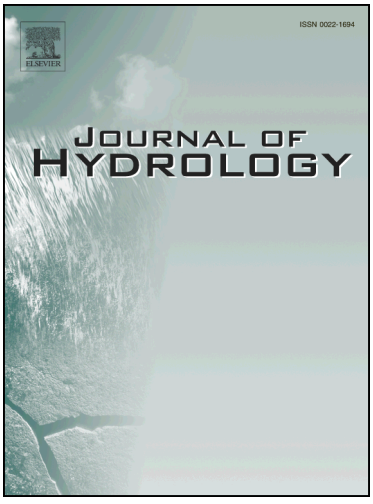

Research papers

Hydrological Dynamics of Tropical Streams on a Gradient of Land-use Disturbance and Recovery: A Multi-Catchment Experiment

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Hydrological Dynamics of Tropical Streams on a Gradient of Land-use Disturbance and Recovery: A Multi-Catchment Experiment

A. Nainar [a, b] *, N. Tanaka [a], K. Bidin [b], K. V. Annammala [c], R. M. Ewers [d], G. Reynolds [e], R. P. D. Walsh [f]

[a] Ecohydrology Research Institute, The University of Tokyo Forests, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Japan

[b] Water Research Unit, Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Malaysia

[c] Centre for Environmental Sustainability and Water Security, Universiti Teknologi Malaysia, Malaysia

[d] Faculty of Natural Sciences, Department of Life Sciences (Silwood Park), Imperial College London, United Kingdom

[e] The South East Asia Rainforest Research Partnership (SEARRP), Danum Valley, Malaysia

[f] Department of Geography, Swansea University, Swansea, United Kingdom

*Corresponding author: nainar.sci@gmail.com

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Authors' full names and addresses:

Author 1 (corresponding author) [a, b, *]

Given name : Anand

Family name : Nainar

Email : nainar.sci@gmail.com

Mobile : +81 70 4482 6238

Postal address : Ecohydrology Research Institute, 11-44 Goizuka, Seto, 489-0031 Aichi, Japan

Author 2 [a]

Given name : Nobuaki

Family name : Tanaka

Email : tnk.nobu@gmail.com

Postal address : Ecohydrology Research Institute, 11-44 Goizuka, Seto, 489-0031 Aichi, Japan

Author 3 [b]

Given name : Kawi

Family name : Bidin

Email : kawibidin@gmail.com

Postal address : Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, Malaysia

Author 4 [c]

Given name : Kogila Vani

Family name : Annammala

Email : a.kogilavani@gmail.com

Postal address : Centre for Environmental Sustainability and Water Security (IPASA), Research Institute for Sustainable Environment (RISE), Block C07, Level 2, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor

Author 5 [d]

Given name : Robert M.

Family name : Ewers

Email : r.ewers@imperial.ac.uk

Postal address : Faculty of Natural Sciences, Department of Life Sciences (Silwood Park), Imperial College London, Buckhurst Road, Ascot, Berks, SL5 7PY, United Kingdom

Author 6 [e]

Given name : Glen

Family name : Reynolds

Email : glen@searrp.org

Postal address : Danum Valley Field Centre, P. O. Box 60282, 91112 Lahad Datu, Sabah, Malaysia

Author 7 [f]

Given name : Rory Peter Dominic

Family name : Walsh

Email : r.p.d.walsh@swansea.ac.uk

Postal address : Department of Geography, Wallace Building, Swansea University, Singleton Park, Swansea, SA2 8PP, United Kingdom

Although erosional impacts of rainforest logging are well established, changes in hydrological dynamics have been less explored especially in the post-logging recovery phase following repeat-logging cycles and mature phase of oil palm plantation cycles. This study addresses this gap by comparing hydrological characteristics of five catchments in a steep land area of Sabah, Malaysian Borneo on a gradient of disturbance and recovery – twice-logged forest, 22 years recovery (LF2); multiple-logged forest, 8 years recovery (LF3); mature oil palm, 20 years old (OP); and two primary forests (PF and VJR) as controls. Each catchment was instrumented with water depth (converted to discharge), conductivity, temperature, and turbidity sensors, and a raingauge connected to a solar-powered datalogger recording data at 5-minute intervals from November 2011 to August 2013. Data were analysed via the flow-duration curve (FDC) supplemented by the runoff coefficient (RR) and coefficient of variation in discharge (QVAR) for aggregated characteristics, as well as via a combination of the Dunn's test and multiple-regression at the storm event scale for focused hydrological dynamics. Results show that OP is characterised by a relatively low RR (0.357) but with high responsiveness during storm events and very low baseflow (38.4 % of total discharge). Discharge in the LF3 (RR = 0.796) is always the highest while having an intermediate level of responsiveness. LF2 with longer-term recovery shown a reduction in terms of discharge (RR = 0.640). Being the benchmark, the undisturbed forest (PF) has the most buffered storm response with the highest baseflow (67.9 % of total discharge). Stormflow and baseflow are anomalously high and low respectively in the near-primary VJR catchment, but this probably reflects the shallow soils and short-stature rainforest associated with its igneous and metamorphic lithology. From a management aspect, although hydrological recovery is more advanced in the 22 years than in the 8-years post-logging catchment, full recovery is still to be achieved and might be hastened by enrichment planting of the degraded forest. The low baseflow and flashy nature of the mature oil palm have major implications for downstream water supply in ENSO periods and flooding in La Nina periods. Steep lands in the humid tropics are best avoided from any form of landscape disturbance.

Keywords: Hydrology; tropical; forest; logging; oil palm; streamflow

1. Introduction

While developed nations have already reached a relatively stable land-use pattern, developing countries are still actively undergoing major land-use change (Alcántara-Ayala and Dykes, 2010; Samek et al., 2012; Wolfersberger et al., 2015). In addition to urbanisation, logging (Ewers, 2006; Richardson and Peres, 2016; Zimmerman and Kormos, 2012) and conversion into agricultural and forestry plantations (Ewers et al., 2011; Walsh et al., 2006) are still widespread in parts of the ever-wet tropics. Although the peak of timber exploitation of primary forest is past, landscape disturbance now often involves repeat rounds of timber harvesting and eventually clearance-logging for conversion into plantations (both forestry and agricultural – and especially oil palm) (Reynolds et al., 2011).

These subsequent rotations of logging and plantation land-use modify both soil properties and ground cover and involve complex temporal changes in evapotranspiration components, runoff processes and streamflow regimes and flood magnitude and frequency (Hotta et al., 2010; Malmer, 1992; Shamsuddin et al., 2014). Both on-site and downstream ecological (Luke et al., 2017; Sulai et al., 2015) and erosional (Douglas, 1999; Ismail and Najib, 2011; Najib et al., 2017; Walsh et al., 2011) impacts associated with some of these land-use changes have been well-documented.

Though substantial attention have been given to landscape-scale and/or longer-term catchment hydrological response to land-use change in temperate regions (Gomyo and Kuraji, 2013; Hotta et al., 2010; Ilstedt et al., 2016; McGuinness and Harrold, 1971; Ochoa-Tocachi et al., 2016b; Qazi et al., 2017; Wine and Zou, 2012), studies of land-use–hydrology relationships in the humid tropics have largely focussed on short-term change with little attention given to the longer-term effects of, for example, multiple logging and oil palm (and other plantation) life cycles. The main focus of detailed studies in the humid tropics has been on impacts of logging on suspended sediment (Chappell et al., 2004, 1999, Douglas, 2003, 1996, Douglas et al., 1999, 1993, 1992) with hydrological effects being assessed within these. This may reflect the fact that water availability (until recently) has rarely been a problem in the humid tropics, so that research and management have focussed on the quality rather than quantity of water.

Earlier research on the hydrological effects of land-use change in the wet tropics was comprehensively reviewed by Anderson and Spencer (1991), and Douglas (1999), with a contrast being drawn between the low soil permeability and enhanced overland flow responses of disturbed or converted terrain and the very high topsoil permeability and muted overland flow and streamflow responses of primary forest terrain. Bidin *et al.* (1993) highlighted the high responsiveness of a shallow water table in an undisturbed tropical forest in Borneo where only few mm of rain was

enough to trigger the filling of macropores. Although done on a single catchment, this was crucial as a pioneer study as it provided catchment characterisation information to many future studies. The same study also noted that although water table filling is rapid, saturation-excess overland flow was infrequent (only 22 events per year). Later studies at the site demonstrated that pipeflow (rather than overland flow was the dominant storm runoff process, but with frequent and widespread Hortonian flow becoming more important on steeper terrain (Sayer et al. 2004, 2006; Clarke & Walsh, 2006). The review of Douglas et al. (1999) highlighted hydrological results extracted from unpublished PhD theses (Balamurugan, 1997; Yusop, 1996) that showed immediate increases in discharge following logging. Other early studies (Malmer, 1992; Nik, 1988; Nik and Yusop, 1994) showed a reduction in discharge one or two years after plantation establishment. Recent years have seen a surge in *modelling-based* studies (Birkel et al., 2012; Brauman et al., 2012; Chappell and Tych, 2012; Gerold, 2010; Shiraki et al., 2017) – but each with different findings that are area-specific. In addition, Shamsuddin *et al.* (2014) carried out a field-based paired-catchment study that focused on the impact of forest clearance and replanting on water yield. Detailed studies of hydrological dynamics (not limited to water yield alone) greater than five years after logging, following multiple logging cycles and in mature forestry and oil palm plantations remain lacking - despite the greatly increasing areas with such land-use histories (Giambelluca, 2002), Furthermore, with the depletion of timber from primary forests, repeat- and/or clearance-logging of regenerating forests are set to

continue. Also, driven by high demand and prices, oil palm continues to constitute an attractive land-use in countries where its cultivation is feasible (Corley, 2009; Corley and Tinker, 2003).

