Simulating the Overland Flow in Prospectively Cleared Tropical Forest or Expressway Using Airborne LIDAR & High Resolution Optical Images

Abd. Ramlizauyahhudin Mahli, Mohd. Rizaludin Mahmud and Mohd. Nadzri Mohd. Reba

February 15, 2020

Simulating the Overland Flow in Prospectively Cleared Tropical Forest for Expressway Using Airborne LIDAR & High-Resolution Optical Images

Abd. Ramlizauyahhudin Mahli[1], Mohd. Rizaludin Mahmud[2], Mohd. Nadzri Mohd. Reba[3]

[1] Faculty of Built Environment & Surveying,
Universiti Teknologi Malaysia, 81310, Johor Bharu, Malaysia
[2] Geoscience & Digital Earth Centre (InsTeG), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia, 81310, Johor Bharu, Malaysia

Email: ramli.mahli@gmail.com; rizaludin@utm.my; nadzri@utm.my

Abstract. This study simulates the overland flow using the forest structural parameters and high-resolution terrain information attained from the airborne LIDAR, the high resolution (HiRes) optical imagery and rainfall data in the potentially cleared tropical forest due to road development. Significant overland flow would affect the driving convenience in the prospective road. Measuring the overland flow using field measurement was constrained by small site coverage, enduring harsh tropical forest environment, complex computation with various input variables and time-ineffective. A substitute or support methodology is required in order to measure the throughfall for large areas in economic time frame. Prior to that, an experiment was conducted in Limbang, one of the prospective Pan-Borneo routes located in the state of Sarawak in Borneo Island. The overland flow is simulated for two conditions, (i) present situation (natural condition), and (ii) prospective future situation (cleared forest condition and terrain changes). Canopy throughfall is derived from the three-dimensional tree canopy structure using the LIDAR information and HiRes optical images. The simulation of the future overland flow after the road development is carried out by quantifying the amount of run-off with the areas involve with the actual road alignment is removed. Subsequently, the overland flow value before and after the prospective road development is compared. The output of this study would be useful to understand the aftermath effect of tropical forest removal to driving convenience; one of the critical aspects that influenced the sustainable transportation and environmental safety in the humid tropics.

Keywords: Rainfall, Airborne remote sensing, Forest hydrology

Introduction

Drastic forest clearing for road development in humid tropical landscape would result significant hydrological changes that affect the road and driving safety. Tropical forest is known for having high canopy interception. Its removal has significant implication on the increase of throughfall that will create an inconvenience driving environment including limited visibility. Adaptation to these changes require accurate and fine scale information regarding the types of the impacts and its severity, prone locations, and period of occurrence. Using field-based measurement require an expensive, time consuming, and laborious works; therefore, opting for an aerial survey with precise laser scanners would be a useful substitute. Such investigation in the humid tropical landscape are scarcely found especially at the high precision engineering scale, reaching 1 meter. Anticipating this gap by formulating an appropriate operational methodology with minimum field variables would enable effective assessment of the hydrological impacts to road driving at precise working scale.

LIDAR was proven to be useful tool in forestry especially in height characterization of the tree structure and also the forest landscapes (Goodwin et al. 2006; Lovell et al. 2003; Kelly & Tommaso, 2015). Together with the integration of digital optical camera, the horizontal canopy crown information is effectively captured. Scientific studies showed that various efforts had been done in studying the crown morphology using these two variables (e.g., Shamsoddini et al. 2013, Jing et al. 2014). In estimating rainfall interception, indirect method was theoretically possible using both the vertical and horizontal canopy morphology information together with auxiliary information. Tree height information would enable estimation of canopy vertical thickness. Meanwhile, the crown canopy optical photo can provide rough estimation on the canopy closure which associated to the throughfall (amount of rainwater penetrated the canopy and reach the ground). However, reliable computation is rarely found.

As for overland flow estimation, the role of the LiDaR is primarily in providing high resolution 3D information of the terrain. Upon the development, the properties of slope and topographic changes that occur would affect the movement of the water. Many present hydrological simulations had embedded digital terrain model in their modeling for accurate representation of hydraulic properties (Barber & Shortridge, 2013). If high resolution digital elevation model is used, then it is possible to modeled the overland flow for the current and post development at high resolution engineering scale simulation. Hence, tropical rainforest of Borneo received substantial amount of annual rainfall (> 2000mm) and intense storm (~25mm/d), therefore slight forest canopy losses might cause significant hydrological effects. While the theory is scientifically sound, evidences are hard to find and require thorough study.

