Variations in Suspended Sediment Yield and Dynamics in Catchments of Differing Land-use in Sabah

Anand NAINAR[1], Kawi BIDIN[2], Rory P. D. WALSH[3], Robert M. EWERS[4] & Glen REYNOLDS[5]*

[1]Faculty of Science and Natural Resource, Universiti Malaysia Sabah, Kota Kinabalu, MALAYSIA
[2] Natural Disaster Research Unit, Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Kota Kinabalu, MALAYSIA.
[3] Department of Geography, Swansea University, Swansea, WALES.
[4] Department of Life Sciences, Imperial College London, Ascot, ENGLAND.
[5]South East Asia Rainforest Research Partnership, Danum Valley
*Corresponding author: nainar.sci@gmail.com, Tel: +6088-320000, Fax: +6088-320223

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Abstract

Variations in suspended sediment dynamics in different land-use were observed over the period of 2011 to 2014 in the SAFE Project area (www.safeproject.net). Five catchments of different land-use namely primary forest (PF), old regrowth-virgin jungle reserve (VJR), twice-logged regenerating forest (LFE), thrice-logged regenerating forest (0 m) and oil palm (OP) were instrumented with Campbell data loggers and sensors to record at five-minute intervals water level, turbidity, electrical conductivity and water temperature. Turbidity is converted to suspended sediment concentration (SSC) using algorithms derived from calibration experiments. This paper focuses mainly on duration of high discharge, peak SSC, duration of high SSC and sediment yield during selected storm events. It was found that the primary forest has longer duration of high discharge which points to good infiltration and better water-holding capacity. The oil palm has a short duration of peak flow. The highest peak SSC and duration of high SSC was almost always found in the oil palm. The peak SSC and duration of high SSC of the thrice-logged forest is lower than that of the primary forest in medium to large storms indicating the important role of understory vegetation for erosion protection. Sediment yield is the highest in the oil palm catchment and the lowest in the thrice-logged forest therefore highlighting the role of forests (even disturbed forests) in the regulation of sediment export.

Background

High suspended sediment concentration (SSC) is usually found in rivers of the tropics especially in downstream areas (Sammori et al., 2004; Douglas, 1978). Suspended sediment in a stream originates either from the stream itself, or from the catchment upslope. During rainfall, erosion and sediment transport down the catchment is caused by rain droplets hitting the ground surface followed by overland flow. Erosion becomes more severe as the overland flow channelizes to form rills and gullies (Sidle et al., 2006; Poesen et al., 2003).

Due to the erosion process, suspended sediment occurs in natural streams. However, human activities especially deforestation and agriculture greatly accelerates the erosion rate by 10 to 100-fold (Glendell, 2014; Montgomery, 2007) and thus contributes to SSC many times higher than that of a natural, undisturbed catchment (Chappell et al., 2004; Sammori et al., 2004; Bruijnzeel, 1992).

Logging and agricultural plantations increase erosion and suspended sediment up to varying degrees (Thompson et al., 2014; Collins et al., 2012; Silgram et al., 2010; Withers and Haygarth, 2007; Withers et al., 2006). The reduction of canopy decreases interception and causes raindrop to fall directly to the ground with higher kinetic energy. Ground disturbances such as skid trail and soil compaction increases overland flow and the amount of erodible sediment.

Increased rate of erosion and sediment transport to streams causes pollution and has various adverse effects. According to FAO (1996), pollution by sediment has two major dimensions. One is the physical dimension where the sediment itself acts as the pollutant. The second is the chemical dimension whereby the sediment act as a carrier of adsorbed chemicals especially phosphorus, chlorinated pesticides and most metals – usually associated with finer sediment (< 63 microns). On-site problems include loss of soil especially the fertile top soil (Thompson et al., 2014; Bilotta et al., 2012; FAO, 1996). This is a costly issue to be fixed by land owners and plantation managers. Other off-site problems include the destruction of aquatic life and habitat (Heywood and Walling, 2007; Chappell et al., 2004; Greig et al., 2005; Yamada and Nakamura, 2002; Martin-Smith, 1998; Quinn et al., 1992; Cloern, 1987), the reduction of quality water supply (Chappell et al., 2004), reduction in channel capacity (Chappell et al., 2004; Sheffield *et al*., 1995) and the inundation of offshore corals (Chappell et al., 2004; MacDonald *et al*., 2001). Furthermore, economic activities that rely on river water such as fish farming, hydroelectric power generation as well as factories that utilises river water for cooling will be affected, if not halted altogether (Cooke and Doornkamp, 1990).

Over the last three decades, there have been numerous studies on catchment suspended sediment (e.g. Olive and Rieger, 1985; Jansson, 2002) especially that relating to logging and agriculture because of the need to determine downstream geomorphic effects of sediment transport. Examples of local studies include Malmer (1990), Malmer and Grip (1992), Douglas et al. (1999, 1993, 1992) and Bidin et al. (1993). Douglas et al. (1992) studied sediment yield from logged catchments in Sabah and found that annual sediment yields rose to 14 times greater compared to that of undisturbed forest, but dropped to only 2.5 times greater two years after logging. Sources of sediment post-logging include compacted grounds and gullied skid trails.

Suspended sediment is generally high during periods of high discharge and the highest transport suspended sediment load is concentrated during storm events (Webb and Walling, 1982; Mano et al., 2009; and Rodriguez-Blanco et al., 2010). Extreme storm events can release stored sediment equivalent to that of several normal years (Soler et al., 2008).

Few have done follow up studies for periods of post-logging and other land-use changes – Clarke and Walsh (2006) and Walsh et al. (2006) being notable examples. Clarke and Walsh (2006) proposed a four-phase sediment yield model for the logging process. The first phase ranges from during logging to up to two years post logging. This phase sees a spike in sediment yield. The second phase is two to five years after logging where sediment yield dropped to levels close to pre-logging. The third phase, five to eight years is when sediment yield peaked again followed up by the fourth phase of low sediment yield (eight to fifteen years after logging). The sediment dynamics is described in detail in the paper and the reader is referred to Clarke and Walsh (2006) for more information.

Focus of study

This paper presents the difference in suspended sediment concentrations for streams of different land-use (primary forest, virgin jungle reserve (old-regrowth), twice-logged regenerating forest, thrice-logged regenerating forest and oil palm plantation) as well as a brief look in suspended sediment concentration and peak sediment export in selected storms for the different streams. This paper is an extension of the works presented in Nainar et al. (2014), Nainar et al. (2012) and Annammala et al. (2012).

