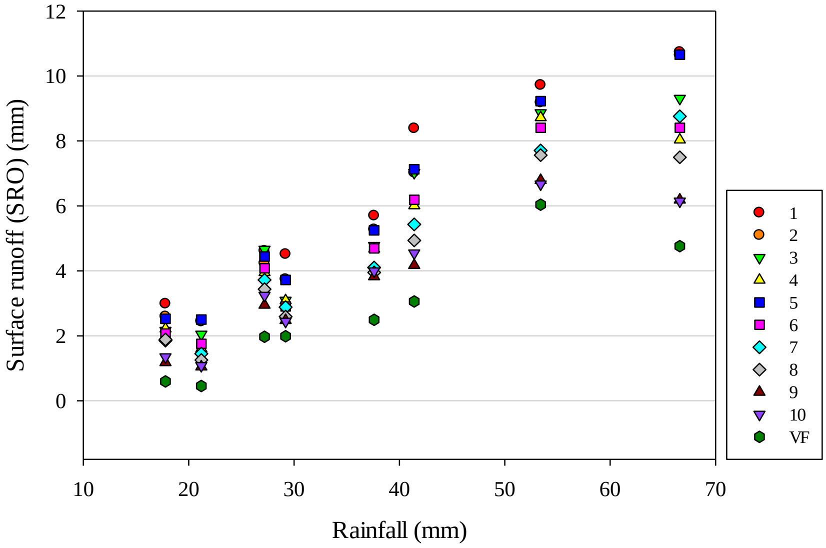


Figure 4.16 Relationship between rainfall and surface runoff.

Figures 4.15 and 4.16 show the data on SRO at all sites over different rainfall events. IFMS treatment changed the vertical drainage in surface soil.

For a Ip of less than 30 mm h^{-1}, the relationship between Ip and Qp revealed large differences of Qp between the VF site and disturbed sites (Figure 4.15). When the Ip exceeded 30 mm h^{-1}, no large differences were found between the plots. This indicates that forest interception (include canopy interception and forest floor interception) in the VF site has contributed to reduce the Qp, particularly for a Ip of less than 30 mm h^{-1}.

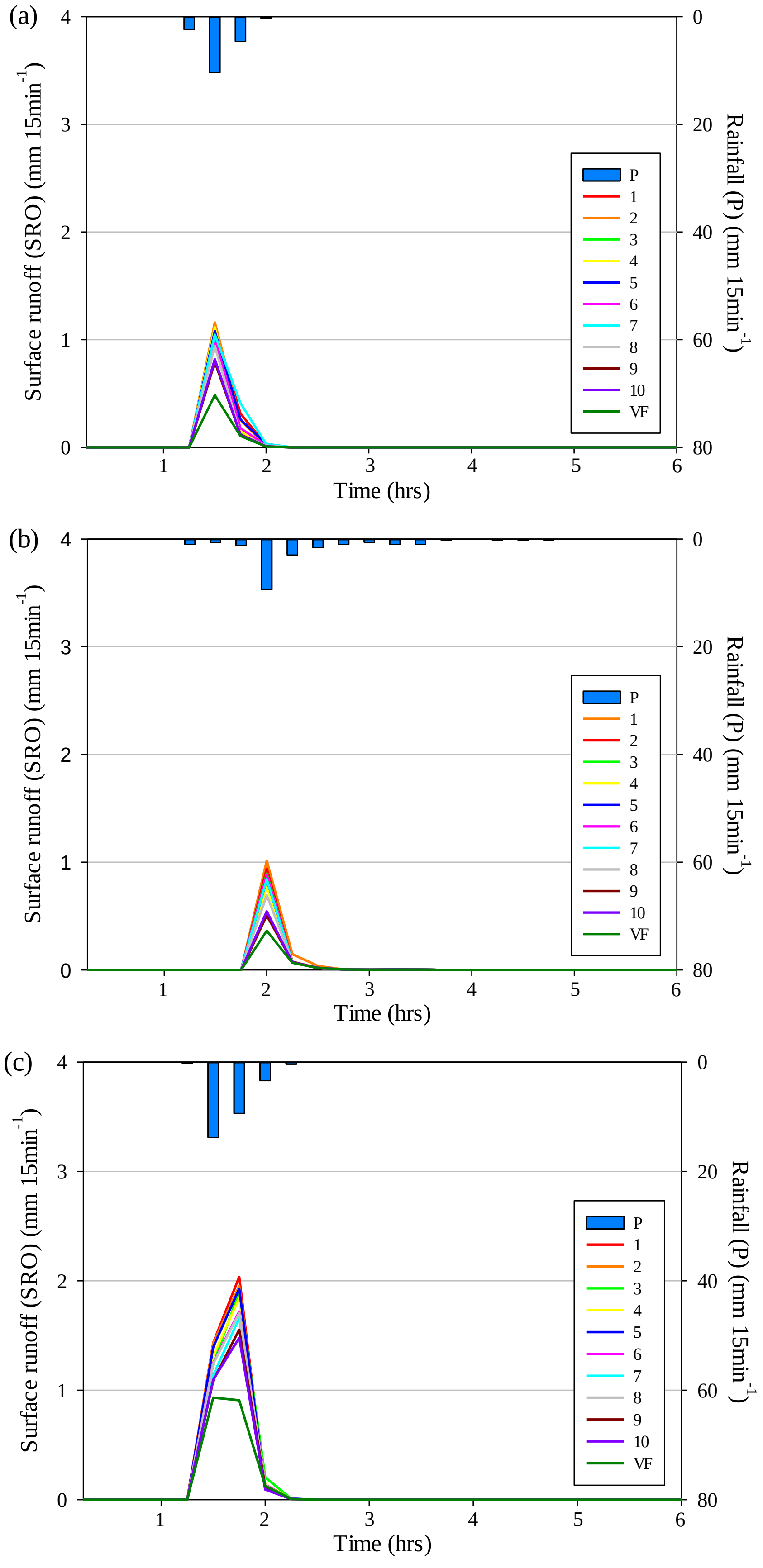
In the VF site, the average canopy interception was 23.8% of rainfall and the average forest interception was 91.7% (Suryatmojo *et al*., 2011).

Figure 4.16 showed that when the amount rainfall was less than 40 mm, the relationship between rainfall amount and total SRO revealed no large differences of SRO between the VF site and disturbed sites, with the lowest value recorded in VF site. When the amount of rainfall exceeded 40 mm, large differences were found between the plots. Greater rainfall produced greater differences between VF site and disturbed sites. This also indicates that forest interception in the VF site has contributed to reduce the SRO, particularly for a rainfall amount of less than 40 mm. A higher canopy density contributes to capture and stored the rainfall in the canopy layer. Undisturbed forest soil contributes to infiltrates the net rainfall and reduces the SRO.

4.3.4.2 Effectiveness of a river buffer on surface runoff flow

River buffer is used to reduce the impact of logging on runoff and erosion. This simulation combined buffer area in each treatment area as shown in Figure 4.17. The slope angle was assumed to be 30°. Several rainfall events (17.8, 21.2, 27.2, 29.2, 37.6, 41.4, 53.4 and 66.6 mm) were used to generate the surface runoff hydrograph shown in Figure 4.18.

Figure 4.17 Simulation scenario of the effectiveness of a river buffer on surface runoff flow.

(a)
Surface runoff (SRO) (mm 15min^{-1})
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Surface runoff (SRO) (mm 15min^{-1})
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Rainfall (P) (mm 15min^{-1})
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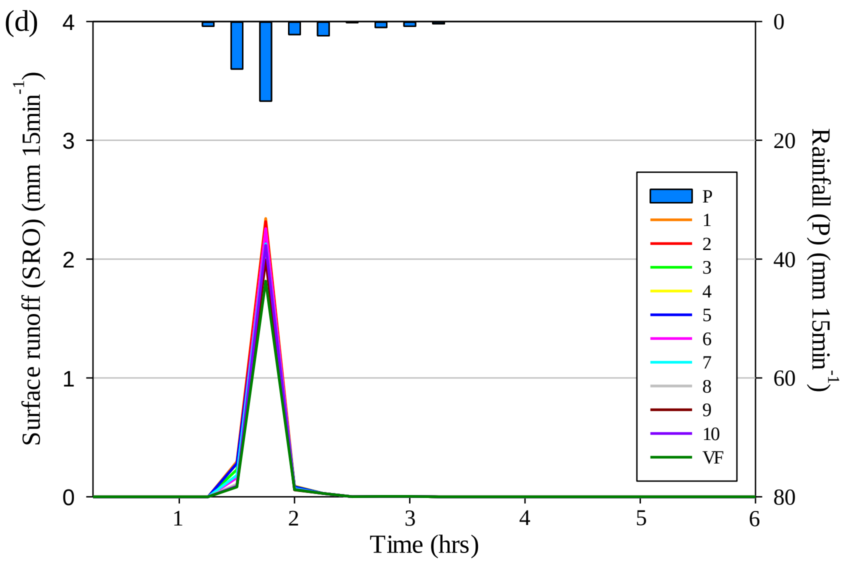
(d)
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Rainfall (P) (mm 15min^{-1})
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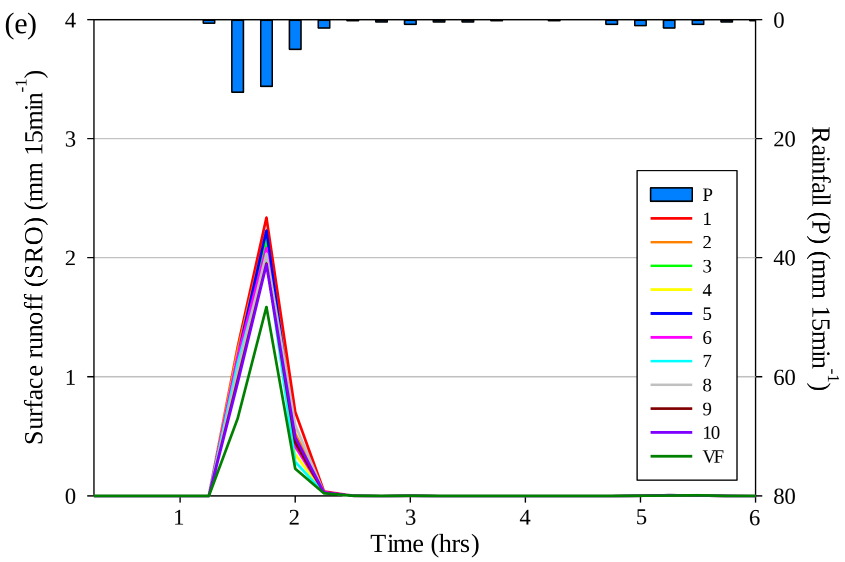
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Surface runoff (SRO) (mm 15min^{-1})
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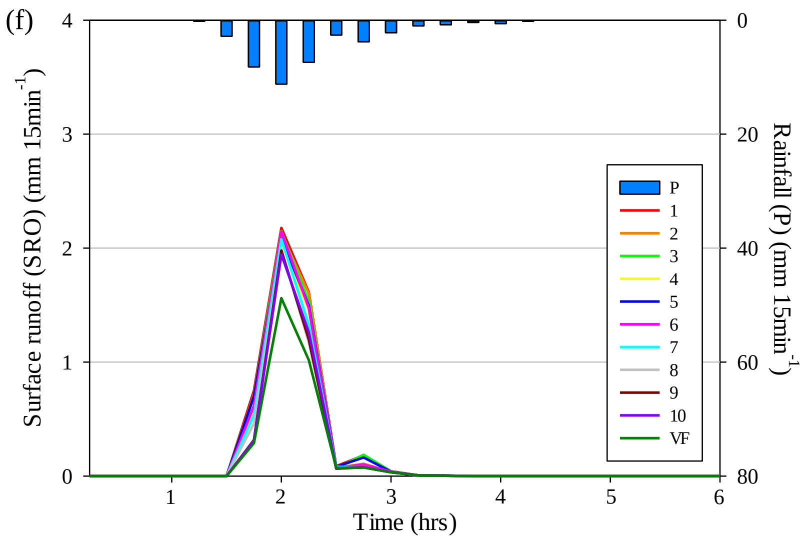
(f)
Surface runoff (SRO) (mm 15min^{-1})
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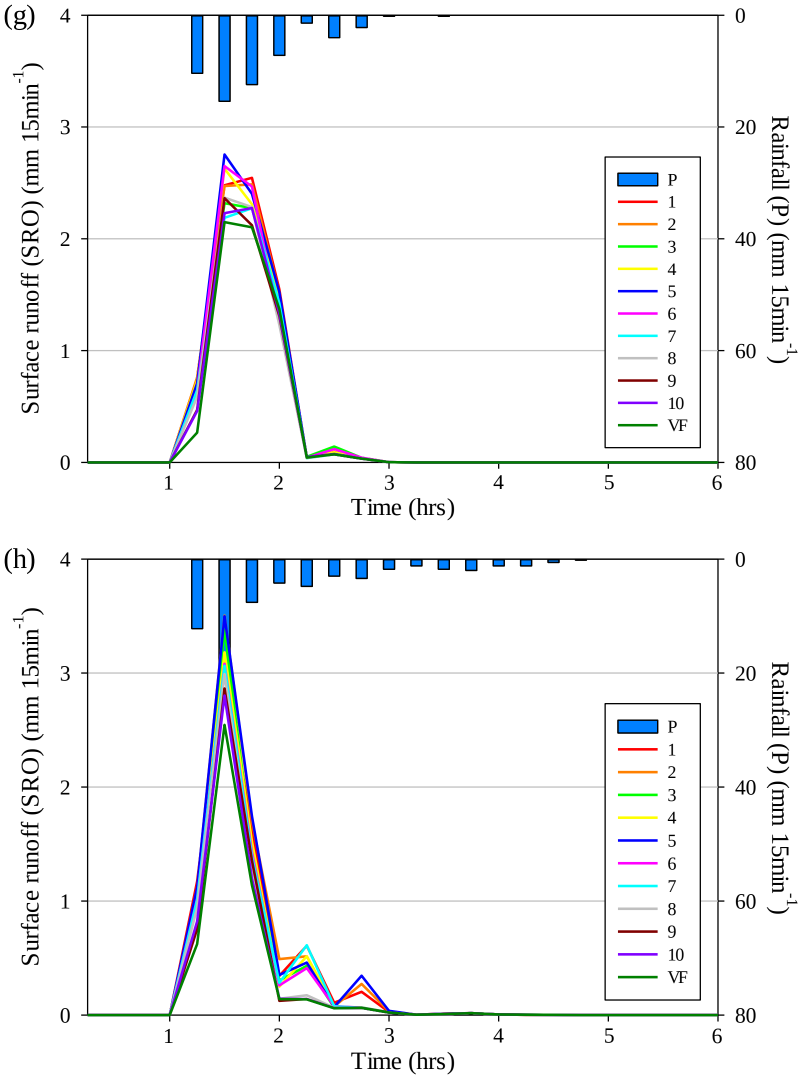

Figure 4.18 Surface runoff hydrograph generated from rainfall events. (a) 17.8 mm, (b) 21.2 mm, (c) 27.2 mm, (d) 29.2 mm, (e) 37.6 mm, (f) 41.4 mm, (g) 53.4, and (h) 66.6 mm.

As shown in Figures 4.14 and 4.18, there were clear differences in the surface runoff hydrograph between scenarios with and without the use of a buffer. The SRO hydrograph indicated that there was a significant difference between plots during rainfall events (Figure 4.18). The difference between the VF site and 10-year-old site were slightly smaller than that in the scenario without buffer area (Figure 4.14). This indicates that buffer area have significant influence in reducing the SRO hydrograph in the disturbed sites. Figure 4.19 shows the relationship between peak rainfall intensity and Qp, and Figure 4.16 shows the relationship between rainfall and total SRO.

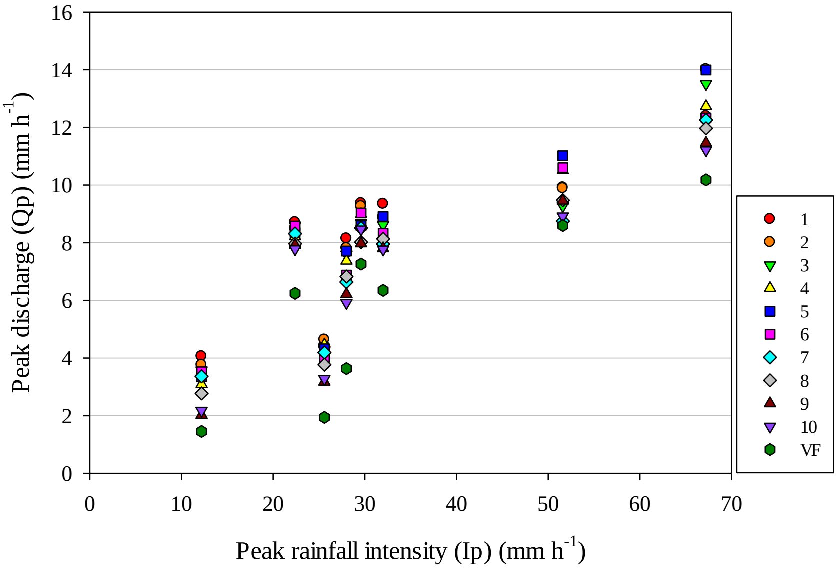

Figure 4.19 Relationship between peak rainfall intensity and peak discharge.

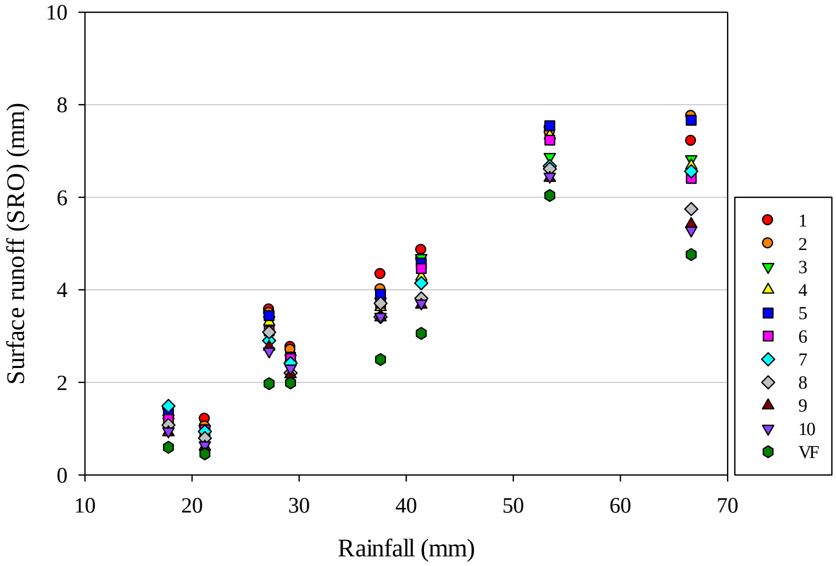

Figure 4.20 Relationship between rainfall and surface runoff.

Figures 4.19, and 4.20 show the data on surface runoff at all sites over different rainfall events. The relationships between Ip-Qp and rainfall-SRO showed the same trend as in the scenario without a buffer area, but different in the gap between VF site and disturbed sites. To clarify the differences, direct comparison was presented in Figures 4.21 and 4.22.