Prior to the aforementioned circumstance, this study has taken initiative to formulate an appropriate LIDAR and spatial methodology to assess the future overflow prior to the road development in humid tropics. The chosen experimental site would be the specific Limbang interchange road network to Brunei, which is approximately 5km of length. The current interception & expected overland flow for the potential future highway will be computed on quadrat basis and its spatial variation will be mapped. There are two major significant contribution of this study, first is the operational methodological development using LIDAR and ancillary data to perform efficient large-scale interception and second to obtain knowledge on the possible amount of throughfall impact upon the highway development. The output of this study is useful for preventive, mitigation and adaptation action to reduce the risk of driving safety in humid tropics.

2.0 Materials & Method

2.1 Method

This method is separated into two sections, (A) the three-dimensional (3D) canopy interception estimation, (B) overland flow simulation. In section A, there are three main steps in computing the volumetric canopy infiltration in this study; (1) compute the horizontal (2D) canopy relative openness using UAV orthophoto images, (2) compute the vertical canopy thickness using LIDAR data, and (3) compute the 3D volumetric canopy infiltration. Instead of computing the canopy infiltration for individual crown which a common approach in forestry sciences and ecology, we chose to compute it at 10 meter grid, as for two reasons; first is delineating individual tree crown in tropical forest is extremely challenging where many studies are not reaching reliable independent results and second is the remote sensing measurement are based on the average reflective signals of electromagnetic wave at specific field of view rather than individual canopy.

In section B, two steps are involved, first is the estimation of post road development rainfall at various intensity, and second is the computation of the present and post development of overland flow. The resolution of the overland flow is 0.5 meters.

2.1.1 Horizontal (2D) canopy openness estimation using UAV orthophoto images (HCO)

Due to limited available technique to indirectly estimate the canopy openness using high resolution of remotely sensed image or aerial photo without using too many support variables which are limited in the study area, the fundamental technique applied in computing canopy closure using hemispheric photo is adapted.

The fundamental approach is by computing the ratio between the numbers of bright pixel (non-leaf area) over the dark pixel (canopy leaf). High number of ratios mean large canopy openness. By using that principle on greyscale digital aerial photograph, one can also estimate the canopy openness. Bright pixel represents areas that covered by the canopy leaf, and dark pixel represent the uncovered canopy areas. For default to 8-bit photo, the threshold brightness value for the dark pixel will be defined as below than 10, meanwhile the rest are considered bright pixel. The equation below expressed the mathematical concept.

$$\text{Horizontal Canopy openness, HCO , per grid (\%)} = \left(1 - \frac{\text{No. of pixelwith BV<10}}{\text{No. of pixel with BV>10}}\right) * 100\% \quad (1)$$

where BV is brightness value.

2.1.2 Vertical canopy infiltration (VCI) estimation using LIDAR data

The estimation of the vertical canopy thickness is done by subtracting the maximum tree height with the average tree height found in each of the 10m grid. The tree height in the meantime were obtained by subtracting the surface model height (2nd pulse LIDAR return) with the terrain model height (1st pulse LIDAR return). In realizing the throughfall phenomena, we assumed that high thickness canopy would have higher interception of rainfall and vice versa, therefore the calculation of vertical canopy infiltration (VCI) is acquired by substracting the percentage of vertical canopy thickness (against average tree height) with 1 (perfect interception). Figure below illustrated the two processes.

$$\text{VCI, per grid (\%)} = \left(1 - \frac{\text{CT}}{\text{Th}}\right) * 100\% \quad (2)$$

where Th is average tree height (m), CT is canopy thickness (m).