Methodology

(i) Experimental Design

Within the Benta Wawasan oil palm plantation area, four catchments of different land-use have been identified and selected to represent land-use at a gradient of disturbances. They are the old-regrowth – termed "Virgin Jungle Reserve" (VJR), twice-logged and regenerating – termed "Logged Forest Experiment" (LFE), thrice-logged and regenerating forest (0 m), and oil palm plantation (OP). A primary forest (PF) catchment located approximately 23 km away from the main experimental area in the Danum Valley Conservation Area (DVCA) was also included in this experiment.

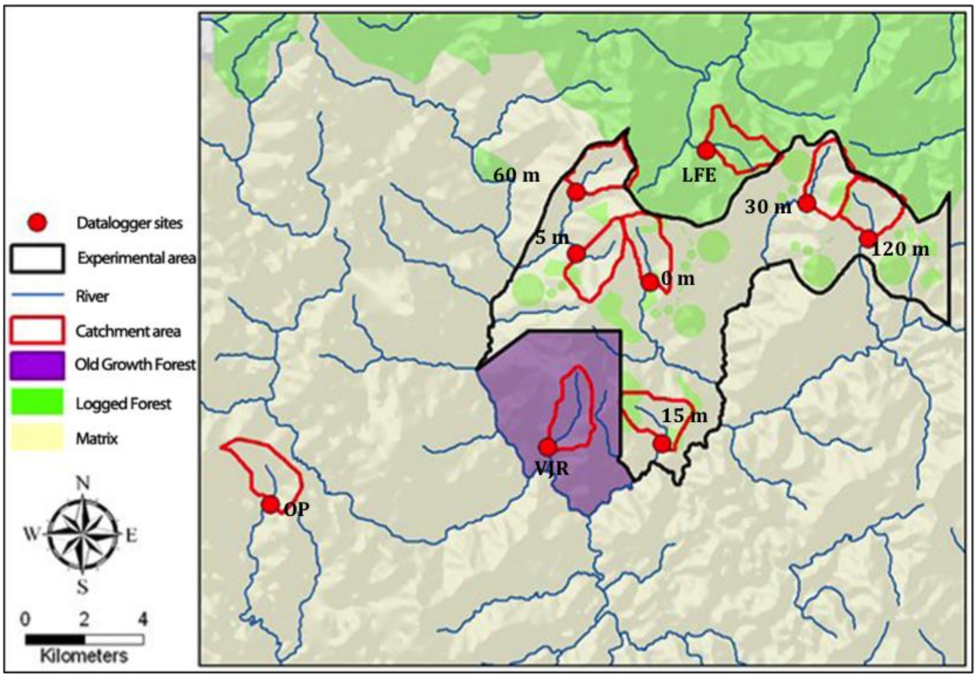

Figure 1: A map of the study area showing the experimental catchments.

Note: The other catchments (5 m, 15 m, 30 m, 60 m, 120 m) are part of another study under the SAFE Project and not used in this paper. The PF catchment (23 km away) is not shown in this map.
Source: safeproject.net

Unlike what its name suggests, the Virgin Jungle Reserve is actually an old-growth forest that has recovered from very light logging (Singh et al., 2015; SAFE Project, 2015). The name Virgin Jungle Reserve and the abbreviation VJR used in this study is in accordance to the names used by the Forestry Department, the Land and Survey Department and the Sabah Foundation Conservation and Environmental Management. The logged forest experiment (LFE) is a twice logged and regenerating forest. The 0 m is a thrice logged and regenerating forest. Both the LFE and 0 m were named as such based on the names used in a large-scale ecological experiment – the Stability of Altered Forest Ecosystems (SAFE Project). The oil palm (OP) catchment is a matured oil palm plantation of approximately 18 years of age. The primary forest (PF) catchment refers to the West 8 catchment located in the DVCA and is a true pristine forest (Class 1 forest reserve). The PF, VJR, LFE, 0 m, and OP catchments have an area of 1.7, 3.08, 4.64, 2.78, and 3.27 km^2 respectively and each have a slope gradient of 16° ± SD 2.

(ii) Study Area

The area of study (SAFE project) is located in the town of Kalabakan just three hours by road from Tawau, Sabah (North Borneo). The entrance into the area of study is via the gate of the Benta Wawasan oil palm plantation. At present, the SAFE area consists mainly of logged forest. The area was formerly dominated by dipterocarp, but logging for more than two times has severely deteriorated its cover and quality.

The average annual rainfall for DVCA for the past ten years (2002 to 2011) is 3052.4 mm (MMD, 2011). The month of lowest rainfall for the past ten years occurs in August with an average of 165.8 mm whilst October to January are considered wet months with January having the highest monthly rainfall averaged at 328.9 mm (MMD, 2011). Total annual rainfall of the SAFE Project experimental area averaged over 18 months of data logging is 2717 mm as measure by the gauging station in the OP catchment. Total annual rainfall for the other catchments is not yet available at time of writing. The maximum recorded daily rainfall is 82 mm in VJR, 58.8 mm in LFE, 86.4 mm in 0 m and 99 mm in OP. The maximum temperature of DVCA for the period 1986 to 2010 is 31.3 °C while the minimum is 22.6 °C. For the SAFE experimental area, the maximum and minimum temperature is 30.5 °C and 21.3 °C respectively. The climate is similar throughout the experimental catchments with high annual rainfall and similar temperature ranges in a day.

The SAFE Project experimental catchments are of the Class II – Commercial Forest Reserve with exception to the VJR and OP that falls in Class IV – Virgin Jungle Reserve and the state government owned SSSB (Sabah Softwoods Sdn. Bhd.) timber plantation category respectively (SFD, 2010). The natural vegetation of the SAFE experimental catchments is of the lowland and upland mixed dipterocarp forest while the VJR catchment is made up of upland ultramafic forest. At present, the SAFE area consists mainly of logged forest (SFD, 2010). The area was formerly dominated by dipterocarp, but logging for more than two times has severely deteriorated its cover and quality. No study was published on the vegetation of the entire catchment yet, but Singh et al. (2015) in their study investigated the aboveground biomass and tree diversity in the riparian areas of the SAFE Project. It was reported that the OP catchment has the highest tree species richness contributed by trees with DBH between 2 to 10 cm. Species similarity is high for the VJR and LFE catchments, but low for the 0 m and the OP catchments. Table 1 and 2 shows the above ground forest parameters and the species composition of trees across different catchments respectively. For more detailed information, the reader is referred to Singh et al. (2015).