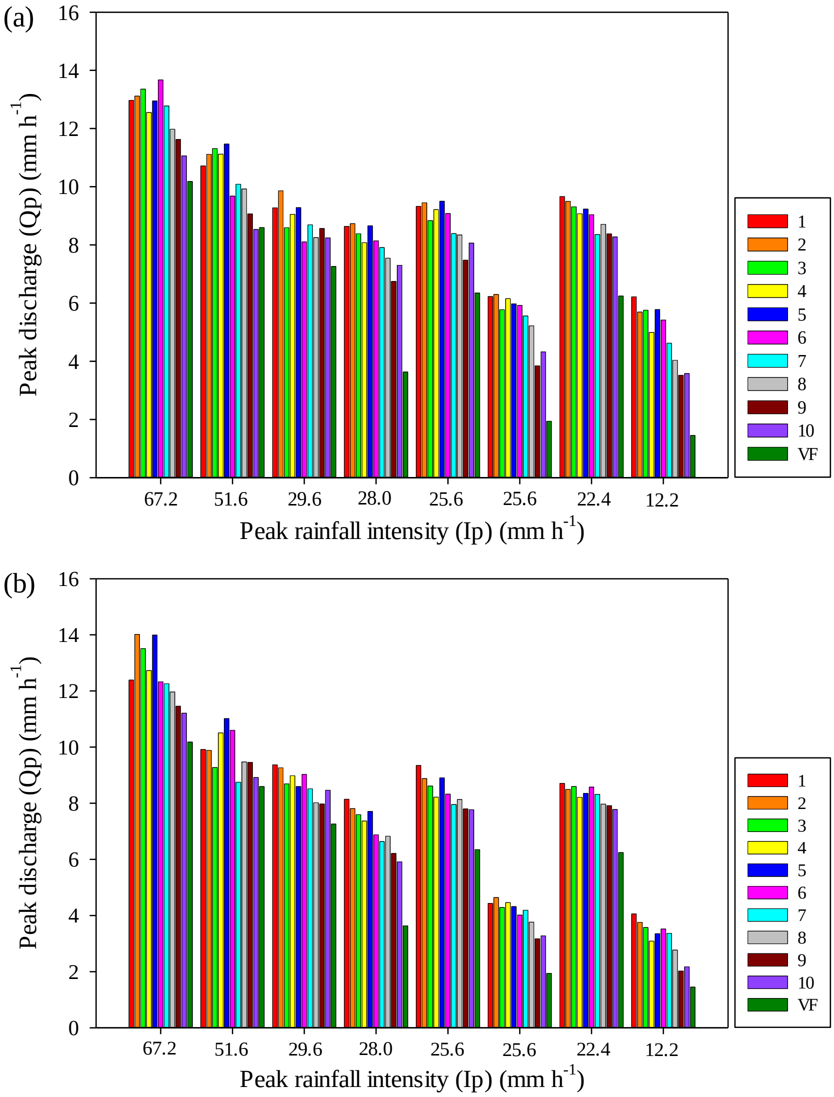

Figure 4.21 Comparison of peak discharge response between different scenarios of buffer area. (a) Without buffer area. (b) With buffer area.

Figure 4.21 showed that buffer area significant to reduce Qp in the disturbed sites, especially in the Ip less than 30 mm h^{-1}. Buffer area was less effective in reducing Qp in the 1-year-old site. The 10-year-old site with buffer area produced lower Qp and close to the Qp in the VF site than that in the scenario without buffer area.

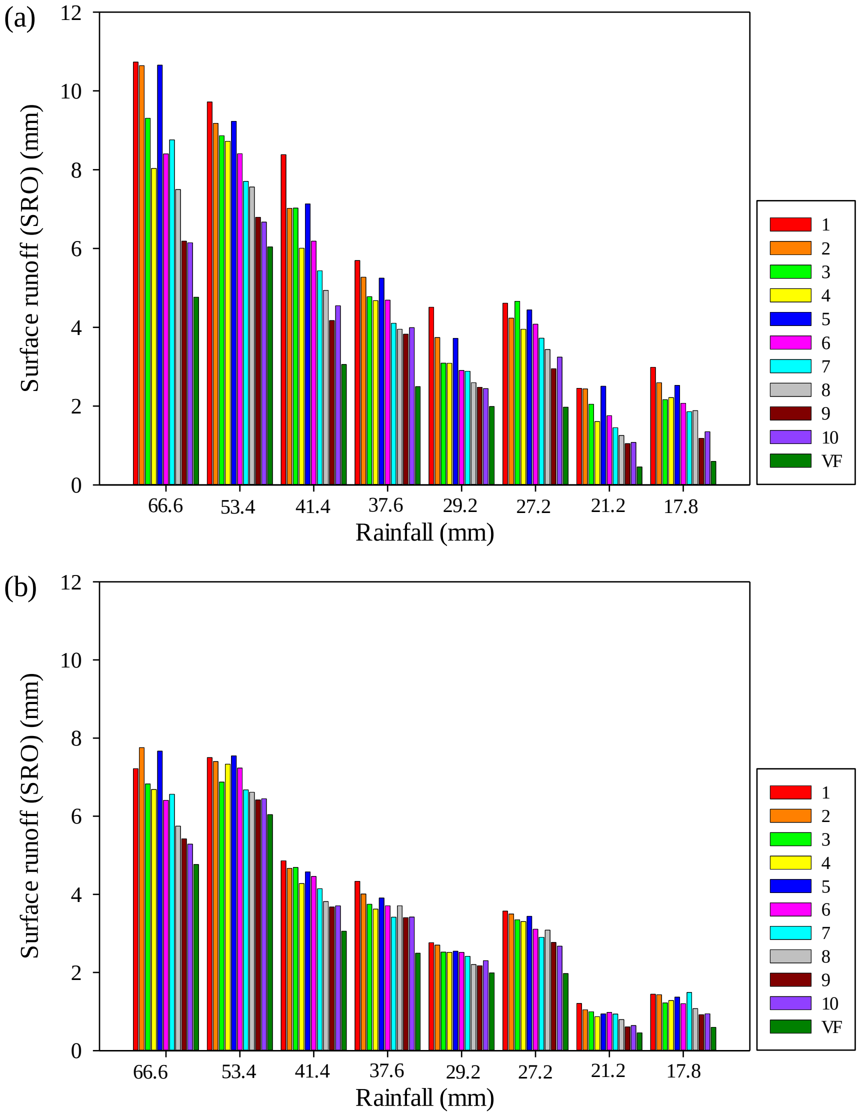

Figure 4.22 Comparison of surface runoff between different scenarios of buffer area. (a) Without buffer area. (b) With buffer area.

Figure 4.22 showed that buffer area significant to reduce SRO in the disturbed sites, especially in the 1-year-old site. Undisturbed soil hydraulic properties in the buffer area are effective to infiltrating the SRO and reduce the SRO in the stream channel.

To clarify the differences between scenario with and without buffer area, the coefficient of Qp and SRO shown in Figure 4.23.

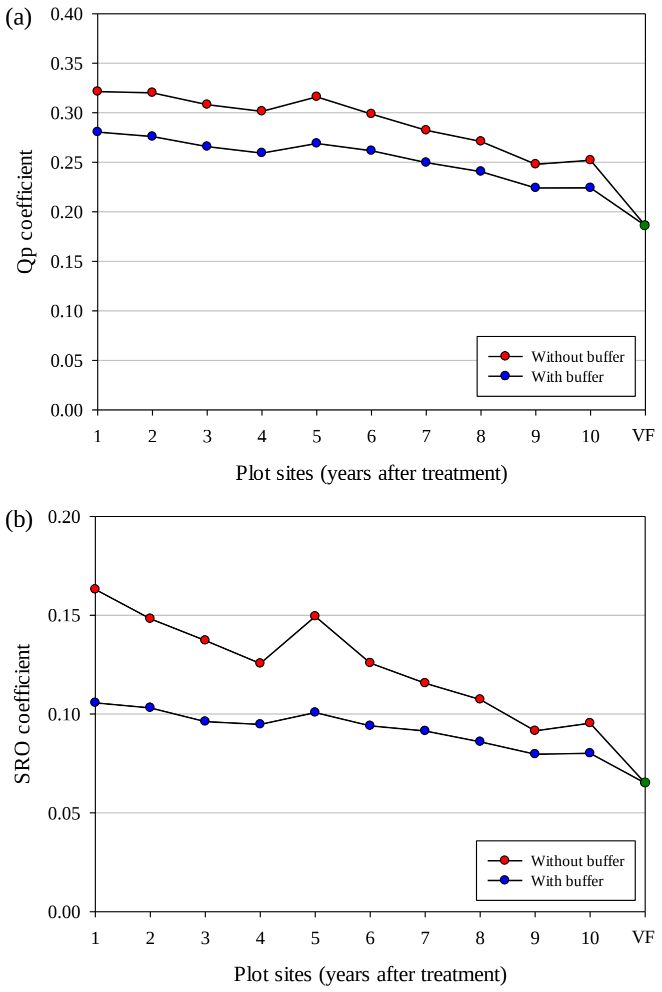

Figure 4.23 (a) Coefficient of Qp to peak rainfall intensity. (b) Coefficient of total SRO to the amount of rainfall.

Soil hydrologic properties at the disturbed sites were changed and produced higher Qp and SRO coefficients, compared to the VF site (Figure 4.23). However, the Qp and SRO coefficients dropped at disturbed sites over time, indicating that soil hydraulic properties slowly recovered. A smaller Qp coefficient indicates a greater potential for a forested catchment to reduce Qp (Figure 4.23a). In the early years after IFMS treatment, a large gap of Qp and SRO was found between the scenario with and without buffer area (Figures 4.22 and 4.23). Buffer area is effective to reduce the Qp and SRO coefficients dropped at each site over time. The buffer area canopy serves as a barrier against precipitation reaching the ground. The high canopy cover density in buffer area controlled the net precipitation by canopy interception. Treated area had less canopy cover, compacted soils, and low infiltration capacities. Consequently, these conditions reduced the forest interception, evapotranspiration, and infiltration volumes, creating a quick surface runoff response and increased the percentage of rainfall to surface runoff in the model. Undisturbed soil hydraulic properties played a major role as a high infiltration capacity. Combination between high canopy interception and high infiltration capacity in the buffer area has a significant role in the SRO reduction that occurred in the early period after treatment (Figure 4.23b). In the VF site, 17.5% of the Ip became Qp in the river channel, while in the 1-year-old site, 31.6% of Ip became Qp. As shown in Figure 4.23b, 10 years after the initiation of the IFMS, the SRO coefficient of disturbed sites was reduced and was similar to that of the VF site. These results suggest that the disturbed sites need at least 15 years to recover their soil hydraulic properties to levels that are similar to those in VF site.

4.4. SUMMARY AND CONCLUSIONS

Forest disturbance affects soil hydraulic properties, and therefore results in differences in the propensity to generate surface runoff flow in different types of forested sites. Although the data collected in this study were from a relatively small area, and could not account for the influence of soil heterogeneity on the variability of hydraulic properties, the following specific conclusions can be drawn:

1. The fundamental IFMS activities associated with mechanized selective logging and intensive line planting have reduced the soil hydraulic properties, including infiltration characteristics, soil compaction, and hydraulic conductivity within the near-surface profile. A reduction of the infiltration capacity results in a greater likelihood of surface runoff flow. The emergence of secondary vegetation results in a faster recovery in infiltrability, thereby reducing the propensity of surface runoff.
2. Ground-based harvesting using skidder tractors has significantly increased the rate of soil compaction. During the 10-year period following the abandonment of skidder tracks, the rate of soil compaction was still high and did not reach the recovery levels. Over the same time period, sites experiencing other surface disturbances recovered to levels close to those of a virgin forest.
3. Soil compaction has changed the soil pore distribution and has affected soil moisture characteristics. In natural conditions, water retention curves for surface soils (0–50 cm deep) tend to display greater changes in θ than subsurface soils

(50–150 cm deep). Intensive root growth at depths of 0–50 cm was effective for increasing the number of macro-pores and the porosity.

4. There were low surface K_s values on skidder tracks compared to other surface disturbance types. Reductions in surface K_s may increase the frequency of surface runoff, particularly during large seasonal storms. Consolidated surfaces such as skidder tracks, line-planted areas, cleared areas, and logged areas contribute disproportionately to the stormflow response because low K_s values (compared to natural conditions) lead to surface runoff for low rainfall intensities.
5. Forest disturbances have altered the typical surface hydrological pathways, thereby creating the conditions for more surface runoff on disturbed surfaces than on undisturbed surfaces. Maintaining the buffer area is effective to reduce the Qp and SRO in the stream channel.
6. Consolidated surfaces, which are an inherent part of a fragmented forest, contribute disproportionately to the associated hydrological impacts. The recovery time for near-surface K_s on non-skidder tracks was between 10–15 years, while in the skidder tracks it was more than 20 years.

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Chapter V

RUNOFF AND SOIL EROSION CHARACTERISTICS IN DIFFERENT RECOVERY PERIODS OF THE INTENSIVE FOREST MANAGEMENT SYSTEM

Abstract

Tropical Indonesian rainforest is managed using an intensive forest management system (IFMS). The main activity is selective logging for timber harvesting and intensive line planting to enrich the standing stock. These activities significantly alter the forest canopy cover and the hydrologic response of catchments, including peak discharge, direct runoff and soil erosion. Understanding the hydrologic effects in an IFMS is helpful to develop a forest management strategy. The study was conducted in tropical rainforest at the Bukit Baka Experimental Catchments, Central Kalimantan, Indonesia. This study investigated the impact of vegetation changes on runoff and soil erosion characteristics in different periods of an IFMS resulting from their respective forestry treatments. This study was conducted in a tropical rainforest in Central Kalimantan, Indonesia. Runoff and soil erosion characteristics were investigated in three small catchments, a virgin forest catchment (C1), a 10-year-old line plantation catchment (C2) and a 1-year-old line plantation catchment (C3). The IFMS has increased in large-scale of open forests and exposed the bare soil, especially in the early years after forest operation. This condition has changed drastically in the catchment hydrologic responses. The increase in discharge, direct runoff, and suspended sediment discharge in the C3 were higher than those in the C2 and C1, particularly for large rainfall events. The proportion of annual rainfall as water yield in the C1, C2, and C3 were 27%, 30%, and 41%, respectively. The annual suspended sediment yield in the C1, C2, and C3 were 0.15 t ha^{-1} y^{-1}, 3.6 t ha^{-1} y^{-1}, and 14.9 t ha^{-1} y^{-1}, respectively. Reducing canopy cover and high surface soil disturbance in the early year after IFMS are significant affected both runoff and soil erosion. The results showed that the magnitude of runoff and soil erosion depends on the interaction among the rainfall, forest cover changes, forest treatment applied and catchment characteristics. 10 years after forest operation, forest cover has recovery close to natural condition, but still there are differences in hydrological response. Controlling the logging activities by reducing the impact of logging and combining ecologically based vegetation structure design is an effective way to reduce runoff and soil erosion.

5.1 Introduction

Indonesia has a large forested area, which covers 60% of total country area or 10% of the total world tropical rainforest. A key resource of tropical rainforests is forest timber, but land conversion and timber extraction are threatening biodiversity and hydrologic responses. Tropical Indonesian rainforest is managed by an Intensive Forest Management System (IFMS), which commenced in 2002. The main activity of IFMS is selective logging for timber harvesting and intensive line planting to enrich the standing stock. Timber extraction using heavy machines destroys soil structure, which plays an important role in water and nutrient cycling, and accelerates soil erosion rates (Nussbaum and Hoe, 1996). Heavy machines in timber collection areas and on skidder roads increase soil compaction by up to 40% of the natural condition (Nussbaum and Hoe, 1996; Nussbaum *et al*., 1996), and 10–30% of the soil surface may become bare due to logging roads, skidder tracks and log landings (Bruijnzeel, 1992; Van Der Plas and Bruijnzeel, 1993). The use of heavy equipment tends to compact topsoil, setting in motion a negative spiral of reduced infiltrability and increased frequencies of overland flow and sheet erosion, thereby hindering the establishment of a new protective layer of vegetation and litter (Van Der Plas and Bruijnzeel, 1993).

Different land-use practices affect soil infiltration rates in different ways depending on their effects on the intrinsic properties of the soil (Osuji *et al*., 2010). Additionally, selective logging and intensive line planting systems are suspected to dramatically impact soil properties. In a previous study, the infiltration capacity of a tropical rainforest 1 year after selective logging and intensive line planting treatment decreased to 81.8% that of a virgin forest (Suryatmojo *et al*., 2009). The effect of human activities on runoff regimes has been demonstrated by several experimental studies in various parts of the world. Much research has focused on monitoring the influence of changes in land cover, mainly deforestation and afforestation processes (Moody and Martin, 2001; Huang et al., 2003; Covandey *et al*., 2005; Chavez *et al*., 2008), the influence of cultivated areas (Klocking and Haberlandt, 2002; Robinson *et al*., 2003; Montagnini and Jordan, 2005) and the impact of logging (Standtmueller, 1990; Douglas *et al*., 1992; Douglas, 1999; Douglas, 2003).

Runoff responses and soil erosion rates are significantly different with changes in land cover. Many studies have considered runoff and soil erosion in tropical forests around the world (Abdulhadi *et al*., 1990; Anderson, 1990, Hendrison, 1990; Van Der Plas and Bruijnzeel, 1993; Chavez *et al*., 2008; Robinson *et al*., 2003; Douglas *et al*., 1992; Douglas, 1999; Douglas, 2003). In Southeast Asia with its great geological diversity, the study of runoff and erosion in tropical forests is dominated by research in Thailand and Malaysia, but is very limited in Indonesia. Rainfall intensity in the tropical rainforests on Kalimantan Island, Indonesia, is high; therefore, hydrologic responses such as peak discharge, direct runoff, water yield, and soil erosion can potentially become problems when land use or forest cover changes. The IFMS is a unique system that was developed solely for Indonesian tropical forest. The main activities covered by the IFMS are selective logging and intensive line planting. Several studies have investigated the rainfall–runoff–erosion in Kalimantan, Indonesia (Standtmueller, 1990; Hartanto *et al*., 2003; Ruslan and Manan, 1980; Suryatmojo *et al*., 2010). Research concerning the IFMS in tropical Indonesian rainforest is still limited (Suryatmojo *et al*., 2011).

Therefore, a need exists to investigate the hydrologic response of tropical rainforests managed under an intensive forest management system. This chapter investigated the impact of runoff and soil erosion characteristics in different recovery periods of the IFMS resulting from their respective forestry treatments. Thus, this chapter reports the results of an analysis of the hydrologic response of peak discharge direct runoff, water yield, and suspended sediment yield (SSY) among three small forested catchments: an undisturbed (virgin) forest, a 10-year-old intensive line plantation, and a 1-year-old intensive line plantation.

5.2 Methods

5.2.1 Research catchment

This research was conducted in an natural undisturbed forest (reffered as C1) and two disturbed forest with IFMS treatment (treated catchments) (Figure 5.1). The treated catchments were forest that had been selectively logged and intensively line planted in 1999 or 10-year after IFMS treatment (reffered as C2), and a forest that had been selectively logged and intensively line planted in 2008 or 1-year after IFMS treatment (reffered as C3). The research catchment maps are shown in Figure 5.2. Physical characteristics are given in Table 5.1 (Gordon *et al*., 1992).

