

Time Step Issue in Unit Hydrograph for Improving Runoff Prediction in Small Catchments

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ABSTRACT

Unit hydrograph is a very practical tool in runoff prediction which has been used since decades ago and to date it remains useful. Unit hydrograph method is applied in Way Kuala Garuntang, an ungauged catchment in Lampung Province, Indonesia. To derive an observed unit hydrograph it requires rainfall and water level data with fine time scale which are obtained from automatic gauges. Observed unit hydrograph has an advantage that it is possible to derive it for various time steps including those with time step less than an hour. In order to get a more accurate unit hydrograph, it is necessary to derive a unit hydrograph with small time step for a small catchment such as those used in this study. The study area includes Way Kuala Garuntang and its tributaries, *i.e.* Way Simpur, Way Awi with areas are 60.52 km², 3.691 km², and 9.846 km² respectively. The results of this study highlight the importance of time step selection on unit hydrograph, which are shown to have a significant impact on the resulting unit hydrograph's variables such as peak discharge and time to peak.

Keywords: Unit Hydrograph; Time Step; Peak Discharge; Time to Peak

1. Introduction

The development of hydrology model in runoff prediction is very advance, in which there are several methods that can be used in runoff prediction in ungauged basin. Especially with the existence of PUB (Prediction in Ungauged Basin) [1,2], there are several supporting tools and methods which makes prediction possible in such catchments. The choice of methods and tools are based on available data in that region. The limitation of fine data such as data from radar, leave little choice to carry out prediction in some catchments. As many other catchments in many parts of the world, Way Kuala Garuntang is an ungauged catchment. There was no runoff measurements recorded before. This increasingly grows into significant matter as floods occur more frequently in this region recently [3]. It is believed that one of the best options to do runoff prediction is by taking runoff measurements [4]. Therefore this study deals with instrumenting this ungauged catchment to gain important information and carry out necessary analysis, as well as predicting runoff using observed unit hydrograph (UH) method.

Despite its conservative method, the unit hydrograph approach to rainfall-runoff modelling remains a very useful and practical approach to deal with operational

hydrological forecasting [5]. In this case UH model structure is assumed to be appropriate to represent catchment behavior by assuming two separately acting functions, *i.e.* the production and the transfer functions [5]. When a certain amount of rainfall reaches the ground, some will loss due to infiltration or others, and there remains a reduced part called the effective rainfall which then transformed into direct runoff. This runoff is then delayed and transferred to the outlet by various routing mechanisms. Unit hydrograph is a linear transfer function that represents those mechanisms with an assumption that the mechanisms behave similarly from event to event.

The choice of using observed unit hydrograph, because this method is capable in predicting time to peak of runoff more accurately as this method can do the computation for time step less than one hour. This obviously an advantage of using observed unit hydrograph compared to synthetic unit hydrographs (SUH) such as Nakayasu, GAMA I and Snyder and other kind of SUH which have time step of hour [6-9]. Time step becomes an issue here as the selected catchments are small catchments less than 100 km² of area, which may need short time concentration for the flow to propagate to the outlet. Hence, this study aims to investigate the impact of time

step selection in resulting unit hydrograph.

2. Methodology

2.1. Description of Study Area

The work took place in Way Kuala Garuntang catchment including its two sub-catchments, Way Simpbur and Way Awi as presented in **Figure 1**). Way Simpbur and Way Awi are two neighbouring sub-catchments, while those two sub-catchments are cascading to Way Kuala Garuntang catchment. The catchments located in Lampung Province, Indonesia. The area of Way Simpbur, Way Awi and Way Kuala Garuntang catchments are 3.691 km², 9.846 km² and 60.52 km² respectively. Three runoff measurements were carried out, two in the tributaries *i.e.* Way Simpbur, Way Awi and one in the downstream of Way Kuala Garuntang River. There is no runoff measurements in these catchments before. In order to construct an observed unit hydrograph, several things need to be prepared. Three automatic water level recorder (AWLR) needs to be installed in those locations, one for each point. There is one tipping bucket raingauge located in Way Kuala Garuntang catchment and the rainfall data obtained from this raingauge is used to calculate the unit hydrographs for each catchment.