Table 1: Above ground forest parameters for SAFE Project catchments (Singh et al., 2015).

Parameter	Catchments			
	VJR	LFE	0 m	OP
Basal area (m^2 ha^{-1})	55.00 ± 8.15	49.75 ± 9.19	29.15 ± 5.52	34.18 ± 3.21
Basal area of trees with DBH > 10 cm (m^2 ha^{-1})	54.49 ± 7.98	48.00 ± 9.74	25.29 ± 5.18	32.44 ± 3.18
Tree height (m)	18.90 ± 1.31	22.70 ± 1.44	9.20 ± 0.33	9.70 ± 0.25
Stem density (ha^{-1})	714	629	840	1056
Stem density of trees with DBH				
> 10 cm (ha^{-1})	481	456	440	601
< 10 cm (ha^{-1})	233	173	400	455
Fisher's alpha index	123.26	132.30	164.10	174.77
SØrensen index of similarity	0.72	0.65	0.56	0.49

Table 2: Species composition (%) of trees across different catchments (Singh et al., 2015).

Species	VJR	LFE	0 m	OP
Glochidion borneensis	11.16	4.00	2.43	3.76
Pternandra coerulescens	0.63	0.55	0.14	0.00
Walsura pinnata	4.46	4.19	3.64	5.39
Macaranga beccariana	3.18	2.91	14.30	4.98
Dryobalanops lanceolata	3.98	3.83	4.45	0.92
Nauclea subdita	8.77	1.82	2.69	2.23
Dendrocnide elliptica	0.96	3.64	3.64	3.86
Shorea johorensis	0.79	0.90	0.14	0.20

The ICZM (1998) reports that the geology of Kalabakan is generally argillaceous (clayey deposits). According to the GSM (1985), the lithology of the study area is of the Oligocene-Middle Miocene formation, which is a mélange of slumped breccia and sequences of interbedded mudstone, tuff, tuffaceous sandstone, shale, conglomerate with minor chert and limestone. Almost all of the VJR and 5 m catchments as well as part of the 60 m catchment consist of the Cretaceous-Early Tertiary formation, that is gabbro, dolerite, serpentinite, peridotite, dunite and pyroxynite. Figure 2 shows the soils of the SAFE project area to be mainly Orthic Acrisols; Chromic and Orthic Luvisols; Dystric and Eutric Cambisols; Lithosols; Rhodic and Orthic Ferralsol. The geology of the DVCA where the PF catchment is located is complex and poorly understood. Close to the DVCA, the geology consist mostly of the Miocene Kuamut Formation which is a mélange of slumped sedimentary and volcanic rocks with interbedded sandstones, mudstones and tuffs collectively known as slump breccia (Leong, 1974; Marsh and Greer, 1992), but older Chert-spilite formation and metamorphic and igneous gabbro, diorite and granite rocks of the Lower Triassic Crystalline Basement are dominant in the

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mountainous headwaters (Walsh et al., 2011; Clarke and Walsh, 2006; Leong, 1974; Marsh and Greer, 1992). The complex geology of the area lead to very heterogeneous soils. The soils of the Kuamut formation is of the Band Association (Wright, 1975) and are dominantly USDA Ultisols – which is equivalent to the Acrisol–Alisol groups of the FAO-UNESCO (1990) (Clarke and Walsh, 2006; Walsh et al, 2006).

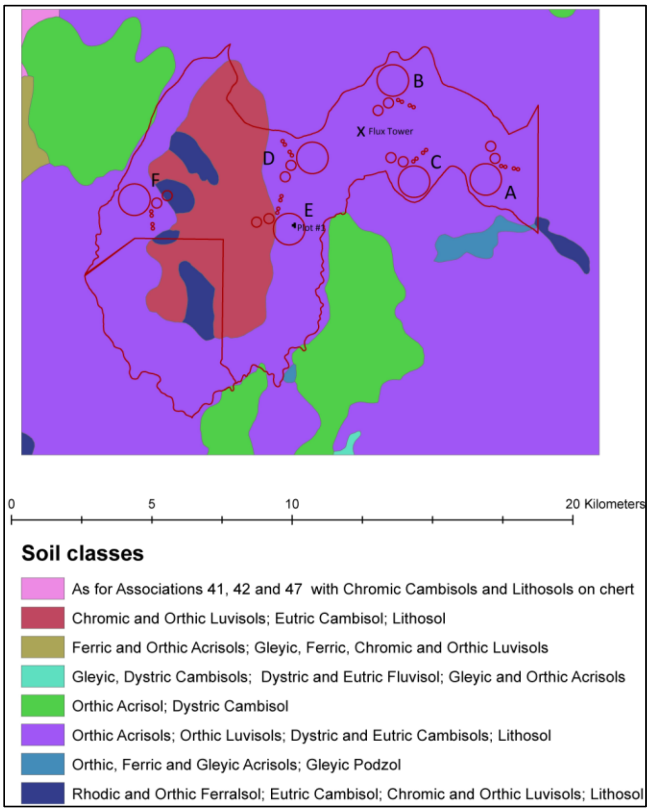

Figure 2: A figure showing the soil types of the SAFE project area (Adapted from DOS 2010)

In accordance with the state government plan, these logged forests will be cleared to make way for an oil palm plantation in the near future, with exception to the VJR and LFE.

(iii) Methods

At each catchment, a gauging station was established where a depth sensor, a turbidity sensor, a conductivity sensor and a tipping bucket raingauge is connected to a solar-powered Campbell Scientific CR850 datalogger. This system records water level, turbidity and conductivity every 5 minutes and gives an average every hour and at the end of each day. With such high resolution of data-logging, the datalogger can store up to a maximum of 3 months of data before it starts to overwrite older data. The gauging station was visited every month to have the data downloaded and for periodic maintenance to be done. Data logging started since January 2012 and still continues.