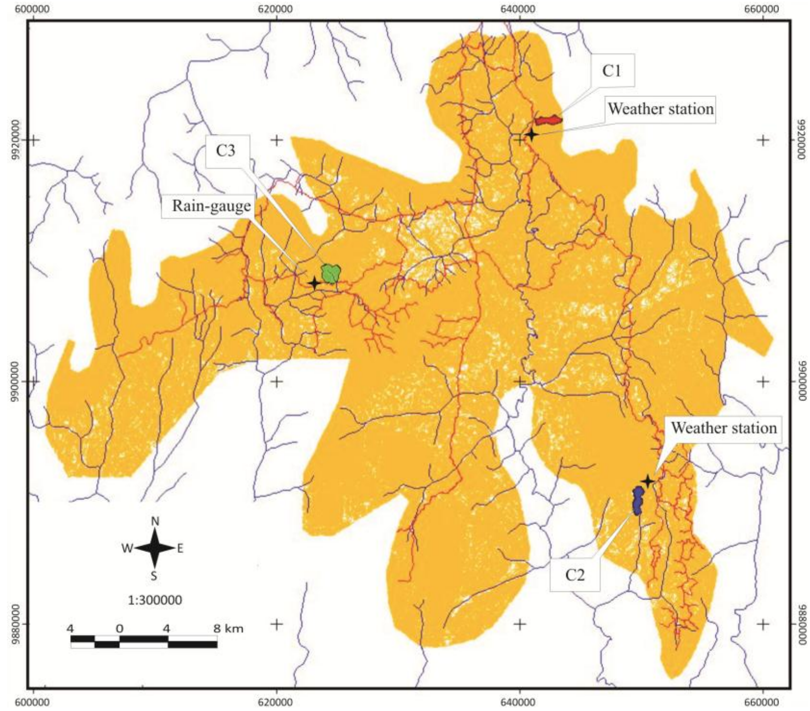


Figure 5.1 Research catchments in the study site of Sari Bumi Kusuma (SBK) area, Central Kalimantan.

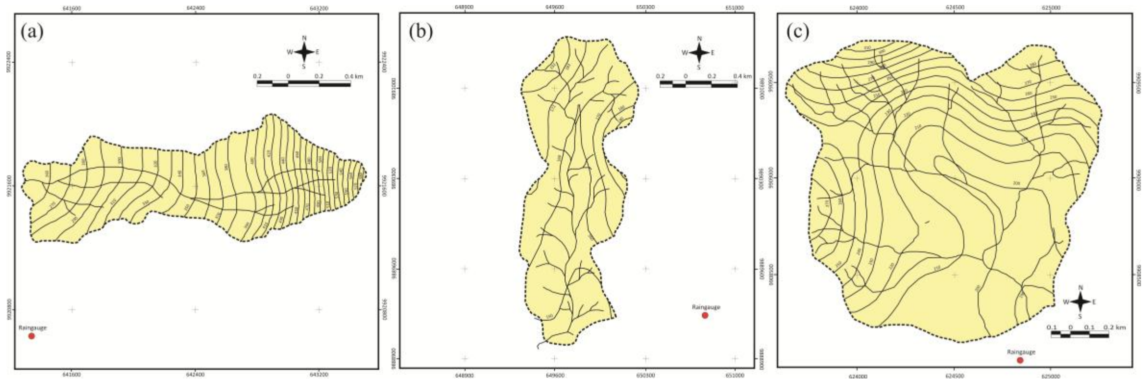


Figure 5.2 Research catchments. (a) C1, (b) C2, and (c) C3.

Table 5.1 Physical characteristics of the three catchments.

Catchment	Drainage area (km^2)	Catchment circularity[a]	Catchment slope (%)	Drainage density (km/km^2)	Main river length (km)	Main river slope (%)
C1	1.10	0.22	11.36	3.30	2.0	12.48
C2	1.49	0.26	5.49	6.05	2.4	8.65
C3	1.91	0.78	5.1	5.76	2.1	4.85

[a] $Rf = \frac{A}{L^2}$ A = catchment area; L = length of the catchment

Catchment circularity will contribute to the speed in which the surface runoff reaches the river channel. Circularity affects the bifurcation ratio, whether streams join the main channel successively or whether tributaries all have about the same length and feed water into the stream simultaneously thus creating a higher flood peak than in a long narrow catchment. Catchment slope will contribute to accelerate the surface runoff flow do the downstream. Combination between circular shape and steep slope will contributes to the direct runoff amount and the increase in discharge to the peak at the catchment outlet. Greater drainage density appears to be associated with flashier runoff behavior, greater total surface runoff and less ground water storage. Main river length appears to be affecting the lag time and time concentration. A long main river produce longer time concentration and lower peak flow than that in a short main river.

5.2.2 Observations and analysis

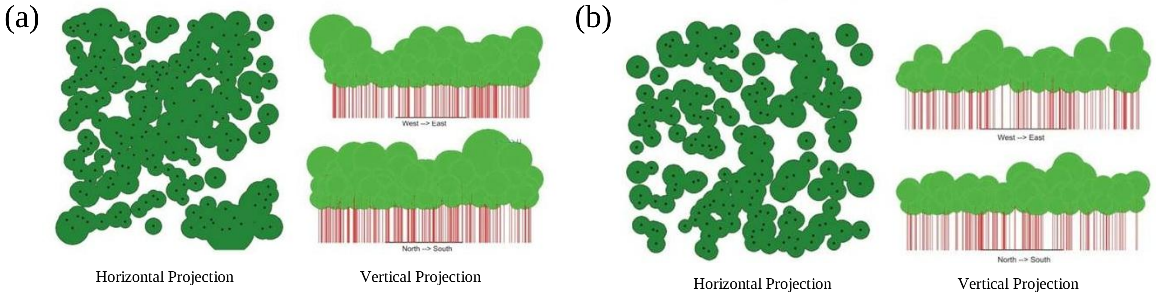
To clarify the characteristics of rainfall among three catchments, three automatic tipping-bucket rain gauges (logging time, 15 min) were installed at each catchment and deployed near the outlet catchment. A Parshall flume and a water-level logger with a time interval of 15 min were installed at each catchment outlet. The 2.5 m flume width was divided into three cross sections, and the water discharge and suspended sediment was measured at each section. Water discharge was measured with a current meter. Suspended sediment was measured using a suspended sampler above the bed layer.

A paired of single storm rainfall with single peak rainfall which cause a single runoff hydrograph shape was collected for each catchment. The minimum time interval between storm rainfall events that used was 24 hours. During 1-year observation period, the number of storm events used for paired hydrological analysis in the C1, C2 and C3s were 35, 46 and 39, respectively. The hydrograph analysis was undertaken by dividing the runoff into direct runoff and base flow using a straight-line method and then calculating the direct runoff volume for each hydrograph of each catchment. Direct runoff is the sum of surface runoff, subsurface flow, and channel interception. This is the part of the hydrograph of interest when floods and flood-producing characteristics of catchments are analyzed. Soil erosion was calculated from the suspended sediment concentration (SSC) using the equal-discharge-increment (EDI) method (Nolan *et al.*, 2005). The objective of the EDI method is to collect a discharge-weighted sample that represents the entire flow passing through the cross section by obtaining a series of samples, each representing equal volumes of stream discharge. The EDI method requires that three criteria be met: samples are collected isokinetically; the vertical represents the mean concentration and particle-size distribution for the subsection sampled; and the discharges on both sides of the sampling vertical are predetermined proportions of the total discharge. The flume cross section was divided into three sections of equal discharge increments, and a sample was collected from the midpoint of each increment. An isokinetic depth-integrating sampler (US-DH-81 sampler with 600 ml bottle sampler) was moved up and down at the same rate in a vertical direction across the flume, which allowed the sampler to integrate sampling in relation to depth and velocity at each vertical point. The volumetric sediment concentration (mg/l) was measured by the evaporation method (Nussbaum *et al*., 1996). The three catchments were analyzed by comparing the direct runoff, peak discharge increase from base flow to peak discharge, annual water yield, and annual erosion yield to understand the hydrological impact of vegetation changes in the IFMS.

5.3 Results

5.3.1 Forest canopy cover changes

The IFMS changed the forest canopy cover. The profile of vegetation structure and composition was monitored in a permanent sample plot (PSP) in each catchment. As shown in Table 5.2, there were fewer trees and poles in the C3 after IFMS implementation than in the C1 and the C2, and there were more saplings and seedlings. Selective logging and intensive line planting significantly decreased forest canopy cover by reducing the number of trees. Tree canopy cover conditions in the catchment area are shown in Figure 5.3.



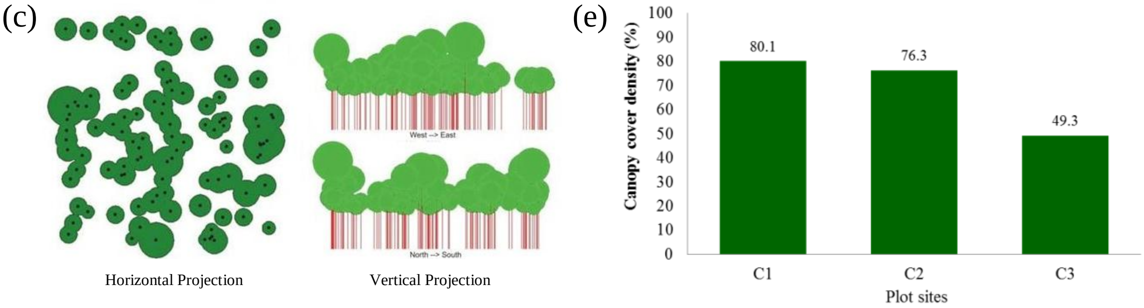


Figure 5.3 Tree canopy cover in the PSP of C1 and after IFMS implementation. (a) C1, (b) C2, and (c) C3.

Table 5.2. Vegetation structure of the three catchments.

Catchment	Individual amount per-hectare (N/ha)			
	Tree[a]	Pole[b*]	Sapling[c*]	Seedling[d*]
C1	212	208	1027	690
C2	153	181	1472	8600
C3	113	152	3226	18433

[a] Tree is vegetation with diameter > 20 cm (at 1.3 m above land surface)

[b] Pole is vegetation with diameter 10-20 cm

[c] Sapling is vegetation with diameter < 10 cm and height > 1.5 m

[d] Seedling is vegetation with height < 1.5 m

[*] The number of poles, saplings and seedlings calculated from the extrapolated of 25 subplots.

The percentage tree canopy cover was 80.1% in the C1 (Figure 5.3a). Canopy cover decreased to 49.3% in the C3 (Figure 5.3b). Thus, IFMS has decreased the canopy cover by approximately 38.5% (Suryatmojo *et al.*, 2009).

5.3.2 Hydrological characteristics

Physical catchment parameters such as slope, shape, main-stream slope and drainage density affect stream flow and influence the shape of the hydrograph through catchment storage, runoff speed, infiltration and soil water content. The hydrologic behavior of small catchments tends to be different from that of large catchments. A small catchment is very sensitive to high-intensity rainfall of short duration and to land cover characteristics (Chang, 2006). The response of the runoff hydrograph to rainfall in the three catchments during a 1-year monitoring period (November 2010–October 2011) is shown in Figure 5.4.

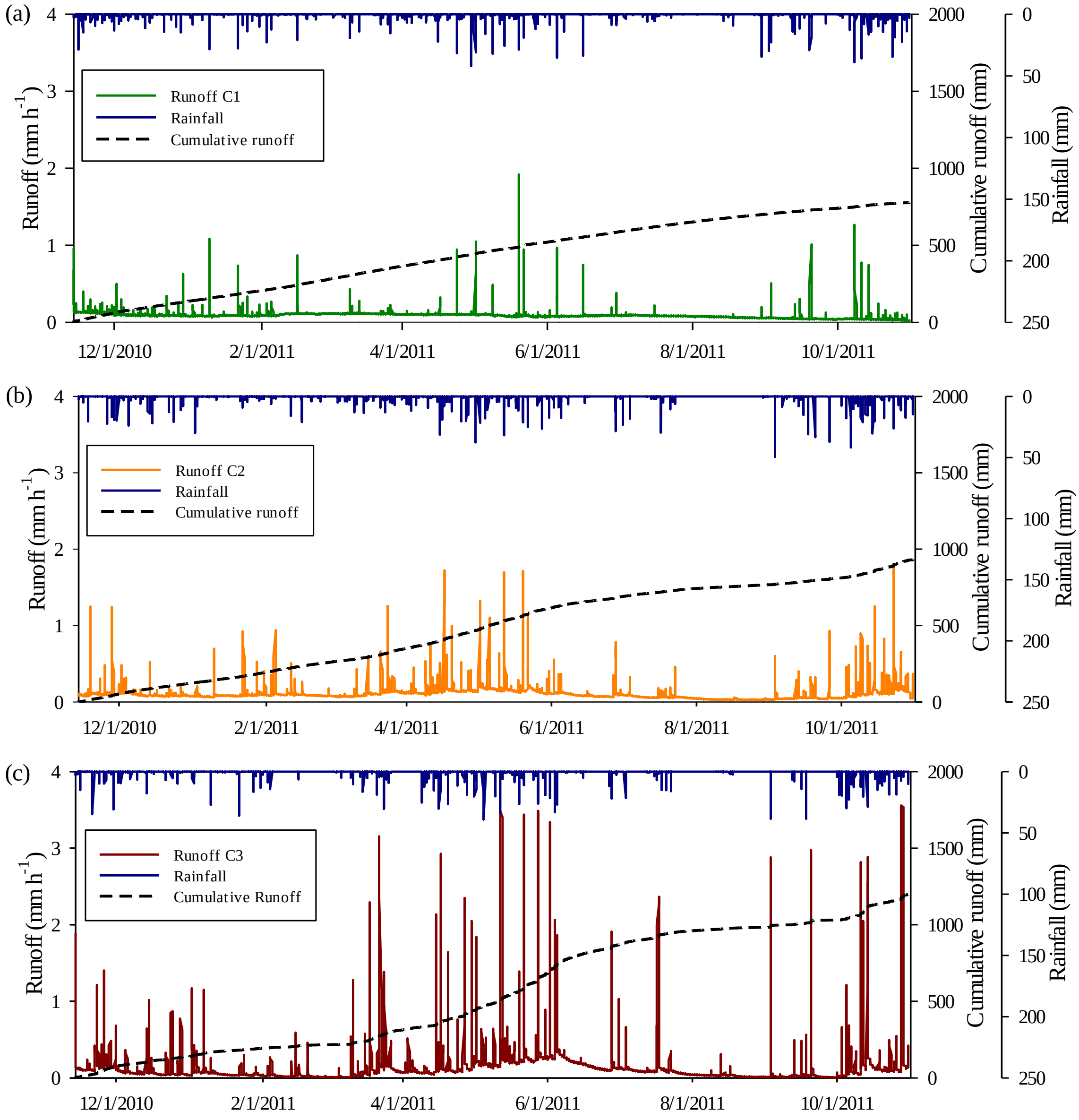


Figure 5.4 Relationship between rainfall and the runoff hydrograph. (a) C1, (b) C2, and (c) C3.

The C1 had a relatively constant base flow compared to the C2 and C3. The runoff hydrograph in the C3 produced the largest response to rainfall events. IFMS treatments lead to the formation of large canopy openings, resulting from tree felling, skid trails and haul roads constructions. A large open canopy in the C3 reduced the forest interception and transpiration, increasing net rainfall reaching the forest floor and may increasing the soil moisture. Consequently, these conditions creating quick runoff responses that was dominated by surface flow and increased the percentage of rainfall to runoff in the catchment (Figure 5.4).

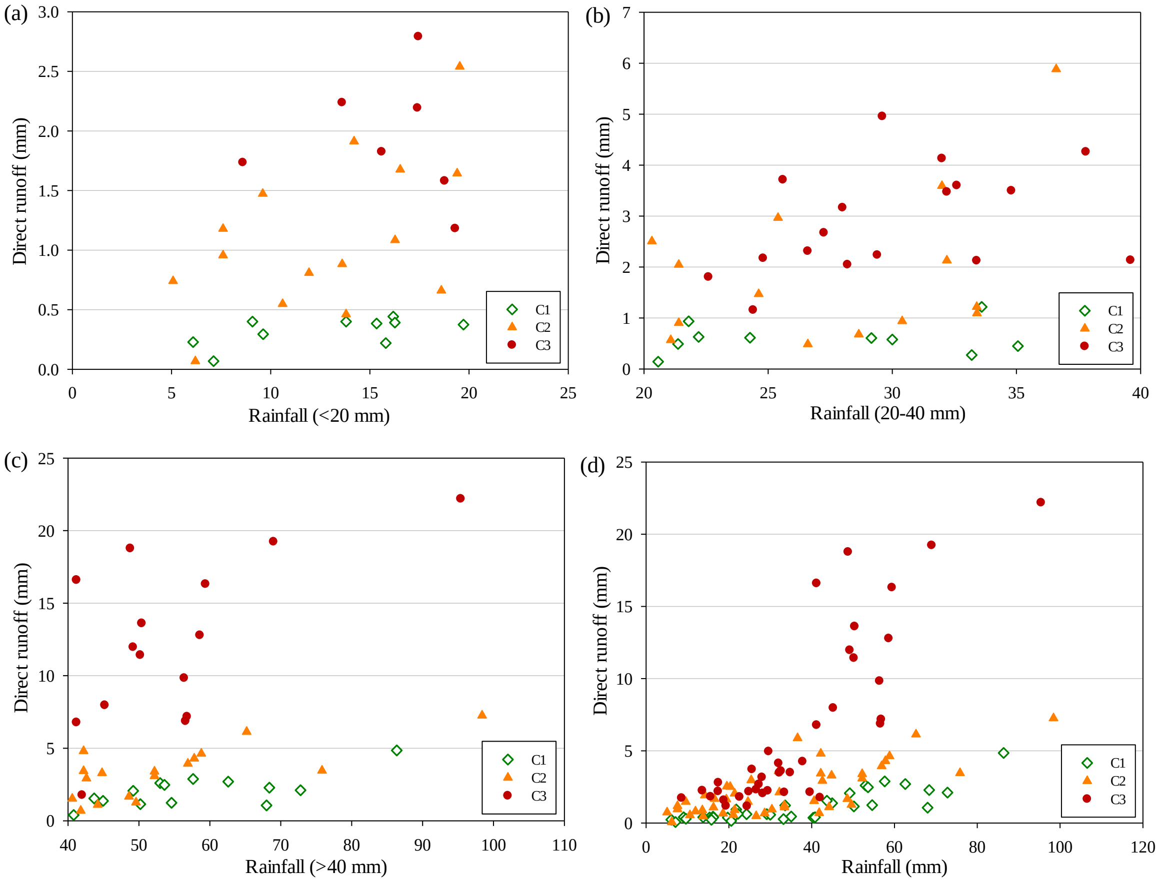


Figure 5.5 Direct runoff for different sizes of rainfall event. (a) Small rainfall events. (b) Medium rainfall events. (c) Large rainfall events. (d) All rainfall events.

An individual rainfall event and a single runoff hydrograph at each catchment was selected during a 1-year monitoring period to clarify the direct runoff and peak discharge increase from base flow. The results showed that the C3 produced the highest direct runoff compared to the C2 and C1. In the small rainfall event (<20 mm), the C1 produced lower direct runoff than that in the C2 and C3 (Figure 6a). In the medium rainfall event (20–40 mm), the C2 and C3 produced a similar direct runoff response, which was higher than that in the C1. In the large rainfall events (>40 mm), the C3 responded more strongly than the C2 and C1. Considering all rainfall events, the direct runoff in the C1 was lower than those in the C2 and C3. Reduced canopy cover in the C3 led to direct runoff.

The relationships between the increase in discharge from base flow to peak discharge and the amount of rainfall to peak discharge, and peak rainfall intensity are shown in Figure 5.6.