The topography of upstream part of the catchment is hilly and the slope is flatter toward downstream catchment. Way Simpbur and Way Awi, they are neighbouring catchments but the catchment characteristic is slightly different. Way Awi catchment is highly populated where their house is located close to each other, therefore most rainfall is transformed into runoff. During intense storm event, flood comes quickly, but then releases in short

period of time. The channel width varies, where the width at the location study is 8 meters. Way Simpbur is also a rural catchment and highly populated. The slight difference is during intense storm event, flood comes quickly but releases slight longer period of time compared to release time in Way Awi. The channel width at the location of study in Way Simpbur is 7.5 meters and in Way Kuala Garuntang the river has 9 meters width.

2.2. Rating Curves

Measurements of discharges and water levels at those three points were carried out during wet season October 2009-April 2010. Velocities were measured using current meter and water levels were observed using peil-schaal attached on the river bank. Based on those measurements, a rating curve for each point is determined and results are presented in **Figure 2**. Rating curve for Way Simpbur (**Figure 2(a)**) shows the increase of water levels resulted in lower increase of discharges compared to that for Way Awi (**Figure 2(b)**), which is presented by sharper slope of Way Awi's rating curve. Please note that the scales of rating curves for both Way Simpbur and Way Awi are the same, but differ from those of rating curve for Way Kuala Garuntang. Rating curve for Way Kuala Garuntang (**Figure 2(c)**) shows the extensive range of discharges, which in the measurement for 1.2 m water level causes discharge of about 25 m³/s.

2.3. Effective Rainfall

This study used a classic ϕ_{index} approach to determine the effective rainfalls. Although there are quite a number of approaches used to determine the effective rainfalls such

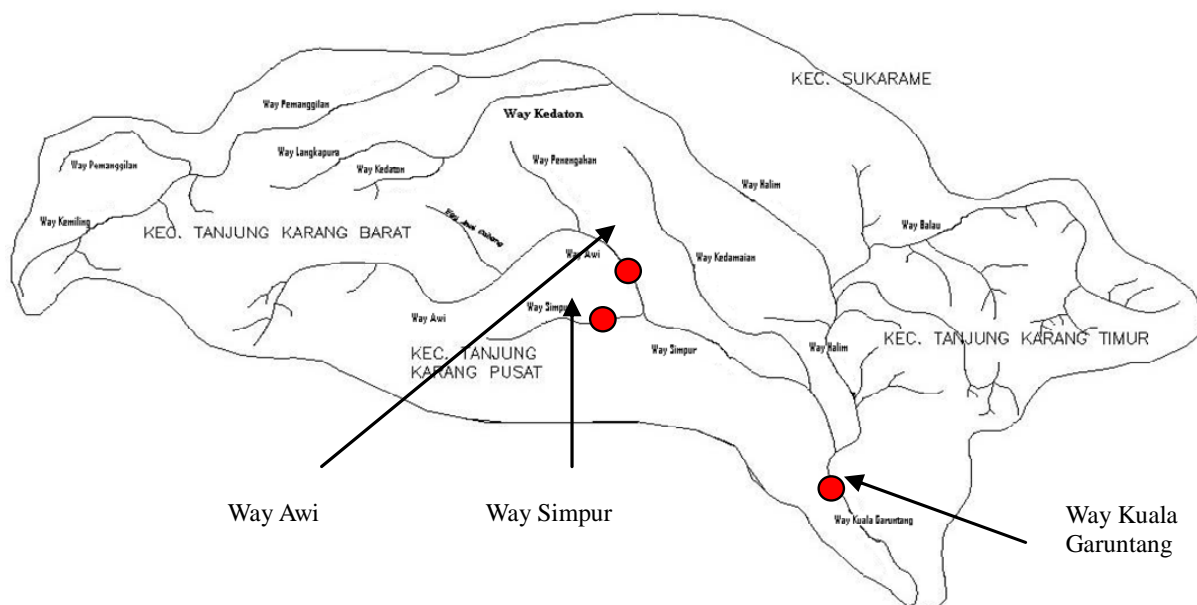


Figure 1. Way Simpbur, Way Awi and Kuala Garuntang catchments and the locations of the runoff gauges.

as Green Ampt infiltration and others, ϕ_{index} approach is still widely used due to its simplicity. The approach produces a series of excess rainfall (PE) or effective rainfall values from the observed gross rainfall (PG) values. The only constraint is to fit the overall so-called “stormflow” volume which is thought to have become runoff. Subsequently, the computed series of excess precipitation and the observed discharge (Q) are used to calibrate the UH in a ‘known input known output’ context [5].