This paper addresses some of the research gaps identified above by focussing on the following unanswered questions:

1. How does stream hydrology compare between areas covered by primary rainforest, by regenerating rainforest of varying logging history, and by mature (20-year-old) oil palm plantation?
2. Is stream hydrological characteristics after 8-22 years post-logging regeneration (for twice-logged and multiple-logged forest) and of a 20-years stabilisation period (for oil palm) comparable to that of primary forest?
3. Is stream hydrology in a mature (20-year-old) oil palm or after 8-22 years post-logging regeneration closer to that of primary forest?

Using a *field experiment* approach, the paper compares discharge characteristics at the *overall* and *storm-event timescales* between five catchments on a gradient of land-use disturbance and recovery in a humid tropical area with a history of multiple logging and conversion to oil palm.

The study thus focuses not only on differences in total discharge and the relative importance of baseflow and stormflow, but also on differences in streamflow response to rainstorms.

2. Study Area

2.1. Site description

This study compares stream hydrological dynamics across five small (1.70-4.64 km^2) tropical headwater catchments in Sabah, Malaysian Borneo (Figure 1) that have been subjected to varying histories and intensities of land disturbance in the past – primary forest (PF), virgin jungle reserve (VJR), twice-logged and regenerating forest (LF2), multiple-logged and regenerating forest (LF3) and a 20-year-old mature oil palm plantation (OP). The PF catchment is located in the Danum Valley Conservation Area (DVCA) and is part of the Segama river system, while the others are located approximately 29 km SSW within the Brantian (LF2, LF3, and VJR) and Kalabakan (OP) river systems. Catchments were selected to be as similar as possible in catchment size, slope, climate, geology, and soil type. The geology of the LF2, LF3, OP and PF catchments consists of Oligocene to Middle Miocene rocks of the Kuamut and Kalabakan Formations, which comprise a melange of sedimentary and volcanic rocks, including slump breccia and interbedded mudstones, tuffs,

tuffaceous sandstones, shale, conglomerate, chert and limestones (Leong, 1974). The VJR catchment, however comprises Cretaceous to Early Tertiary igneous and metamorphic rocks (mainly gabbro, dolerite, serpentinite, peridotite, dunite and pyroxenite) (Geological Survery of Malaysia, 1985). Topography wise, all catchments are mountainous but vary from steep (VJR) to mild (PF) as shown in Table 1.

Figure 1: Location and land-use of study area

Produced using map layers from the SAFE Project repository (SAFE Project, n.d.) and information from existing publication (Douglas et al., 1992; Ewers et al., 2011; Luke et al., 2017; Pfeifer et al., 2016) via the ArcMap GIS software version 10.4.

Table 1: Catchment characteristics

[a] The PF catchment is known as the West Catchment in the Danum Valley Conservation Area. The VJR, LF2, LF3 and OP (Selangan Batu Estate) catchments are all located within the Benta Wawasan Plantation/SAFE Project area.

Elevation information was obtained from GIS layers from the SAFE Project repository (SAFE Project, n.d.) via the ArcMap GIS software version 10.4. Information of Leaf Area Index (LAI) and Above Ground Biomass (AGB) are derived from Ewers *et al.* (2011); tree density information is from Singh *et al.* (2015) and Newbery *et al.* (1999).

Climate is hot and wet throughout the year. Mean annual rainfall and temperature (July 1985-June 2016) recorded at the Danum Valley Field Centre (DVFC) close to the PF catchment are 2870.3 mm and 27°C respectively. Rainfall records over the period 2011-16 indicate that annual rainfall in the SAFE Project area (VJR, LF2, LF3, OP) is around 400-500 mm lower than at Danum (Table 2).

Table 2: Annual rainfall in the general area of the catchments in the years 2011-12 to 2015-16

Danum raingauge – adjacent to PF catchment; SAFE raingauge – recorded at basecamp for VJR, LF2, LF3 and OP.

All catchments are (or were originally) covered by lowland mixed-dipterocarp except for the VJR, the upper part of which is covered by upland ultramafic forest vegetation (Sabah Forestry Department, 2010). Since previous logging has extracted most of the original canopy trees, the LF2 and LF3 is characterised by young regrowth of varying species (mostly *Macaranga*). Details of forest quality are shown in Table 1. The oil palm catchment consists of 20-year-old trees of the *Elaeis guineensis* species. A detailed list of vegetation in the area is documented in past studies (Newbery et al., 1999; Singh et al., 2015).

2.2 Brief land-use history

The primary forest (PF) catchment lies within the Danum Valley Conservation Area (DVCA), which now comprises one of the largest areas of lowland primary forest remaining in Southeast Asia (Reynolds et al., 2011). The 438 km^2 DVCA is classified by the Sabah Legislative Assembly as a Class I protected forest reserve within the Yayasan Sabah (Sabah Foundation) Forest Management Area and is reserved for conservation purposes. Areas surrounding the DVCA were selectively logged in the 1980s and there is an access road to the field centre.

The Virgin Jungle Reserve (VJR) catchment lies within a forest area that was lightly logged around the boundary to make an access road, but where the remaining forest in the catchment itself resembles primary forest. The area has been gazetted as a Class IV protection forest and reserved for recreational purposes. The twice-logged LF2 and multiple-logged LF3 catchments were first logged in the 1970s where an average of 113 m^3 ha^{-1} were extracted. The LF2 was then logged for the second time in the 1990s, extracting an average of 37 m^3 ha^{-1} (Struebig et al., 2013), while the LF3 underwent three more rounds of logging over 1990–2004, extracting 26, 22 and 18 m^3 ha^{-1}, respectively, with trees as small as 30 cm diameter at breast height (dbh) being logged (Struebig et al., 2013). Since the cessation of logging, the LF2 and LF3 catchments have been regenerating with young stands and low-lying understorey with different degree of forest cover at present (Ewers et al., 2011; Struebig et al., 2013). The LF2 is characterised by a more extensive and taller tree cover due

to fewer rounds of harvesting and a longer recovery period whereas the LF3 has a mainly low vegetation cover with few canopy trees. The OP catchment is a mature oil palm plantation (approximately 20 years of age at time of study) with bench-terracing and a dense network of dirt access roads and tracks which is typical of hilly oil palm plantations in this region (Ewers et al., 2011; Luke et al., 2017). Forest riparian buffers are absent as the estate was established before the legislation of a mandatory 30 m buffer width (Ewers et al., 2011).

3. Methodology

3.1. Research design and data collection

The research design involved the collection, analysis and comparison of discharge and rainfall data (and derived key hydrological parameters) for five small catchments of contrasting logging and land-use history within the upper Brantian, Kalabakan and Segama river systems. In all catchments, a gauging station was established at the outlet of each stream. Campbell Scientific instrumentation installed at each station comprised a water depth (CS450), turbidity (OBS3+), conductivity and temperature (CS547a) sensors as well as a 0.2 mm tipping-bucket raingauge (ARG100) connected by cables to a CR850 solar-powered datalogger. Data were recorded at 5-minute intervals with

hourly averages and calendar day averages also calculated. Records from November 2011 to August 2013 (22 months) were used in this study. Data downloading and station maintenance were carried out monthly. In the PF catchment, a sharp-crested 120° v-notch weir established in a previous study was used and hence water level data were converted to discharges utilising the appropriate weir equation. Weirs could not be used at other catchments, as the combination of steep gradients, high bedload and floating log debris in high flow events would have led to weir destruction or weir pool sedimentation. At these catchments, station sites with stable cross-sections (and where possible natural downstream bedrock control) were selected and water level data were converted to discharge by means of a calibration curve produced by the relative-method salt-dilution gauging (Littlewood, 1986) for lower flows and the slope-area method for high flows (as the remoteness and mountainous nature of sites precluded on-site systematic measurement of high flows). With the slope-area method, at each site cross-sectional areas at different water-levels were precisely measured and used along with channel gradient measurements and velocities (calculated using the Manning's equation) to derive discharges. The necessary values of Manning's *n* were derived using the procedure developed by Chow (1959) and the derived velocities in LF2 were of the same order of those recorded by video at high flow in that catchment. Although not ideal, the derived high flow discharges are considered reasonable estimates given the regular and stable cross-sectional sites used at each site. At the PF catchment, rainfall data from a Casella natural siphon raingauge at the nearby DVFC were used.

