DEVELOPMENT OF CANOPY PROPERTIES USING LIDAR AND HIGH RESOLUTION AERIAL PHOTOGRAPH FOR SIMULATING THROUGHFALL IN FORESTED AREA

ABD. RAMLIZAUYAHHUDIN BIN MAHLI

UNIVERSITI TEKNOLOGI MALAYSIA

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ABD. RAMLIZAUYAHHUDIN BIN MAHLI

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DEDICATION

To my parents, family, and friends I dedicate this thesis to them. Without the Almighty's permission, I would never finish this thesis and degree. Special thanks go to the supervisor, co-supervisor and everyone who assist me along the way.

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ABSTRACT

Mapping high-resolution throughfall in the tropical forest by ground measurement is impractical due to several prominent factors including thick and dense canopies which give rise to several constraints such as physical access, induce threat from animals, and requiring a long sampling period for alarger area. As such, using LIDAR and high-resolution images is an alternative that provides the ability to measure canopy properties at a fine scale. Nonetheless, an appropriate and operational approach is still lacking. Many throughfalls or interception studies utilizing remote sensing data were either focusing on a regional scale (>500 m), two-dimensional perspectives (2D images), or limited to the assessment of the vertical canopy thickness or properties only. Therefore, this research was aimed to initiate a simplified and practical method to estimate the throughfall by the function of the canopy properties in the tropical forest of Limbang, Sarawak. This study utilized the volumetric canopy density (VCD) to represent the canopy properties that characterize the interception process. The VCD was derived by two major inputs, (1) the horizontal canopy closure (HCC), and (2) volumetric canopy depth (VCT) from LIDAR and high- resolution images respectively. The VCD was used to modify the canopy storage component in the Gash interception analytical model. The throughfall estimates were obtained from the modified equation and later calibrated using the localized Dykes throughfall model applied in nearby sites. The derived HCC and VCT showed from good to a moderate agreement with the in-situ measurement at a correlation of 0.638 and 0.522 respectively. The correlation between LIDAR derived throughfall and the simulated throughfall based on in-situ biophysical data was about 0.765. The average quantitative error was 0.01 mm/hr. Validation against the in-situ throughfall in the nearby sites of Batu Apoi Forest reserve showed the LIDAR derived throughfall produced a good correlation ($r^2 = 0.9703$) and a low error (1.2 mm/hr). This study has demonstrated the capability of LIDAR and high-resolution images to provide an effective mapping of the high-resolution throughfall.

ABSTRAK

Pemetaan jatuhan langsung beresolusi tinggi di hutan tropika dengan pengukuran tanah adalah kurang praktikal disebabkan beberapa faktor utama termasuk litupan hutan tebal dan padat yang menimbulkan beberapa halangan seperti kemasukan secara fizikal, menerima ancaman dari haiwan dan memerlukan tempoh cerapan yang panjang bagi kawasan yang luas. Oleh itu, penggunaan teknologi LIDAR dan imej beresolusi tinggi adalah alternatif yang memberi kemampuan untuk mengukur sifat kanopi pada skala terperinci. Namun begitu, kaedah yang sesuai dan boleh guna masih kurang. Kebanyakan kajian pemetaan jatuhan langsung atau pintasan menggunakan data penderiaan jauh sama ada tertumpu kepada skala serantau (>500m), penilaian dua dimensi (imej 2D), atau terhad kepada penilaian ketebalan kanopi menegak atau ciri-cirinya sahaja. Oleh itu, kajian ini bertujuan untuk memulakan kaedah yang mudah dan praktikal untuk menganggarkan jatuhan langsung berasaskan fungsi sifat kanopi di hutan tropika diLimbang, Sarawak. Kajian ini menggunakan *Volumetric Canopy Density* (VCD) untuk menunjukkan sifat kanopi yang menerangkan proses pintasan. VCD dikeluarkan dari dua input utama iaitu, (1) *Horizontal Canopy Closure* (HCC) dan (2) *Vertical Canopy Depth* (VCT) masing-masing daripada LIDAR dan imej beresolusi tinggi. VCD digunakanuntuk mengubah suai komponen simpanan kanopi dalam model pintasan analitikal Gash. Nilai anggaran jatuhan langsung yang diperoleh daripada rumus yang diubah suai dan kemudiannya ditentukur menggunakan model jatuhan langsung Dykes tempatan yang digunakan dalam lapangan terdekat. Maklumat HCC dan VCT yang diperoleh menunjukkan hubungan yang baik ke sederhana dengan cerapan di lapangan masing- masing pada nilai korelasi 0.638 dan 0.522 setiap satu. Nilai korelasi antara nilai jatuhan langsung dari LIDAR dan kaedah simulasi berdasarkan cerapan biofizikal di lapangan adalah 0.765. Purata selisih kiraan adalah 0.01 mm/j. Pengesahan dengan cerapan lapangan jatuhan langsung pada lapangan yang berdekatan Hutan Simpan Batu Apoi menunjukkan nilai jatuhan langsung dari LIDAR memberikan korelasi yang baik (r^2 = 0.9703) dan selisih yang rendah (1.2 mm/j). Kajian ini telah menunjukkan keupayaan LIDAR dan imej beresolusi tinggi untuk pemetaan jatuhan langsung pada resolusi tinggi.