The equation used to calculate ϕ_{index} is shown in Equations 1 and 2, where runoff depth (Q_{DR}) is a result of volume of direct runoff (V_{DR}) divided by catchment area (A). Thus ϕ_{index} is the difference between gross rainfall (P) and runoff depth (Q_{DR}) divided by time (t). Excess precipitation or effective rainfalls are obtained as gross precipitation subtracted by ϕ_{index} .

$$Q_{DR} = \frac{V_{DR}}{A} \tag{1}$$

$$\phi_{index} = \frac{P - Q_{DR}}{t} \tag{2}$$

3. Results and Discussions

3.1. Flood Events, Time Steps and ϕ_{index}

There are several flood events recorded during wet season 2009-2010, and the events are presented in Tables 1 to 3 for flood events selected for Way Simpur catchment (Table 1), Way Awi catchment (Table 2), and Way Kuala Garuntang catchment (Table 3). For each event, other related parameters such as rainfall depth, rainfall duration, calculated ϕ_{index} are also presented. Please note that the calculated ϕ_{index} are for three time steps, *i.e.* 10, 30 and 60 minutes.

It can be seen that the first recorded flood event was in December, although the start of wet season is in October. This happened because the first few rains were mostly infiltrated to fulfill soil moisture capacity. Furthermore, flood events presented in Table 1 to Table 3 are those which can be used to develop unit hydrograph. The advantage of using observed unit hydrograph to synthetic unit hydrograph such as Nakayasu, Snyder and GAMA 1, is the possibility to develop a unit hydrograph with finer

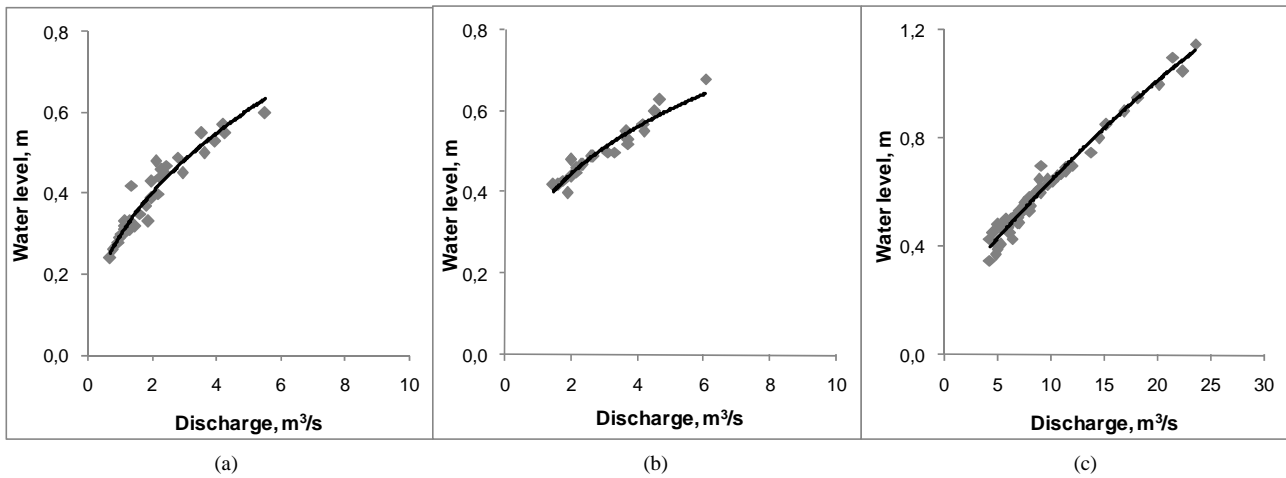


Figure 2. Rating curves for (a) Way Simpur; (b) Way Awi; and (c) Way Kuala Garuntang.

Table 1. Flood events selected for Way Simpur catchment.

No.	Date	Peak Discharge (m³/sec)	Rainfall Depth (mm)	Rainfall Duration (hours)	ϕ_{index} Time step 1 hr	ϕ_{index} Time step 30 min	ϕ_{index} Time step 10 min
1	16-01-2010	3.453	8	1	7.617	6.012	5.544
2	17-01-2010	6.437	6	1	5.225	2.908	-
3	17-01-2010	4.050	5.6	1	4.511	3.024	2.591
4	31-01-2010	3.769	10.8	2	9.273	4.044	2.006
5	01-02-2010	20.015	22.2	2	7.622	-	-
6	04-02-2010	2.705	7.2	1	4.676	2.768	-
7	06-02-2010	1.339	2.8	1	2.554	1.854	0.757

Table 2. Flood events selected for Way Awi catchment.