Water level and turbidity are converted to discharge (Q; m^3 s^{-1}) and suspended sediment concentration (SSC; mg L^{-1}) respectively. For the logged and oil palm catchments, water level was converted to discharge via dilution gauging for the low flows and via Manning's Equation for the medium to high flows. The PF catchment has an existing combination weir (a 120° v-notch sharp crested and a rectangular broad crested weir) and hence, was utilised for discharge calculation. SSC and TDS values were derived from a calibration curve, obtained from a series of calibration experiments according to the methods in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

(iv) Data Selection

Maximum, minimum and mean values of discharge and suspended sediment is calculated from January 2012 until August 2013 (18 months). For analysis of storm events, storms of three different sizes (discharge of 0.5, 1.0 and 10.0 L s^{-1} ha^{-1}) were compared. One storm from each discharge class was randomly selected from each catchment.

Results and Discussion

(i) Overall discharge and suspended sediment concentration

The mean discharge and maximum discharge decreases when going up the gradient of disturbance from primary forest to oil palm plantation (Table 3). Most studies (Malmer, 1992; Nik 1988; Hibbert, 1967) reported significant increase in water yield after logging of tropical forests - especially during the first and second year post logging. The logged and regenerating catchments in this study had its last logging around 15 years ago. Most of the degraded areas are re-vegetated with multiple layers of young trees. Asdak et al. (1998) stated that interception could be higher in logged forests. This also suggests the possibility that transpiration from several younger trees and plants has a bigger effect on soil moisture compared to a large, matured tree. Hibbert (1967) mention that the establishment of vegetation on sparsely vegetated land decreases water yield which is consistent with the results of the LFE and 0 m – a much higher value is expected in newly logged forests. Douglas et al. (1993) found that water yield of a logged catchment fell below that of an undisturbed catchment just 12 months after logging ceased due to transpiration by regenerating forest in the Danum area. For the same PF catchment, similar results of flashy stream response was found by Chappell et al. (2004) in an adjacent catchment, but without a conclusive explanation. Later studies on the same area then concluded that rapid stream response to rainfall is generated by fine surfaced root mat and matted leaf litter, but of more significance is pipeflow (Walsh et al., 2006; Sayer et al., 2006). Other explanation for the higher mean and maximum peak discharge in the PF stream is explained by the low storage capacities of the smooth and leathery forest leaves; and the fact that most of the rainfall comes in large rainstorms in which only a small proportion of rainfall is intercepted and evaporated (SEARRP, 2015). The oil palm crown makes a good, single story canopy cover. The understory is spacious and more exposed to solar insolation, evaporation and drying by wind. The large number of adult trees per unit area produces high evapotranspiration. Table 1 shows that the stem density gets progressively higher from forested catchments to the oil palm plantation. Bosch and Hewlett (1982) reviewed a total of 94 clearing and planting experiments [including 39 already reviewed by Hibbert (1967)] but criticized Hibbert (1967) that water yield responses on afforestation and deforestation are highly unpredictable and vegetation dependent.

Table 3: Discharge and suspended sediment concentration parameters for the different streams throughout 18 months (January 2012 – August 2013)

Stream	Mean Discharge ($m^3 s^{-1} km^{-2}$)	Max Discharge ($m^3 s^{-1} km^{-2}$)	Mean SSC ($mg L^{-1}$)	Max SSC ($mg L^{-1}$)
PF (Primary Forest)	0.088	12.845	278	34252
VJR (Virgin Jungle Reserve)	0.066	10.814	489	25869
LFE (Twice logged; Regenerating)	0.067	10.864	157	35500
0 m (Thrice logged; regenerating)	0.070	8.598	100	23199
OP (Oil Palm)	0.035	6.503	621	31013

The maximum peak SSC for the OP catchment is not much higher than the other catchments despite being the most disturbed catchment. The PF catchment on the other hand has the highest recorded maximum peak SSC among all the catchments. This can be attributed to the loose nature of the un-compacted soil in the PF catchment. Another plausible factor is the height of the crown in the PF catchment. Pristine tropical rainforest have trees with heights of 30 – 50 m, and where a height of 60 m is not uncommon. The crown drip from these canopies have much more kinetic energy and therefore eroding ability compared to lower canopies of the OP and logged forest. The crown and leaves of a primary forest also has the ability to accumulate raindrops before being released in a bigger drop, or in a flow (Geißler et al., 2013; 2010a; 2010b). A combination of these factors can contribute to the release of sediment in the PF catchment in areas that are low in leaf litter. This possibility however is extremely atypical of primary forests and is limited to where uncovered grounds exist. Other proven factors for high suspended sediment in the PF are (i) the relatively erodible soils and sedimentary rocks of the region (Walsh et al., 2006; Sayer et al., 2006); and (ii) transport of sediment through pipeflow (Walsh et al., 2006; Sayer et al., 2006). Logged forests have abundant young trees, low-lying plants and creepers that act to reduce the momentum of raindrops before hitting the soil. (Asdak et al., 1998) stated that the interception in logged forests could be higher than in primary forests, but effective interception could be less due to large open areas such a log landing sites. The oil palm catchment has less of these low-lying plants but, a good amount of old palm fronds that serves the same function. However, the amount of bare ground in the OP catchment is plenty.

The mean SSC for the OP catchment is the highest among all the catchments despite the maximum SSC being approximately the same. This is due to the OP stream having high turbidity levels for extended periods especially after a storm event (Figure 4, 6, and 8). This will be shown and explained more in the sections below. The highly disturbed and compacted soil of the oil palm catchment may be a contributing factor for this. Instead of infiltrating, rainwater can stay waterlogged and be released over time into the stream, carrying with it sediment from the catchment. The stream banks of the OP catchment is also more bare and exposed compared to the forested catchments (including logged forests) which acts as a continuous slow-release source of sediment (NIWA, 2014; Parkyn et al., 2005).

(ii) Small Storm (Discharge of 50 L s^{-1} km^{-2})

Figure 3 and Table 4 shows the discharge against time curve and discharge analysis respectively for storms of approximately 50 L s^{-1} km^{-2}. In Table 4, it was observed that the time for peak discharge to drop by 50% per unit area and the duration of high flow per unit area is the highest for the PF stream and lowest for the OP stream. This is due to high infiltration rate and high storage capacity of the PF catchments - typical of pristine forest catchments. Bidin et al. (1993) found for the same area that only 22 events in a year resulted from surface runoff. The OP catchment has a high rise in discharge; but the fastest time for peak discharge to drop by 50% and the lowest duration of high flow – signs of severely compacted soils with poor porosity and storage capacity, typical of oil palm plantation. These findings are in accordance to what EWRC (2009) had when comparing infiltration between forests and agricultural lands. Although the VJR catchment is supposed to be similar to the PF catchment, it shows a very short time for discharge to drop. This is most probably due to the different soil type as shown in the soil map (Figure 2).

