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Analysis of rainfall intensity impact on the lag time estimation in tropical humid rivers

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ABSTRACT

Rainfall intensity is considered as one of important hydrological variables affecting the lag time in tropical humid rivers. The lag time is the time interval from the time of maximum rainfall intensity to the time of the peak rate of stream flow. The main objective of this paper is to study the influence of the rainfall intensity and other related variables on the lag time between the upstream and downstream stations in tropical humid rivers. The lag time was estimated using 95 high rainfall-stream flow events. The Rainfall and water level data was collected from 4 upstream stations that were selected in accordance with data availability. The results indicated that the lag time is inversely proportional with rainfall intensity in a moderate strength relationship. The moderate relationship can be explained by the high complexity and the interaction of the other variables influencing the lag time. This approach is potential to be used in many future hydrological applications, especially those related to the surface water hydrology and river basin integrated management.

1. Introduction

One of the significant components in modeling river flow at particular station is relying on the travel time between the current station and another known monitoring station. According to the historical researches, travel time is also known as time of concentration or lag time (Lt) from the hydrological perspective (Green and Nelson, 2002; McMillan et al., 2013). In other words, Lt is more relevant to estimating the travel time between two different locations. The hydrological Lt definition is the difference in time between the center of effective rainfall (RF) mass and the center of direct stream flow (SF) mass, or the time interval from the time of maximum RF intensity to the time of peak runoff rate (Viessman and Lewis, 2003; Abon et al., 2011). It was reported in the literature that, there are two principal theoretical methods have been applied to estimate the Lt. The first method is using empirical formulas in which out of several empirical formulas applied to estimate Lt, only 14 formulas with different data requirements for estimating Lt have been presented and evaluated by Li and Chibber (2008). The second method is to employ observed RF and SF data through one or more hydrological (operational) definitions of Lt or the cross correlation between the observed hydrological data at two gauging stations (Reusser et al., 2009).

Lt is influenced by numerous elements of the watershed including the basin parameters, SF path and RF characteristics. The basin parameters that affecting Lt is the area extent, surface topography, vegetation, and land use. Whereas, the SF path characteristics impact on Lt is slope, length, roughness, flow depth and antecedent soil moisture. The RF characteristics influenced Lt based on intensity and duration. In addition to the mentioned parameters, there are other parameters affecting Lt such as wind speed, relative humidity and weather conditions (Singh, 1988; Green and Nelson, 2002; Sabzevari et al., 2010). These parameters are very complex, thus rendering studies difficult and time consuming. Owing to the complexity of describing all physical and hydrological characteristics of the entire flow path and other basic parameters influencing Lt, numerous empirical equations and estimation approaches have been derived based on

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flow path and basin average parameters to simplify the estimation of Lt (Green and Nelson, 2002; Singh, 1976). In reality, perfect estimation of Lt is not achievable, as it requires infinite, steady and continuous RF, which are impossible conditions (Saghafian and Julien, 1995).

Investigating the hydrological parameters most likely to affect Lt is very important in SF modeling and time detection in high SF events. Generally, Lt reflects the speed at which the river basin responds to RF events (Pavlovic and Moglen, 2008). RF intensity and SF are considered the main variables affecting Lt. To study the influence of these parameters on Lt, RF intensity was represented by two variables, peak rainfall intensity (Rf) and previous 48-hour rainfall (Rf48), while SF was represented by peak SF and previous 48-hour stream flow (Sf48). Rf48 and Sf48 denote the degree of saturation in a river basin (Simas and Hawkins, 1996). To study the influence of these variables on Lt, Lt was estimated based on RF and SF data events using the hydrological definition of Lt: the interval from the time of maximum RF intensity at upstream stations to the time of the SF rate peak at downstream stations.