No.	Date	Peak Discharge (m ³ /sec)	Rainfall Depth (mm)	Rainfall Duration (hours)	ϕ_{index} Time step 1 hr	ϕ_{index} Time step 30 min	ϕ_{index} Time step 10 min
1	08-01-2010	21.693	7.4	1	6.346	4.025	2.517
2	16-01-2010	17.354	7	1	5.640	3.038	3.147
3	17-01-2010	19.043	6.2	1	2.589	5.251	4.364
4	12-02-2010	14.426	8.6	2	6.170	4.965	2.868

Table 3. Flood events selected for Way Kuala Garuntang catchment.

No.	Date	Peak Discharge (m ³ /sec)	Rainfall Depth (mm)	Rainfall Duration (hours)	ϕ_{index} Time step 1 hr	ϕ_{index} Time step 30 min	ϕ_{index} Time step 10 min
1	25-12-2009	12.770	28.4	1	26.746	25.734	16.044
2	28-12-2009	31.426	10.2	1	5.315	3.717	1.259
3	31-12-2009	9.413	9.4	1	8.484	8.347	4.541
4	08-01-2010	14.111	7.4	1	5.826	1.790	4.506
5	10-01-2010	26.606	31.6	4	10.076	-	-
6	13-01-2010	9.413	8.6	2	3.372	2.381	0.982
7	14-01-2010	19.509	5.8	1	3.184	2.44	-
8	16-01-2010	21.089	8	1	4.744	3.406	3.320
9	20-01-2010	19.234	8.2	1	5.516	5.646	2.216
10	27-01-2010	48.232	44.6	2	35.135	25.128	11.431
11	28-01-2010	15.205	19.6	1	18.054	18.053	12.834
12	01-02-2010	38.442	22.2	2	18.337	10.393	-
13	04-02-2010	23.164	7.2	1	3.935	1.832	0.700
14	05-02-2010	47.388	14	3	5.594	2.351	-
15	08-03-2010	28.895	15.8	1	13.869	6.698	-
16	10-03-2010	30.537	18.8	2	7.031	-	-
17	13-03-2010	11.889	5.6	1	3.071	2.253	1.792

time step, *i.e.* less than 1 hour. In this study time steps of 10, 30 and 60 minutes are used as presented in **Tables 1-3** and **Figures 4-6**.

Calculated ϕ_{index} for each event and time step are presented in the last three columns of **Tables 1-3**. The first event which is in December 25, 2009 shows large value of ϕ_{index} , which can be understood as a lot of portion of rains were infiltrated. The value of ϕ_{index} decreases for the next few events, but increases considerably for these subsequent events of 27-01-2010, 28-01-2010 and 1-02-2010 and again on 8-03-2010. Therefore, it cannot be concluded that the value of ϕ_{index} will decrease toward the peak of wet season (*i.e.* in January-March). In fact, the value of ϕ_{index} is defined in such a way that the computed series of excess precipitation suitable with the observed

discharge. In contrast to the absence of trend of ϕ_{index} values in the flood events, the value of ϕ_{index} tends to decrease for smaller time step.

The results presented in **Tables 1-3** and **Figures 4-6** show that not all events which can be used to develop unit hydrographs for a certain time step can be used to develop those for smaller time steps. This may happen as the within storm rainfall pattern (distribution of rainfall depth for each time step) is more detail for smaller time step, so that for particular rainfall is not possible to get the ϕ_{index} and volume of effective rainfall which fit runoff volume. This may also due to the selected method for calculating effective rainfall which uses a linear approach rather than non-linear approach such as Green-Apmt or other methods.