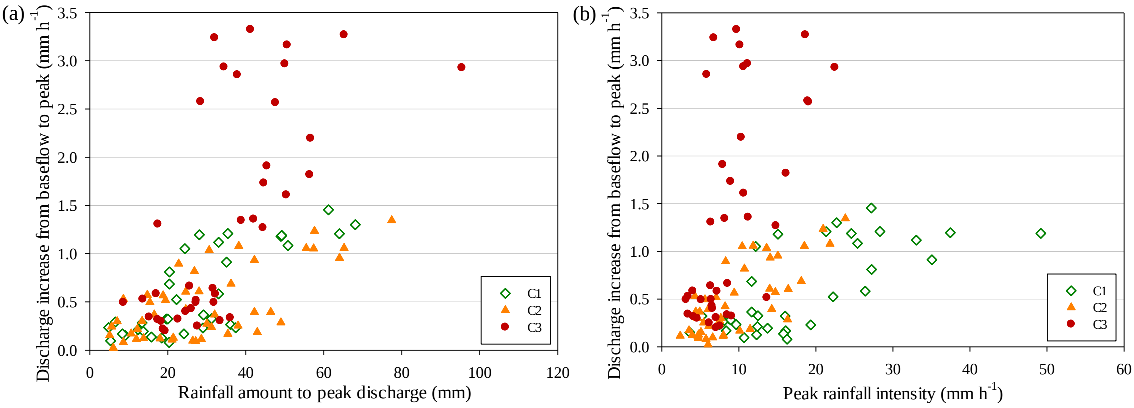


Figure 5.6 Relationship between the discharge increase from base flow to peak discharge and (a) rainfall amount to peak discharge, (b) peak rainfall intensity.

Figure 5.6 showed that no large differences were observed among the three catchments when the amount of rainfall to peak discharge and peak rainfall intensity were lower than 10 mm. With increasing peak rainfall intensity, the increase in discharge from base flow to peak discharge was highest in the C3, followed by the C2 and then the C1. The scatter in discharge in the C3 is high in both amount and intensity of rainfall. Physical catchment characteristics of catchment circularity might be contributes in the direct runoff and peak discharge responses. C3 has more circular shape than those in the C2 and C1s (Table 5.1). Catchment circularity contributes to the speed in which the surface runoff reaches the river channel. Circular shape in the C3 accelerates the surface runoff flow and contributing the increase in discharge from baseflow to the peak much higher than those in the C2 and C1s.

5.3.3 Suspended sediment yield

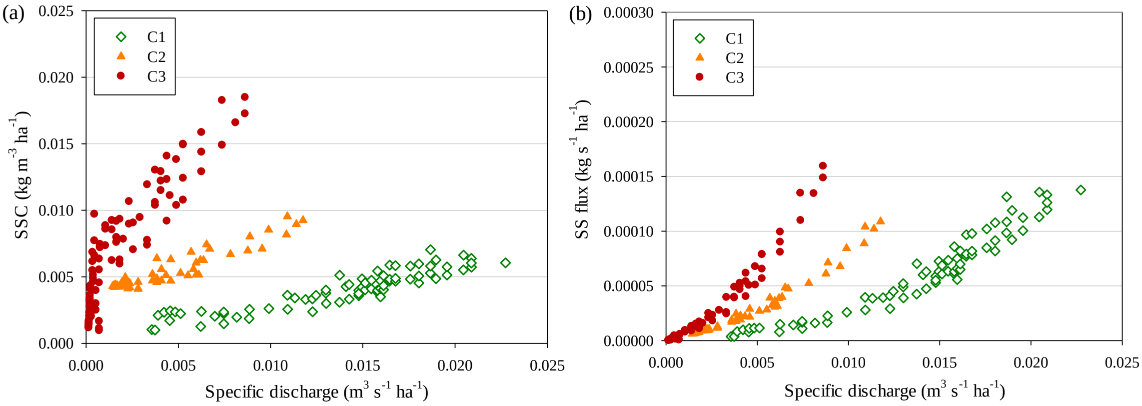


Figure 5.7 Suspended sediment in the three catchments. (a) Suspended sediment concentration (SSC). (b) Suspended sediment flux (SS flux).

As shown in Figure 5.7, treated forest in the C2 and C3 had higher SSD and SS flux than the undisturbed forest in the C1. The SSY is defined as the total sediment outflow from a catchment, measurable at a cross-section or outlet in a specified period. The SSYs of the three catchments during a 1-year monitoring period (November 2010–October 2011) are shown in Figure 5.8. The C3 had the largest cumulative SSY (Figure 5.8c). The cumulative curves of SSY indicated that the C3 loads increased significantly after late March 2011. The largest sediment production occurred in late April until the beginning of the June 2011 period that experienced high rainfall events and produced higher runoff (Figs. 5.4c and 5.8c).

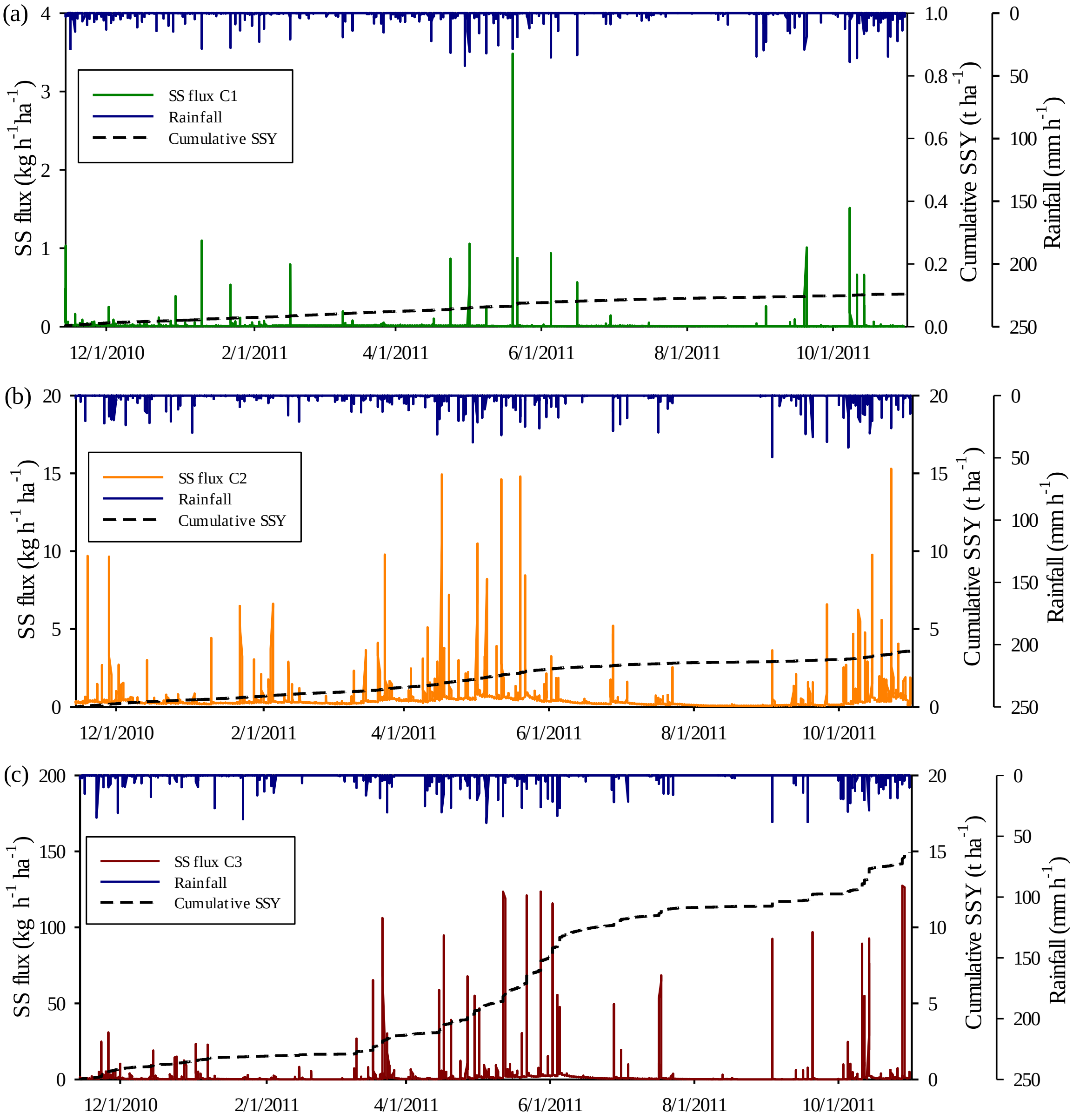


Figure 5.8 Suspended sediment flux (SS flux) and cumulative SSY. (a) C1, (b) C2, and (c) C3.

During the monitoring period from the Environment Division of Sari Bumi Kusama company reported that there were no landslide events occurred and recorded during 1998-2012 in the three catchments. The results indicated that sediment yield in the C2 and C3 dominantly come from soil destruction by tractor machine during timber logging and log-hauling activities.

To clarify the impact of IFMS on the treated forest catchment, the annual water yield from cumulative runoff and the erosion yield from cumulative SSYs were analyzed (Table 5.3). The annual water yield in the C1 and C2 and C3s were 27%, 30%, and 41% of annual rainfall, respectively. The erosion yields were 0.15 t ha^{-1} y^{-1}, 3.6 t ha^{-1} y^{-1}, and 14.9 t ha^{-1} y^{-1}, respectively.

Table 5.3. Total runoff and suspended sediment yield of the three catchments

Catchment	Total rainfall (mm)	Total runoff (mm)	Percentage of runoff from rainfall (%)	Total suspended sediment yield (t ha^{-1} y^{-1})
C1	2978	777	27	0.15
C2	3065	932	30	3.6
C3	2937	1200	41	14.9

5.4 Discussion

5.4.1 Effect of the IFMS on runoff responses

A change in land use in a catchment may lead to changes in its water balance. The response time of stream flow is generally determined by climate (mostly rainfall), vegetation characteristics, catchment properties, and vegetation management practices (Alice *et al.*, 2005). The forest canopy serves as a barrier against precipitation reaching the ground. Selective logging activity using tractors has opened and destroyed approximately 4–6% of the soil surface of the forested area by creating skid trails and a further 60–75% by pulling logs using a tractor winch. Manual land clearing for intensive line planting has opened approximately 15–20% of the forested area in the study catchment.

Growth of vegetation in the C2 (Table 5.2) increased canopy interception and forest floor retention. For small rainfall events, most precipitation was trapped by the canopy in the C1 and C2, leading to negligible direct runoff responses to rainfall (Figure 5.5b). Although the canopy cover in the C2 became almost the same as that in the C1

(Figure 5.3), canopy interception and evapotranspiration rates were slightly lower than that in the C1. In the natural forest, the annual evapotranspiration ranged from 1246 to 1519 mm (see Chapter III). Canopy cover reduction led to lower evapotranspiration and higher net precipitation in the C2 and C3. For small, medium, and large rainfall events, the net precipitation in the C1 and C2 was still lower than in the C3. In the C3 with a low canopy cover density there was a large net precipitation and increased amounts of direct runoff. The high canopy cover density in undisturbed areas controlled the net precipitation by canopy interception and evapotranspiration.

In addition to the rainfall interception due to canopy cover, catchment topography also affected the runoff, particularly in the response of the increase in discharge from base flow to peak discharge. Catchment shape, drainage density, catchment slope and the main-river slope affects how quickly surface and subsurface runoff reach the outlet of catchment. The highest increase in discharge from base flow to peak discharge was in the C3 (Figure 5.6). The higher circular shape and drainage density in the C3 (Table 5.1) affected the rapidity with which water could flow to the catchment outlet. The circular shape may have concentrated rainwater toward the catchment outlet faster than that of a non-circular catchment. The C3 with a circular shape may have accumulated all runoff in the catchment outlet at the same time, leading to a fast peak time, and an increase in peak discharge. Catchments with steep slopes also had the potential to deliver rainwater to catchment outlets. The rapid response of the increase in discharge from base flow to peak discharge in the C1, similar to the C3 (Figure 5.6a), may have been influenced by the catchment slope. The increase in discharge from base flow to peak discharge in the C2 with a non-circular and lower slope was the smallest of all catchments (Figure 5.6b).

The changes in soil characteristics by selective logging activities are also important factors for hydrological processes. Selective logging significantly increased the soil compaction and reduced the infiltration capacity, particularly in the skid trails. The removal of vegetation by mechanized and manual means has changed the hydraulic properties of soils. The water impeding layers in the soil surface can reduce the soil infiltration and yield surface runoff which affects the volume of direct runoff. As the proportion of precipitation that occurs as surface runoff increased, the volume of direct runoff and the rate of flow to the catchment outlet increased. Although the recovery of forest floor vegetation in the C3 may reduce the surface runoff, considering the results above, the effects of total open area and soil characteristic changes are important for runoff responses. Therefore, the C3 responded quickly to rainfall, and produced an annual water yield of 41% of the total annual rainfall Table 5.3).

Logged forest had less canopy cover, compacted soils, and low infiltration capacities. Consequently, these conditions reduced the forest interception, evapotranspiration, and infiltration volumes, creating a quick runoff response that was dominated by surface runoff and increased the percentage of rainfall to runoff in the catchment. With the effect of catchment topography in the forested catchments, the change of forest cover and destruction of soils are the dominant factors impacting runoff responses.

5.4.2 Effect of IFMS on soil erosion

Erosion is one of the most serious problems in the Kalimantan tropical rainforest. Soil organic matter in the Kalimantan forest is very shallow at about 2–5 cm (Widiyatno, 2010). Ruslan and Manan, 1980 reported that erosion and surface runoff decreased after skidding roads were abandoned in South Kalimantan, and that trees, grasses and shrubs re-colonized the bare ground. However, such secondary forest cover neither protects soil in the same way that primary forest does nor is able to easily compensate for the physical damage already done to the soil (i.e. compaction, loss of soil structure and removal of organic litter) (Stadtmueller, 1990). Hartanto *et al.*, 2003 reported runoff and soil erosion in Central Kalimantan using plot-level monitoring. The presence of organic forest floor materials, such as a litter layer and woody debris, is very important for preventing soil detachment in the control and harvest plots and providing surface roughness, thus, reducing runoff and soil particle movement downslope. The absence of soil cover and surface roughness at the skid trail plots increased runoff and soil detachment by raindrops, and provided unobstructed movement of runoff and soil particles downslope.

The use of selective logging and intensive line planting has dramatically changed the vegetation structure, soil properties and infiltration capacity of the study area. These changes were compounded because of the fragile Ultisol of the humid tropics. In the humid tropics, poor soil cohesion, high rainfall and high temperatures give rise to highly erosive soils that are very sensitive to the impacts of heavy machinery and cleared vegetative cover (Lal, 1985; Hendrison, 1990; Huang and Laflen, 1996; Hartanto *et al.*, 2003). Furthermore, Ultisol is acidic and its acidity decreases with soil depth, making it more susceptible to disruption. These soil characteristics made the study area more sensitive to logging and line planting, which in turn augmented runoff and erosion. High rainfall intensity leads to high rainfall erosivity, as the organic soil layer is easily eroded, decreasing soil fertility. Once a forest or even a small patch of forest is cleared, organic matter within the soil is quickly lost. With the disappearance of soil organic matter, the ability of soil to recycle nutrients is also quickly lost, soil fertility rapidly declines and the ecosystem loses its productive capacity (Jordan, 1985; Montagnini and Jordan, 2005). Erosion control initiatives should be implemented immediately, followed by restoration of the vegetation.

Previous studies have reported that reduced rain splash due to vegetation cover leads to less soil loss (Anderson, 1990; Douglas, 2003). The high canopy-cover density in the C2, which was close to that of C1, may have increased rainfall interception, reduced rain splash, and subsequently lowered the soil loss. Indeed, the annual SSY in the C2 was 3.6 t ha^{-1} y^{-1} (Table 5.3), higher than that in the C1 (0.15 t ha^{-1} y^{-1}). C1 had the higher catchment slope, compared to C2 (Table 5.1). This characteristic may produce higher SSY that come from surface erosion of the steeper slope in the C1 than in C2. However, the SSY investigation showed that the C2 had higher annual SSY than in the C1 (Figure 5.8 and Table 5.3). These results indicated that the C2 with similar canopy cover conditions after forested managements still yielded more suspended sediment relative to the C1. This suggests that not catchment topographical characteristics but forested managements (land use) directly affected the suspended sediment yield. A previous study reported an SSY of 4.1–6.85 t ha^{-1} y^{-1} in disturbed dry dipterocarp forest in Mae Thaang, Thailand (Douglas, 1999). Other catchments in Sarawak Malaysia that were logged 10 years previously had a lower soil loss of 0.11–0.36 t ha^{-1} y^{-1} (Douglas, 1999). These results show that changes in forest cover and soil physical properties significantly affect the runoff response to rainfall, particularly regarding soil erosion and sediment discharges into the stream channel.

The degree to which the canopy affects erosion depends on the per cent of the forest floor covered by the understory and the density of the canopy (Toy *et al.*, 2002).

More understory and a denser canopy cover lead to greater rainfall interception and retention. Although canopy density in the C3 was lower than that in the C2, the former had more understory vegetation, leading to more forest floor interception. Although the C3 had more understory vegetation, the annual sediment yield was still high (Table 5.3). Commercial logging with road construction has created new routes for surface runoff. Roadside drainage and gullies have developed by bank erosion and operate as part of the channel sediment supply. Steep slopes along roads and on mounds of weathered material produced by tractors during logging activities provide potential sediment sources. Line clearing patterns for intensive line planting often cut the contours and may produce rill erosion.

SSC was higher in the C2 and C3 than in the C1 (Figure 5.7a). The amount of SSC in the stream channel affected the amount of SS flux. High SSC in the C3 produced a high SS flux (Figure 5.7b). Annual SSY in the C1 was 0.15 t ha^{-1} y^{-1} (Table 5.3). Compared to data from other undisturbed forest catchments, the SSY of C1 was estimated to be low. A study on three catchments in Thailand (Huai Bo Thong, Lam Thakhong, and Kogma) indicated that sediment yields from undisturbed forests range from 0.06 t ha^{-1} y^{-1} in mixed deciduous forest to 0.35 t ha^{-1} y^{-1} in hill evergreen forest. Soil loss in the primary forest of Sarawak Malaysia is 0.8–0.31 t ha^{-1} y^{-1} (Douglas, 1999). Studies on four forested catchments in Malaysia (Cameron Highlands, Johor, Selangor, and Ulu Segama) have reported sediment yields of 0.41–3.12 t ha^{-1} y^{-1} (Sayer *et al*., 2006; Sinun, 1992). SSY in a tropical rain forest of Panama was reported to be 2.04 t ha^{-1} y^{-1} (Zimmermann *et al*., 2012).

In the present study, annual SSY in the C3 was 14.9 t ha^{-1} y^{-1} (Table 5.3) and the difference between C1 and C3 was 14.75 t ha^{-1} y^{-1}. SSY observations in Ulu Segama, Malaysia, after road construction and commercial logging increased to 16 t ha^{-1} y^{-1} and the increase from undisturbed to disturbed catchments was 12.88 t ha^{-1} y^{-1} (Douglas *et al*., 1992). It is possible that rates of erosion vary in different rainforest types in relation to the differences in rates of rainfall, interception, and the nature of the ground cover. Although the values cannot be compared directly, the results suggest that an IFMS producing a large open forest area will produce high soil erosion yields. A management strategy is required to control the runoff and soil erosion.