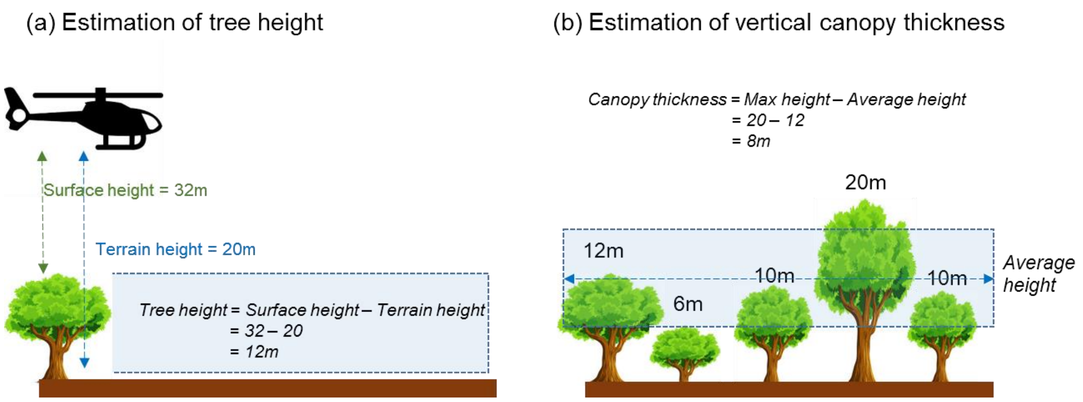

Figure 1. Schematic diagram of the tree height and vertical canopy thickness estimation

2.1.3 *3D volumetric canopy throughfall (VCT)*

The average volumetric canopy throughfall (VCT) is obtained by computing the average of vertical and horizontal canopy thickness. The amount of canopy throughfall (mm/hr) is computed by multiplying it with the actual rainfall intensity (mm/hr) for each quadrat. Based on the literature review and observation dataset in the humid tropics, we adapted the theory that throughfall is proportional with canopy openness either horizontal or vertical. Because throughfall is also depending on the intensity of rainfall, we also take into consideration the effects of canopy saturated condition. Evidences had showed that throughfall is 100% when the rainfall intensity exceeding 40mm/hr (CITA). The corresponding VCT computation is expressed in the equation below.

$$\text{VCT, per grid (mm)}= \left(\frac{\text{VCI} + \text{HCO}}{2}\right) * \text{R} \tag{3}$$

where VCT is the volumetric canopy throughfall (mm/hr), VCI is vertical crown thickness, HCO is canopy openness, and R is rainfall in mm/hr. For R <5mm/hr, the VCT value is set to zero as all the rainfall is intercepted by the canopy, R>35mm/hr, the VCT value is set to 100% as all the rainfall will penetrate the canopy.

2.1.2 *Overland flow simulation*

In simulating the overland flow, we used the rational method. To represent the overland flow after road development, the surface run-off coefficient is change to parking land use from forest (Table 1). Slope value is obtained and computed from the digital surface model of the study area. Equation (4) expressed the computation process while table 1 showed the run-off co-efficient.

$$\text{Overland flow, per grid } (m^3/s)= (C * i * A) \; * \text{cf} \tag{4}$$

where C is the is run-off coefficient, i is the net rainfall (Precipitation-Interception), and A is pixel area (in hectares), cf is the conversion factor to S.I. units, 0.0028.

Land use / Slope	Soil group A			Soil group B			Soil group C			Soil group D		
	<2%	2-6%	>6%	<2%	2-6%	>6%	<2%	2-6%	>6%	<2%	2-6%	>6%
Forest	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Meadow	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Pasture	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Farmland	0.14	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Res. 1 acre (100%)	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.4	0.31	0.35	0.46
Res. 0.5 acre (50%)	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.46
Res. 0.3 acre (30%)	0.28	0.32	0.35	0.3	0.35	0.39	0.33	0.38	0.45	0.36	0.4	0.5
Res. 0.25 acre (25%)	0.30	0.34	0.37	0.33	0.37	0.43	0.36	0.4	0.47	0.38	0.42	0.52
Res. 0.13 acre (13%)	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Industrial	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.9	0.89	0.89	0.9
Streets	0.76	0.77	0.79	0.8	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Parking	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97
Disturbed area	0.65	0.67	0.69	0.66	0.68	0.7	0.68	0.7	0.72	0.69	0.72	0.75

Table 1. Surface run-off coefficient for various land use types and slope effects.

2.2 *Rainfall data*

To provide the information on the daily rainfall, the satellite data from the Global Precipitation Mission satellite be used. The average daily rainfall was obtained from the half-hourly rain rate estimates. The size of this data is re-gridded from 0.1° resolution to 0.01° using inverse distance weight interpolation scheme. However, because our experimental site in this preliminary study is relatively very small, we assumed constant rainfall were occurred for all the respective grids.

2.3 *Terrain and tree height from LIDAR data*

The high precision terrain height and tree height information were obtained through a LIDAR scanning. The measurement was done at 4 discrete returns per pulse - 1st, 2nd, 3rd, and last. The aerial scanning was done by following the proposed highway path with 100-meter buffer. The measurement of up to 4 intensity readings per pulse, with 12-bit dynamic range. To ensure extensive coverage and sufficient instantaneous field of view of the scanning, a minimum sidelap of 20% between swathes and half-scan angle of 20% was chosen. The scanning was done using narrow beam divergence with footprint of under 0.4m. The digital terrain model was produced by processing the last return signals. Meanwhile, the digital surface model was generated using the information from the first return. Other information about flying and scanning details were provided in the table below.