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LIST OF ABBREVIATIONS

LIDAR	-	Light intensity detection and Ranging
LAI	-	Leaf Area Index
SAR	-	Synthetic Aperture Radar
TRMM	-	Tropical Rainfall Measuring Mission
MODIS	-	Moderate Resolution Imaging Spectroradiometer
CMORPH	-	Climate Prediction Center morphing method
DID	-	Department of Irrigation & Drainage
DSM	-	Digital Surface Model
DTM	-	Digital Terrain Model
HCC	-	Horizontal Canopy Closure
VCT	-	Vertical Canopy Depth
VCD	-	Volumetric Canopy Density
SAM	-	Spectral Angle Mapper
NDVI	-	Normalized Difference Vegetation Index
VAI	-	Vegetation Area Index
FCC	-	Fractional Canopy Cover
GPS	-	Global Positioning System

LIST OF SYMBOLS

Tr	-	Throughfall
Pg	-	Gross rainfall
Th	-	Tree height
Ps	-	Rainfall needed to saturate the canopy
Ec	-	Evaporation rate
Sc	-	Saturated canopy storage
S	-	Canopy storage capacity
c	-	Canopy closure
k	-	Constant
Ps	-	Precipitation needed to saturate the canopy
Ic	-	Interception
mSc	-	Modified storage capacity
R	-	Runoff
G	-	Groundwater
T	-	Transpiration
I	-	Infiltration

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A - In-situ data and throughfall over Batu Apoi site.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Throughfall is one of the critical hydrological variables in the tropical forest including water resources and forest ecological sustainability (McDowell et al., 2020). Although the throughfall measurement can be obtained via field based measurement and numerical modelling with good accuracy, its practicality is hindered when it comes to large areas estimation. In the context of thick, dense, difficult access and challenging landscapes of tropical forest, the field based measurement is having disadvantages. It includes laborious efforts, time-consuming and even physical threat from wild faunas (i.e., insects, reptiles, predatory mammals)(Marvin et al., 2014). In addition, previously, the large areas throughfall mapping was done by upscaling the plot scale measurement under assumption that the canopy properties is homogeneous with the plot scale; although eventually the heterogeneity can be high (Pancel & Kohl, 2016). Consequently, an alternative methodology is required to provide measures to this resolve this matter.

Major factors that characterized the throughfall in tropical forest despite the intense and amount of rainfall received, is the dense, thick and multi layered tree canopy (Amatya et al., 2016). Therefore, an effective characterization of the canopy parameters that can be conducted via remote, non-physical contact and cover large areas played key role to the large areas throughfall estimation and mapping. The remote sensing approach that provides information about the spectral features through aerial platform is an ideal option. Since 1980's satellite remote sensing has been widely used for environmental monitoring including forestry and its related peripherals. The evolvement of the sensors; from multi-spectral to hyperspectral and low resolution to high resolution had enabled new opportunities for throughfall estimation improvement (Cui et al., 2014; Tanvir Hassan et al., 2017; Li Jia & Zheng, 2018).

The high resolution aerial images or photograph had allowed precise crown morphology identification. The use of medium to high resolution satellite imageries (10-30 m) including IKONOS, Worldview, Quickbird, Kompsat, and Sentinel had lead to numerous development of identification techniques to delineate tree crown (Wagner et al., 2018) and characterization of other related variables such as leaf area index (Darvishzadeh et al., 2018). The trend continues with the advent of low altitude platform such as airborne and drone with high resolution cameras or hyperspectral sensors. Detail crown characterization is plausible with varied techniques determined by simplicity, complexity of the forest structure, sensors, and mathematical algorithm. Despite the advancement, the characterization of canopy properties using high resolution photographs and satellite images is limited to two dimensional perspectives.

LIDAR was proven to be useful tool in forestry especially in height characterization of the tree structure and also the forest landscapes (Alexander et al., 2018; Kelly & Tommaso, 2015). Together with the integration of digital optical camera, the horizontal canopy crown information can be effectively captured. Scientific studies showed that various efforts had been done in studying the crown morphology using these two variables; height and horizontal crown information including (Wan Mohd Jaafar et al., 2018; Panagiotidis et al., 2017). In estimating the throughfall, indirect method was theoretically plausible because the volumetric canopy density strongly influenced the amount of rainfall being intercepted (Chang, 2013). Accurate tree height and its related vertical crown properties can be characterized by LIDAR (Ganz et al., 2019, Zhou et al., 2020). Meanwhile, the crown canopy optical photograph can provide rough estimation of thee canopy closure which is associated with the rainfall interception. Theoretically, the integration of both the canopy closure and vertical canopy thickness could characterize the canopy properties in three dimensional; reflecting the actual field-scale situation and subsequently be utilized for throughfall estimation.