5.5 Conclusions and Recommendations

The effect of the IFMS on the hydrological responses in a tropical Indonesian rainforest was investigated using three different forested catchment experiments. The IFMS is an important factor in the catchment hydrology and forest management. The IFMS has increased in large-scale of open forests and exposed the bare soil, especially in the early years after forest operation. This condition has changed drastically in the catchment hydrologic responses. The data provide strong linkages between IFMS activities and direct runoff–soil erosion response. There was more direct runoff in the C3 than in the C2 and C1. The percentage of annual rainfall that became runoff in the C1, C2 and C3 were 27, 30, and 41%, respectively. In the natural conditions of the C1, 27% of annual rainfall became runoff and the rest became groundwater or was evapotranspired. The annual SSY in the C1, C2 and C3 were 0.15, 3.6, and 14.9 t ha^{-1} y^{-1}, respectively. This study demonstrated that direct runoff and sediment yield increased dramatically during the early years after IFMS implementation. Reducing canopy cover and high surface soil disturbance in the early year after IFMS are significant affected both runoff and soil erosion. The magnitude of runoff and soil erosion depends on the interaction among the rainfall, forest cover changes, forest treatment applied and catchment characteristics. Forest cover recovery decreased direct runoff and soil erosion significantly. 10 years after forest operation, forest cover has recovery close to natural condition, but still there are differences in hydrological response. Proper protection of the forest floor with an understory would also contribute in controlling the direct runoff and soil erosion.

Forest managers implementing the IFMS in tropical rainforests should consider changes in peak discharge, direct runoff and soil erosion, particularly during the early years after selective logging and intensive line planting. A proper monitoring system would allow more direct associations to be made between management practices and their impacts, thereby enabling managers to identify problems and take appropriate preventive measures to improve management. The recommendation to control runoff and soil erosion from logging activities in a tropical Indonesian rainforest should be implemented to reduce the impact of logging techniques and combine ecologically based vegetation structure design.

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Chapter VI

RUNOFF AND SUSPENDED SEDIMENT YIELD CHARACTERISTICS DURING DIFFERENT OPERATIONAL STAGES OF THE INTENSIVE FOREST MANAGEMENT SYSTEM

Abstract

One potential tool for managing tropical rainforests in Indonesia is an intensive forest management system (IFMS), characterized by selective timber harvesting and intensive line planting, to enrich the standing forest stock. This study was conducted in a tropical rainforest of the Bukit Baka Experimental Catchments, Central Kalimantan, Indonesia. We investigated and evaluated the impact of forest management treatments from different IFMS stages on runoff and suspended sediment yield (SSY) using a paired-catchment approach. Runoff and SSY were investigated in three small catchments: a natural forest (catchment A), an IFMS with intensive strip-line planting (catchment B), and an IFMS catchment with intensive contour-line planting (catchment C). Implementation of IFMS had a significant effect on catchment hydrology in terms of runoff and sediment yield. There were significant differences in the runoff hydrographs and suspended sediment hydrographs both between different IFMS stages and between catchments B and C. This study demonstrated that direct runoff (DRO), peak discharge (Qp), suspended sediment discharge (Qs) and SSY, increased dramatically during all stages of IFMS. Implementation of the intensive contour-line planting method was effective in reducing direct runoff and peak discharge. SS discharge in the catchments B and C still increase in the initial stage of post line planting. These results illustrate that the magnitude of runoff and SSY depend on interactions between the rainfall, forest cover changes, catchment topography, and surface disturbance that occur during forest management practices. Forest management practices should consider, and attempt to minimize, disturbance during each IFMS stage to control runoff and sediment yields. Adequate protection of the forest floor may be achieved by implementing strict controls over logging activities and by combining harvesting with intensive contour-line planting. Together, these practices can reduce the impacts of logging and meet the requirements of sustainable forest management.

6.1 Introduction

Many of the world’s tropical forests are being managed unsustainably, generally due to the intensity of timber harvest and lack of adequate techniques to preserve sustainability; that is, to preserve ecosystem structure and function and ensure the ability of forests to regenerate populations of desirable tree species. Sustainable forest management (SFM) is the management of natural forests in such a way as to minimize the negative impacts associated with timber extraction. Traditional forest management in Indonesia consisted of the Indonesian selective cutting and replanting system (TPTI). The TPTI system conducts replanting in open forest areas including the log-landing areas, logging-road buffers and ex-cutting areas. Forest growth depends on the growth of natural regeneration. In the harvesting periods that followed TPTI, forest poroductivity was found to decrease over the first harvesting period. It has been shown that TPTI does not succeed in restoring forest potency in the harvesting periods that follow (Sianturi and Kanninen, 2005). To achieve SFM and maintain forest productivity, the management of tropical Indonesian rainforests then changed to an Intensive Forest Management System (IFMS), which was implemented officially in 2002. The IFMS primarily involves selective logging and intensive rehabilitation with line-planting to enrich the forest’s standing stock in the next harvesting period (Suryatmojo *et al.*, 2011a). Essentially IFMS is a modified TPTI that focuses on intensive rehabilitation to increase forest productivity in the next harvesting periods. Timber harvesting involves logging road construction, tree cutting, log skidding in skid trails, log hauling to log yard and transportation. Intensive rehabilitation involves line clearing and intensive line planting.

Runoff response and soil erosion rates change significantly with changes in land cover. Many studies have examined runoff and soil erosion in tropical forests globally (*e.g.*, Abdulhadi *et al.*, 1981; Standtmueller, 1990; Anderson, 1990; Hendrison, 1990; Douglas *et al.*, 1992; Van Der Plas and Bruijnzeel, 1993; Baharudin and Abdul Rahim, 1994; Noguchi *et al.*, 1997; Douglas, 1999; Douglas, 2003; Robinson, 2003; Chappell *et al.*, 2004; Ziegler *et al.*, 2006; Chaves *et al.*, 2008; Zimmermann, 2012). These previous studies suggest that timber harvesting using heavy machines destroys soil structure, which plays an important role in water and nutrient cycling, and accelerates soil erosion rates (Malmer, 1996a; Nussbaum and Hoe, 1996; Sidle, 2004; Ziegler *et al.*, 2004; Chappell *et al.*, 2005; Sidle, 2006). Heavy machines in timber collection areas and on skidder roads increase soil compaction by up to 40% over natural conditions (Nussbaum and Hoe, 1996; Nussbaum *et al.*, 1996); 10–30% of the soil surface may become bare due to logging roads, skidder tracks and log landings (Bruijnzeel, 1992; Van Der Plas and Bruijnzeel, 1993). The use of heavy equipment tends to compact topsoil, setting in motion a negative feedback cycle of reduced infiltrability and an increased frequency of overland flow and sheet erosion, thereby hindering the establishment of a new protective layer of vegetation and litter (Van Der Plas and Bruijnzeel, 1993).

Southeast Asia is marked by immense geological diversity. To date, the study of runoff and soil erosion in tropical forests has been dominated by research on the impacts of selective logging (*e.g.*, Baharuddin, 1983; Douglas *et al.*, 1992; Abdul Rahim and Harding, 1992; Baharudin and Abdul Rahim, 1994; Brooks *et al.*, 1994; Malmer, 1996; Noguchi *et al.*, 1997; Douglas, 1999; Hartanto *et al.*, 2003; Chappell *et al.*, 2004); however, research concerning IFMS in Indonesian rainforests has been limited (Suryatmojo *et al.*, 2011b). The IFMS potentially increases forest potency through intensive rehabilitation, but on the other hand, intensive line planting techniques increase the amount of open forest area compared to the TPTI system. Reductions in vegetation cover from forest harvesting generally change the hydrologic response by increasing the average surface runoff volume and sediment yield for a given area of land; and the IFMS is suspected to dramatically impact the hydrologic response to wider forest clearings. Therefore, a need exists to quantitatively evaluate the hydrologic response of tropical rainforests managed under IFMS. This chapter investigated the impact of different IFMS stages on runoff and suspended sediment yield resulting from their respective forestry treatments using a paired-catchment method. Paired-catchment studies have been widely used to determine the magnitude of hydrologic responses resulting from changes in vegetation (Brown *et al.*, 2005). Paired-catchment methods are the foundation of many studies and key reviews of the impact of forestry on hydrology (Bosh and Hewlett, 1982, Stednick, 1996, Watson *et al.*, 2001, Brown *et al.*, 2005).

6.2 Methods

6.2.1 Study site

The study was conducted in a tropical rainforest at the Bukit Baka Experimental Catchments, which are located in the headwater region of the Katingan watershed. This study used three paired small catchments. Catchment A was monitored as a control. Catchment B was supervised and treated with standard IFMS. Catchment C was supervised and treated with modified IFMS. Runoff and suspended sediment yield were investigated in the three paired, small catchments A, B and C (Figure 6.1).

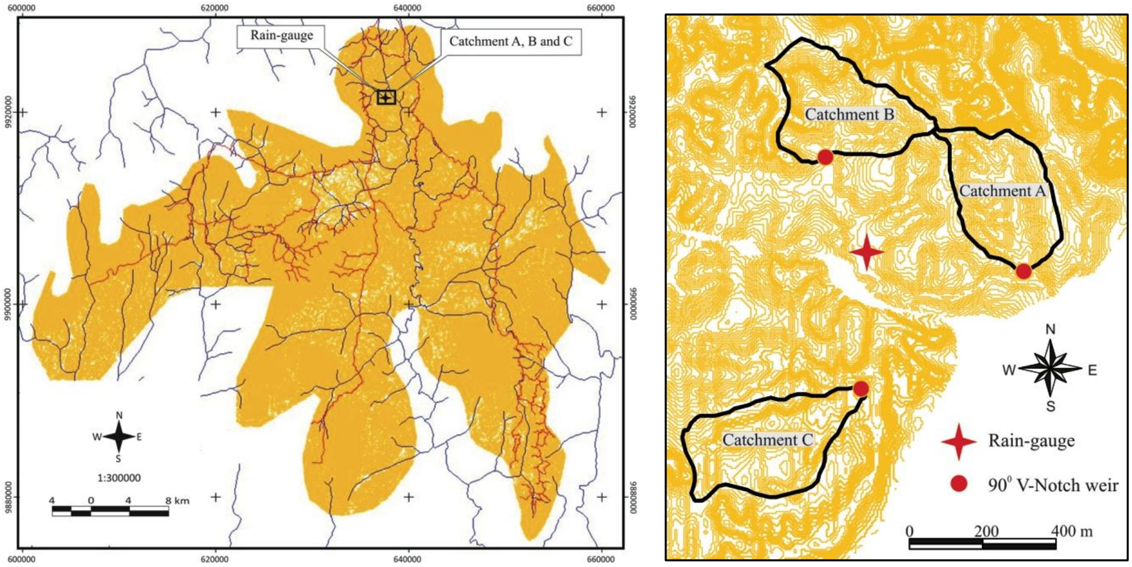

Figure 6.1 Catchment experiments at the study site and the three paired, small catchments.

Table 6.1 Physical catchment characteristics of the three paired catchments used in this study.

Physical characteristics	Catchment A	Catchment B	Catchment C
Drainage area (km^2)	0.087	0.087	0.094
Catchment circularity[a]	0.57	0.80	0.34
Catchment slope (%)	30.9	32.5	22.4
Drainage density (km/km^2)	17.84	15.66	15.28
Main river length (km)	0.47	0.38	0.52

Catchments A, B and C all had similar physical characteristics, except for catchment circularity and slope. Specifically, catchment B had a much steeper slope than catchment C. Catchment B had the highest level of catchment circularity, meaning that this catchment had the most circular shape. Catchment shape contributes to the rate at which surface runoff reaches the river channel. For instance, a long thin catchment will take longer to drain than a circular catchment. Combined with a steeper slope angle, catchment B was expected to have accelerated surface runoff and to contribute runoff to the peak at the same time as the storm rainfall is over the catchment outlet. Catchment shape also influences peak flow during storm rainfall. Greater drainage density appears to be associated with more extreme runoff behavior, greater total surface runoff and less ground water storage; whereas the length of the main river appears to affect the lag time and time concentration. The longer the river, the longer the time concentration and the lower the peak flow compared with a shorter main river.

6.2.2 IFMS in paired catchment sites

The three paired, small catchments (Figure 6.1) were established to evaluate the effects of IFMS on the hydrologic responses of runoff and suspended sediment yield.

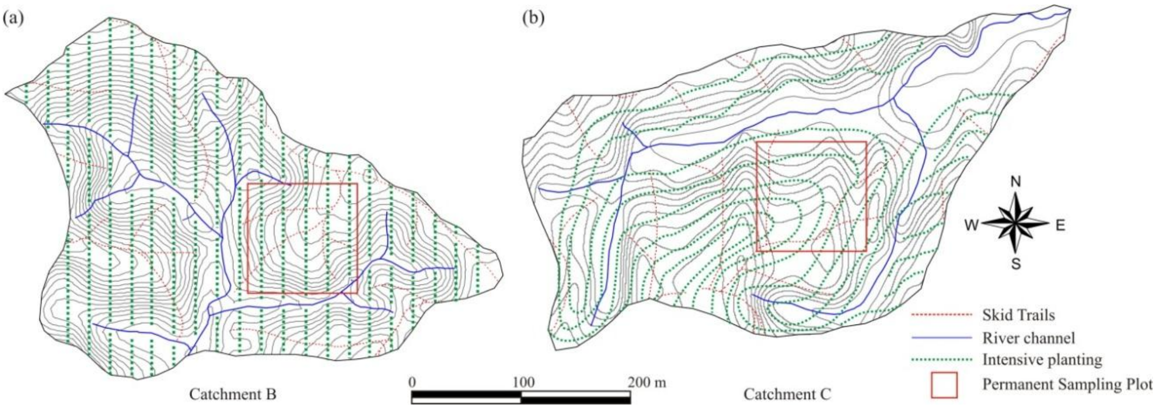

Figure 6.2 Implementation of IFMS in catchments B and C with (a) strip-line planting; and (b) contour-line planting.

Although no forestry operations were conducted in catchment A, IFMS-based selective logging and intensive line planting were conducted in catchments B and C (Figure 6.2). The schedule of forestry operations is shown in Figure 6.3. Selective logging (SL) was operational in catchments B and C and carried out in December 2011. The intensive line planting (ILP) operational period in the catchments B and C were conduced in November 2012.

Rainfall, runoff and suspended sediment were investigated from May 2011–February 2013 (Figure 6.3). The pre-treatment periods for catchments A and B were May–November 2011, while pre-treatment period for catchment C was in November 2011. Data obtained in the pre-treatment period were used for calibrations to establish the hydrological relationships between the control and treated catchments. For each stage of IFMS, the data following a specific operational period were used in the analysis. That is, data observed for 10 months were analyzed in the post-SL period, and data observed for 3 months were analyzed in the post-ILP period (Figure 6.3). Data obtained in the post-SL and post-ILP periods were used to evaluate the effects of forest operations on storm discharge and suspended sediment yield during each stage of IFMS.

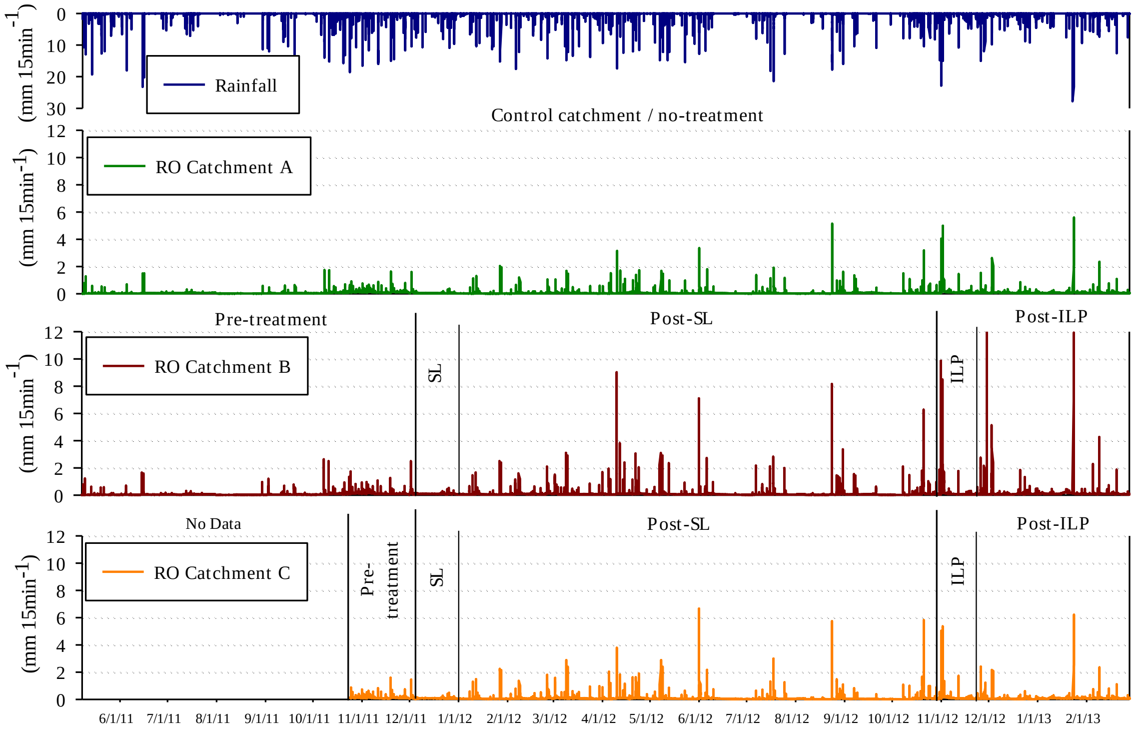

Figure 6.3 Runoff hydrographs in control catchment A, and in catchments B and C, during different IFMS stages.

In the SL operational period, 4-m wide skid trails were constructed in catchment B and C (Figure 6.2). In the ILP operational period, a 3-m wide strip of line planting was conducted in catchments B and C. In catchment B, intensive strip-line planting was conducted, which is a standard rehabilitation method that uses a North–South direction to establish the planted lines as shown in Figure 6.2a. Spacing between each planting line was 20 m. In catchment C, intensive contour-line planting was conducted, which is a modified rehabilitation method that considers catchment topography (as shown in Figure 6.2b), and was expected to reduce the hydrological impacts of logging on surface runoff and soil erosion.

Table 6.2 summarizes surface disturbance from IFMS in catchments B and C. In the SL operation period, skidder tractors can cause compaction by a combination of tread pressure, kneading action, vibration, scarification and pressure from a turn of logs being skidded. The skid trail disturbances were slightly more severe in catchment B than in catchment C. Although the skid trail disturbance area during the SL operational period was less than 10% in both catchments (Table 6.2), actual disturbance occurred throughout the entire catchments. For instance, forest harvesting in the SL operational period had a large area of surface disturbance from tree cutting, log-felling, and log-hauling using a skidder tractor, which can lead to the development of erosional landforms. In comparison with the SL operational period, manual line-clearing in the ILP operational period had less surface disturbance, which occurred only in the line planting area shown in Figure 6.2. The area of total forest floor disturbance from IFMS was similar between catchments B and C (Table 6.2).

Table 6.2 Surface disturbances area in catchments B and C for each IFMS operational periods.

Catchment	Disturbance area (percentages of catchment area)		
	Selective logging (Skid trails)	Intensive line planting	Total*
B	0.77 ha (8.8%)	1.22 ha (14%)	1.99 ha (22.9%)
C	0.54 ha (5.7%)	1.33 ha (14%)	1.87 ha (19.9%)

*Excluding disturbance from log-felling and -hauling using a skidder tractor.

Changes in forest canopy cover were monitored in a permanent sample plot (PSP) in each catchment, as shown in Figures 6.2 and 6.4. PSP are used for the long-term observation of forest growth, including measurements of diameter increment, volume increment and stand structure dynamics. The PSP consisted of one square hectare of forest area that was randomly located in the middle slope of each catchment. The number of trees was counted under natural conditions (N), and during the post-SL and -ILP periods (Table 6.3). Tree canopy cover was calculated using conversion equations from tree diameter to canopy area for each tree species.