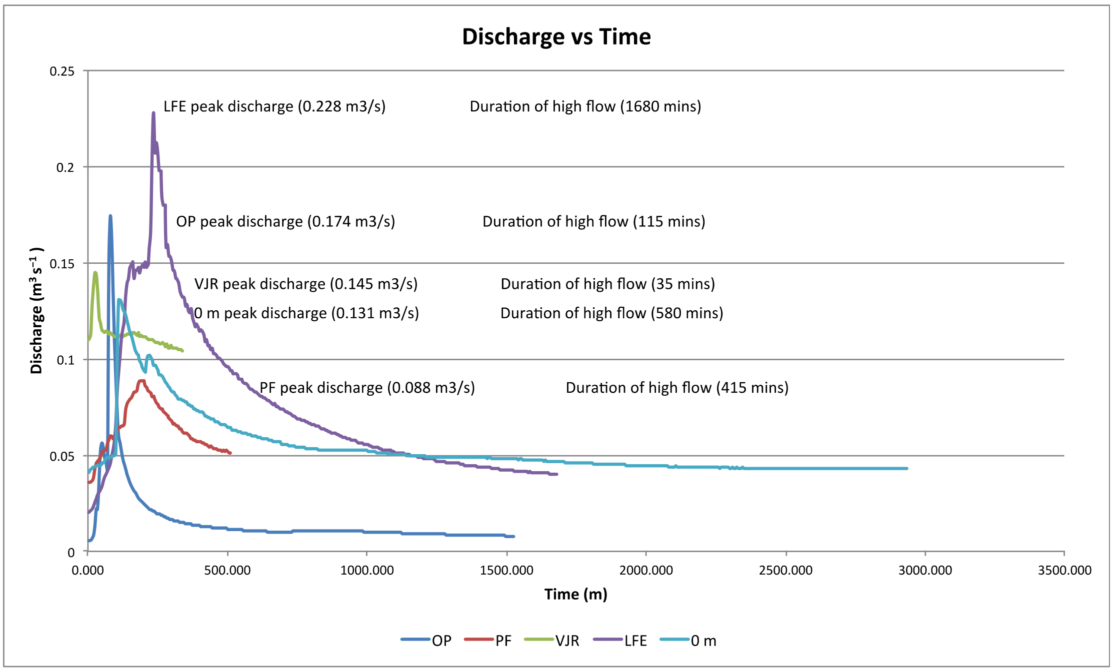

Figure 3: Discharge vs time curve for storms of approximately 50 L s^{-1} km^{-2} for all catchments

Table 4: Discharge analysis for storms of approximately 50 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Peak discharge per unit area (m^3 s^{-1} km^{-2})	0.052	0.047	0.049	0.047	0.053
Discharge rise per unit area (m^3 s^{-1} km^{-2})	0.031	0.011	0.045	0.032	0.051
Time peak discharge drop 50% per unit area (mins km^{-2})	85.294	4.870	29.095	64.748	7.645
Duration of high flow per unit area (mins km^{-2})	244.118	11.364	362.069	208.633	35.168

The PF catchment has no detected rise in SSC while the OP catchment has the highest peak SSC that is 12553 mg L^{-1}. The value increases gradually across the gradient of disturbance with the exception to the LFE catchment having higher values (492 mg L^{-1}) than the more disturbed 0 m catchment (175 mg L^{-1}). The OP catchment has the longest duration of SSC above 100 mg L^{-1} among all catchments as it takes a longer time for SSC to drop back to pre-storm levels (Figure 4).

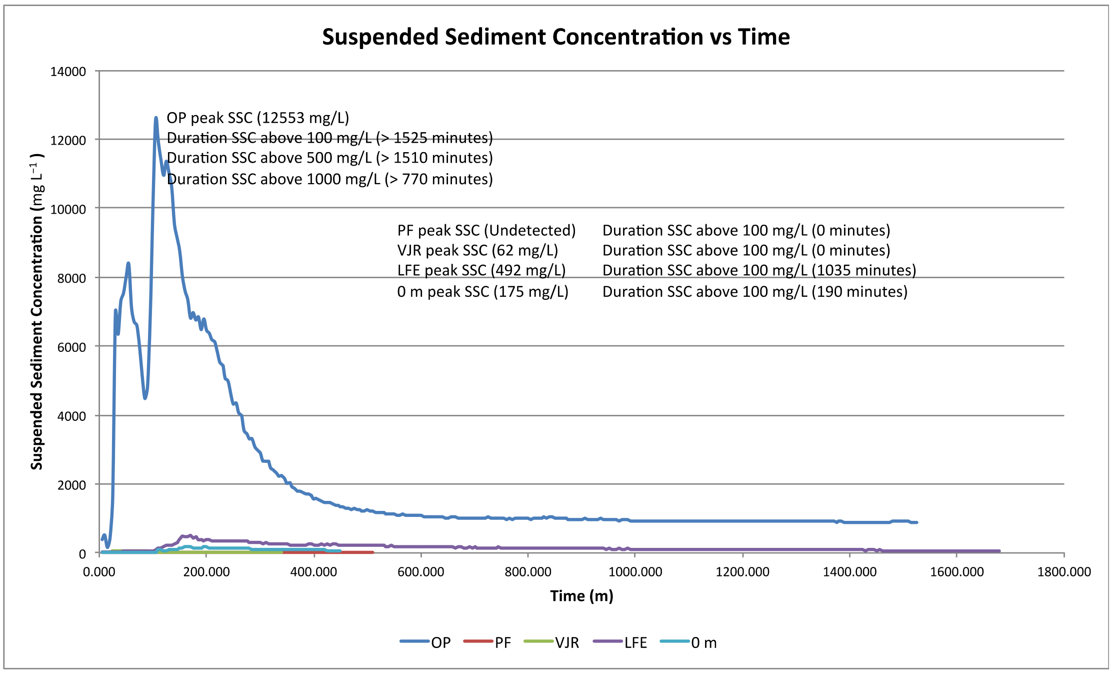

Figure 4: SSC vs time curve for storms of approximately 50 L s^{-1} km^{-2} for all catchments

Table 5: SSC analysis for storms of approximately 50 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Peak SSC (mg L^{-1})	ND	62	492	175	12553
SSC rise (mg L^{-1})	ND	45	466	169	12173
Duration SSC above 100 mg/L (mins)	0	0	1035	190	1525
Duration SSC above 500 mg/L (mins)	0	0	0	0	1510
Duration SSC above 1000 mg/L (mins)	0	0	0	0	770

**ND – Not Detected (out of detection range)*

Table 6 shows the total sediment export for all catchments for storms with peak discharge of approximately 50 L s^{-1} ha^{-1}. The amount of sediment increases with increasing disturbance inline with other notable studies (Douglas, 2011, 1999, 1996; Greer, 1995). The LFE catchment is an exception and has to be investigated further.