Although the availability of empirical equations to estimate Lt is extensive (Li and Chibber, 2008; Grimaldi et al., 2012), the influence of the hydrological parameters likely to affect Lt, such as RF and SF, has not been studied intensively. Yu et al. (2000) examined the relationship between runoff rate and Lt and the effects of surface treatment at plot scale. They used 1 min interval RF and runoff data to accurately determine the time difference between peak RF intensity and peak runoff rate. They proved that a power function can be used to characterize the relationship between lag time and peak runoff rate. Seyam and Othman (2014) investigated the influence of accurate Lt estimation on the performance of SF data-driven based models. They developed a new graphical hydrological approach to estimate the Lt between water level upstream stations and downstream station and employed the results of the graphical approach in their investigation. Bezak et al. (2015) investigated the flood events in Slovenian streams. They employed three parameters including peak discharge (Q), flood event volume (V), and flood event duration (D), for improving the understanding of complex hydrological processes. More than 2,500 flood events were defined based on the annual maximum (AM) peak discharge. The results indicate that some climatic factors like mean annual precipitation and catchment related attributes as for example catchment area have notable influence on the flood event elements. Dvořáková et al. (2014) studied the impact of evapotranspiration on discharge in small basins. They employed the Linear Storage Model to simulate the influence of the evapotranspiration on discharges. They found that the time delays between minimum and maximum discharge during the day reach up to about 20 hours.

The main objective of the research is to investigate the impact of rainfall intensity in addition to other hydrological related parameters on the lag time (travel time) between up-stream and down-stream stations. The inspected case study in this research was located in humid tropical environment particularly Selangor River basin, Malaysia.

2. Study area

The Selangor River Basin is one of the main rivers in Malaysia. The basin is located in the north part of state of Selangor, covering an area of approximately 1960 km^2. The Selangor River streams roughly 110 km from the northeast to the southwest (Hassan et al., 2004; Samsudin et al., 2011). About half of the water consumption in Selangor and Kuala Lumpur comes from the Selangor River (Subramaniam, 2004). Fig. 1 presents a location map of the Selangor River Basin in peninsular Malaysia. The average flow of the Selangor River is 57 m^3/s (Nelson, 2002).

The climate of the Selangor River Basin is humid and tropical with unique features like uniform temperatures with minimal variation through the year. On average, daytime temperatures can reach up to 32° C and drop to 23° C at night. The average annual RF varies between 2000 and 3000 mm annually throughout the basin (Shafie, 2009; Breemen, 2008).

2.1. Data collection

Hydrological data was obtained from hydrological stations in the Selangor River Basin. Downstream flow records were extracted from the Rantau Panjang gauging station, which is situated downstream of the Selangor River. WL and RF data was collected from 4 upstream stations that were selected in accordance with data availability. Fig. 2 presents a location of the hydrological stations of Selangor River Basin. The study was carried out using observed RF and SF data events from 3 years (2009, 2010 and 2011).

2.2. Investigating the relationship between lag time and hydrological variables

Lt was estimated using the hydrological definition of Lt (the time interval from the time of maximum RF at the upstream stations to the time of the peak rate of runoff at the downstream station). Around 95 high SF events were applied to estimate the Lt between the downstream SF station and 4 RF upstream stations. Lt was estimated according to observed RF and SF event records. Subsequent to estimating Lt, the 4 hydrological variables were calculated to build combination values of Rf, Rf_{48}, SF, Sf_{48} and Lt for every event. The high complexity of surface water systems and interaction among the variables influencing Lt justify the necessity to analysis of the impact of rainfall intensity and other related variables on the lag time estimation. The variables of these are Rf, Rf_{48}, Sf and Sf_{48}. The variables were determined based on the outcome from 95 RF and stream flow events to estimate Lt and assess the correlation coefficient between the 4 variables and Lt.

