Space based observations: A state of the art solution for spatial monitoring tropical forested watershed productivity at regional scale in developing countries

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This paper presents the simplified and operational approach of mapping the water yield in tropical watershed using space-based multi sensor remote sensing data. Two main critical hydrological rainfall variables namely rainfall and evapotranspiration are being estimated by satellite measurement and reinforce the famous Thornthwaite & Mather water balance model. The satellite rainfall and ET estimates were able to represent the actual value on the ground with accuracy under considerable conditions. The satellite derived water yield had good agreement and relation with actual streamflow. A high bias measurement may result due to; i) influence of satellite rainfall estimates during heavy storm, and ii) large uncertainties and standard deviation of MODIS temperature data product. The output of this study managed to improve the regional scale of hydrology assessment in Peninsular Malaysia.

1. INTRODUCTION

There is growing conflict of interest for developing nation in the tropics in assessing the watershed productivity where yield is high due high rainfall excess amount. Executing an effective watershed monitoring works require a several requirements such as effective distribution of rain gauges, meteorological stations, streamflow stations, and also efficient data communication which are among main constraint concern on those nations [1,2]. In tropics where spatio-temporal of critical variables of rainfall and evaporation variations are very high, intense measurement are strongly required for water yield monitoring. However, it appears that the rain gauge and meteorological stations distribution were sparse especially in remote, thick forest, and inaccessible upper watershed [e.g.,3]. The use of space based observation may provide a useful solution since there are increasing high open sources data sharing options which operates at regular and temporal basis.

Unfortunately selecting an appropriate data, algorithm, and manipulation techniques becoming an increasingly a challenging task due to wide range of options selection. Since remote sensing measurement exhibit uncertainties from various factors [4], a successful approach requires careful data and algorithm fitting to localize environment [e.g., 5]. Comprehensive validation works are strongly necessary since many remote sensing dataset are set for global scale monitoring as well as the related remote sensing biophysical variables retrieval model (e.g., Surface Energy Balance SEBAL, Tropical Rainfall Measuring Mission TRMM).

As a reflection to the mentioned issues, hereby we proposed an efficient, simplified and cost effective approach to operationally mapping the water yield distribution from tropical watershed at regional scale using multi sensor space based remote sensing observations. Two main critical hydrological rainfall variables namely rainfall and evapotranspiration is being estimated by satellite measurement and reinforce to
the famous water balance model by [6]. Three satellite data, i) updated version of monthly data product from Tropical Rainfall Measuring Mission (TRMM) known as TRMM Multi Satellites Precipitation Analysis (TMPA ) 3B43, ii) Moderate Imaging Spectrometer (MODIS) Surface Temperature Product (MOD21) and iii) MODIS Normalized Difference Vegetation Index (NDVI) Data Product (MOD11) are used as main data in this study. The output of this study can be utilized for regional based monitoring and assessment the productivity and condition of the watershed which is useful for water resources and management purposes.

2. STUDY SITE DESCRIPTION

The study area is Peninsular Malaysia which experiences wet and humid tropical climate throughout the year. High monthly rainfall especially during monsoon seasons (~ 300mm) and evapotranspiration (120-160mm) are the main variables drive the yield of the local catchment. The rainfall distribution pattern over Peninsular Malaysia is strongly influenced by the regional wind flows and therefore, it is significant to describe them based on the seasonal monsoon flows [7]. Spatial rainfall patterns experienced by Peninsular Malaysia are determined by the two main period; i) the northeast monsoon (Nov- Feb) – east coast, and ii) southwest monsoon (May - Aug) and inter monsoon (April-May & Oct - Nov) – west, middle and southern. From 1977 to 2001, Peninsular Malaysia produced about 580 cubic kilometres of natural renewable water resources where 97.6% were generated from the surface water and only small amount was from the groundwater recharge (2.4%). The surface water of Peninsular Malaysia is produced by nearly 120 major river basins.

3. MATERIALS AND METHODS

3.1 Forest Water Yield Retrieval Algorithm Using Operational Multi Sensor Data

Two operational satellite data products were used in this study, namely TRMM 3B43 from Tropical Rainfall Measuring Mission (TRMM) and MODIS Land Surface Temperature (MOD11) and Normalized Difference Vegetation Index (NDVI) (MOD11) to estimate rainfall and ET respectively. The TRMM 3B43 provides satellite estimate the rain rate every 3 hour, while MODIS satellite provides twice measurement daily. Both of the data are downloaded via internet through open sources data provider of http://www.mirador.gsfc.nasa.gov and http://webmodis.iis.u-tokyo.ac.jp. The satellite derived rainfall and ET were used as major input in the classical water balance equation by Thornthwaite and Mather [8]. The forest water yield algorithm is developed at monthly basis estimation. The validation assessment of the algorithm was conducted at two phases; (i) validate the satellite derived hydrological variables using in-situ data, (ii) validate the satellite based estimated water yield with in-situ stream flow at selected river basin. The schematic diagram of the algorithm is illustrated in figure 3.1.