3.2. Data processing and analysis

Because of the adverse environment (damage to equipment in flood events and by elephants and other wildlife), perfect-continuous datalogging and comparison of full hydrological years between catchments were not possible. Inter-catchment comparison of common storm events is also inappropriate due to the highly localised nature of most rainstorms in the region. Data were therefore explored in two ways: (i) via flow-duration curve (FDC) utilising the daily discharge records for each catchment and; (ii) a comparison of selected hydrological variables at the storm event-scale. In each case analysis utilised all available data for each catchment in the 22-month period.

In the FDC analysis, daily discharges for each catchment were first computed and sorted in descending order. Only full-day records (1,440 minutes – 288 readings of 5-minute data) were used. Daily discharge percentage exceedance plots were produced for each catchment. Percentage exceedance ranges of 0-20%, 20-80%, 80-95%, and 95-100% were defined as high flows, regular flows, low flows, and drought flows respectively. A rain-duration curve was produced in the same manner by using daily rainfall data. Table 3 shows meteorological- and runoff-related indices (Ochoa-Tocachi et al., 2016b) computed and used for comparing the flow characteristics of each catchment.

Table 3: Meteorological- and runoff-related indices (Ochoa-Tocachi et al., 2016b) used for inter-catchment flow regime comparisons

A more focused approach involving analysis of individual storm hydrograph responses to rainstorms is reported in the second part of the results. This analysis utilises the 5-minute interval data of all available storm events for each catchment within the common 22-month period. To filter unduly small events, a storm event was defined as a successive rise of at least 6 cm in water level for at least 15 minutes (3 consecutive 2 cm rises).

Hydrograph separation into quickflow and baseflow were carried out using the Hewlett-Hibbert method (Hewlett and Hibbert, 1967). This method was selected for a three main reasons. First, many of the more recent separation techniques are based on there being discrete and identifiable individual storm runoff and baseflow processes with distinguishable solute (conductivity) characteristics. Use of such techniques was considered unjustified and inappropriate in the study area, as previous detailed runoff process studies in the primary forest catchment location (Sinun et al. 1992; Sayer et al., 2006; Clarke and Walsh, 2006) have shown (i) that both pipeflow and Hortonian overland flow are important storm runoff processes with rapid responses to rainfall

that are difficult to distinguish in terms of their conductivity dynamics and (ii) that pipeflow moreover contributes both to stormflow and baseflow. Second, the Hewlett-Hibbert method provided a standardized separation method that proved capable of use in analysing all the storm hydrographs of the five catchments, whereas the Recursive Digital Filter (RDF) technique of Eckhardt (2015) could not produce realistic separations for temporally adjacent storm hydrographs within the record and was found therefore to be unsuitable for application in a wet tropical environment where such storms comprise a significant proportion of storm events. A third reason for deciding to use the Hewlett-Hibbert technique was that for those events in which the RDF technique could be used, the differences in separation and percentages of baseflow and quickflow between the two techniques were relatively small (Figure 2).

In applying the Hewlett-Hibbert method, a linear plot of slope 5.4666 x 10^{-4} m^3 s^{-1} km^{-2} (HH slope) was drawn starting from the beginning of the rise in discharge (Bidin and Greer, 1997; Hewlett and Hibbert, 1967). By this common rule, boundaries were set for each hydrograph (Figure 2) and values of the hydrological variable of interest (Table 4) were derived. In total 134 storm events were analysed from the PF catchment, 82 from VJR, 110 from LF2, 125 from LF3 and 117 from OP.

Figure 2: a) Example of a separated hydrograph with its hydrological variables. b-f) Examples of storm hydrographs separated using the Hewlett-Hibbert (dotted lines) and Recursive Digital Filter (dashed lines) techniques.

Table 4: Hydrological variables investigated at the event-scale

After hydrograph separation and data extraction (of selected variables) via programming in a FORTRAN compiler (gfortran/GCC 4.9.2), the hydrographs and extracted data were then inspected individually. Finally, using (i) the stormflow and baseflow data for all individual storms of each catchment dataset and (ii) the baseflow data for all between-storm sections of the discharge record for each catchment, overall percentages of total discharge of each catchment being contributed by baseflow and quickflow were calculated.

3.3 Statistical methods

To detect overall differences between the different land-use, the Kruskal-Wallis H test followed by the *post-hoc* Dunn's test ($\alpha = 0.05$) was used. Results are displayed in box-and-whisker plots supplemented by alphabet groupings (Yamada, 2013).

To control for the effects of rainfall, P, multiple regression was performed on each hydrological variable (Chappell et al., 1999; Staelens et al., 2008) via the analysis of covariance (ANCOVA) framework in R software v.3.4.1. The dependent variable of interest, Y ($Q_{initial}$, Q_{end}, Q_{peak}, T_{peak}, Q_{tot}, Q_{quick}, Q_{base}), with a significant relationship to the covariate, P ($\alpha = 0.05$), were regressed with "P · LU" (rainfall with land-use interaction), followed by with "P + LU" (rainfall and land-use without interaction). Analysis of variance was then performed to ascertain the parsimonious model for each Y ($\alpha = 0.05$). Regression coefficients were acquired by means of the "lm" command in R via the distinct-slopes model. The goodness-of-fit of each model was shown by the adjusted r-squared (R_a^2) to account for the varying number of variables used. These steps to control for the effects of rainfall were performed on all catchments except the PF.

Results from the more inclusive Dunn's test are first reported as an overall comparison. Then, results from the multiple-regression are reported to control for the effects of rainfall in the VJR, LF2, LF3 and OP catchments. As the PF catchment serves as a benchmark and control against the other human-modified landscapes, the unavailability of continuous rainfall data is considered to be of minimal impact to the objective of this study. Integration and synthesis of results from both tests (Dunn's and ANCOVA) are discussed in later sections.

4. Results

4.1. Flow-Duration Analysis

Figure 3 shows daily totals for rainfall and discharge derived from continuous 5-minute data throughout the datalogging period (November 2011-August 2013). The sample size (*n*, number of days) used in generating the frequency-duration curve (FDC) differs between the catchments: - PF (344 days), VJR (278 days), LF2 (401 days), LF3 (440 days) and OP (359 days).

Figure 3: Stream discharge and rainfall over the period of data collection

OP had the lowest daily discharge values throughout the FDC (Figure 4a) despite higher rainfall than in other catchments (Figure 4b). This is especially clear when comparing against LF2 and LF3 (Figure 4) and is further confirmed by the lowest RR value of 0.357 (Table 5). The OP showed the most variable streamflow (QVAR=2.062), despite both PVAR (1.604) and DAYP0 (0.253) values being moderate compared with values for other catchments (Table 5).

Table 5: Computed meteorological- and runoff-related coefficients of the different catchments

* Raingauge partially affected by canopy. Correction performed by means of LF2-LF3 (adjacent catchment) rainfall ratio.

Figure 4: a) flow-duration curve; b) rain-duration curve; c) rainfall-runoff ratio (RR)

For logged forests, RR values for LF2 (0.640) and LF3 (0.796) ranked third and first respectively (Table 5). Daily discharge fluctuation indicated by QVAR was 2.025 and 1.486 for LF2 and LF3 respectively (Table 5) – LF2 being the second highest and LF3 is similar to VJR. The FDC plot for LF2 is almost parallel with but higher than that for LF3 throughout the percentage exceedance range except for at high flows (Figure 4a).

VJR is characterised by very stable flows as seen in the FDC (Figure 4a) and the second lowest RR (0.615, Table 5), thereby signifying well-regulated streamflow. This is further affirmed by the second lowest QVAR of 1.527 very close to the PF value (Table 5). The rainfall pattern in VJR is characterised by a higher frequency of smaller storms compared to that of other catchments (Figure 4b).

The primary forest (PF) catchment recorded the highest number of days without rainfall (DAYP0=0.337, Table 5), while having the highest mean annual rainfall and a higher frequency of

large storms compared to the other catchments (Table 2, Figure 4b). The RR value of the PF (0.789) ranked second after the LF3. The FDC showed that PF had the largest daily discharge for most of the range of percentage exceedance, except the very highest flows above 88% (Figure 4a). PF had the highest coefficient of variation of daily discharge (QVAR=1.231, Table 5).