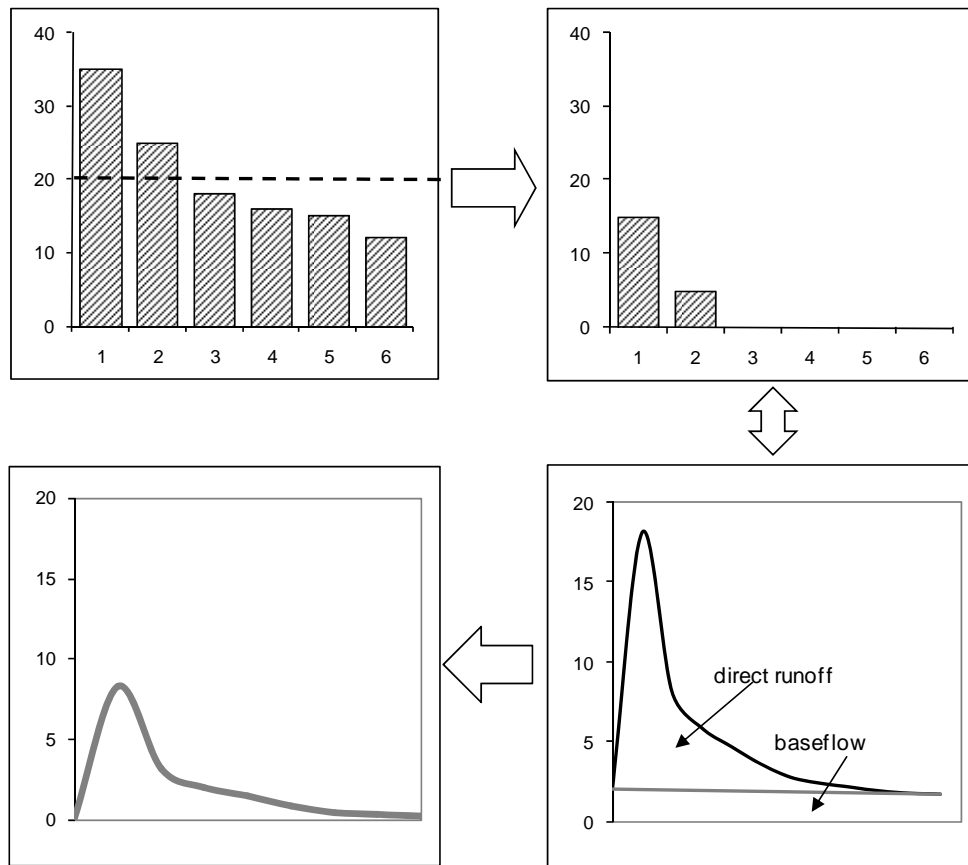


Figure 3. Effective rainfall, baseflow separation and unit hydrograph.

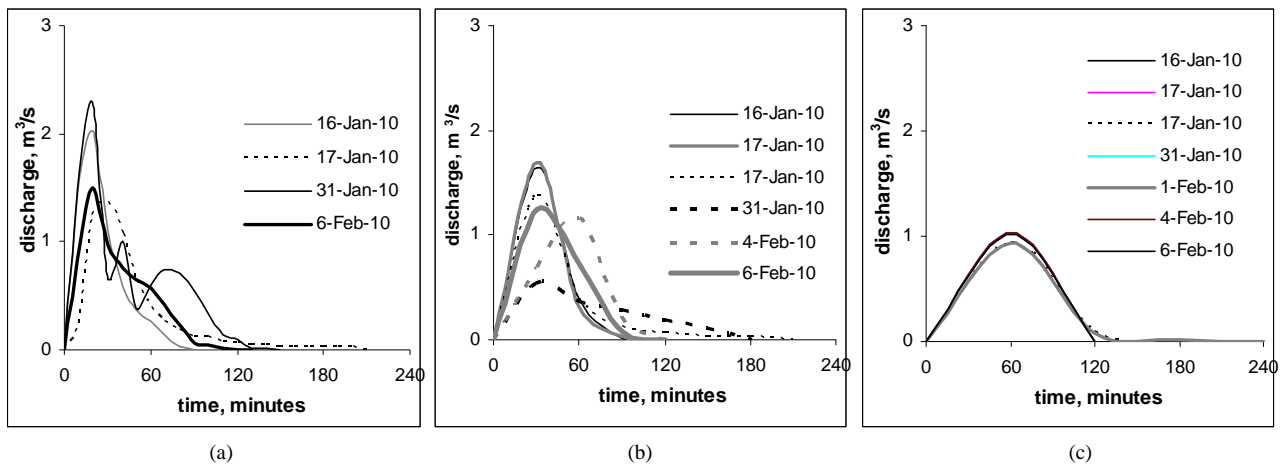


Figure 4. Observed unit hydrographs for Way Simpur using time steps (a) 10; (b) 30; and (c) 60 minutes.