![Figure 3.1 Schematic flow of the methodology](image-url)
3.2 Computation of Forest Water Yield

The water yield is measured based on the net value of the rainfall minus evapotranspiration, applying the same principle of the conventional water balance equation. Uniquely in this study, both variables are estimated using the satellite-based data, eliminating dependencies on any ground measurement data. Equation 1 below expressed the satellite-based water yield calculation and complete flowchart of the computation process can be found in [9]:

\[ W_i = R_i - E \pm \Delta S \quad (1) \]

Where \( W \) is the water yield at month \( i \) in mm, \( R \), \( E \) and \( \Delta S \) is the total amount of rainfall, ET and soil moisture changes at month \( i \) respectively.

3.2.1 Retrieval of Monthly Rainfall Estimates from TRMM 3B43

The rainfall which is one of the primary variables in the model is retrieved from the rain rate information given in the Version 6 of TMPA 3B43 data product. The monthly average rain rate provided by the data product is then rescaled to the total amount of monthly rainfall as shown in equation 2. The pixel size of the TMPA data is downscaled into 1km x 1km grid size to produce a continuous rainfall surface over the study area.

\[ R_i = M_i \times N_i \times 24 \quad (2) \]

where \( M \) is the monthly average rain rate of month \( i \) in mm/hour, \( N \) is the number of days of month \( i \) and 24 is the total number of hours per day.

3.2.2 Estimating Monthly Basis Evapotranspiration from MODIS Satellite Data

The other crucial parameter, evapotranspiration is estimated using the simplified surface energy balance based ET algorithm known as Satellite-based Daily Evapotranspiration which also known as SatDAET was developed by Jiang et al [10]. The advantages of this algorithm lies on their simplicity of operation where make it suitable for practical and operational purposes, and also it is developed on tropical condition environment where is quite identical with the climatic condition of our study area. Since the objective of this study is to assess the algorithm based on monthly basis ET, some additional modification is done where all the input variables are changed to monthly average basis instead of daily to acquire monthly average evapotranspiration. Detail explanation of the SatDAET algorithm can be found in [10].

3.2.3 In-Situ Evapotranspiration, Rainfall, and Streamflow

In order to evaluate the accuracy of the proposed algorithm, three types of in-situ measurement data were used. One year period of in-situ ET is used to validate the satellite-based ET. The Thornthwaite method is used to compute the ET from the measured temperature from ten meteorological stations. Complete ET computation procedures can be found in the earlier work of this study in [11]. Meanwhile, 10 years rainfall records from 27 rain gauges are used to verify the accuracy of the satellite derived rainfall. The in-situ stream flow data from three watersheds are used to determine the reliability of the satellite derived water yield. The watersheds represent three major hydrological forested watershed zone in Peninsular Malaysia; (i) Sg. Lebir – Kelantan watershed (Northeast region), (ii) Sg. Kuantan – Pahang (East), and (iii) Sg. Plus at Lintang – Perak watershed (West). All the in-situ data in this study were acquired from Malaysian Meteorological Department and Department of Drainage and Irrigation, Malaysia.

4. RESULTS

4.1 Satellite-based Rainfall Estimates Validation

The differences and average ratio between the TRMM satellite rainfall estimates and rain gauge measurement from 1998 to 2007 is presented in Table 4.1. There is a good agreement between both measurements at all peninsular regions. However, interpolated correlation (Figure 4.1a) showed that it were varies within local rainfall zones. High bias measurements were likely to be concerned due to Northeast monsoon seasons where high intensity rainfall occurred (Figure 4.2). Gradual pattern of average error (Figure 4.1b) were identified from Northwest (low) to South (high).
Such local trend behavior patterns were also identified in nearby regions of Thailand [3] and may indicate that the TRMM rainfall estimates performance in the Southeast Asia region could be influenced by local seasonal rainfall patterns and intensities. Based on this evidence, therefore, proper validation and post-calibration at local scales is strongly needed to minimize measurement uncertainties.

Figure 4.1. Interpolated correlation and error between TRMM rainfall estimates and rain gauge data.

Figure 4.2. Time-series between TRMM rainfall estimates and rain gauge data from 1998 to 2007.