4.2 Event-scale

Figure 5 (a-f) displays for each hydrological variable, the differences between catchments tested via the Dunn's test, whilst Figure 5 (g-l) displays the regression (hereafter ANCOVA) lines of hydrological variables against event rainfall for each catchment. The ANCOVA results for all hydrological variables are summarised in Table 6.

Results from the Dunn's test show that Q_{tot} values differ significantly between land-uses, where LF2 is the highest, followed by the LF3, PF, VJR and OP. According to the alphabet groupings, the logged-forests show the highest values followed by natural forests, and then oil palm plantation (Figure 5a). By the more thorough ANCOVA, Q_{tot}-rainfall relationships are also statistically significantly different among the different land-uses (Table 6). The regression lines shown in Figure 5g thus have differing slopes and intercepts. Both LF3 and OP (especially LF3) have distinctly shallower slopes which translates to less response towards storm magnitude just as in

Q_{end}, Q_{base} and Q_{peak}. Because Q_{quick} comprises most of Q_{tot} resulting in similar ranks, its figures and results were omitted for conciseness. Q_{quick} is however not statistically significantly different, signifying that differences are contributed by baseflows (indicated by Q_{end} and Q_{base}).

Q_{peak} does not differ significantly between land-uses but does differ significantly in their interaction with rainfall (Table 6). The different land-uses show increasing rate of change with rainfall in the order of LF3, LF2, OP and VJR (Figure 5h). In contrast, T_{peak} differed significantly between catchments (Figure 5c) where PF and OP show the highest and lowest values respectively whilst others (VJR, LF2 and LF3) differed among one another but not by a significant margin. T_{peak} was not explored with the ANCOVA procedure due to its non-relationship with the covariate, rainfall (Table 6).

The Dunn's test revealed $Q_{initial}$ as being significantly different between catchments with PF having the highest value, followed by the VJR, LF3 LF2 and OP (Figure 5d). Due to the lack of significant interaction with the covariate, rainfall (Table 6, Figure 5j), the ANCOVA procedure was also omitted for $Q_{initial}$.

Both Q_{end} and Q_{base} differed significantly between catchments (Figures 5e and 5f) using the

Dunn's test. For these variables, PF and OP have the highest and lowest values respectively whilst VJR, LF2 and LF3 have intermediate values and do not differ significantly. Using ANCOVA, interactions of both Q_{end} and Q_{base} with rainfall (Figures 5k and 5l) were found to be statistically significantly different (Table 6) between the land-uses. More specifically, the LF3 showed a distinctively higher Q_{end} for small events but has a milder rate of increase with event rainfall (Figure 5k). VJR, LF2 and OP on the other hand have varying values during small events, but VJR and OP have similar rates of increase with event rainfall (Figure 5k). In addition, differing initial values and rate of increase were found for Q_{base} where LF2, LF3 and OP were less responsive to rainfall input compared to the other catchments as seen in the slopes in Figure 5l.

Table 6: F-statistics for land-use (LU) and land-use-rainfall interaction (LU · P) for the different hydrological variables (multiple-regression only)

* **Bold** indicates statistical significance ($\alpha = 0.05$). ANCOVA omitted for $Q_{initial}$ and T_{peak} (no relationship with covariate, P).

Figure 5: Differences in hydrological variables (a-f, Dunn's test; g-l, multiple-regression) between the catchments.

* Q_{quick} is similar to Q_{tot}, hence omitted from display.

The resulting distinct-slope regression model (equation 4) can be computed by substituting in values of the covariate, rainfall (P) as well as the coefficients listed in Table 7.

$$Y = (a_0 + a_1 + a_2 + a_3) + (b_0 + b_1 + b_2 + b_3) \cdot P$$

$$Y = a_0 + a_1 + a_2 + a_3 + b_0P + b_1P + b_2P + b_3P \quad (4)$$

Table 7: Coefficients of intercept (a) and slope (b), F-value, p-value and adjusted r-squared (R_a^2)

Using all the available storm event and between-event discharge data, percentages of total discharge contributed by baseflow and quickflow (stormflow) were calculated for each catchment (Table 8). The mature oil palm catchment is by far the flashiest catchment, with its 61.6 % quickflow and 38.4 % baseflow values being 29.5 % higher and lower respectively than values for the primary forest catchment. Values for the logged catchments are intermediate, but with higher percentage quickflow in the twice-logged LF3 than the multiple-logged LF2 catchment. Percentage quickflow is second highest (and percentage lowest second lowest at the VJR catchment, despite its near-primary vegetation.

Table 8: Percentage quickflow and baseflow contributions to total discharge at the five study

catchments over the whole study period

5. Discussion

This section synthesises (i) the various indices and hydrological variables into catchment hydrological components (Table 9) as well as (ii) the analyses at different timescales. Consideration of the FDC together with the meteorological and runoff indices (Buytaert et al., 2007; Ochoa-Tocachi et al., 2016b, 2016a; Yadav et al., 2007) enables intuitive data visualisation and objective comparison (Cole et al., 2003; Liucci et al., 2014) in a period-normalised manner – where steeper slopes signify high flashiness to precipitation input while flatter curves point to muted response and larger storage capacity. DAYP0 (0.201-0.337) and PVAR (1.570-1.810) values are within the range reported for homogenous equatorial climate (Feng et al., 2013; Kumar, 2013; Ochoa-Tocachi et al., 2016a, 2016b; Pascale et al., 2015) and signify good coverage over a range of storm magnitudes, which is a key requirement highlighted by hydrologists (Silberstein, 2005; Soulsby et al., 2008). The lower number of rain days in the PF while having the highest annual rainfall points to larger storm magnitudes – consistent with observed data (Table 2).

Table 9: Rank order of land-uses for various key catchment hydrological parameters

5.1. Mature Oil Palm Plantation

Total discharge – The lowest total discharge at both the mean daily- and event-scale in the OP (Table 5, 9; Figure 5) despite its high and frequent rainfall (DAYP0 = 0.253, Table 5) is probably afforded by the enhanced interception and transpiration from the high density of oil palm trees. Reforestation is known to reduce streamflow due to enhanced ET (Ayer, 1968; Bart et al., 2016; Yang et al., 2014; Zou et al., 2016) and is used in some areas as a method of streamflow regulation and flood-control (Van der Walt et al., 2004). Though studies comparing water usage of oil palm to adjacent natural forest are lacking, studies (Niu et al., 2015; Röll et al., 2015) have demonstrated that water use by oil palm is high regardless of vapour pressure deficit. In addition Hardanto *et al.* (2017) showed that water use by oil palm is consistently higher than that of rubber over a range of environmental conditions. This effect is further enhanced as the palms are planted as closely together as possible (120-200 trees/ha) so as to optimise planted area and maximise production (Latif et al., 2003; Woittiez et al., 2017). With regards to total event discharge against rainfall, the OP catchment shows a gentler relationship than at the VJR and LF2 (Figure 5g). A possible explanation is that overland flow responses (from tracks and slopes) to even small rainstorms in OP are significant, whereas rainstorm thresholds for streamflow response are higher in the other catchments. Also, the rain water that enters the soil on slopes may mostly simply recharge soil water and be subsequently utilised by

oil palm trees in transpiration rather than contribute as subsurface flow to streamflow. Although plantation lands in the region are known to have extensive roads and bench-terracing (Barclay et al., 2017; Nainar et al., 2017) that generate runoff and impede infiltration, planted areas are required to have good soil properties for productivity (Abdul Rashid et al., 2015), though in OP the limited vegetation cover compared with in oil palm catchments in other locations may negate this (and overland flow has been observed to generate within minutes of the onset of rain). In selectively logged catchments, clear reductions in permeability have been documented due to logging roads and compaction by dragging logs (Brooks and Spencer, 1997; Chappell et al., 2006), but the proportion of the catchment affected is less than in the bench-terraced OP catchment in single-logged terrain, but may be much higher in the twice-logged LF2 and multiple-logged LF3 catchments..

Baseflows – OP recorded the lowest pre- and post-storm baseflows (Figure 5, Table 9) as well as by far the smallest percentage baseflow contribution to total discharge over the study period (Table 9), signifying the driest catchment condition of the study catchments – consistent with the lowest total discharge at the FDC (Table 5 and Figure 5d). From the aspect of response to rainfall, total baseflow and post-storm baseflow in the OP is less responsive than in the VJR but comparable to the LF2 as shown in Figure 5k and 5l. This could be caused by time-lag between infiltration and subsurface flow recharge due to the extreme low level of pre-storm baseflow ($Q_{initial}$, Figure 5d). The very low

baseflow of OP certainly in part reflects the very high % quickflow that results from the high density of access roads and tracks of the steep bench-terraced terrain and low permeability of the rather unvegetated and (because of bench terracing) structureless soil characteristics of the OP catchment. These reduce infiltration with the high transpiration of oil palm further reducing groundwater recharge and the supply of stream baseflow.