Table 6: Total discharge per unit area and total sediment export per unit area for storms of approximately 50 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Total discharge per unit area (m^3 km^{-2})	1143	745	1614	3370	454
Total sediment export per unit area (kg km^{-2})	0	21	317	132	1811

(iii) Medium storms (Discharge of 500 L s^{-1} ha^{-1})

Figure 5 and Table 7 shows the discharge against time curve and discharge analysis respectively, for storms of approximately 500 L s^{-1} km^{-2}. The time for peak discharge to drop by 50% is the highest for the PF stream and lowest for the OP stream – similar to storms of 50 L s^{-1} ha^{-1} shown in the previous section.

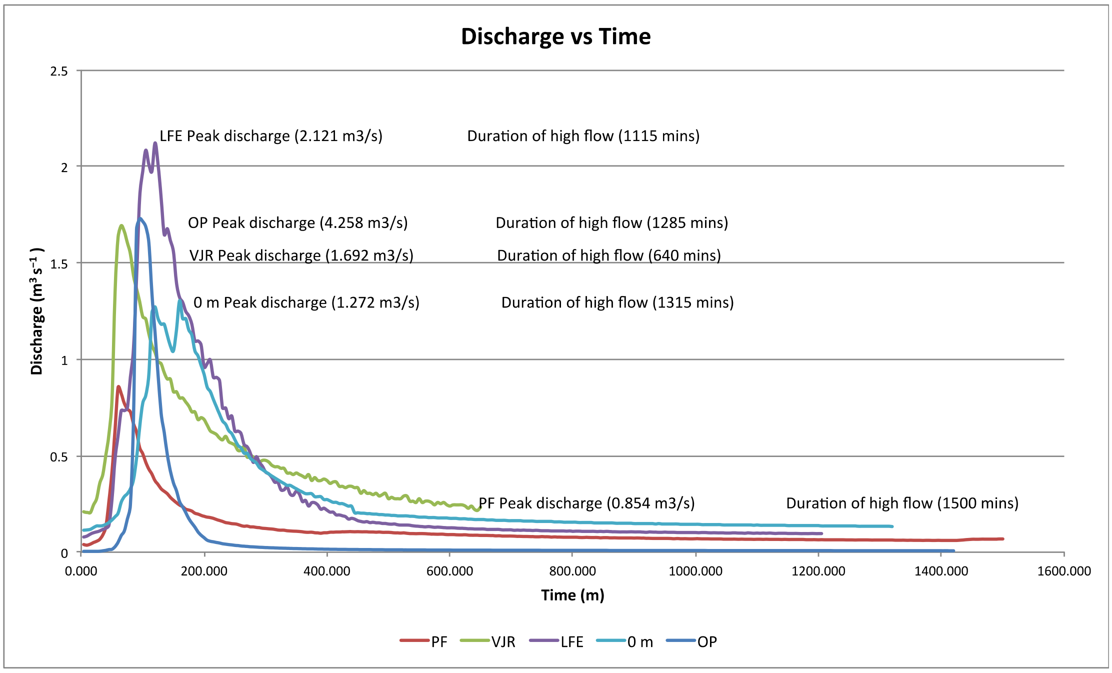

Figure 5: Discharge vs time curve for storms of approximately 500 L s^{-1} km^{-2} for all catchments

Table 7: Discharge analysis for storms of approximately 500 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Peak discharge per unit area (m^3 s^{-1} km^{-2})	0.502	0.549	0.457	0.458	0.528
Discharge rise per unit area (m^3 s^{-1} km^{-2})	0.481	0.482	0.440	0.417	0.527
Time peak discharge drop 50% per unit area (mins km^{-2})	35.294	27.597	20.474	41.367	12.232
Duration of high flow per unit area (mins km^{-2})	882.353	207.792	240.302	473.022	56.575

The PF catchment recorded 1186 mg L^{-1} (lowest) of peak SSC while the OP catchment recorded the highest at 12112 mg L^{-1} (Table 8). The 0 m, LFE and VJR recorded levels of 381, 1205 and 2712 mg L^{-1} respectively. For the duration of high SSC, the OP recorded short durations compared to the LFE and VJR – unlike small storms. Exhaustion of sediment can happen in cases where sediment is delivered in large quantities over a short period of time, creating a spike in the sedigraph (Gellis, 2013; Hudson, 2003). The bulk of the sediment in the OP catchment comes from the spike as shown in Figure 6 and this could be the cause of the low duration of high SSC (temporary sediment exhaustion) in the OP stream.