Table 4.1. Ratio between the mean rain gauge rainfall and TRMM rainfall estimates

| Region  | No. of Gauges | Rain Gauge Mean (mm) | Satellite Rainfall Estimates Mean (mm) | S/G Ratio |
|---------|---------------|----------------------|--------------------------------------|-----------|
| Northwest | 6            | 202.15               | 172.83                                | 0.90      |
| East    | 10           | 225.24               | 219.59                                | 0.68      |
| Southwest | 3           | 167.59               | 131.23                                | 0.79      |
| West    | 9            | 210.21               | 187.34                                | 0.92      |
| Peninsular | 28          | 201.30               | 155.25                                | 0.82      |

Table 4.2. Monthly and daily error of the satellite ET estimates

| Station     | Ground ET (mm) | MODIS SatDAET (mm) | Monthly Error (mm) | Daily Error (mm) |
|-------------|----------------|--------------------|--------------------|------------------|
| P2 (Chuping) | 147.3          | 205.4              | 58.1               | 2.0              |
| P3 (A. Setar) | 149.5         | 126.3              | 23.2               | 0.8              |
| P4 (B’worth)  | 169.9          | 106.3              | 63.6               | 2.2              |
| P5 (K. Bharu) | 135.6          | 119.0              | 16.6               | 0.6              |
| P6 (K. Tganu) | 237.7          | 166.8              | 70.9               | 2.5              |
| P7 (Ipoh)    | 155.6          | 133.0              | 22.6               | 0.8              |
| P9 (Kuantan)  | 123.9          | 87.2               | 36.7               | 1.3              |
| P10 (Subang)  | 133.6          | 139.5              | 5.9                | 0.2              |
| P11 (Melaka)  | 132.8          | 79.5               | 53.1               | 1.9              |
| P12 (Senai)  | 129.5          | 60.9               | 68.6               | 2.4              |

Table 4.3. Comparison between the satellite estimated ET

| Author                  | Study Area     | RMSE (mm/day) |
|------------------------|----------------|---------------|
| Rizaludin Mahmud       | Tropical Forest| 0.92          |
| Wu et al. 2008         | Tropical Forest| 1.35          |
| Sobrino et al. 2007    | Woodland       | 1.40          |
| Teixeira et al. 2009   | Semi-arid      | 0.38          |
| Ayenew et al. 2008     | Semi-arid      | 5.2           |

Figure 4.3. Comparison between MODIS satellite data temperature product and meteorological station standard deviation values.
4.2 Satellite-based ET Estimates Validation

The monthly and daily basis differences and error between the ground data computed ET and satellite estimated ET is included in Table 4.2. Those value of differences is caused by the large standard deviation values of MODIS satellite derived temperature product compared to the ground temperature data (Figure 4.3). This condition can be associated with large measurement uncertainties from the satellite derived temperature product. However, relative comparison between the errors obtained from satellites derived ET using SatDAET algorithm and other similar studies indicates that the ET estimated in this study is comparable and can be tolerably accepted (Table 4.3).

4.3 Forest Water Yield Estimation

The satellite derived water yield showed good agreement and correlation with the actual streamflow at all three watersheds especially during heavy storm period (Figure 4.4). However, varies performance of NSEI and bias showed from the discrete based validation (Figure 4.5). This indicates that combined uncertainties from both satellite rainfall and ET estimates at ~15km compared are large since measurement represent by the rain gauge and meteorological stations are limited to the surrounding areas (~4-5km). The significant contribution of this study is it able to improve the regional scale assessment of water resources on Peninsular Malaysia and enhance the spatial variation of the catchment (Figure 4.6).

Figure 4.4. Comparison between the satellite derived water yield and actual stream flow.

Figure 4.5. Nash-Sutcliffe Efficiency Index and bias of the satellite derived water yield against the ground data computer water yield at discrete gauge based locations.

Figure 4.6. Regional scale of water resources mapping of Peninsular Malaysia (1976 – 2003).
5. DISCUSSION

There are two major discussions indicated from the output of this study:

i) The information from the satellite derived water yield using space based remote sensing observations could be used as mitigation and support tools for dealing with water security and related environmental issues which becoming a raising issues in Asian countries. The amount of deforestation, forest land use changes, urbanization has caused various water induced disasters in recent decades.

ii) Further utilization of the proposed system in this study could provide wide opportunities in enabled the spatio-temporal analysis to increase understanding on the ecological hydrological phenomena which becoming one of the recent major concern among scientists. The spatial basis regional analysis could provide a wider representative picture on improving understanding and fill in gaps where the conventional discrete measurement had limitation. In addition, the amount of land use changes in tropical region where hydrological process is very active such as Southeast Asia is steadily increasing and had resulted devastated consequences such as flood, drought, and landslide.

6. CONCLUSION

A simplified approach of estimating water yield in tropical watershed using space based multi sensor remote sensing data is presented in this paper. The satellite rainfall and ET estimates were able to represents the actual value on the ground on certain accuracy under considerable conditions. The satellite derived water yield had good agreement and relation with actual streamflow. A high bias measurement may resulted due to main circumstances; i) influence of satellite rainfall estimates during heavy storm, and ii) large uncertainties and standard deviation of MODIS temperature data product. The output of this study able to improved the hydrology assessment on regional scale of watershed in Peninsular Malaysia.

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