Daily fluctuation & event responsiveness – From the FDC (Figure 4a, Table 5), OP shows the highest variation in runoff (QVAR) in relation to variation in rainfall (PVAR). At the event-scale, the effects of rapid rainwater channelling by the extensive network of roads and ditches is also reflected in its shortest time-to-peak (Figure 5c). Past studies of logged catchments (Douglas, 2003, 1999; Sinun et al., 1992; Walsh et al., 2011) attributed such runoff characteristics to the extensive network of compacted ground, including roads and roadside ditches, skid trails and log-landing areas. As reported in more recent studies (Barclay et al., 2017; Luke et al., 2017; Nainar et al., 2017), networks of access roads and tracks are typical of oil palm terrain in the region. Although studies directly ascribing high streamflow response in oil palm plantations to dirt roads are yet to be published, previous studies in the study area (Douglas, 2003, 1999; Douglas et al., 1992) and wider SE Asia region (Ziegler et al., 2001; Ziegler and Giambelluca, 1997) have demonstrated the significance of runoff from logging roads in storm runoff generation and sediment delivery to streams in logged

terrain – and their role is oil palm terrain (both young and mature) is likely to be greater given the higher dirt road density.

5.2. Recovering logged-forests

Total discharge – The RR values from Table 5 show the LF3 and LF2 to be ranked the highest and third respectively. The high RR value in the LF3 is consistent with studies elsewhere (Hayashi et al., 2011; Hotta et al., 2010b; Tan-Soo et al., 2016) that found that timber harvesting or deforestation causes increased discharge and attributed this to the reduction in evapotranspiration. This shows that a post-logging stabilisation period of 8 to 22 years (LF3 and LF2 respectively) is insufficient for vegetation and soil properties to recover to levels of undisturbed forests (Bruijnzeel, 2004; Gomyo and Kuraji, 2013, 2012; Malmer, 1992; Nik, 1988; Qazi et al., 2017). At the storm event-scale, both logged catchments have the highest total discharge when compared to other land-uses but do not differ significantly among themselves (Table 5, 8; Figure 5a). Despite having a large runoff coefficient, total discharge in the LF3 shows the smallest increment with rainfall. The LF2 on the other hand is ranked the second in terms of change with rainfall (Figure 5g).

Baseflows – Baseflow for both the LF2 and LF3 is lower than the PF but higher than the OP, where this is true both at the event-scale and the over the entire study period (Table 9). Despite the highest

total discharge in the LF3, baseflow is lower than in the PF which may reflect the higher rainfall of PF (Table 2) and superior hydrological regulation capacity in primary forests (Bruijnzeel, 2004; Ismail, 1997). Repeat topsoil compaction, removal and exposure of subsoil may also play a part in reducing soil storage capacity that sustains baseflow. Baseflow during storm events of the less recovered LF3 is less responsive towards changes in storm magnitude as shown in Figure 5k and 5l. This may be attributed to the reduced infiltration and storage capacity typical of a logged catchment that leads to higher direct runoff (Brooks and Spencer, 1997; Chappell et al., 2006). Pre-storm baseflow, however, is higher for LF3 than for LF2 (Figure 5d) suggesting that although groundwater recharge during storm events may be impeded owing to the degraded soils of the logged catchments (Douglas, 1999; Nainar et al., 2015), the water that infiltrates will be subject to reduced transpiration by low biomass regrowth. Such asynchronous characteristics are also documented elsewhere and linked to changes in soil depth, rooting zone and phenology (Liu et al., 2017).

Daily fluctuation & event responsiveness – The partly recovered forest conditions of LF2 and LF3 have reduced storm runoff responses but with responsiveness and fluctuation values still higher than those for primary forest, (Figure 5, Table 9) in line with findings for regenerated forests elsewhere (Bruijnzeel and Vertessy, 2004; Gomyo and Kuraji, 2013, 2012; Qazi et al., 2017; Walsh et al., 2011). These results suggest that leaving a catchment to regenerate may reinstate runoff control (either

increased infiltration or buffered runoff). However, the future speeds of forest regeneration and how long it takes for re-attainment of primary forest remain unanswered questions. Walsh *et al.* (2011) highlighted that enhanced sediment delivery (a function of degraded catchment hydrology) persisted up to 15 years post logging. This current study demonstrated that a 22-year recovery period has shown hydrological improvements but is still not on par with undisturbed forests.

5.3. Primary and near-primary forests

Total discharge – In terms of total discharge, the primary forest catchments are ranked in-between the oil palm and the LF3 in both the mean daily- and event-scale analysis (Table 5, 9; Figure 5). This intermediate position is only in part in line with what one might expect from a land-use point of view, which would be lowest total discharge associated with the greatest evapotranspiration losses and storage and regulating capacity of primary forest (Bruijnzeel, 2004). Thus the lower total discharge of both PF and VJR than for the logged-forest catchments is consistent with past hydrological studies of land-use change (Ayer, 1968; Bart et al., 2016; Yang et al., 2014), in which discharge in disturbed catchments is increased because of reduced evapotranspiration due to the reduced tree stands. The higher total discharge of the primary forest catchments than in OP may be due to different reasons for the PF and VJR catchments. In the case of the PF catchment, the reason may be the significantly higher annual rainfall compared to that in the OP catchment (as well as high

evapotranspiration of mature oil palm). Annual runoff increases with annual rainfall within the rainforest tropics (Walsh and Blake, 2009) as only a small part of additional rainfall is lost to evapotranspiration and the majority results in greater streamflow. This would also explain the high RR value for the PF catchment similar to that of the LF3 (Table 5). In the case of the VJR, the reason for its higher total discharge may be the igneous and metamorphic geology (and associated very steep relief, shallow soils and reduced stature of the ultramafic forest) of the higher parts of the VJR catchment. This may be responsible for reduced evapotranspiration and enhanced quickflow (Table 9) of the catchment and hence its high total discharge. With regards to total event discharge against rainfall, VJR started off at the lowest level, but increases at a higher rate than other catchments (Figure 5g). This suggests that during smaller storms, most of the rainwater is infiltrated owing to good soil properties typical in primary forest catchments (Bidin et al., 1993; Hotta et al., 2010; Liu et al., 2011). However, as storm magnitude increases, the overriding effects of gravity and shallow soils may exert dominance resulting in overland flow – in agreement with past studies on other steep catchments (Hagedorn and Whittier, 2015; Mu et al., 2015; Pike and Scatena, 2010) as well as in the PF catchment itself (Bidin et al., 1993; Clarke and Walsh, 2006).

Baseflows – Event baseflow, event pre-storm baseflow and overall percentage baseflow are all highest in the primary forest (PF) catchment (Figure 5 and Table 9) which can be attributed to good

soil properties that promote recharge as well as the higher rainfall. The very high relief and shallow soils of the upper part of the VJR may be the reason for its lower event baseflow than for PF, though values are still higher than for the LF2 and OP (Figure 5). As baseflow is sustained by subsurface flow, this suggests that primary forests have the highest subsurface flow which may also in part account for the high total discharge of the PF and VJR in the FDC (Table 5, Figure 4). The VJR has the highest rate of increase in baseflow (Q_{end} and Q_{base}, Figure 5) against increasing rainfall magnitude, indicating the best groundwater recharge. Although this could not be confirmed for the PF, the 95-100% range of the FDC (Figure 4a) and previous studies in the PF itself (Bidin et al., 1993; Clarke and Walsh, 2006) suggests this behaviour.

Daily fluctuation & event responsiveness – As an undisturbed catchment with superior soil properties and hydrological regulation, the PF served its purpose well as a benchmark where despite higher rainfall and larger storms, it is still the most buffered catchment as also documented by other authors (Bruijnzeel and Critchley, 1994; Bruijnzeel, 2004; Ellison et al., 2017). In contrast, the high event responsiveness of the VJR catchment , can once again be linked to the excessively steep terrain and shallow soils associated with its igneous and metamorphic geology. It may be that the effects of gravity that have been found to override other factors in steep headwater catchments elsewhere (Hagedorn and Whittier, 2015; Mu et al., 2015; Pike and Scatena, 2010) may also apply in the VJR.

Using the longer daily discharge dataset, however, the FDC for the VJR plots closer to the PF across all discharge levels (Table 5).

6. Conclusions

This paper set out to answer three questions relating to catchment hydrology and land-use differences and stabilisation/recovery in steep terrain in Sabah, Malaysian Borneo. The main findings are summarized by considering each question in turn.