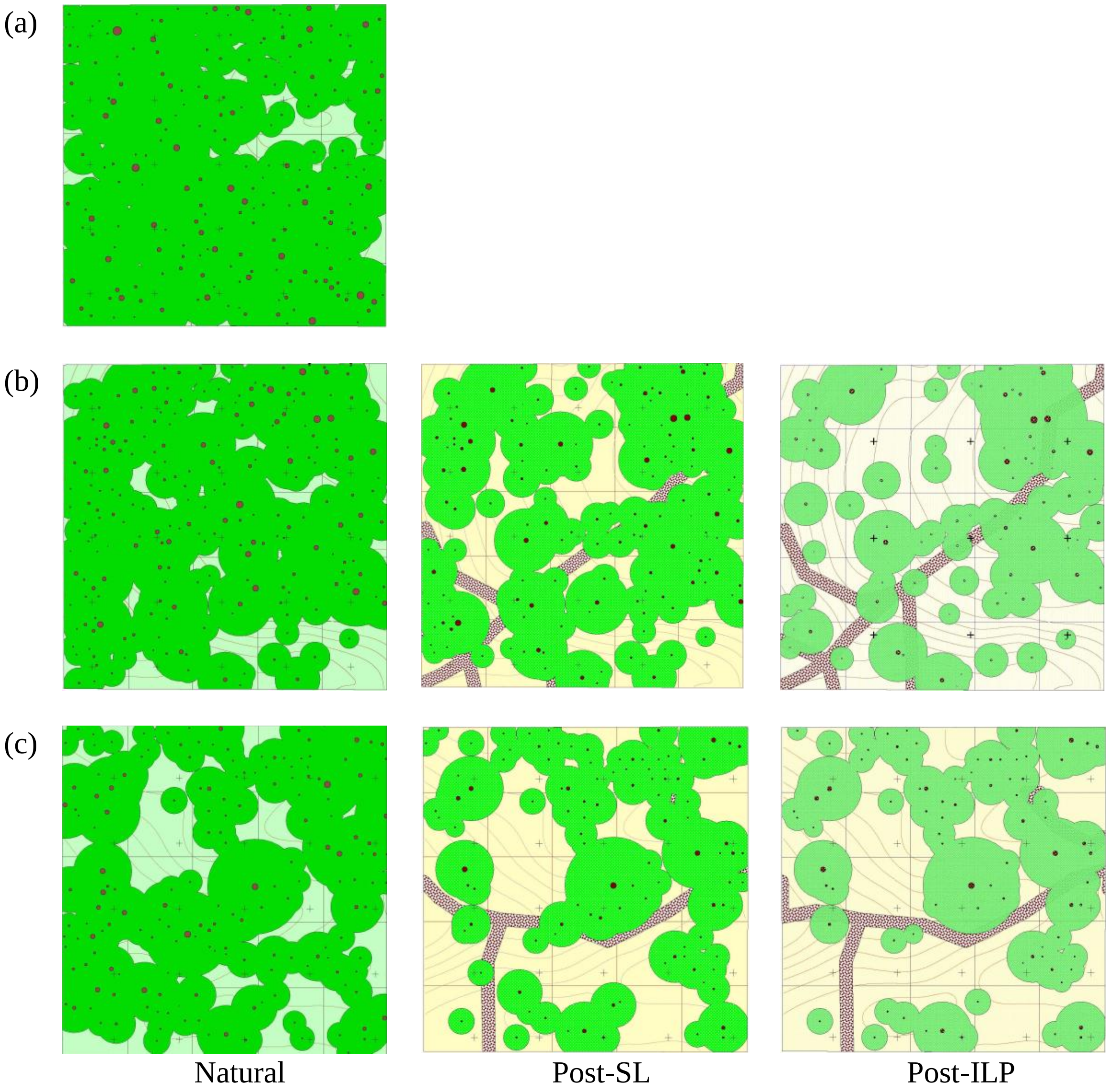

Figure 6.4 Horizontal projection of canopy cover changes from natural conditions in catchment A; (b) catchment B; and (c) Catchment C.

Table 6.3 Number of trees and tree canopy cover in catchments A, B and C based on PSP measurements.

Catchment	Number of tree*			Tree canopy cover (%)		
	Natural	Post-SL	Post-ILP	Natural	Post-SL	Post-ILP
A	206			95%		
B	218	135	80	88%	60%	54.5%
C	170	102	81	79%	56%	50.6%

*Tree is vegetation with diameter > 20 cm (at 1.3 m above land surface)

Based on PSP measurements, the SL operational period greatly decreased forest canopy cover by reducing the number of trees. The ILP operation also significantly reduced the number of trees and canopy cover. Under natural conditions, the percentage of tree canopy cover in the three catchments ranged from 79–95%. Catchment C had the smallest canopy cover of the three catchments. In the post-SL period, differences in canopy cover between catchments B and C were reduced to 4%. In the post ILP period, differences in canopy cover between catchments B and C were similar as 3.9%.

6.2.3 Paired catchment observation and analysis

Precipitation was monitored using an automatic tipping-bucket rain gauge (logging time, 15 min.) near the three catchments. The discharge rates were measured using 90° V-notch weirs (0.9 × 1.4 × 3m) and water-level loggers (HOBO U-20) with a time interval of 15 min at each catchment outlet (Figure 6.1). The observed runoff hydrograph was divided into direct runoff and base flow using a straight-line method (Black, 1991).

At each weir, sediment concentration was measured using a rising stage suspended sediment sampler (Gordon *et al.*, 1992). Rising stage suspended samplers work on the siphon principle from the inlet-pipe to bottle samples. In this method, water samples including suspended sediment were collected for each water level. A rising stage was installed at a sidewall of the weir and attached to 60 inlet pipes (3.5 mm in diameter with a distance of 1 cm for each pipe). The inlet-pipe connected to a number of bottles (260 ml in volume) arranged on top of each other in frame, installed near the rising stage. Each bottle is fitted with a two-hole stopper, one hole for the sample inlet and one for the air exhaust. Suspended sediment samples were collected during storm rainfall occurrences. Suspended solids were determined gravimetrically by filtering the suspended sample (260 ml) using filter paper (pore size, 2.5 μm). The volumetric sediment concentration (mg/l) was measured by the evaporation method using oven-dried suspended filter papers at 108°C for a minimum of 2 h (Julien, 2010). The suspended sediment discharge (Qs) was calculated as the product of sediment concentration and discharge rate.

The numbers of storm events used for paired hydrological analysis in the pre-treatment, the post-SL, and post-ILP periods were 63, 46 and 36, respectively. In the post-SL period, the total numbers of suspended sediment samples collected in catchments A, B and C were 83, 100 and 90, respectively. In the post-ILP period, the total numbers of suspended sediment samples collected in the catchment A, B and C were 41, 75 and 74, respectively.

6.3 Results and discussion

6.3.1 Direct runoff

Runoff hydrographs were investigated in catchments A, B and C during the observation period in May 2011–February 2013. During the pre-treatment period, all three catchments produced similar storm hydrographs (Figure 6.3). The data suggested that during the post-SL and post-ILP periods, storm discharge tended to be greater in catchments B and C than in catchment A. The changes in runoff hydrographs in the post-SL and post-ILP periods are shown in Figure 6.5.

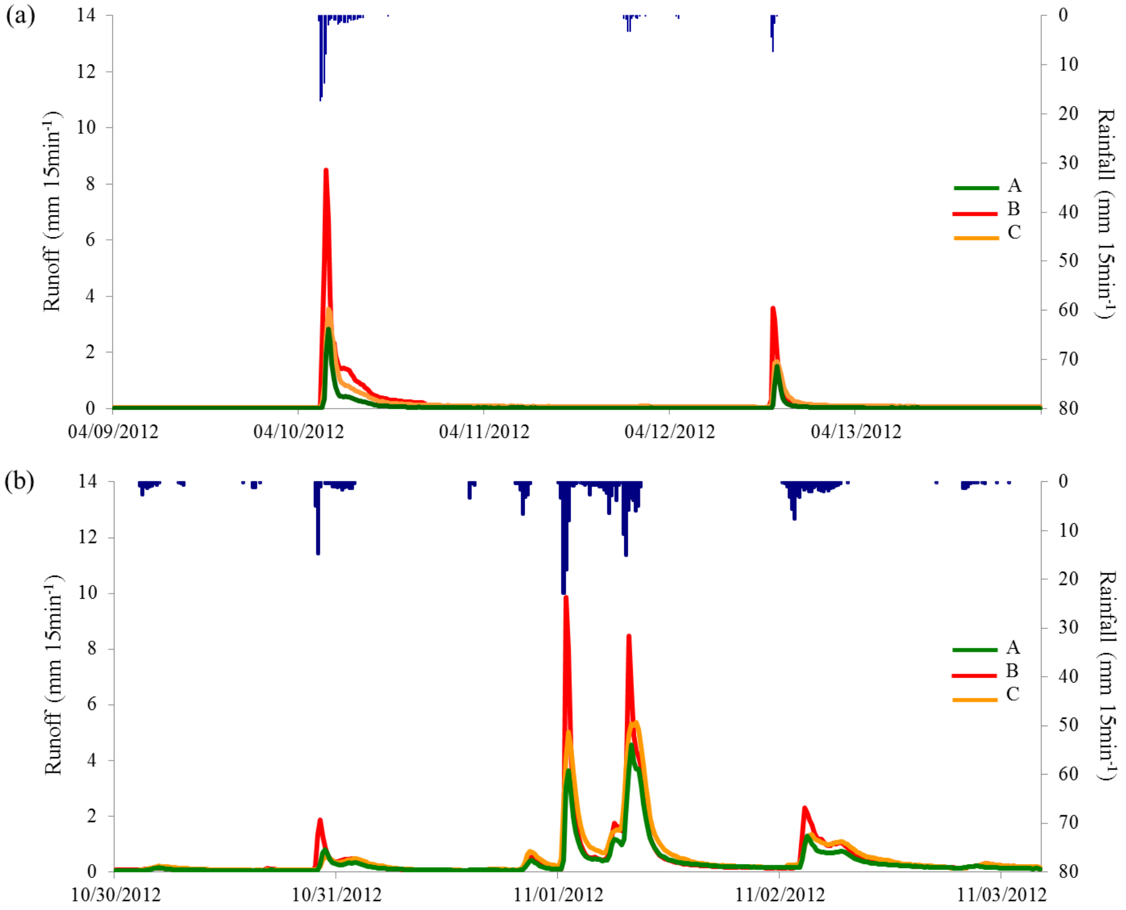

Figure 6.5 Runoff hydrograph responses in catchments A, B and C during (a) the post-SL period; and (b) post-ILP period.

To make direct comparisons, Figure 6.6 shows the relationship between direct runoff (DRO) in catchment A and the DRO of catchments B and C in which the IFMS operations were conducted.

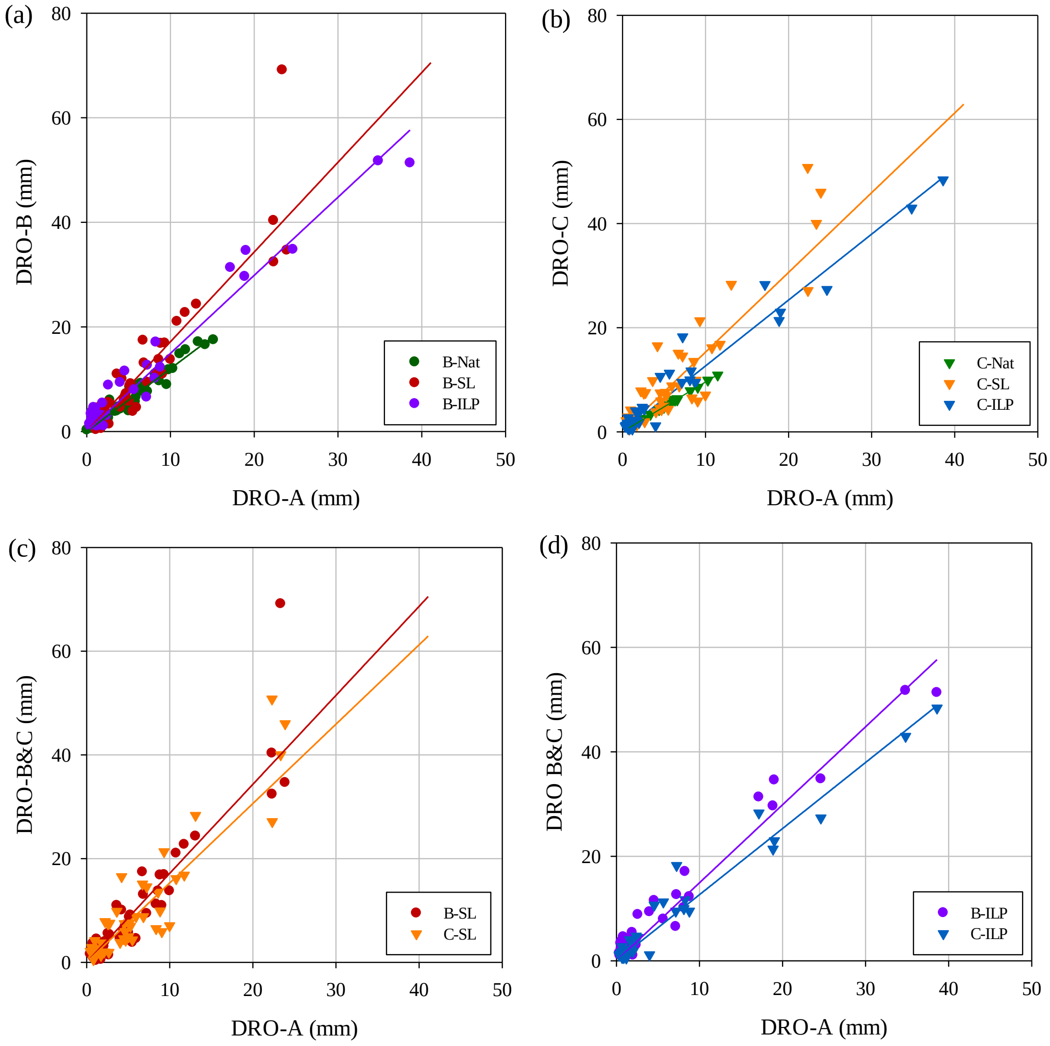

Figure 6.6 Comparison of DRO between the natural catchment (A) and treated catchments (B and C) during different IFMS periods. (a) DRO of catchment B; (b) DRO of catchment C; (c) DRO of catchments B and C in the post-SL period; and (d) DRO of catchments B and C in post-ILP period.

Figure 6.6a shows that, during the pre-treatment period, DRO in catchment B was similar to that in catchment A. DRO in catchment B increased during the post-SL period. In the post-ILP period, DRO in catchment B was decreased in comparison with DRO during the post-SL period, but still greater than DRO during the pre-treatment period.

Figure 6.6b shows that DRO in catchment C was similar to DRO in catchment A during the pre-treatment period. During the post-SL period, DRO in catchment C increased, and then decreased during the post-ILP period, but remained greater than during the pre-treatment period. During the post-SL period, DRO in catchment B was greater than DRO in catchment C (Figure 6.6c). This trend was also observed during the post-ILP period; that is, the DRO in catchment B was greater than in catchment C (Figure 6.6d).

Figures 6.6a and 6.6b suggest that DRO in the three catchments exhibited similar responses in the pre-treatment period. Similar vegetation cover (Table 6.3) and similar physical catchment characteristics, except for slope gradient (Table 6.1), produced similar responses in DRO between the two catchments. As shown in Table 6.3, the SL operations system led to the formation of large canopy openings, resulting from tree felling and skid trail hauling road construction. The large open-forest area reduced forest interception and transpiration, increasing net rainfall reaching the forest floor and increasing soil moisture. Logging using heavy machinery significantly increased soil compaction and reduced infiltration capacity, particularly on the logging roads and skid trails (Van Der Plas and Bruijnzeel, 1993, Williamson and Neilsen, 2000, Suryatmojo *et al.*, 2009, Osuji *et al.*, 2010). These conditions created quick runoff responses that were dominated by surface flow, and also increased the ratio of rainfall to runoff in the catchment during the post-SL period.

The ILP operations in catchments B and C with manual line clearing left biomass litter on the forest floor. This led to increases in surface roughness and reduced surface runoff flow to the stream channel, resulting in declines in DRO during the post-ILP period.

During both the post-SL and post-ILP stages, catchment B produced greater DRO than catchment C (Figure 6.6c and 6.6d). Catchment B had slightly more surface disturbance from skid trail construction during the SL operational period (Table 6.2) than catchment C. It is likely that, following disturbance from SL operation, the steeper catchment slope in catchment B produced more DRO than in catchment C. These results indicate that slope angle is one of the most important factors influencing the hydrological impacts of SL operation.

During the post-ILP period, the difference in DRO between catchments B and C was more pronounced (Figure 6.6d). This might be attributable to differences in the line planting method. That is, strip-line planting in catchment B did not consider the catchment contour (*i.e.*, Figure 6.2a), which led to the catchment being more sensitive to accelerating surface runoff flow downstream, producing greater DRO. Modified IFMS in catchment C using intensive contour-line planting (*i.e.*, Figure 6.2b), likely reduced surface runoff flow downstream and produced a smaller DRO than catchment B.

6.3.2 Peak discharge

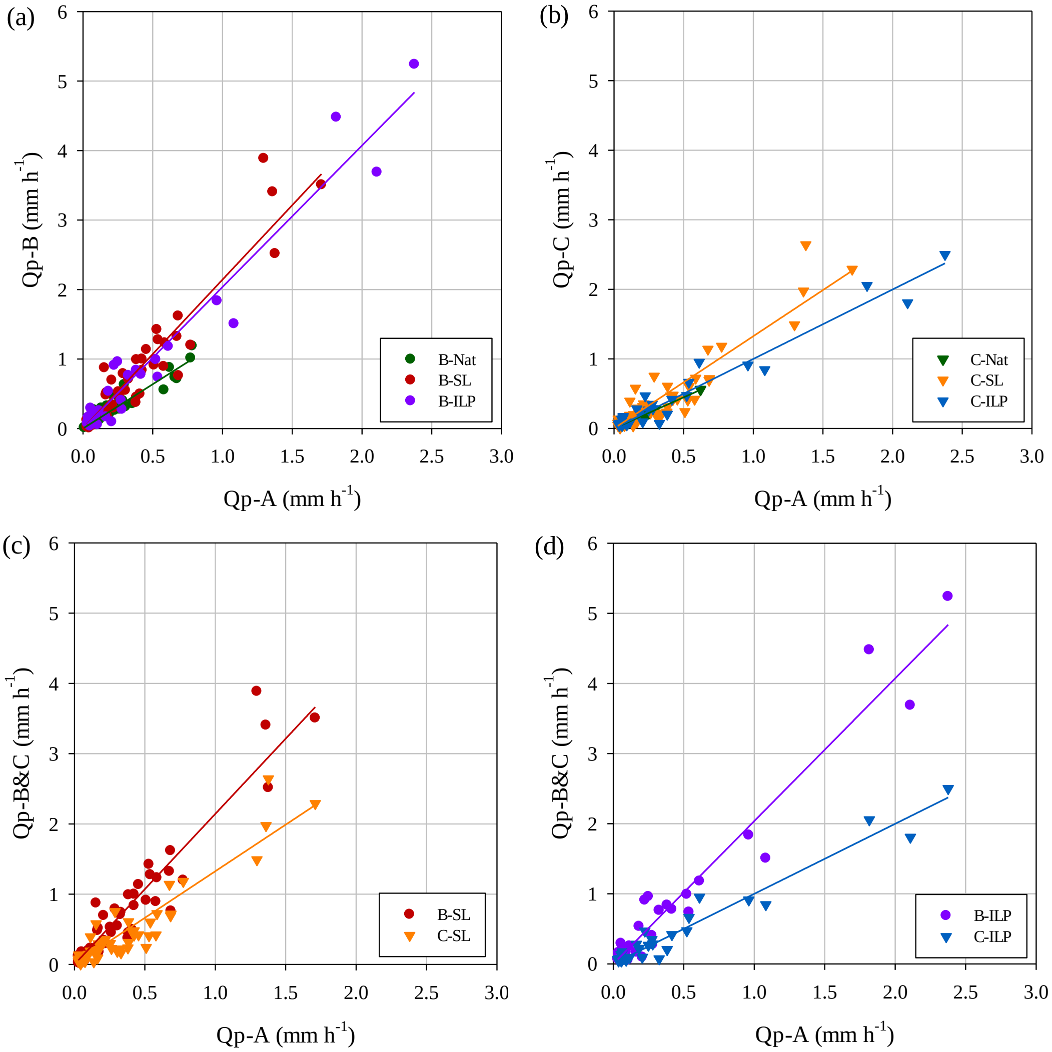

Figure 6.7 Comparison of peak discharge (Qp) between natural catchment (A) and treated catchments (B and C) during different stages of IFMS, including (a) Qp of catchment B; (b) Qp of catchment C; (c) Qp of catchments B and C in the post-SL period; and (d) Qp of catchments B and C in the post-ILP period.