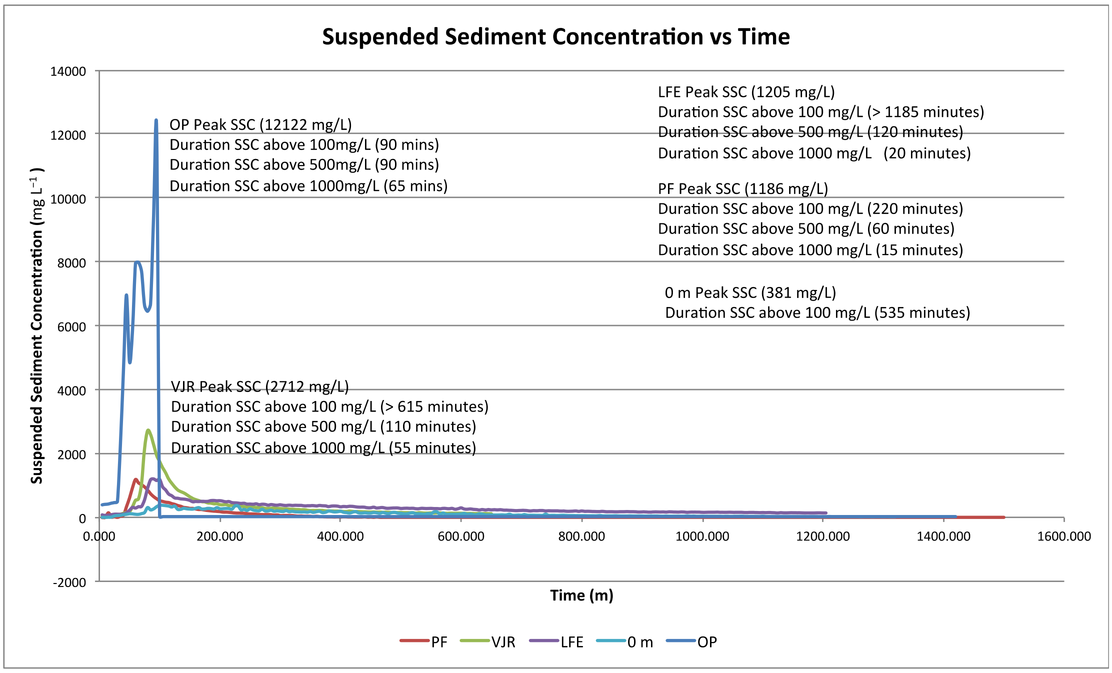

Figure 6: SSC vs time curve for storms of approximately 500 L s^{-1} km^{-2} for all catchments

Table 8: SSC analysis for storms of approximately 500 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Peak SSC (mg L^{-1})	1186	2712	1205	381	12,112
SSC rise (mg L^{-1})	1186	2658	1141	378	11,720
Duration SSC above 100 mg/L (mins)	220	615	1185	535	90
Duration SSC above 500 mg/L (mins)	60	110	120	-	90
Duration SSC above 1000 mg/L (mins)	15	55	20	-	65

Once again, the PF catchment delivered the least sediment (1551 kg km^{-2}) during a storm event (Table 9). The OP catchment delivered 4295 kg km^{-2} but the VJR is slightly higher at 4396 kg km^{-2}. This is possibly attributed to the different soil type (as mentioned in previous sections) and/or the possibility of a large source of erodible sediment (i.e. un-vegetated field, exposed bank, landslide) (Syvitski, 2003; Sidle et al., 2004). In the records of the 0 m, there were two storm events before the storm event that was analysed here that may have caused an exhaustion of sediment (Gellis, 2013; Hudson, 2003). One storm was three days before with a total rainfall of 17.2 mm and sediment yield of 782 kg km^{-2}. Another one was just one day before with a total rainfall of 19 mm and sediment yield of 39867 kg km^{-2}.

Table 9: Total discharge per unit area and total sediment export per unit area for storms of approximately 500 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Total discharge per unit area (m^3 km^{-2})	6278	6749	5192	8121	1892
Total sediment export per unit area (kg km^{-2})	1551	4396	2612	1487	4295

(iv) Large Storms (Discharge of 1000 L s^{-1} ha^{-1})

For storms with discharge of 1000 L s^{-1} ha^{-1}, the time taken for the discharge to drop by 50% is 60 minutes for the VJR, LFE and OP catchments followed by the PF and 0 m with 45 and 20 minutes respectively (Figure 7 and Table 10). The duration of high flow is the longest in the OP, followed by the PF, VJR, LFE and 0 m. Both the LFE and 0 m show signs of poor infiltration and that most of the water were channelled via surface runoff. This is due to the short time for discharge to drop and short duration of high flow. This property is usually associated with the OP catchment as shown in previous sections.

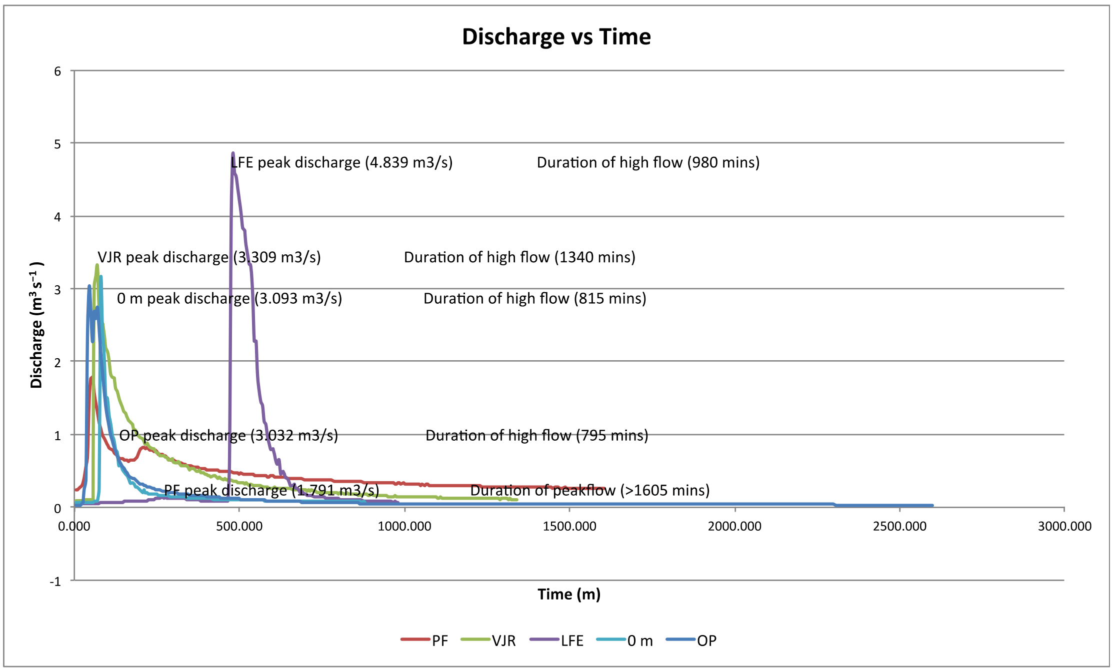

Figure 7: Discharge vs time curve for storms of approximately 1000 L s^{-1} km^{-2} for all catchments

Table 10: Discharge analysis for storms of approximately 1000 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Peak discharge per unit area (m^3 s^{-1} km^{-2})	0.915	1.045	1.032	1.092	1.131
Discharge rise per unit area (m^3 s^{-1} km^{-2})	1.555	3.218	4.788	3.037	3.698
Time peak discharge drop 50% per unit area (mins km^{-2})	45	60	60	20	60
Duration of high flow per unit area (mins km^{-2})	1605	1340	980	815	2585

From Table 11, the lowest peak SSC is from the 0 m catchments with 808 mg L^{-1}, followed by the PF (1386 mg L^{-1}), LFE (1475 mg L^{-1}), VJR (4424 mg L^{-1}) and OP (23608 mg L^{-1}). The thrice-logged forest (0 m) once again shows the lowest peak SSC even for a large storm. All catchments show increasing peak SSC with increasing disturbance with exception to the VJR where it has peak SSC that is higher than the LFE. The oil palm catchment has the highest duration of SSC above 100, 500 and 1000 mg L^{-1} while the PF is the lowest. The LFE catchments shows higher durations of high SSC compared to the other forested catchments for a large storm.