Specification	Description
Flying height	~ 800-1100 meter above the terrain
Point spacing	1.4m along track; 0.8 across-track
Frequency	50-500Hz
Scan density	1-4 points per meter square
Pulse recording	4 discrete returns per pulse
Pulse rate	100 000Hz

Table 2. LiDaR scanning specification

2.4 *Aerial orthophoto*

In order to provide tree canopy information of the study area, aerial orthophoto will be used. This data was obtained simultaneously during the LiDaR scanning process. 16 mega pixels with 12-bit radiometric digital based frame camera is used. This colored orthophoto was mosaicked prior to the rectification geo-tagged imageries with 15-60cm ground sample distance (GSD).

2.5 *Pan Borneo Highway support documents*

There are several informations that are required in this study which includes; (1) the proposed road network, (2) the proposed road design. The proposed road network comprises the path of the highway; primarily consisting its location and length. Because our study area relatively covered a small portion of the whole PBE route, specific proposed road network for Limbang section is obtained from the Lebuhraya Borneo Utara Sdn. Bhd. Meanwhile, the proposed road design containing information about the width, types of lanes, reserve road areas, and targeted elevation of the road. This information is crucial in mapping the risk areas for the throughfall and run-off at pre and post highway development. The proposed road design is shown in figure below.

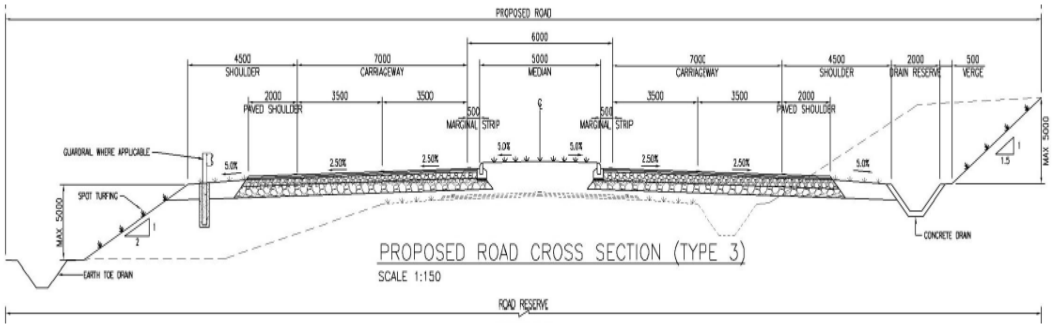

Figure 2. Proposed road design in Limbang section (Source: L&P associates)

2.6 Study Area Description

Limbang was a district located at Sarawak which situated at the border between Sabah and Brunei Darussalam. The total length of the Pan Borneo Highway of Limbang section is 48.15 km which includes construction of 15.91km of new highway. There is a newly proposed route also known as Limbang conceptual alignment (blue route in Figure 1) which deviated from the existing alignment at about 3km south of Limbang town; a specific linkage route to Brunei. Like any other region in Sarawak, Limbang received significant large amount of rainfall; maximum occurred from October to December (>300mm/month). The climate is strongly influenced by the monsoon and the surge cold Borneo flux (Tangang et al. 2009) which resulted extreme anomalies including strong prevailing wind. For this study we chose a small experimental site inside the proposed road alignment in order to test the reliability of our method. The main reason for this selection is to reduce the complexity of abundance pixel during processing and also to assist our understanding since the sample were relatively small.