During the pre-treatment stage, peak storm discharge (Qp) in catchment B was similar to Qp in the catchment A (Figure 6.7a), whereas Qp in catchment B increased during the post-SL period. During the post-ILP period, Qp in catchment B was similar to that during the post-SL period, and remained higher than that in catchment A. Figure 6.7b shows that the Qp in catchment C was similar to that in catchment A during the pre-treatment phase. Qp in catchment C increased during the post-SL period and then decreased in the post-ILP period, becoming similar to Qp under natural conditions. During the post-SL period, Qp in catchment B was higher than that in catchment C (Figure 6.7c); and during the post-ILP period, Qp in catchment B was markedly higher than that in catchment C (Figure 6.7d).

During the post-SL period, a larger open-forest area and higher rate of surface disturbance from skid trails caused Qp to increase in both catchments B and C. The effect was more pronounced in catchment B, which was characterized by steeper topography. In catchment B, Qp remained high throughout the post-ILP period, suggesting that the traditional North–South line-planting method, which does not consider topography, is not effective in reducing peak storm discharge. During the ILP period, Qp in catchment C decreased and became similar to Qp under natural conditions (Figure 6.7b). That is, the implementation of intensive contour-line planting in catchment C effectively reduced Qp compared to the traditional intensive strip-line planting utilized in catchment B.

6.3.3 Total discharge increase from selective logging

For the 10 months of the post-SL period, total runoffs from catchments A, B, and C were 1560, 2633 and 2298 mm, respectively. The ratios of total runoff to total rainfall were 51.7, 87.4 and 76.3 for catchments A, B, and C, respectively. That is, the total runoff of catchments B and C were greater than that of catchment A by 68.8% and 47.3%, respectively.

Research into the impacts of logging on increases in runoff has also been conducted in other tropical countries. Paired catchments in Mendolong, Sabah, Malaysia, reported runoff increases of 71–94% due to various clear-felling treatments (Malmer, 1992). The effect of forest conversion at the Sungai Tekam experimental catchment in Malaysia showed an increase in annual water yield from 85% to 470% in a clear-felled catchment (Douglas, 1999). Runoff increases in Mendolong and Sungai Tekam were higher than those reported here. These differences are due to variations in forest operation. The forest operation conducted in this study was selective logging, while the studies in Mendolong and Sungai Tekam used clear felling with no vegetation remaining in the catchments.

Selective logging operations similar to those used in this study were found in two catchments in Bukit Berembun, Malaysia. In the first 3 years, commercial selective logging that extracted 40% of the stand volume and did not utilize any reduce impact logging (RIL) techniques recorded increases in water yields of 53–72%. In supervised logging with 33% extraction of the standing volume and that implemented the RIL technique, the water yield increased by 28–44% (Bruijnzeel, 1990, Chuan, 2003). In comparison with previous studies, runoff increases in catchment B following SL operations were of a similar rate to those following commercial selective logging. However, for catchment C, the runoff increased at a lower rate and was similar to supervised logging in Bukit Berembun.

Both catchments B and C underwent selective logging, but exhibited different total runoffs following these treatments. Catchments B and C had similar canopy cover densities in the post-SL operation (Table 6.3), but different rates in surface disturbance and differing slope angles of their catchments. Catchment B had a slightly higher rate of surface disturbance from skid trails than did catchment C (Table 6.2). Surface disturbance from skid trails affects soil compaction and produces greater surface runoff. Combined with a steeper slope, catchment B experienced accelerated surface runoff flow, producing greater DRO (Figure 6.6c) and higher Qp (Figure 6.7c) from storm rainfall compared with catchment C. Catchment C had a lower rate of surface disturbance from skid trails and a lower slope angle than catchment B. Lower rates of surface disturbance produced smaller DRO amounts, and a gentler slope angle produced a lower surface runoff velocity to the river channel and a lower Qp in the catchment outlet.

6.3.4 Suspended sediment concentration

SL and ILP operations destroyed surface soil in the catchments, and surface disturbances from skid trails and line clearing increased the suspended sediment concentration (Figure 6.8).

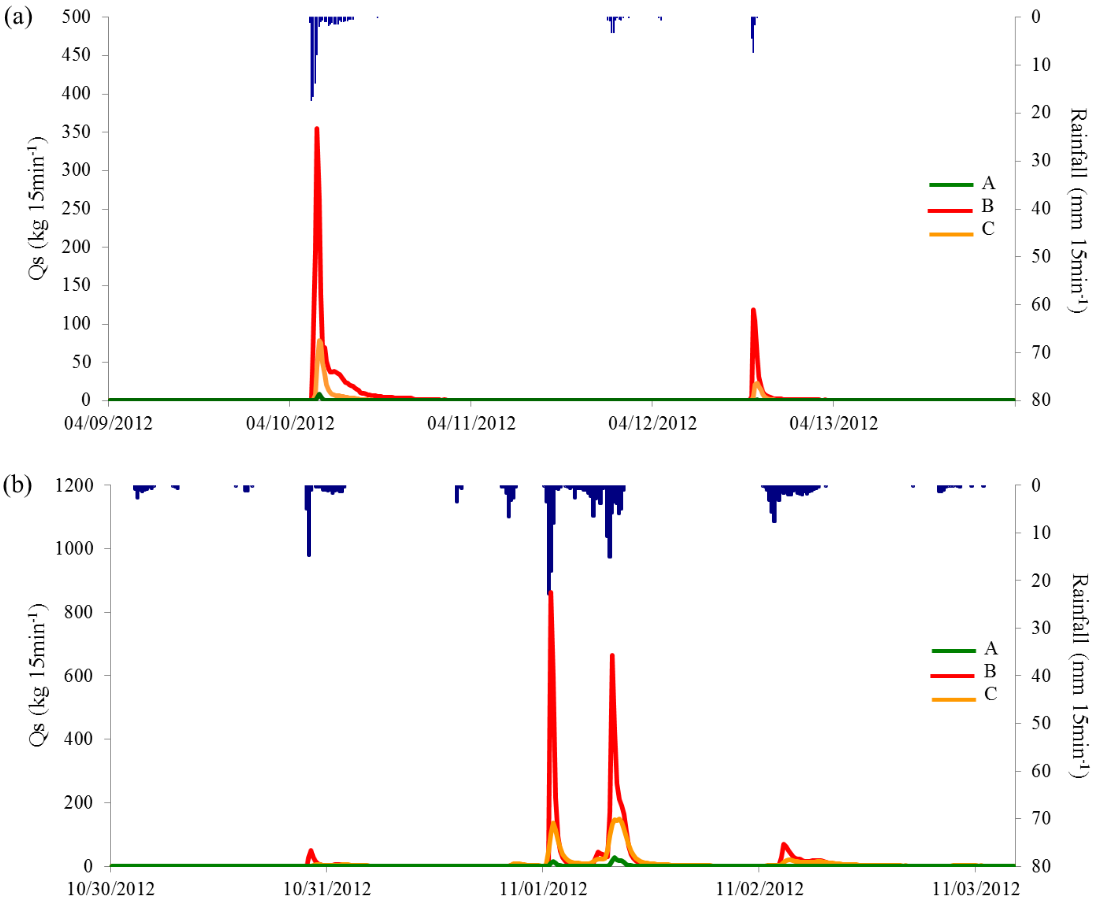

Figure 6.8 Qs in catchments A, B and C, during (a) the post-SL period; and (b) the post-ILP period.

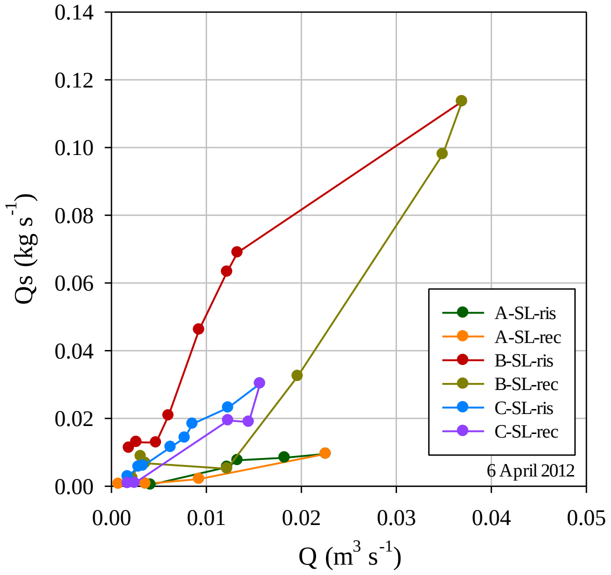

Figure 6.9 Hysteresis loop of changes in suspended sediment discharge with discharge in catchments A, B and C as observed during the post-SL period on April 6, 2012. (ris = rising-limb; rec = recessing-limb).

Figure 6.9 shows the results of suspended sediment flux measurements conducted for storm events on April 6 2012, during the post-SL period. The hysteresis loops for suspended sediment discharge show a characteristic clockwise pattern. The figure indicates that catchment B produced a clear hysteresis loop in discharge (Q) and suspended sediment discharge (Qs) relationship. This means that sediment concentration for the rising-limb (SL-ris) was greater than sediment concentration for recessing-limb (SL-rec). The hysteresis loop was not as pronounced for catchments A and C. During the post-SL period, catchment B produced a clear hysteresis loop in Q and Qs relationship for most of the storm events (Figure 6.10). Again, no clear hysteresis loop was found for catchments A and C during the same period.

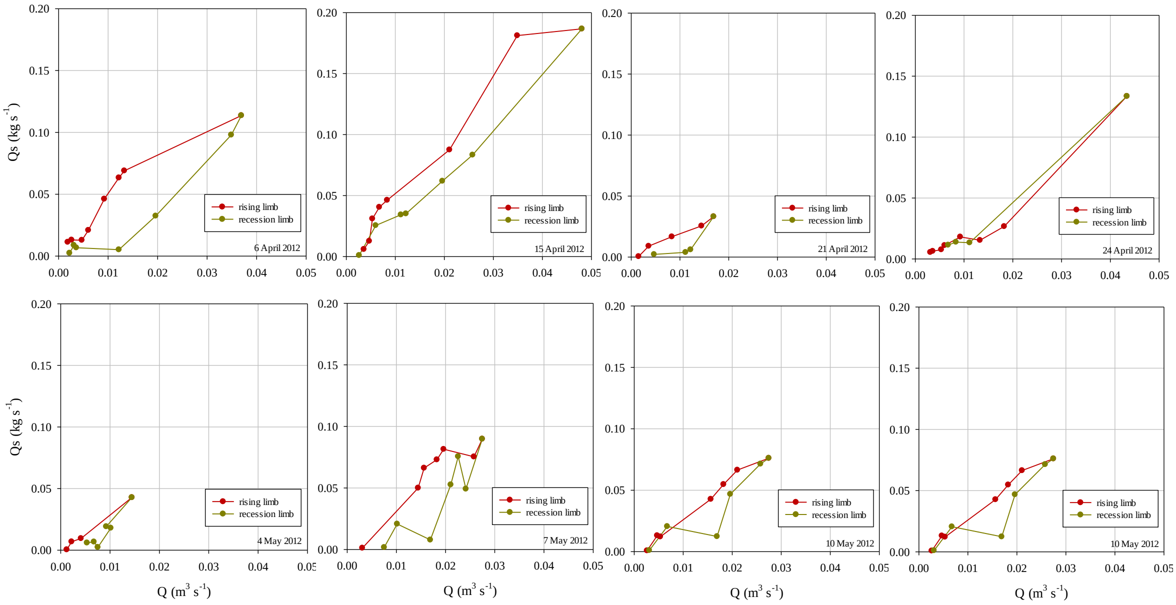

Figure 6.10 Variation in suspended sediment discharge (Qs) loops in catchment B during the post-SL period.

As shown in Figure 6.10, during the post-SL period, the hysteresis loop was found only in catchment B. Physical catchment characteristics influenced the shape of the hydrograph. Catchment B had a circular shape and steeper slope angle than catchment C (Table 6.1). Catchment B also had greater DRO and higher Qp than catchment C (Figures 6.6c and 6.7c). A greater volume of surface runoff and higher slope gradient created an enhanced opportunity for transporting suspended sediment. Therefore, the availability of sediment sources is a controlling factor in the concentration of suspended sediment in runoff. Large quantities of suspended sediment material are washed away in the rising-limb, while suspended sediment concentrations decline in the recessing-limb due to a lack of suspended sediment material. In contrast, the ability of suspended sediment to be transported by surface flow was the controlling factor in catchment C. Therefore, the relationship between Q and Qs in catchment C was similar in both the rising- and recessing-limb parts of the hysteresis loop hydrograph.

During the post-ILP period, the hysteresis loop became unclear in catchment B. In catchment C, no hysteresis loop was found during the post-ILP period or LP period. The ILP operations left forest biomass and litter on the forest floor, which led to increases in the surface roughness and reduced surface runoff flow to the stream channel. Moreover, the biomass litters act as traps for the flowing sediment material. Therefore, ILP operations greatly reduced the transportation of suspended sediment in catchment B. Consequently, the sediment production rate was not controlled by the availability of sediment, but by the ability of that sediment to be transported, which resulted in the diminishing of the hysteresis loops.

Figure 6.11 shows the relationship between Q and Qs for each catchment and each IFMS operation period. For catchment B, data obtained during the post-SL period were divided into the rising- and recessing-limbs, due to the clear hysteresis loop (Figures 6.9 and 6.10).

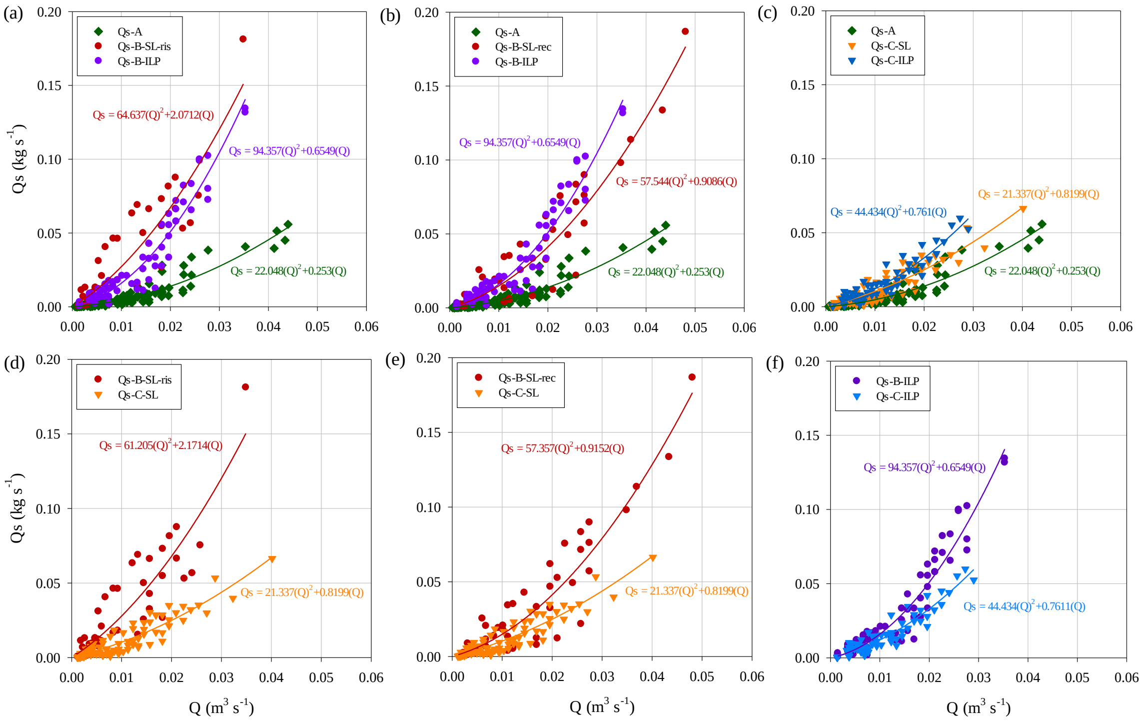

Figure 6.11 Changes in Qs between the natural catchment (A) and treated catchments (B and C) during different IFMS treatment periods, including (a) Qs of catchment B in the rising-limb in the post-SL period; (b) Qs of catchment B in the recessing-limb in the post-SL period; (c) Qs of catchment C; (d) Qs of catchments B and C in the post-SL period in the rising-limb of B; (e) Qs of catchments B and C in the post-SL period in the recessing-limb of B; (f) Qs of catchments B and C in the post-ILP period.

The IFMS treatments resulted in higher suspended sediment concentrations in catchments B and C than in catchment A, which was kept under natural conditions as a control (Figure 6.11a, b and c). The Qs in catchment B during both the post-SL and post-ILP periods was higher than that in catchment A (Figure 6.11a, and b). Catchment

B produced greater Qs in the rising-limb during the post-SL period than during the post-ILP period (Figure 6.11a). In the recessing-limb during the post-SL period, catchment B produced lower Qs than during the post-ILP period (Figure 6.11b). Overall, in catchment B, Qs was similar during the post-SL period to Qs during the post-ILP period. Fig 6.8c shows that during the post-SL period, catchment C exhibited slightly higher Qs than catchment A. Furthermore, the Qs of catchment C during the post-ILP period was higher than that during the post-SL period.

Figures 6.11d and 6.11e show that during the post-SL period, both the rising-limb and the recessing-limb of the Q-Qp relationship in catchment B produced higher Qs than the Q-Qp relationship in catchment C. This result indicates that the suspended sediment concentration in catchment B was greater than that in catchment C during the post-SL period. Surface disturbance during SL operations created zones of rain-splash and surficial wash on haulage roads and skid trails. A combination of the larger skid trail area (Table 6.2) and steeper catchment topography (Table 6.1) in catchment B caused the greater magnitudes of suspended sediment transport.

During the post-ILP period, catchment B also produced greater Qs than catchment C (Figure 6.11f). However, the differences between catchments B and C were smaller in comparison with those during the post-SL period. In catchment C, the sediment concentration during the post-ILP period was slightly higher than that during the post-SL period (Figure 6.11c). This increase was likely related to the addition of surface disturbance caused by ILP operations. Although the manual line clearing operation left biomass litter on the forest floor, ILP caused an increase in surface disturbance area (Table 6.2) and an overall decrease in canopy coverage (Table 6.3). The effects of such disturbances likely outweigh the effects of biomass litter cover on the forest floor, resulting in an increase in suspended sediment (SS) concentration. Therefore, our observations during the initial 3 months of the post-ILP period suggest that the contour-line planting conducted in catchment C was not necessarily effective in reducing the SS concentration in discharge water.