Question 1: Some major and statistically significant differences were found in stream hydrology parameters between the five catchments investigated. The primary forest catchments were found to support the highest stream baseflow (67.9 % of total discharge), good runoff regulation and smaller quickflow responses in storm events than all other catchments. The near-primary VJR catchment, however, while likewise exhibiting good runoff regulation, experienced relatively high runoff ratio, high quickflow (57.8 %) and low baseflow (42.2 %); this was considered to result from its igneous and metamorphic geology, which a combination of rapid runoff from shallow soils and low relatively low evapotranspiration from reduced stature mafic forest. The mature oil palm catchment has highly

variable discharge, quick responses during storm events but exceptionally low baseflow at all times (comprising just 38.4 % of total discharge). The multiple-logged forest catchment (LF3, 8 years post-logging) experienced the highest total discharge and relatively high event responsiveness and daily flow variation but these values reduce in the twice-logged LF2 catchment, which has experienced longer natural recovery (22 years). Baseflow levels in the recovering logged forest catchments are less than that in primary forest forests but higher than in oil palm.

Question 2: The answer to the question as to whether stream hydrological characteristics after 22 years of post-logging recovery or a 20 years stabilization period for oil palm are comparable to those of primary rainforest is clearly no in both cases.

Question 3: It is very clear from all the data presented that stream hydrology in a mature (20-year-old) oil palm is much less close to that of primary forest than is the case for catchments after 8-22 years post-logging regeneration. Thus, storm event responsiveness, daily flow fluctuation, event and pre-storm baseflow and the percentage contributions of stormflow and baseflow to total discharge for the logged-forest catchments are all in-between the undisturbed forest and the oil palm catchment. Thus, whereas recovery from logging with time is substantial, with most hydrological parameters becoming closer to primary forest levels, hydrological impacts of oil palm land-use

remain substantial even for a late mature oil plantation – and hence provides evidence that hydrological impacts are major throughout the productive phase of the plantation cycle.

It is unclear, however, whether these findings for oil palm stream hydrology are particularly marked because of the steep terrain and bench-terracing character landscape and/or particular management features (e.g. absence of forest riparian buffer strips and the relatively thin ground vegetation cover) of the particular catchment studied. It is arguable that impacts would be much less pronounced for oil palm catchments on moderate or low slope terrain with forest riparian strips and greater maintained ground cover in which much greater infiltration and less overland flow would be promoted.

Implications for management – There are some clear messages for management that arise from this study. First, hydrological consequences of oil palm land-use in steeper terrain are substantial throughout the plantation life-cycle and are not confined to the establishment phase. This is unlike with selective logging land-use, where impacts are severe during logging, but (as this study shows) reduce, but by no means disappear in post-logging time. Downstream impacts of oil palm on flooding, sedimentation and river ecology are therefore also likely to be greater in magnitude and persistent than with selective forestry land-use. A major consequence of the very low baseflow

recorded by this study for the oil palm catchment may be reduced river flows and water shortages especially in ENSO drought years.

There are several ways in which some of the hydrological impacts noted in this study can be reduced. Infiltration can be increased and overland flow and streamflow responses reduced in oil palm by leaving riparian forest buffer strips; maintaining ground vegetation cover on slopes (adopted as policy by some plantation companies and landowners, but not others) and by use of simple road runoff diverter/slope soakaway systems (untested). In post-logged forest catchments, as one reason for continued high discharge is the degraded, low nature of regrowth (because of excessive extraction of canopy trees), programmes of enrichment planting of canopy species can be used to accelerate recovery and thereby increase forest evapotranspiration to primary forest levels. Such programmes are currently underway in eastern Sabah.

Remaining questions and future research needs. Post-logged catchments may see a rise in streamflow which may generate floods for downstream areas especially during La Nina events. Although natural regeneration of up to 22 years have been shown in this study to bring about improvements in streamflow regulation, the time required for primary forest hydrology to be reached remains unknown, whether without or with the aid of enrichment replanting programmes.

Compared to most past research that has focused primarily on the adverse impacts of logging, this study has attempted to assess longer-term recovery and mature plantation phases of forest and oil palm land-uses. The conclusions drawn from this study are clearly limited by the number of experimental catchments, hence the gradient/spectrum of land-use changes and recovery that could be covered. It would be beneficial if future studies can address these limitations especially that pertaining to (i) a longer-term of natural post-logging recovery, (ii) the maximum extent of post-logging recovery, (iii) the establishment and maturing phase of oil palm plantations, and (iv) the maximum extent of recovery throughout oil palm crop cycle. Future studies also need to test the effectiveness of existing (e.g. riparian buffers, ground vegetation covers, enrich planting programmes) and new measures (e.g. integrated road runoff diversion/ slope soakaway systems) in reducing impacts of oil palm plantation land-use and degraded post-logging forests.

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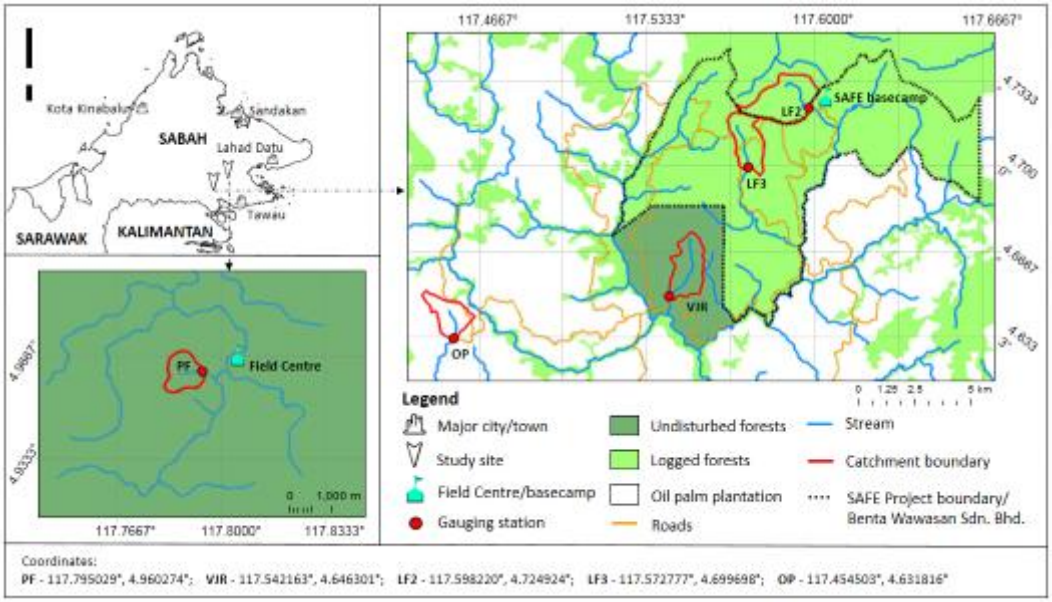


Figure 1: Location and land-use of study area Produced using map layers from the SAFE Project repository (SAFE Project, n.d.) and information from existing publication (Douglas et al., 1992; Ewers et al., 2011; Luke et al., 2017; Pfeifer et al., 2016) via the ArcMap GIS software version 10.4.

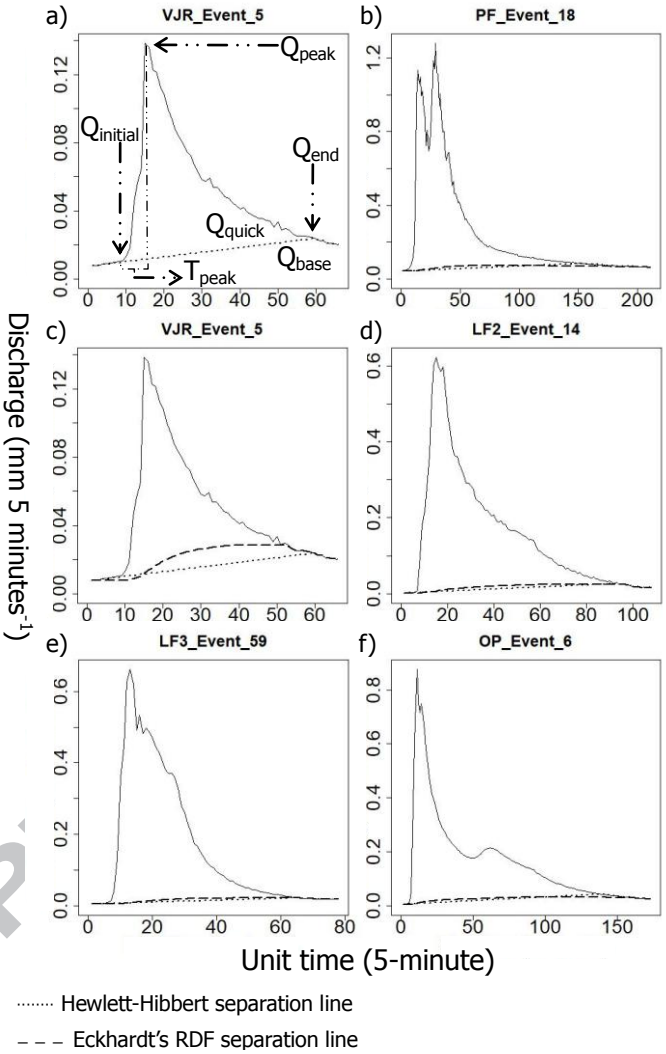


Figure 2: a) Example of a separated hydrograph with its hydrological variables. b-f) Examples of storm hydrographs separated using the Hewlett-Hibbert (dotted lines) and Recursive Digital Filter (dashed lines) techniques.