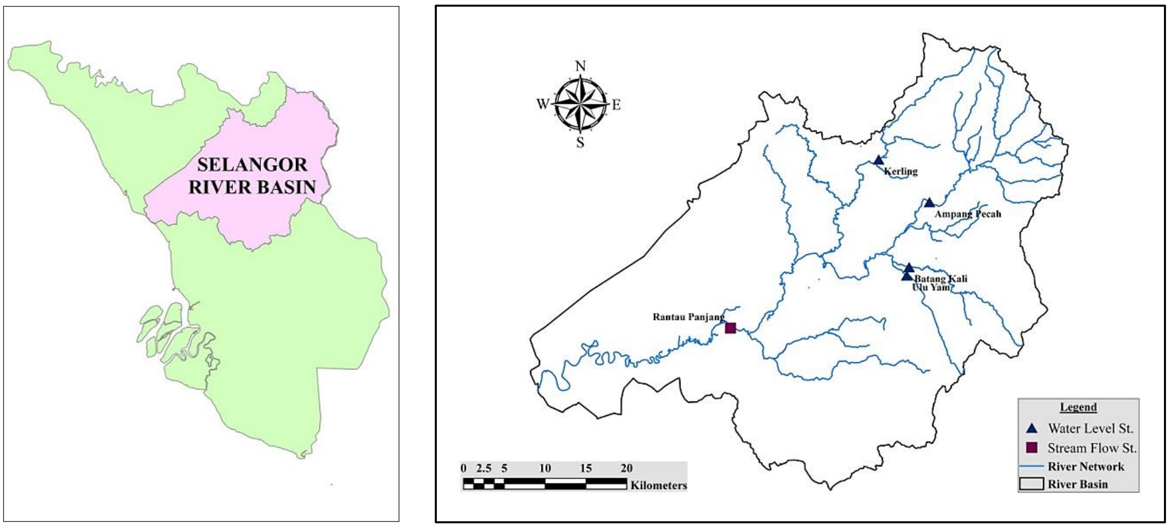

Fig. 1: The location map and hydrological stations of the Selangor River Basin

The correlation coefficient (r) and co-efficient of determination (R^2), are statistical technique used to indicate the strength and direction of a linear relationship between two variables (Perugu et al., 2013; Evans, 1966). In order to verify the level of agreement between Lt and hydrological parameters, r was utilized. There are various methods of calculating the correlation coefficient, with the most common being the Pearson correlation coefficient (r).

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x}).(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2.\sum_{i=1}^{n}(y_i-\bar{y})^2.}} \qquad (1)$$

where n is the number of data pairs; x and y are the variables.

3. Results and discussion

3.1. Lag time estimation

The group of results for Rf, Rf_{48}, SF, Sf_{48} and Lt between the Ampang Pecah station and Rantau Panjang station are displayed in Table 1.

Table 1: Peak rainfall intensity, previous 48-hour rainfall, peak stream flow, previous 48-hour stream flow and lag time between the Ampang Pecah and Rantau Panjang stations

SF	SF_{48}	RF	RF_{48}	Lt
m^3/s	m^3/s	mm/hr	mm/hr	hr
166.99	91.28	30.10	1.51	16.00
113.61	55.85	13.10	0.44	17.00
171.59	93.31	42.40	1.83	12.00
136.78	73.35	11.40	0.64	15.00
141.75	110.84	14.30	1.15	16.00
198.07	123.77	3.30	0.72	16.00

The statistical analysis of Lt between the downstream SF station and RF upstream stations is provided in Table 1.

The mean values of Lt between the downstream station and RF stations are as follows: Ulu Yam, Batang Kali, Kerling and Ampang Pecah = 14.44, 14.70, 15.05 and 14.74hr, respectively. Table 2 indicates that the maximum Lt estimated values are 20, 20, 21 and 21hr for the Ulu Yam, Batang Kali, Kerling and Ampang Pecah stations, while the minimum values are 10, 10, 9 and 9hr for the same stations, respectively.

The standard deviation (SD) of the estimated Lt for all stations is very close, as the highest SD value for Ampang Pecah is 2.83 and the lowest for Kerling is 2.5. The coefficient of variation (CV) for Lt is also very similar for all stations, with the highest CV value at Ampang Pecah and Ulu Yam stations (0.19) and at Kerling (0.17).