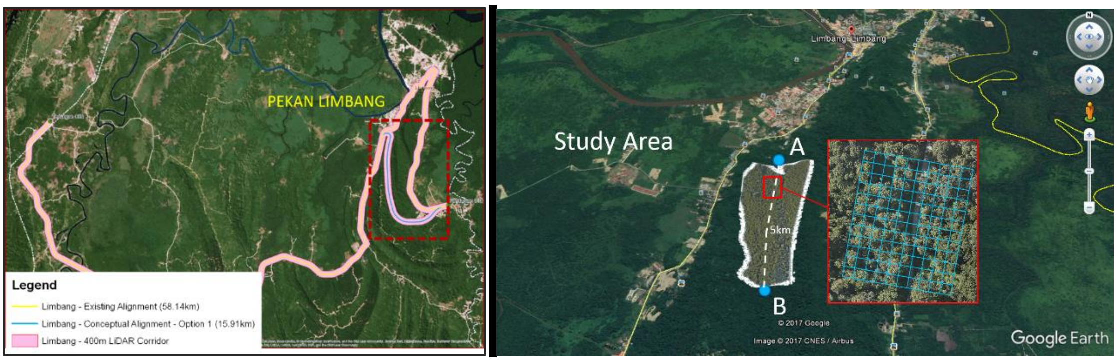

Figure 3. Study area

3.0 Results & Discussion

3.1 Simulated volumetric canopy throughfall changes: Pre and post expressway development

Rainfall intensity	Rainfall intensity (mm/hr)	Volumetric throughfall (*mm/hr*)	
		Pre-expressway development	Post-expressway development
Light	<2	0.013	2
Moderate	5	1.6	5
Heavy	20	6.66	20

Table 3. Average estimated and simulated volumetric canopy throughfall for pre and post expressway development at different rainfall intensity.

Our result showed that the simulated throughfall prior to the expressway development had increased drastically (>100%) with an increasing rainfall from light (<2mm/hr) to moderate (5mm/hr) (Table 3). During the light rainfall, the amount of throughfall is almost none; indicating that the thick and closed canopy coverage of the study area potentially intercept all the rainfall. From the throughfall map (fig. 4), the amount of volumetric canopy throughfall (VCT) had increased as the rainfall intensity increased from light to moderate(2-5mm/hr). Despite the increasing VCT value with increasing rainfall intensity, the spatial pattern of the VCT exhibited during the moderate and heavy rainfall is almost similar.

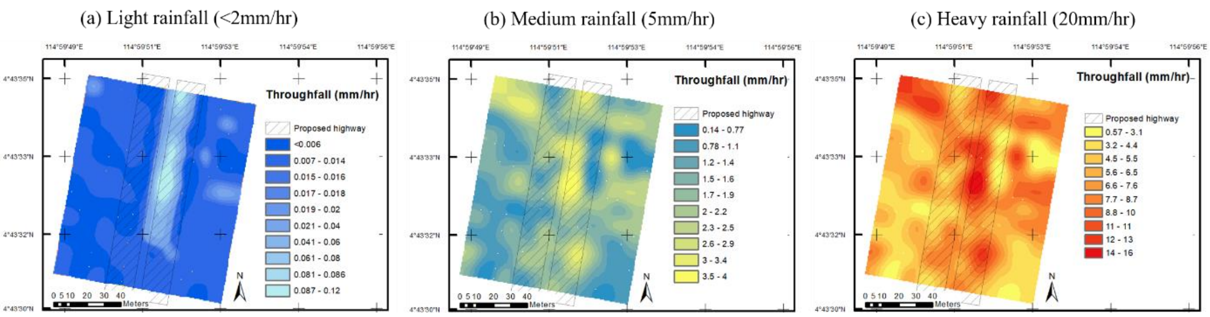

Figure 4. Volumetric canopy throughfall, for light, medium (moderate) and heavy rainfall condition.

3.2 Simulated overland flow changes: Pre and post expressway development

The post expressway development resulted significant increment of overland flow (>100%). The largest increment occurred during the light rainfall (2mm/hr) because most of the rainfall initially is completely intercepted by the canopy. The maps showed that the development of the expressway has completely changed the overland flow pattern and increased its volume; linearly with increasing rainfall. The range of overland flow for light to heavy rainfall has drastically changed from 0.014 - 0.696 cubic mm/s to 0.638 – 6.381 cubic mm/s.

Rainfall intensity	Rainfall intensity (mm/hr)	Average overland flow (mm^3/s)	
		Pre-expressway development	Post-expressway development
Light	2	0.014	0.638
Moderate	5	0.174	1.595
Heavy	20	0.696	6.381

Table 4. Simulated overland flow during pre and post expressway development at different rainfall intensity.