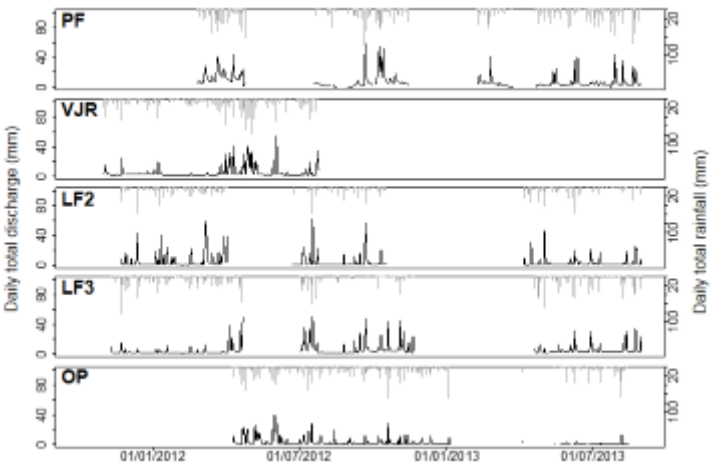


Figure 3: Stream discharge and rainfall over the period of data collection

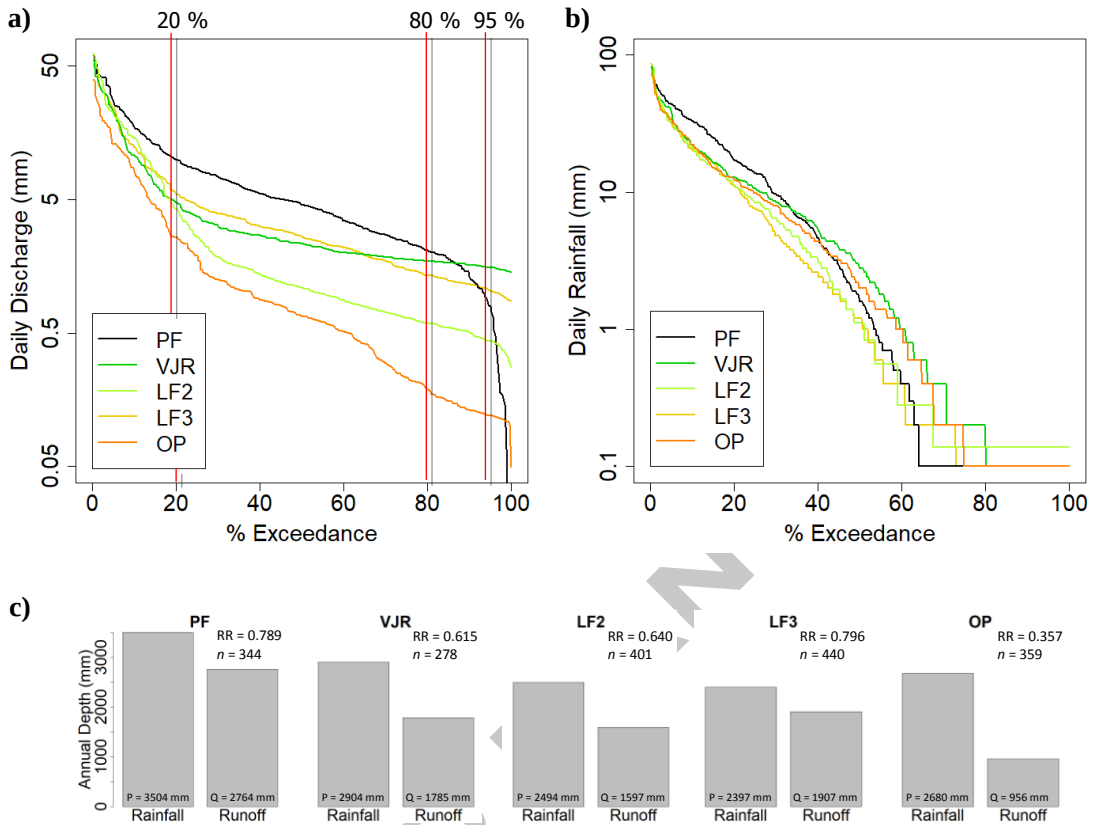
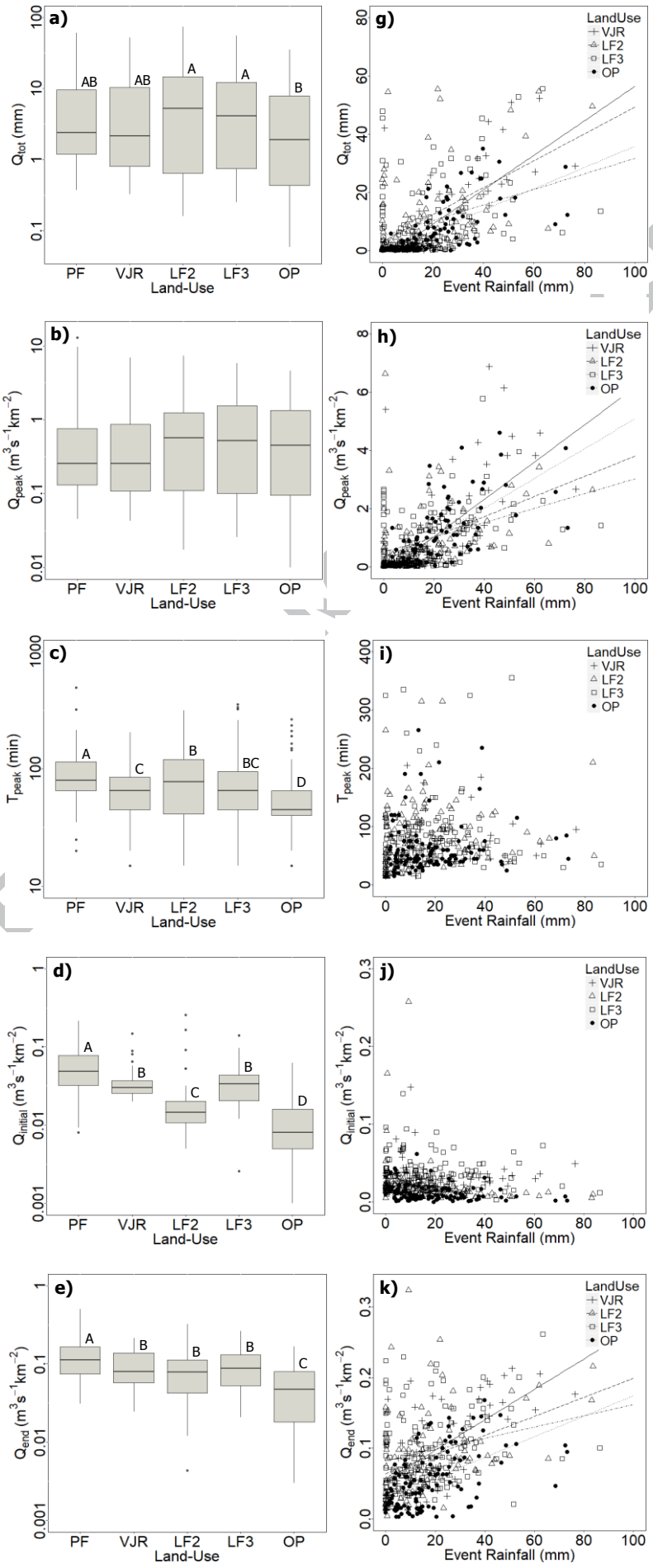


Figure 4: a) flow-duration curve; b) rain-duration curve; c) rainfall-runoff ratio (RR)



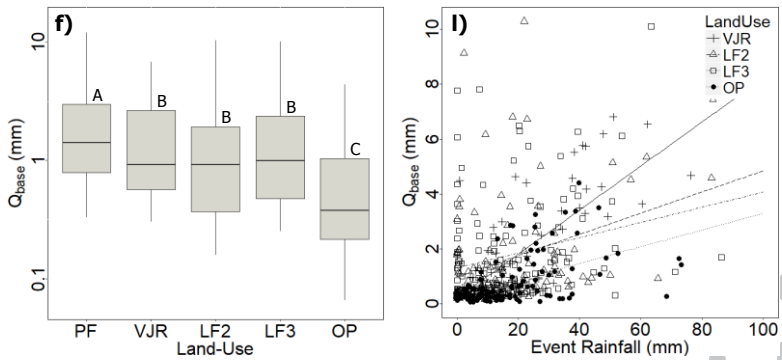


Figure 5: Differences in hydrological variables (a-f, Dunn's test; g-l, multiple-regression) between the catchments.