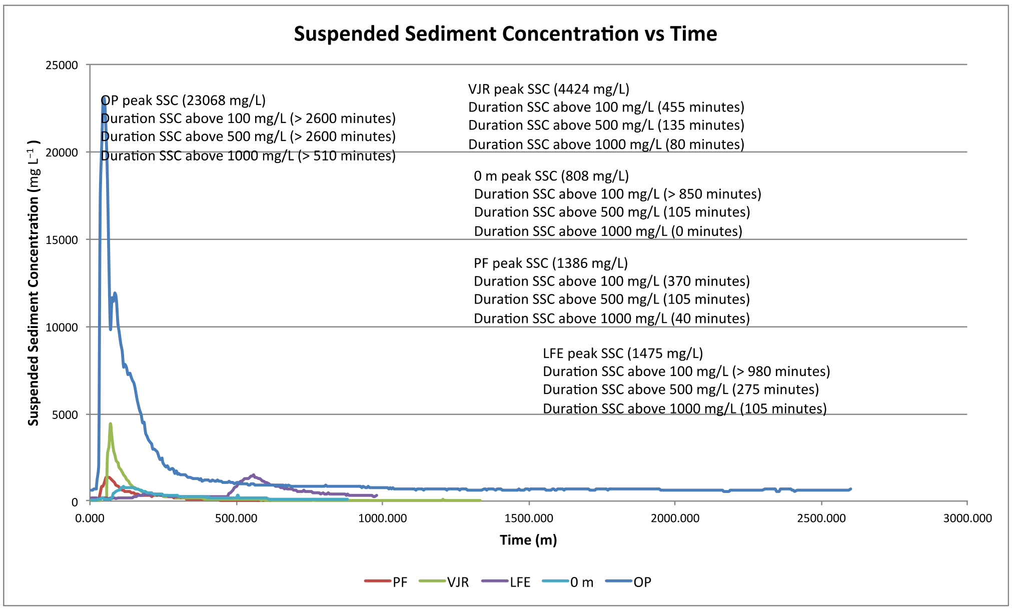

Figure 8: SSC vs time curve for storms of approximately 1000 L s^{-1} km^{-2} for all catchments

Table 11: SSC analysis for storms of approximately 1000 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Peak SSC (mg L^{-1})	1386	4424	1475	808	23,068
SSC rise per (mg L^{-1})	1386	4421	1322	737	22,438
Duration SSC above 100 mg/L (mins)	370	455	980	850	2600
Duration SSC above 500 mg/L (mins)	105	135	275	105	2600
Duration SSC above 1000 mg/L (mins)	40	80	105	-	510

The total sediment export per unit area is the highest in the OP catchment followed by the VJR, PF, LFE and 0 m (Table 12). The sediment export for the VJR catchment is about twice as high as the PF and LFE. This is unexpected as the VJR is supposed to closely simulate the PF. The 0 m catchment has the lowest sediment export of only 1859 mg L^{-1}.

Table 12: Total discharge per unit area and total sediment export per unit area for storms of approximately 1000 L s^{-1} km^{-2} for all catchments

Analysis	Catchments				
	PF	VJR	LFE	0 m	OP
Total discharge per unit area (m^3 km^{-2})	24897	11363	6067	4113	6633
Total sediment export per unit area (kg km^{-2})	5615	10458	5367	1859	53165

Conclusion

For small storms, the oil palm stream shows fast dropping discharge. The best infiltration and water holding capacity is seen in the primary forest where it takes a longer time for peakflow to recess. For medium-sized storms, the 0 m stream takes the longest times for discharge to drop followed by the PF, VJR, LFE and the OP. For large storms, the 0 m has the shortest time for discharge to drop, followed by the PF and VJR, LFE and OP.

For SSC in small storms, the OP catchment has the highest peak SSC and the longest duration of high SSC. The lowest SSC was the PF where no rise was detected followed by the VJR, 0 m and LFE. For medium storms, peak SSC is also the highest in the OP stream and lowest in the PF stream as with the small storms. However the duration of high SSC is the shortest in the OP stream, which is unlike what was shown in the small storms. The longest duration of high SSC for medium storms is in the LFE stream, followed by the VJR, 0 m and PF. Peak SSC in the large storms is highest in the OP followed by VJR, LFE, PF and 0 m. Duration of high SSC is highest in the OP and lowest in the PF.

Hydrological response and SSC dynamics is unique for different land-use and different sizes of storms and hence difficult to predict. Total sediment yield is much easier to determine. The oil palm catchment exports the most sediment during storm events in storms of all sizes with exception to the VJR being slightly higher in the medium storm. The primary forest exports more sediment compared to the regenerating logged forest in large storms, but is the least in smaller storms. For storms of all sizes, sediment yield is the lowest in the 0 m (thrice-logged regenerating) catchment. The VJR catchment has high sediment yield in the medium and large storms, which require more works to be done to understand this catchment. These results show the role and importance of forest in controlling sediment export. Even logged forests have more sediment regulating properties compared to oil palm plantations and bare land.

Limitation of Study and Future Works

The role of the old-regrowth (VJR) in this study is still unclear and needs further investigation as to why do they behave as such. Hydrological response (peak discharge and duration of high discharge) and sediment dynamics (peak SSC and high SSC duration) among the catchments is inconsistent for different storm size and requires analysis or more storm events to get a better picture. Future works in this research project includes this objective with plans of analysing more storms events as well as hysteresis curves.

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