6.3.5 Suspended sediment yield

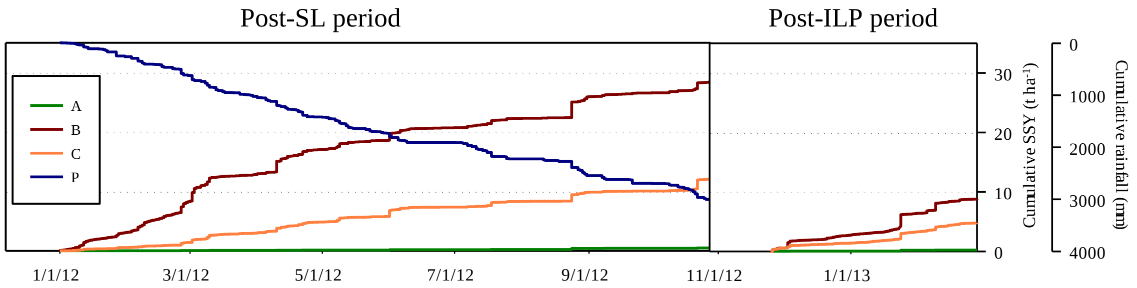

Figure 6.12 Cumulative SSY for catchments A, B and C during the post-SL and post-ILP periods.

Figure 6.12 shows cumulative suspended sediment yields (SSY) for catchments A, B and C during the post-SL and post-ILP periods. During the 10 months of investigation in the post-SL period, catchments A, B and C produced SSY of 0.5, 28.3 and 12.1 t ha^{-1}, respectively. From these values, annual SSY can be estimated as 0.6, 34.0, 14.5 t ha^{-1} y^{-1} for catchments A, B, and C, respectively.

Annual SSY of the natural catchment A was similar to results of previous studies conducted in other undisturbed tropical rainforest in Southeast Asia. Results from forest catchments in Thailand (Huai Bo Thong, Lam Thakhong, and Kogma) indicated that sediment yields ranged from 0.06 t ha^{-1} y^{-1} in mixed deciduous forests, to 0.35 t ha^{-1} y^{-1} in hill evergreen forests. Soil loss in the primary forest of Serawak Malaysia was 0.08–0.31 t ha^{-1} y^{-1} (Douglas, 1999). Studies on four forested catchments in Malaysia (Cameron Highlands, Johor, Selangor, and Ulu Segama) reported sediment yields of 0.41–3.12 t ha^{-1} y^{-1} (Sinun *et al*., 1992, Sayer, *et al*., 2006).

In the post-SL period, the SSYs of catchments B and C increased dramatically (Figure 6.12b). The reduced canopy cover density (Table 6.3) may have increased net precipitation and rain splash on the forest-floor. Several processes in the harvesting system, such as logging roads, skid trails, ground-based yards and other highly disturbed sites, are thought to be primary sediment sources (*e.g*., Baharuddin *et al*., 1995, Malmer, 1996a, Douglas *et al*., 1999, Sidle *et al*., 2004, Sidle *et al*., 2006). During the post-SL period, catchments B and C produced an annual SSY of 34.0 and 14.5 t ha^{-1} y^{-1} (extrapolated from 10 months of monitoring). Previous studies during the year after selective logging in the Jengka catchment, Pahang, Peninsular Malaysia, reported sediment yields of 0.3 t ha^{-1} y^{-1} (Baharuddin and Abdul Rahim, 1994). Investigations of results from two catchments (C1 and C3) in Bukit Berembun, Negeri Sembilan, Malaysia reported a sediment yield of 0.27 t ha^{-1} y^{-1} and 0.11 t ha^{-1} y^{-1} (Zulkifli, 1994). In Baru catchment, Sabah, Malaysia sediment yields of 16 t ha^{-1} y^{-1} were reported following logging operations (Douglas *et al*., 1992). Six years after logging operations and vegetation recovery in the Baru catchment, the sediment yield was found to have decreased by 3.61–14.67 t ha^{-1} y^{-1} (Chappell, *et al*., 2004).

There is a strong relationship between rainfall, surface disturbance and catchment topography in the processes of sediment production and transport. Table 6.4 summarizes the suspended sediment yield from forested catchments following various selective logging treatments.

Table 6.4 Suspended sediment yield after selective logging treatments.

Catchment	Area (ha)	Rainfall (mm)	Skid trails disturbance (%)	Average Slope (%)	Suspended sediment yield (t ha^{-1} y^{-1})
1. Bukit Baka catchment, Kalimantan					
Catchment B	8.7	3,616	8.8	32.5	34
Catchment C	9.4		5.7	22.4	14.5
2. Baru catchment, Sabah					
Baru catchment	56	2,990	na	21.5	16
3. Jengka catchment, Pahang	28.4	3,077	6	28	0.3
4. Bukit Berembun, Negeri Sembilan					
Catchment 1 (stoking removed 40%, without RIL technique)	13.3	2,549	7.3	27	0.27
Catchment 3 (stoking removed 33% with RIL technique)	30.8		5.1	24	0.11

Table 6.4 shows that catchment B produced greater SSY than did the other catchments. A combination of higher annual rainfall amounts, higher surface disturbance from skid trails, and higher slope gradient, dramatically accelerated surface runoff flow and the flushing of bare exposed soil, thereby producing greater SSY in the stream channel. Catchment C had the same annual rainfall as catchment B, but produced SSY at a lower rate. This indicates that surface disturbance and slope gradient are important factors affecting sediment production. Results from the Bukit Baka catchment were similar to those from the Bukit Berembun catchments. With identical annual

rainfall amounts, catchment 1, which had more skid trail disturbance and a higher slope gradient, produced greater SSY than catchment 3.(Tabel 6.4).

These results suggest that the amount of sediment produced from a catchment is a function of climatic, exposed bare soil from surface disturbance and physical catchment characteristics. Logging roads and skid trails that open the forest canopy and compact forest soils, contribute most to sediment loss per unit area within a catchment, especially on steep terrain (Malmer 1996b, Ziegler *et al.*, 2000, Sidle *et al.*, 2004, Sidle *et al.*, 2006).

The dramatic changes in SSY also indicate the vulnerability of soils to land-use changes. These changes were compounded because of the fragile Ultisol (USDA Soil Taxonomy) of the humid tropics in the Bukit Baka catchment. In the humid tropics, poor soil cohesion, high rainfall and high temperatures give rise to highly erosive soils that are sensitive to the impacts of surface disturbance from heavy machinery and cleared vegetative cover (Huang and Laflen, 1996, Hartanto, *et al.*, 2003). The Baru catchment is underlain by the Kuamut geological formation, a mélange comprising largely of mudstone and sandstone. This geology has given rise to unstable soil of the FAO-UNESCO Haplic Alisol (Chappell, *et al.*, 1999, Chappell, *et al.*, 2004). This soil type has similar characteristics with Ultisol in the Bukit Baka catchment, which has unstable soil aggregates. The parent material in the Jengka catchment comprises predominantly shale and sandstones, which results in a clayey and sandy texture (Baharuddin and Abdul Rahim, 1994). The soil in the Berembun catchment contains a high portion of sand with a deeply weathered profile and belongs to the clayey kaolinitic isohyperthermic family (Zulkifli, 1994). Well-drained soils in the Jengka and Berembun catchments may have higher rates of infiltration and produce lower rates of surface runoff. The differences in soil characteristics between the Bukit Baka-Baru and Jengka-Berembun catchments affect the contributions of sediment sources and SSY (Table 6.4).

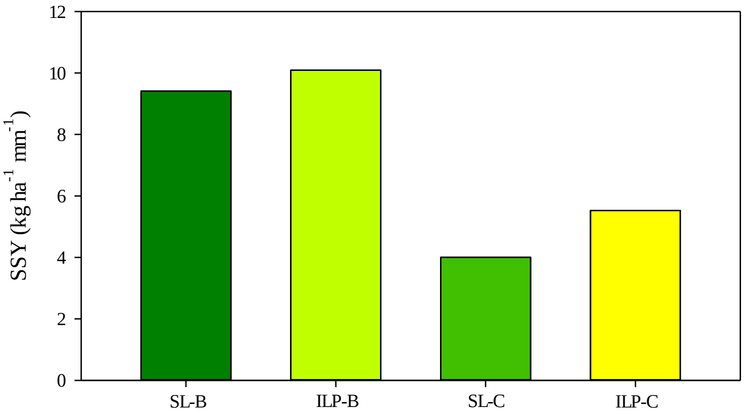

Figure 6.13 Ratio of cumulative SSY to cumulative rainfall during the post-SL and post-ILP periods in catchments B and C.

Figure 6.12 shows that during the initial 3 months following the post-ILP period, the SSY in catchments A, B and C were 0.23, 8.81 and 4.82 t ha^{-1}, respectively. To clarify the differences between the post-SL and -ILP periods, characterized by strip-line and contour-line planting, respectively, the sediment production ratio, which is defined as SSY per unit precipitation, was determined as shown in Figure 6.13. The sediment production ratio was either similar or slightly increased during the initial 3 months of the post-ILP period, compared with the post-SL period. The high production rates during the post-ILP period were likely associated with an increase in the surface disturbance area (Table 6.2) and a decrease in tree canopy coverage (Table 6.3) due to line-planting operations, which exposed bare soil, enlarged raindrop impacts, and accelerated sediment production. Therefore, our results indicate that contour-line planting in catchment C does not reduce suspended sediment discharge during the initial stage of the post-ILP period.

6.4 Conclusions and recommendations

The effects of the IFMS on hydrological responses in a tropical Indonesian rainforest were investigated using three forested catchment sites. IFMS implementation had a significant effect on catchment hydrology in terms of runoff and sediment yield. During the post-SL period, total runoff of catchments B and C increased by 68.8% and 47.3%, respectively, in comparison with catchment A. Surface disturbances and tree canopy reductions associated with SL caused DRO and Qp increases both in catchments B and C. The DRO and Qp increases were more pronounced in catchment B because the greater slope gradient, wider disturbance area by skid trails, and greater amount of tree removal in catchment B caused greater hydrological impacts in this catchment than in catchment C.

During the post-SL period, the greater amount of surface runoff as well as the higher slope gradient of catchment B attributed to high ability for transporting SS, which caused hysteresis in the relationship between water discharge and SS discharge, and resulted in large amount of SS production. During the post-SL period, SS yields for catchments A, B, and C were estimated to be 0.6, 34.0, and 14.5 t ha^{-1} y^{-1}, respectively. Combination among the great surface disturbance by skid trails, large tree extraction ratio, and high slope angle brought the greatest SS yield in catchment B.

In catchment B, SS concentration during the post-ILP period did not decreased in comparison with that during the post-SL period. In catchment C, ILP operations increased SS concentration slightly higher than that during the post-SL period. Thus, both catchments B and C had high SS production rate in the initial stage of the post-ILP period. This was attributed to additional surface disturbances by ILP operations; although the manual line clearing left biomass litter on forest floor, ILP caused increases in soil disturbance area and decreases in canopy coverage. Effects of such disturbances outstripped effects of the biomass litter coverage, resulting in increases in SS concentration.

Implementation of an intensive contour-line planting method is effective in reducing direct runoff and peak discharge. The results showed that the magnitude of runoff and SSY during different forest management treatments depend on interactions among rainfall, forest cover changes, catchment topography and surface disturbance.

Forest management practices should consider and attempt to minimize disturbance during each IFMS stage to control runoff and sediment yield. Underlying climatic and geographic factors that increase runoff and soil erosion risk, even without human intervention, such as steep topography, soil vulnerability, and rainfall characteristics, should also be taken into consideration. Adequate protection of the forest floor with strict control over logging activities, combined with intensive contour-line planting, may also reduce the impacts of logging on runoff and sediment yield.

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Chapter VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Natural forest conversion and degradation in tropical Indonesian rainforest has been a matter of serious problem over time. Forest conversion and degradation involves a change process that negatively affects the characteristics of a forest such that the value and production of its goods and services decline. This change process is caused by disturbance, which may vary in extent, severity, quality, origin and frequency. Runoff and soil erosion occurring naturally in forested catchments do not constitute environmental problems; the problem will occur when human interference the catchments and creates new conditions of the hydrologic processes.

Indonesian cutting systems have experienced in many modifications and the latest cutting system is Intensive Forest Management System (IFMS). When IFMS treatments are implemented in headwater areas, it is important to understand the heterogeneity of processes within a catchment and the vulnerability of different areas to land disturbance. This research investigates the effect of IFMS on runoff and soil erosion characteristics in the landscape and catchment levels. Field investigation and analysis, experimental test and numerical simulation were conducted in this research. Field investigation and analysis were conducted for soil hydraulic properties, runoff and soil erosion in the catchments. The experimental tests were conducted to understand the water movement in the soil under different surface disturbances. Numerical simulation was applied to estimate the surface runoff flow under various forest disturbances. The results of these studies have several important conclusions with respect to the impact of IFMS on runoff and soil erosion characteristics.

In the chapter 2, plot sites and catchment sites of the research were described. Implementation of the IFMS in the plot and catchment sites was described, including the IFMS modification in one of the catchment site area. IFMS has shown to disturb the natural forest with reducing the canopy covers and destruct the surface soil from mechanized harvesting and manual line planting activities. Forest disturbances need to investigated the impact on hydrologic responses.

In the chapter 3, water balance analysis for natural tropical rainforest area using hydrometeorology data is conducted. Long time series of meteorological data were used in the calculation. The results found a good agreement between the predicted and observed monthly streamflows. This method assumed that 50% of the surplus water is actually available as streamflow in any given month, and the rest become detention water to supply soil moisture and ground water. It is also assumed that 50% of detention water is available as streamflow in the next month. During the investigation period, evapotranspiration ranged from 81 to 151 mm m^{-1} (mean = 109.8 mm m^{-1}), the annual evapotranspiration ranged from 1246 to 1519 mm (31.9%–41.2% of the rainfall), and annual runoff ranged from 1242 to 2244 mm (39.9%–54.6% of the rainfall). A total of 13.5%–18.1% of rainfall was detained in the catchment as detention water and stored as soil moisture or groundwater supply. The results indicated that the water balance status and estimated runoff are not experiencing the problems leading to water deficit under natural tropical forest conditions. These results suggest that in the forested area, a strong relationship exists among rainfall, evapotranspiration, and runoff production. Surface disturbance, land-use changes, and reductions in canopy cover potentially impact the water balance—in particular, they influence evapotranspiration and infiltration processes that increase runoff and reduce detention. To understand these hydrological changes, we need detailed within-catchment experimental observations to quantify and predict hydrologic responses under a forest management system.

In the chapter 4, the hydraulic properties of forest soils under IFMS are studied. Field experiments and numerical simulation using two-dimensional saturated soil water flow were presented. This chapter focused on hydraulic properties of infiltration capacity, soil compaction and soil hydraulic conductivity in range of surface disturbance and different periods of the IFMS. Results from field experiments found the fundamental activities associated with mechanized selective logging and intensive line planting reduced soil hydraulic properties, including infiltration characteristics, soil compaction, and hydraulic conductivity within the near-surface soil profile. Ground-based harvesting using a skidder tractor significantly increased the rate of soil compaction, which influenced the infiltration capacity and K_s. Recent forest operations significantly disturbed the soil surface (via compaction and topsoil/subsoil mixing) and produced large variation in the near-surface values of K_s. Surface K_s values were lower on skidder tracks than other disturbed surface types. The recovery time for near-surface K_s on non-skidder tracks was between 10–15 years, while in the skidder tracks it was more than 20 years. Numerical simulation has proven that changes in surface K_s provide evidence that disturbances have altered the typical surface hydrological pathways, thereby creating the conditions for more surface runoff on disturbed surfaces than on undisturbed surfaces. Maintaining the buffer area is effective to reduce the peak discharge and surface runoff in the stream channel.

In chapter 5, the effect of different period of IFMS on runoff and soil erosion characteristics are studied. The study focused on the runoff and soil erosion changes in the different periods of catchment rehabilitation under IFMS. The results showed that reducing canopy cover and high surface soil disturbance in the early year after IFMS treatment significantly affected both runoff and soil erosion. The percentage of annual rainfall that became runoff in the virgin forest, 10-year old site and 1-year-old site were 27, 30, and 41%, respectively. Direct runoff and sediment yield increased dramatically during the early years after IFMS implementation. The magnitude of runoff and soil erosion depends on the interaction among the rainfall, forest cover changes, forest treatment applied and catchment characteristics. 10 years after forest operation, forest cover has recovery close to natural condition, but still there are differences in hydrological response.

In the chapter 6, the changes of runoff characteristics and suspended sediment yields in the different stages of IFMS are studied. This chapter focused on the responses of runoff and suspended sediment yields between catchments in the different rates of catchment disturbances and different rehabilitation technique. IFMS implementation had a significant effect on catchment hydrology in terms of runoff and sediment yield. There were significant differences in runoff and suspended sediment yield among the IFMS stages, and significant differences between catchments B and C. During the post-SL period, total runoff of catchments B and C increased by 68.8% and 47.3%, respectively, in comparison with catchment A. The direct runoff and peak discharge increases were more pronounced in catchment B because the greater slope gradient, wider disturbance area by skid trails, and greater amount of tree removal in catchment B caused greater hydrological impacts in this catchment than in catchment C. During the post-SL period, suspended sediment yields for catchments A, B, and C were estimated to be 0.6, 34.0, and 14.5 t ha^{-1} y^{-1}, respectively. Combination among the great surface disturbance by skid trails, large tree extraction ratio, and high slope angle brought the greatest suspended sediment yield in catchment B. During the initial stage of post-ILP period, both catchments B and C had higher suspended sediment production rate than in the post-SL period. This was attributed to additional surface disturbances by ILP operations. ILP caused increases in soil disturbance area and decreases in canopy coverage. Implementation of an intensive contour-line planting method is effective in reducing direct runoff and peak discharge. The results showed that the magnitude of runoff and SSY during different forest management treatments depend on interactions among rainfall, forest cover changes, catchment topography and surface disturbance. Forest management practices should consider and attempt to minimize disturbance during each IFMS stage to control runoff and sediment yield. Underlying climatic and geographic factors that increase runoff and soil erosion risk, even without human intervention, such as steep topography, soil vulnerability, and rainfall characteristics, should also be taken into consideration. Adequate protection of the forest floor with strict control over logging activities, combined with intensive contour-line planting, may also reduce the impacts of logging on runoff and sediment yield.

7.2 Recommendations

Future study is required to improve the knowledge in this study area. The following points are recommended to consider in order getting better understanding of the hydrological consequences of land-cover transformations in the tropical rainforest with IFMS implementation.

- Analysis of soil water dynamics under different surface disturbances. Field monitoring needs to establish to get better understanding the soil water movement process and can developed in the numerical simulation.
- Hydrological impacts analysis using “on-site” monitoring on runoff and soil erosion under logging roads, skid trails and line planting in the IFMS operations. Hydrological investigation on the specific site could help to get better understanding intra-catchment processes related to IFMS treatment.
- Analysis of runoff hydrograph characteristics after IFMS implementation. Different forest treatments affect to different hydrological process in the

catchment level. Runoff hydrograph as the results of catchment response needs to be analyzed to understanding the impact of forest operations in the catchment. Effect of land-cover changes should be investigated during low flow conditions in this area.

- Analysis of nutrient cycling to determine the nutrient losses after IFMS implementation. Nutrient losses analysis using “off-site” monitoring in the catchment scale could be identify the nutrient balance in the catchment. This study is useful to maintenance the nutrient cycling in the forest under IFMS treatment.