* Q_{quick} is similar to Q_{tot}, hence omitted.

Table 1: Catchment characteristics

Catchment[a]	Area (km^2)	Mean Channel Gradient (deg)	Mean Slope Angle (deg)	Elevation (m.a.s.l)	Mean LAI	Mean AGB (t ha^{-1})	Tree Density (ha^{-1})	
							<10 cm	>10 cm
Primary Forest (PF)	1.70	8.94	9.41	188 - 309	4.74	22.50	1706	453
Virgin Jungle Reserve (VJR)	3.08	38.64	50.48	97 - 859	4.15	9.34	233	48
Twice-logged Forest (LF2)	4.64	12.10	26.11	429 - 864	3.82	5.39	173	456
Multiple-logged Forest (LF3)	2.78	32.81	39.64	277 - 904	4.02	5.90	400	440
Oil Palm Plantation (OP)	3.27	17.39	26.48	199 - 517	2.40	2.07	455	601

[a] The PF catchment is known as the West Catchment in the Danum Valley Conservation Area. The VJR, LF2, LF3 and OP (Selangan Batu Estate) catchments are all located within the Benta Wawasan Plantation/SAFE Project area.

Elevation information was obtained from GIS layers from the SAFE Project repository (SAFE Project, n.d.) via the ArcMap GIS software version 10.4. Information of Leaf Area Index (LAI) and Above Ground Biomass (AGB) are derived from Ewers *et al.* (2011); tree density information is from Singh *et al.* (2015) and Newbery *et al.* (1999).

Table 2: Annual rainfall in the general area of the catchments in the years 2011-12 to 2015-16

Year (July–June)	SAFE Annual Rainfall (mm)	Danum Annual Rainfall (mm)	Daily Rainfall in SAFE >50 mm (max mm d^{-1})	Daily Rainfall in Danum >50 mm (max mm d^{-1})
2011–12	2731.5	3203.8	4 (75.4)	13 (108.2)
2012–13	2569.4	3234.9	7 (76.8)	6 (81.8)
2013–14	2485.7	2998.0	9 (90.0)	13 (95.3)
2014–15	2309.3	2621.3	5 (74.2)	4 (102.1)
2015–16	1896.7	2017.4	1 (64.5)	3 (68.0)

Danum raingauge – adjacent to PF catchment; SAFE raingauge – recorded at basecamp for VJR, LF2, LF3 and OP.

Table 3: Meteorological- and runoff-related indices (Ochoa-Tocachi et al., 2016b) used for inter-catchment flow regime comparisons

Abbreviation	Formula	Units	Definition
PVAR	σ_P/P_{mean}	mm mm^{-1}	Coefficient of variation in daily P. Standard deviation divided by mean.
DAYP0	$D_{P<RGres}/D_{total}$	-	% of days with 0 mm rain
QVAR	σ_Q/Q_{mean}	mm mm^{-1}	Coefficient of variation in daily Q. Standard deviation divided by mean.
RR	Q_{year}/P_{year}	-	Ratio of mean runoff depth over mean rainfall depth.

Table 4: Hydrological variables investigated at the event-scale

Abbreviation	Definition
$Q_{initial}$	Initial discharge. The point on the hydrograph where the HH slope initiates.
Q_{end}	End-of-storm discharge. The end point where the HH slope intersects the hydrograph.
Q_{peak}	Peak discharge. The highest point on the hydrograph.
T_{peak}	Time-to-peak. The timespan from $Q_{initial}$ to Q_{peak}.
Q_{quick}	Quick flow/storm runoff. The area between the hydrograph and the HH slope.
Q_{base}	Baseflow/subsurface flow indicator. The area below the HH slope.
Q_{tot}	Total discharge/water yield (Q_{quick} + Q_{base}) in a storm event. The area under the hydrograph.

Table 5: Computed meteorological- and runoff-related coefficients of the different catchments

Index	PF	VJR	LF2*	LF3	OP
DAYP0	0.337	0.201	0.327	0.273	0.253
PVAR	1.575	1.570	1.810	1.809	1.604
QVAR	1.231	1.527	2.025	1.486	2.062
RR	0.789	0.615	0.640	0.796	0.357

* Raingauge partially affected by canopy. Correction performed by means of LF2-LF3 (adjacent catchment) rainfall ratio.

Table 6: F-statistics for land-use (LU) and land-use-rainfall interaction (LU · P) for the different hydrological variables (multiple-regression only)

Variable	Slope (LU · P)		Intercept (LU)	
	F-value	p-value	F-value	p-value
Q_{peak}	**8.712**	< 0.05	0.213	0.89
Q_{end}	**3.716**	< 0.05	**19.459**	< 0.05
Q_{tot}	**4.897**	< 0.05	**6.112**	< 0.05
Q_{base}	**6.054**	< 0.05	**10.671**	< 0.05
Q_{quick}	**4.784**	< 0.05	**5.742**	< 0.05

* **Bold** indicates statistical significance ($\alpha = 0.05$). ANCOVA omitted for $Q_{initial}$ and T_{peak} (no relationship with covariate, P).

Table 7: Coefficients of intercept (a) and slope (b), F-value, p-value and adjusted r-squared (R_a^2)

Y	VJR		LF2		LF3		OP		F-value	p-value	R_a^2
	a0	b0	a0 + a1	b0 + b1	a0 + a2	b0 + b2	a0 + a3	b0 + b3			
Q_{peak}	-0.245	0.064	0.342	0.035	0.516	0.025	-0.025	0.051	80.93	< 0.05	0.596
Q_{end}	0.054	0.002	0.064	0.001	0.082	0.001	0.029	0.001	192.60	< 0.05	0.779
Q_{tot}	-2.710	0.591	3.215	0.461	5.057	0.266	-0.696	0.365	66.23	< 0.05	0.546
Q_{base}	0.206	0.080	0.981	0.039	1.301	0.028	0.254	0.030	68.29	< 0.05	0.554
Q_{quick}	-2.905	0.511	2.242	0.422	3.767	0.238	-0.945	0.335	64.45	< 0.05	0.539

VJR $Y = a_0 + b_0P$ $(a_0 = b_0 = 1, a_1 = a_2 = a_3 = b_1 = b_2 = b_3 = 0)$

LF2 $Y = (a_0 + a_1) + (b_0 + b_1) P$ $(a_0 + a_1 = b_0 + b_1 = 1, a_2 = a_3 = b_2 = b_3 = 0)$

LF3 $Y = (a_0 + a_2) + (b_0 + b_2) P$ $(a_0 + a_2 = b_0 + b_2 = 1, a_1 = a_3 = b_1 = b_3 = 0)$

OP $Y = (a_0 + a_3) + (b_0 + b_3) P$ $(a_0 + a_3 = b_0 + b_3 = 1, a_1 = a_2 = b_1 = b_2 = 0)$

Table 8: Percentage quickflow and baseflow contributions to total discharge at the five study

catchments over the whole study period

Flow contribution	PF	VJR	LF2	LF3	OP
Quickflow (%)	32.08	57.82	49.16	44.98	61.57
Baseflow (%)	67.92	42.18	50.84	55.02	38.43

Table 9: Rank order of land-uses for various key catchment hydrological parameters

Hydro. Component	Indicated by	Catchment rank				
		Lowest	→			Highest
Mean Daily-Scale						
1. Total discharge	RR	OP	VJR	LF2	PF	LF3
2. Daily fluctuation	QVAR, PVAR	PF	LF3	VJR	LF2	OP
3. % baseflow		OP	VJR	LF2	LF3	PF
Storm Event-Scale						
1. Total event discharge	Q_{tot}	OP^{B}	PF^{AB}	VJR^{AB}	$LF3^{A}$	$LF2^{A}$
2. Event responsiveness	T_{peak}	PF^{A}	$LF2^{B}$	$LF3^{BC}$	VJR^{C}	OP^{D}
3. Event baseflow	Q_{end}, Q_{base}	OP^{C}	$LF2^{B}$	VJR^{B}	$LF3^{B}$	PF^{A}
4. Pre-storm baseflow	$Q_{initial}$	OP^{D}	$LF2^{C}$	VJR^{B}	$LF3^{B}$	PF^{A}

Highlights

1. Primary forests have high baseflow, well-regulated streamflow and storm responses.
2. Streamflow in logged forest reduces with natural recovery.
3. Response of baseflow to precipitation increases with forest recovery.
4. Conversion into oil palm increases stormflow, but greatly reduces baseflow.
5. Hydrological impacts reduce with post logging recovery, but persist in oil palm.