Although the throughfall estimation using remote sensing data has been present, they possessed several limitations. One limitation is that empirical model require localization to be adapted in other sites or the parameterization involved. Secondly, most of the throughfall estimation is conducted based on the horizontal or two dimensional canopy information and neglecting the vertical canopy component including crown depth which may influenced the throughfall. The use of LIDAR would be able to represent the vertical component of the trees. Thirdly, the procedures require significant amount of ground or field survey; a condition which could not be afford for many cases. Therefore, a simplified but reliable method to simulate throughfall that can be operational is required.

Prior to the circumstance, this study has taken initiative to formulate reliable methodology that is operational, less complex and time-efficient characterize the tropical forest canopy properties and simulate the throughfall using the airborne LIDAR and high resolution photographs. The canopy properties that will be studied is the volumetric canopy density; representing the proportion of area that is covered by crown of the trees in horizontal dimension and the respective thickness of the crown trees in vertical dimension. The chosen experimental site would be the tropical rainforest of Limbang, Sarawak, Malaysia. The scope of hydrological time-scale for the experiment is various intensities of hourly rainfall. The output of this study, a fast, simple but reliable procedure for estimating the high resolution volumetric canopy properties and throughfall can be useful to support effective inventory, assessment and monitoring of the thick, remote and tropical forest

1.2 Statement of Problem

Appropriate economical, time-effective and operational methodology to estimate and map one of the key parameters in forest hydrology, the throughfall, at high resolution (<10 m) is yet to be explored. Such methodology is important to characterize the throughfall in high heterogeneity in the thick, dense, and physically challenging access of tropical forest. Many throughfall estimation using remotely sensed data were conducted at global scale (> 0.1°) and impractical to characterize high heterogeneity of canopy properties in the tropical forest. Present approach in airborne remote sensing using hyperspectral sensor were unable to effectively characterize the emergent layers of tropical forest. It only represents the upper canopy of the forest due to the limited signal penetration of the visible to near infrared spectrum. That is the reason for the utilization of LIDAR; a narrow beam light that can give information about the canopy density in three dimensional fashions. An integration with the high resolution cameras could provide comprehensive information on the canopy characteristics; both horizontal and vertical. Another problem is regarding the throughfall modelling using remote sensing data is the adaptation of the stand scale measurement concept to areal grid estimation. Because remote sensing data came in pixels instead of single tree representation, it is suggested that the computation were done in grid representation to compensate both nature of remote sensing data and field-scale plot measurement. This initiative requires substantial amount of evidence and this study wish to investigate to fulfil the gap.

1.3 Research Questions

i. What is the appropriate, simplified and operational method to utilize LIDAR data and high-resolution photographs in characterizing the volumetric canopy density of the tropical forest?

ii. How to estimate the volumetric throughfall using the volumetric canopy properties derived from LIDAR and high-resolution photographs?

iii. How reliable is the throughfall that is estimated using the developed technique?

1.4 Research Objectives

This study has three main objectives:

i. To use LIDAR data and high-resolution photographs in characterizing the volumetric canopy density of the tropical forest.

ii. To estimate the volumetric throughfall using the volumetric canopy properties derived from LIDAR and high-resolution photographs.

iii. To validate the reliability of the developed technique in characterizing volumetric canopy density and throughfall in the tropical forest.

1.5 Scope of research

Three major data from airborne remote sensing were used in this study which includes the digital surface model (DSM), digital terrain model (DTM) and high resolution photographs. The only hydrological variables computed is the throughfall which defined as the net rainfall that reach the ground penetrating the tree canopy in percentage and absolute values; described in millimeter unit per pixel. The measurement scale for both hydrological variables is hourly rainfall. Four types of rainfall intensity categories are adopted includes very light, light, moderate and heavy.

For accuracy assessment, Bboth absolute and relative assessment were conducted to the derived canopy parameters and the estimated throughfall. Absolute validation was conducted on the airborne remote sensing derived canopy parameters including tree height, horizontal canopy closure, and vertical canopy thickness against the actual in-situ measurement. Relative validation on the estimated throughfall value was carried out against the simulated throughfall using the in-situ canopy measurement and actual in-situ input measurement extracted from nearby region of Batu Apoi, Brunei by Dykes (1997).

The in-situ data measurement campaign collects the tree biophysical parameters including tree height, crown height, diameter breast height, and crown width. Trees along the forest trails were selectively samples. The selected experimental site is the lowland dipterocarp forest situated in Bukit Hitam Forest reserve Limbang, Sarawak and its surrounding areas. The site was chosen due to the availability of the airborne remote sensing data; courtesy from the private company that conduct the mission to map the topography characteristics for Pan Borneo Expressway project. Therefore, instead of rectangular shape size of data, the airborne remote sensing data was coming in strip shape representing the proposed expressway route from Limbang town to Brunei intersection.

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