3.2. Time Steps and Time to Peak

The unit hydrographs developed are presented in Figures 4-6, where Figures 4-6 show unit hydrographs of Way Simpur, Way Awi and Way Kuala Garuntang respectively. For each catchment, the unit hydrograph is developed for time step 10, 30 and 60 minutes. The advantage of using small time step is to gain an understanding

about the real time to peak for the catchment. For the case of Way Simpur (Figure 4), using time step of 10 minutes it can show that the average time to peak in that catchment is 20 minutes. While using time step of 30 and 60 minutes show that the averages of time to peak are 30 and 60 minutes respectively. Among those three time steps, it seems that time to peak resulted from time step of 10 minutes is the most reasonable as the catchment is

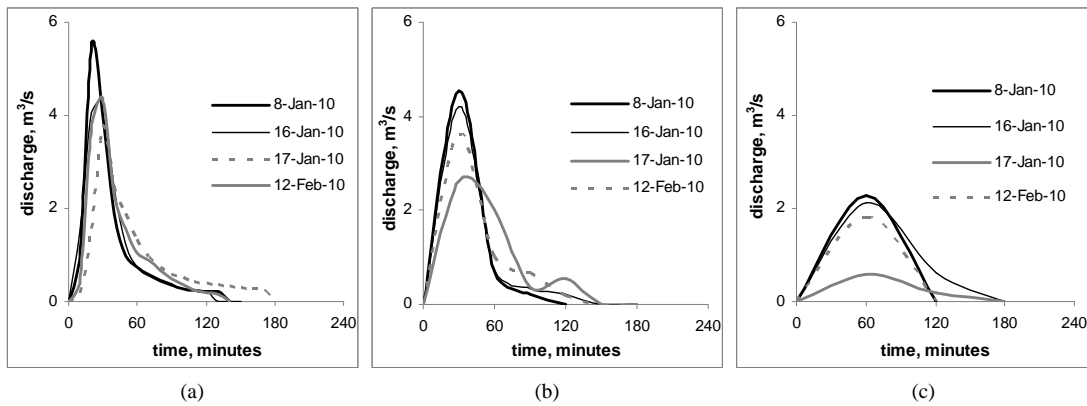


Figure 5. Observed unit hydrographs for Way Awi using time steps (a) 10; (b) 30; and (c) 60 minutes.