Table 2: Basic statistical analysis of the estimated Lt between the downstream station and rainfall upstream stations

Station	Ulu Yam	Batang Kali	Kerling	Ampang Pecah
Mean	14.44	14.70	15.05	14.74
SD	2.76	2.58	2.50	2.83
CV	0.19	0.18	0.17	0.19
Maximum	20.00	20.00	21.00	21.00
Minimum	10.00	10.00	9.00	9.00
Mean+ SD	17.21	17.28	17.55	17.57
Mean - SD	11.68	12.12	12.55	11.91

3.2. The correlation between lag time and hydrological parameters

The association between Lt and the 4 hydrological variables, Rf, Rf_{48}, Sf and Sf_{48}, was analyzed with regard to the estimated Lt. The axiomatic theory indicates that Lt is inversely proportional to flow velocity that is directly proportional to rainfall intensity and stream flow; consequently, Lt should be inversely proportional to rainfall intensity and stream flow. The relationships between Lt and the 4 hydrological parameters are described subsequently.

3.2.1. The correlation between lag time and peak rainfall intensity

The R between Rf and Lt is -0.41 and the R^2 between Rf and Lt is 0.17. Fig. 2 presents the correlation between Rf and estimated Lt based on the observed rainfall and stream flow events. The correlation coefficient and coefficient of determination values indicate that Lt is inversely proportional to Rf in a medium-strength relationship. The medium relation between Lt and Rf along with the remarkable data scatter seen in Fig. 2 can be accounted for the high complexity of the other parameters influencing Lt, which evidently have an influence as well. The effect of these other parameters on Lt, leads to a decreasing correlation between Rf and Lt.

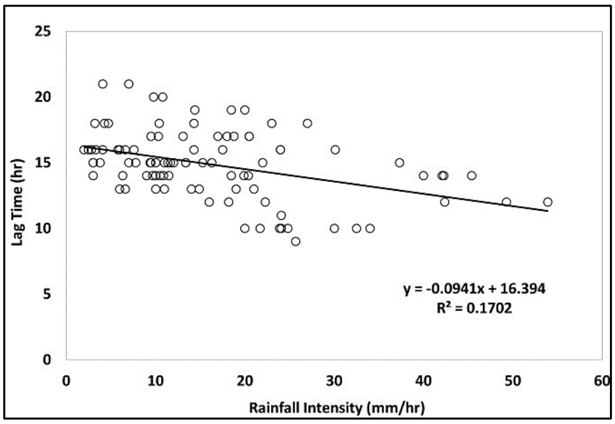

Fig. 2: Peak rainfall intensity versus estimated lag time

3.2.2. The correlation between lag time and previous 48-hour rainfall

The R between Rf_{48} and Lt is -0.32 and the R^2 between Rf and Lt is 0.10. Fig. 5 presents the correlation between Rf_{48} and estimated Lt based on the observed rainfall and stream flow events. The correlation coefficient and coefficient of determination values denote that Lt is inversely proportional to Rf_{48} in a medium-strength relationship. This relationship and the significant data scatter illustrated in Fig. 3 could be due to the high complexity of the other parameters influencing Lt. Thus the existence of influence from different parameters is proven. The effect of other parameters on Lt, results in a declining correlation between Rf_{48} and Lt.

3.2.3. The correlation between lag time and peak stream flow

The R between Sf and Lt is -0.10 and the R^2 between Sf and Lt is 0.01. Fig. 4 presents the correlation between Sf and estimated Lt based on the observed rainfall and stream flow events. The very small correlation coefficient and coefficient of determination values indicate that Lt has a very weak relationship with Sf, as validated by Fig. 4, which also presents remarkable data scatter. The weak relationship between Sf and Lt can be rationalized by the high complexity of the other parameters influencing Lt and also proves there is influence from additional parameters. These other parameters affecting Lt lead to a decreasing correlation between Sf and Lt.