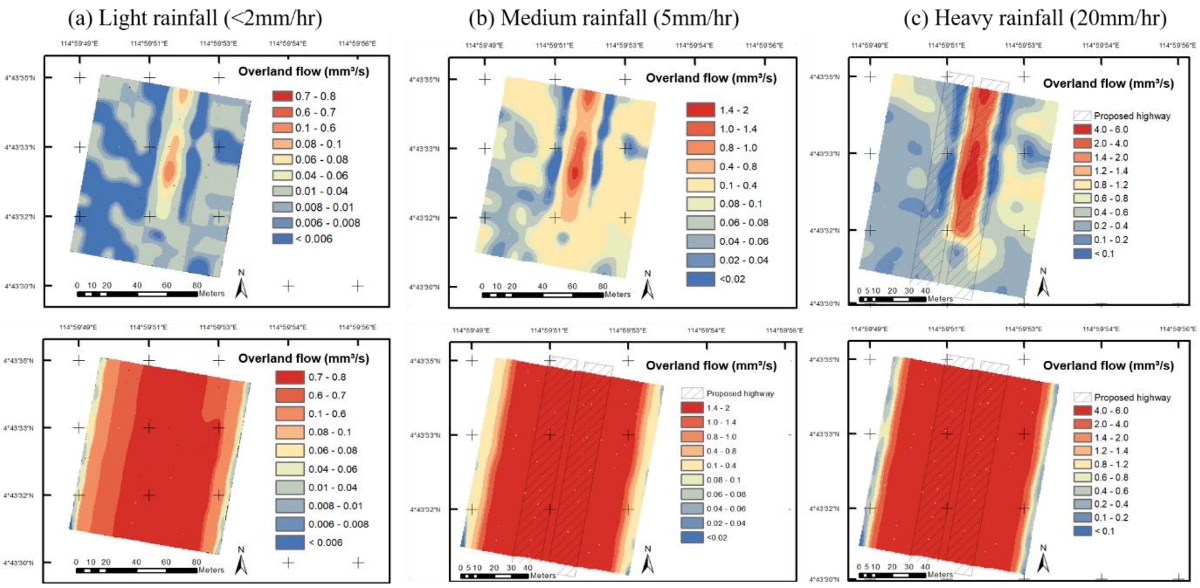

Figure 5. Maps of simulated overland flow during pre and post expressway development at different rainfall intensity.

4.0 Conclusion & Future works

This study has demonstrated the utility of airborne LiDAR and high-resolution optical images to simulate the impact of expressway development towards hydrological variables that affect driving safety and convenience namely throughfall and overland flow. Major findings are the removal of the forest canopy would result drastic increment of throughfall and overland flow (>100%) and also changed the heterogeneous spatial pattern to completely homogenous despite relatively small area of forest removal compared to logging activities. Future works would involve field verification since in-situ validation is absent in this research paper. It would potentially cover the verification of the canopy thickness with in-situ measurement (LAI, hemispheric photo, etc.) and also throughfall via separate on and off canopy gauge measurement.

Acknowledgments
Authors wish to thank Sarawak Forestry Department, collaboration by respective industries, and colleagues who assists the technical stuffs.

References

Barber, C. P., Shortride, A. (2013). Lidar elevation data for surface hydrologic modeling: Resolution & representation issues. Cartography & Geographic Information Science, 32, 4, 401-410.

Goodwin, N.R., Coops, N.C. and Culvenor, D.S. (2006). Assessment of forest structure with airborne LiDAR and the effects of platform altitude. Remote Sensing of Environment, 103, 140- 152.

Jing, L., Hu, B., Li, H., Li, J. Noland, T. (2014). Automated individual tree crown delineation from LIDAR data using morphological techniques. IOP Conf. Ser.: Earth Environ. Sci. 17 012152 .

Kelly, M., Di Tommaso, S. (2015). Mapping forests with Lidar provides flexible, accurate data with many uses. California Agriculture, 69, 1, 14-20.

Konishi, S., Tani, M., Kosugi, Y., Takanashi, S., Sahat, M. S., Nik, A. R., Niiyama, K., Okuda, T. (2006). Characteristics of spatial distribution of throughfall in a lowland tropical rainforest, Peninsular Malaysia. Forest ecology & management, 224, 19-25.

Limin, S. G., Oue, H., Sato, Y., Budiasa I, W., Setiawan, B. I. (2015). Partitioning rainfall into throughfall, stemflow, and interception loss in Clove (Syzgium aromaticum) plantation in upstream Saba River Basin, Bali, Procedia Environmental Sciences, 28, 280-285.

Lovell, J.L., Jupp, D.L.B., Culvenor, D.S. and Coops, N.C. (2003). Using airborne and groundbased ranging LiDAR to measure forest canopy structure in Australian forests. Canadian Journal of Remote Sensing, 29, 607-622.

Shamsoddini, A., R. Turner & J. C. Trinder (2013) Improving lidar-based forest structure mapping with crown-level pit removal, Journal of Spatial Science, 58:1, 29-51, DOI: 10.1080/14498596.2012.759092