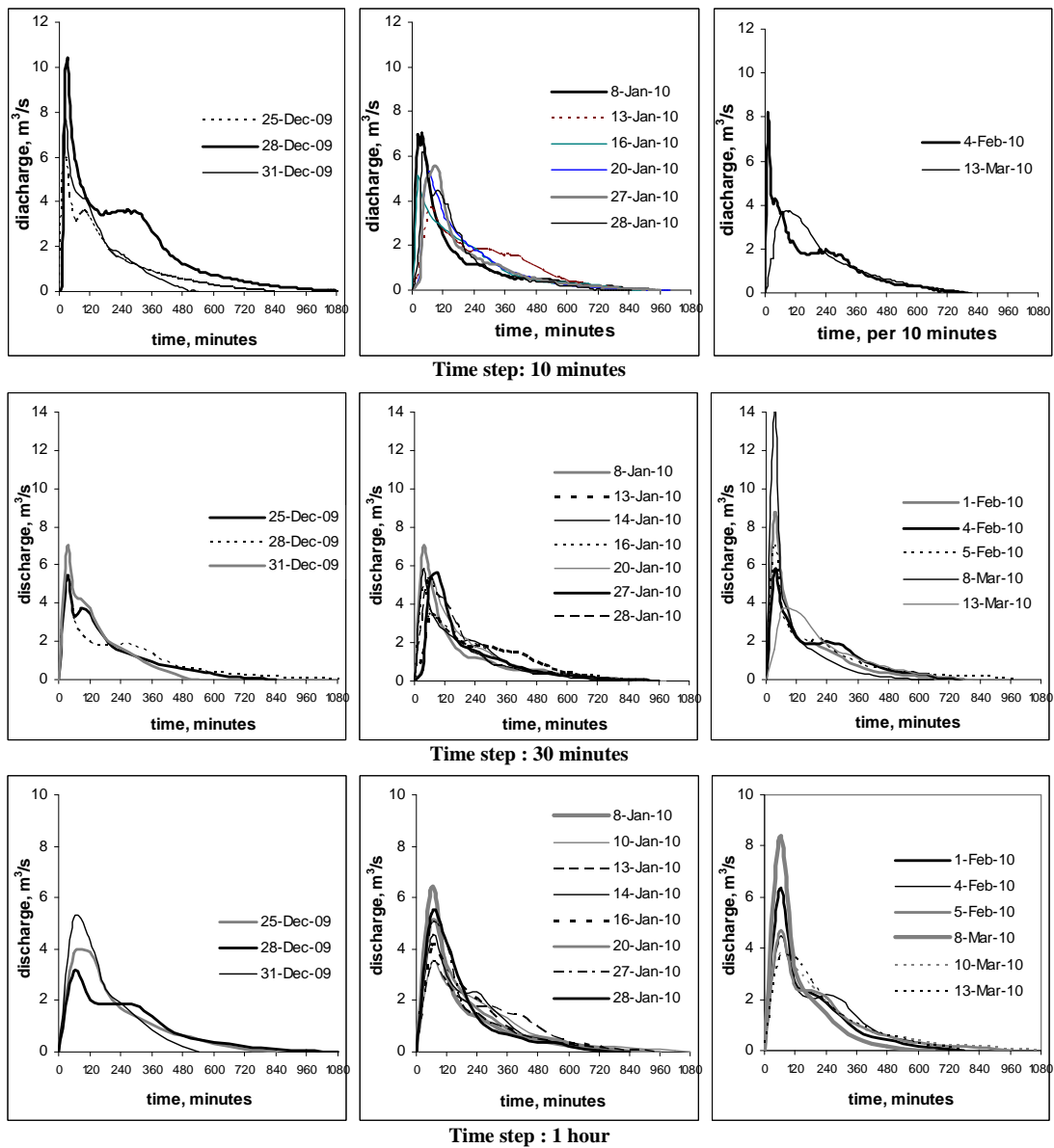


Figure 6. Observed unit hydrographs for Way Kuala Garuntang according to the months using time steps 10, 30 and 60 minutes.

considered small.

For Way Awi (**Figure 5**), using different time steps also show different results for time to peak. Using time step of 10, 30 and 60 minutes resulted in average time to peak of 30, 30 and 60 minutes respectively. Again, smaller time step gives more reasonable results in indicating time to peak.

For Way Kuala Garuntang, in addition to time step, the unit hydrographs are also made into three groups according to the months. The groups are for December, January, as well as February and March events (**Figure 6**). The average time to peak for time step of 10 minutes is 30, 60 and 60 minutes for December, January and February-March events respectively. While the average time to peak for time steps of 10 minutes for overall events is 60 minutes. For time step of 30 minutes, the average time to peak is 30, 60, 60 and 60 minutes for December, January, February-March and overall events respectively. The average time to peak for time step of 60 minutes is 60 minutes for December, January, February-March and overall events. For a larger catchment such as Way Kuala Garuntang, smaller time steps confirm time to peak as resulted from larger time step. In this case, it is predicted that the appropriate time to peak for Way Kuala Garuntang is 60 minutes.

3.3. Time Steps and Peak Discharges

In addition to time to peak, another important issue with regard to unit hydrograph is the peak discharge. For Way Simpung (**Figure 4**) peak discharges for all time steps are in the range of 0.5 - 2.4 m³/s, where the average peak discharges for time steps 10, 30 and 60 minutes are 1.8 m³/s, 1.2 m³/s and 1 m³/s respectively. Please note that in fact there are seven peak discharges in the unit hydrographs for Way Simpung using time step 60 minutes (**Figure 4(c)**), which seems to be sorted into two groups because five of them are in the range of 1.023 - 1.028 m³/s and the other two are 0.931 and 0.937 m³/s. Therefore it looks like there are only two curves as the outcome of seven flood events (**Figure 4(c)**).

For Way Awi (**Figure 5**) the average peak discharges for time steps 10, 30 and 60 minutes are 4.1 m³/s, 3.7 m³/s and 1.8 m³/s respectively. The results show the smaller the time step the larger the peak discharge. This happens because only selected flood events which have high rainfall intensity during short time interval are able to be utilized in constructing unit hydrograph. Therefore, the rainfall intensity is larger at smaller time step which impacts on larger peak discharge.

The average peak discharges for Way Kuala Garuntang for December, January and February-March events (**Figure 6**) using time step 10 minutes are 7.7 m³/s, 4.5 m³/s and 4.2 m³/s respectively, using time step 30 min-

utes are 5.8 m³/s, 4.7 m³/s and 7.4 m³/s respectively and using time step 60 minutes are 4 m³/s, 4.6 m³/s and 5.2 m³/s respectively. While the trend of average peak discharges seem opposite for time step 10 minutes, the trend of those for other time steps shows there is an increase of average peak discharges toward the peak of wet season. For February-March flood events there were only two out of six flood events which were able to be utilized in unit hydrograph using time step 10 minutes, and there were only six out of eight events for January flood events could be utilized for 10 minute time step hydrograph. Meanwhile, all three flood events in December could be used for 10 minute time step hydrograph. Therefore the results from using time step 10 minutes show inconsistent trend with regard to the wetter season as the lack of data.