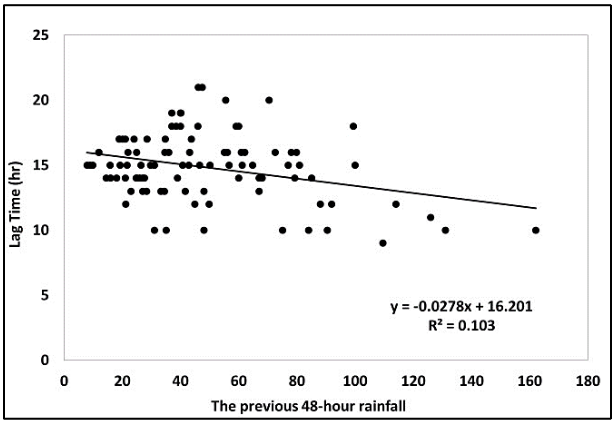

Fig. 3: Previous 48-hour rainfall versus estimated lag time

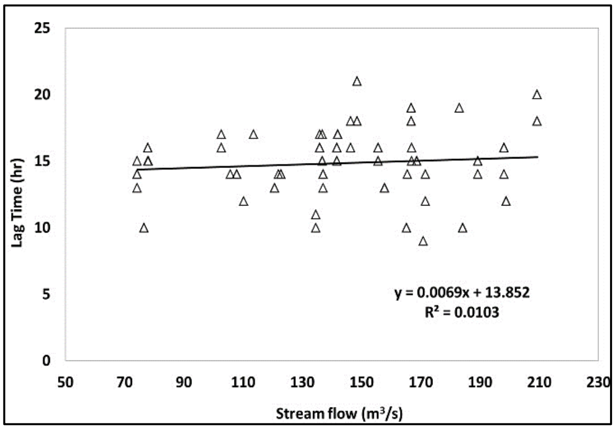

Fig. 4: Peak stream flow versus estimated lag time

3.2.4. The correlation between the lag time and previous 48-hour stream flow

The R between Sf_{48} and Lt is -0.19 and the R^2 between Rf and Lt is 0.037. Fig. 5 presents the correlation between Sf_{48} and estimated Lt based on the observed rainfall and stream flow events. The small values of correlation coefficient and coefficient of determination signify that Lt has a weak relationship with Sf_{48} as shown in Fig. 5, which also displays a significant amount of data scatter. Accordingly, Lt is inversely proportional to Sf_{48} in a weak-strength relationship. The weak relationship between Sf and Lt can be explained by the elevated complexity of the other parameters affecting Lt, proving the existence of effect from additional parameters. The other parameters influencing Lt lead to a weakening correlation between Sf_{48} and Lt.

4. Conclusion

A hydrological approach to estimate the Lt has been performed based on the Lt definition and its results of 95 hydrological events. The results of the correlation analysis between the four hydrological variables and Lt indicate that Lt is inversely proportional to Rf and Rf_{48} via a strong relationship, while it is moderate-inversely proportional to Sf_{48}. Also according to the outcome, the estimated Lt is directly proportional to Sf in a very weak-strength relationship.

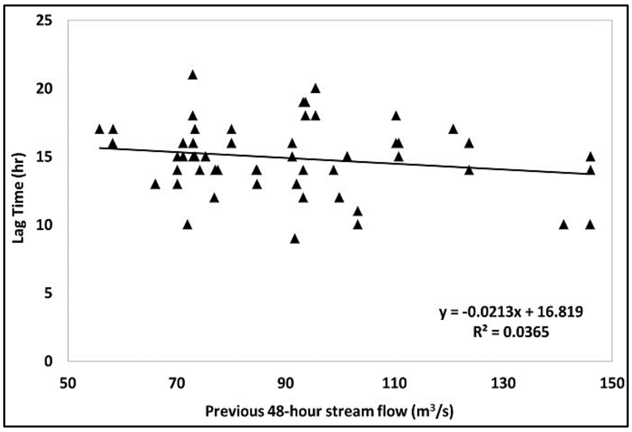

Fig. 5: Previous 48-hour stream flow versus estimated Lag time

The moderate and weak relationships between the hydrological variables and Lt may be justified by the high complexity and interaction between the four hydrological variables and other variables influencing Lt. The effect of the other variables on Lt should be studied more intensively to enhance the efficiency of the results. This approach is potential to be used in many future hydrological applications, especially those related to the surface water hydrology and river basin integrated management.

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