3.4. The Average of Unit Hydrographs for Different Time Steps

Comparing the results between those three catchments there is a general trend of average peak discharge, *i.e.* the higher the time step, the lower the average peak discharge (**Figure 7**). This trend does not fully work for Way Garuntang as the peak discharge using time step 10 minutes is lower compare to that using time step 30 and 60 minutes. Considering overall events for Way Kuala Garuntang, average peak discharges for time steps 10, 30 and 60 minutes are 4.64 m³/s, 5.2 m³/s and 4.7 m³/s. Although in nearly all unit hydrographs, peak discharges resulted from using time step 10 minutes are larger compared to peak discharges resulted from using larger time step. This may happen because the method in calculating the average peak discharge is so simple, that is simply taking the average of the events for particular time step, both for the discharge and time to peak. Furthermore, peak discharge is closely related to time to peak. Using small time step, time to peak may vary significantly between 10 to 60 minutes. Considering peak discharges which occur at various time to peak, this may result in low average of peak discharge as in the case of average peak discharge of Way Kuala Garuntang using time step 10 minutes.

4. Conclusions

This study shows the impact of time steps on unit hydrographs with regard to time to peaks and peak discharges. In general, smaller time step gives more accurate resulted unit hydrographs. It was observed that the average time to peaks for Way Simpung are 20, 30 and 60 minutes using time steps 10, 30 and 60 minutes respectively. The average time to peaks for Way Awi are 30, 30 and 60 minutes using time steps 10, 30 and 60 minutes respectively. And the average time to peaks for Way Kuala Garuntang are

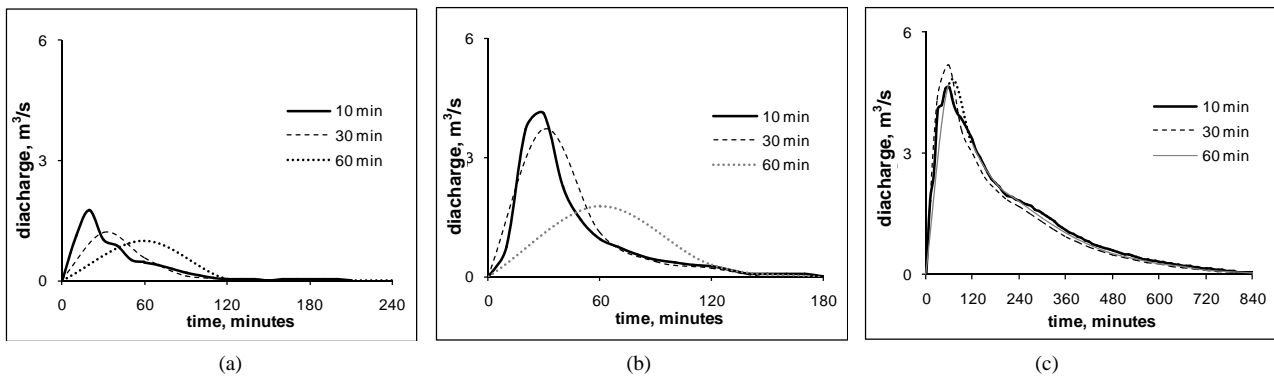


Figure 7. Average of unit hydrographs for time steps 10, 30 and 60 minutes for catchments (a) Way Simpur; (b) Way Awi; and (c) Way Garuntang.

60, 60 and 60 minutes using time steps 10, 30 and 60 minutes respectively.

Time steps used in determining unit hydrographs may produce different peak discharges. The results show that the trend of peak discharges increases by using smaller time step. However, the average peak discharge provided by using time step 10 minutes for Way Kuala Garuntang does not correspond with the trend. For several flood events used in determining unit hydrographs, the time to peaks and corresponding peak discharges using time step 10 minutes vary considerably. Therefore the averaging of those variables causes the average value of peak discharge is not maximum.

In addition to that, the resulted unit hydrographs also show that the trend of peak discharges increases toward wetter months during the wet season. However, the peak discharges resulted from using time step 10 minutes do not show this trend due to limited number of flood events which could be used to calculate the unit hydrograph using such small time step.

5. Acknowledgements

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