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FLASH FLOOD STUDY ON MT. MERAPI SLOPE FOR IMPROVEMENT OF THE MONITORING METHOD

*Adam Pamudji Rahardjo[1], Rachmad Jayadi[1] and Djoko Legono[1]

[1]Faculty of Engineering, Universitas Gadjah Mada, Indonesia

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ABSTRACT: Flash floods with or without debris in the rivers on the Mt. Merapi slope have been causing damage and loss of lives until now even though a series of sabo dams have been built for each river, and warning systems have been established and operated. This study aims to understand the hydrology and hydraulic characteristics in the area, especially of the two important rivers namely Bebeng and Boyong Rivers for flood monitoring improvement. The research verified the results of previous studies on hydrology and hydraulics of the area, approximating flood travel times using a simple formula stepwise, comparing with the result of the analysis using recorded pair data of a precursor rainfall and the related local peak of water level hydrographs. The reference study results show that the South-West slope of Mt. Merapi has a higher risk for flash flood occurrence. Flood travel time in the short upstream reach is well estimated using the simple formula stepwise because the result is similar to the measured one. Based on pairs of precursor rainfall and the related local peak water level data, the local peak water level weakly influences the time lag for those two AWLR Sta. locations. It is proposed to include the flood propagation time in considering the issuance of warning messages.

Keywords: Flash flood, Hydrology and hydraulic characteristics, Flood travel times, Monitoring method.

1. INTRODUCTION

Rivers on the Mt. Merapi slope in Central Java Province and the Special Region of Yogyakarta, Indonesia (See Fig.1) are experiencing flash flood events almost every year. The sediment produced by Mt. Merapi eruptions may persist in the form of ash fall, lava flow, as well as pyroclastic dome formation around the summit of the mountain. Ash fall may cover the ground surface, reducing the soil permeability and thus raising the flow hydrograph and these would trigger flash floods. Flash floods may carry debris [1] or not [2], however, many of them that flow down on Mt. Merapi slope rivers are in form of debris flows [2]. Eruption events data from 1832 to 2010 [3] show that, on average, every 5.4 years the crater of the Merapi volcano erupts and delivers a huge amount of sediment materials [4,5]. This has provided sediment deposits on the most of river's upstream ends [6,7]. Debris flow occurrences have been related to the periods just after any eruption. Less heavy rainfall may cause debris flows when the river's catchment areas are covered by ash from eruption [8].

During the last decades, several series of sabo dams have been constructed in the main rivers such as Pabelan, Blongkeng, Putih, Batang, Bebeng, Boyong, Kuning, Opak, Gendol, and Wara [9]. See Figure 2. Even though, there are still a number of planned sabo dams that haven't been built yet[10], the destructive effects of flash floods on rivers on the Mt. Merapi slope have reduced so much. However, the problems still exist. Sand mining activities in the river valley have been increasing during the last twenty years [11]. The local government has tried to regulate these sand mining activities by issuing allowed zones and registering the miners and their companies. However, not all miners obey these regulations and even illegal miner activities shift upstream since in there it is difficult to monitor them [12,13].

The other vulnerable types of activity are recreational and educational activities in the river valley such as hiking, rafting, camping, etc. Several disaster events have occurred, causing property damage, and in some of them, there was a loss of lives [2].

Non-structural efforts to minimize the loss caused by flash floods and debris flow along the rivers on the Mt. Merapi slope have been done by the government and communities such as providing regulations, early warning systems, and education [14,15]. However, the achievement has not yet been sufficient.

The current rainfall monitoring on the Mt. Merapi slope for debris flow warning is based on the long-term (LRI) versus short-term rainfall (SRI) indices [16]. A snake-line is used to monitor the progress of rainfall events and indicates a warning, evacuation, and critical line crossing. However, floods need to propagate down before reaching the locations of concern. There is a time lag between the precursor, such as high-intensity rainfall series data captured by weather Radar [17] or ARRs, and the arrival of a flash flood.

The LRI-SRI method does not consider time lag.

An improvement by considering this time lag is expected to elevate the warning system's effectiveness. This additional parameter enables an evaluation of the available time for delivering the message of the incoming flood and evacuating those who are in the river valley.

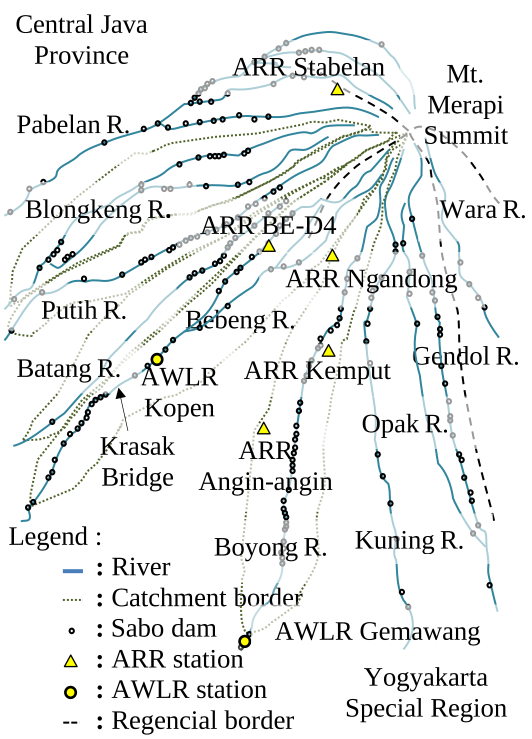

Fig.1 Rivers and location of sabo dams on South and South-West Mt. Merapi slope (sketched from [11]) and observation stations

This study aims to understand the hydrology and hydraulic conditions of two rivers on the Mt. Merapi slope that cause flash floods in order to improve the existing warning system.

The following sections describe the research significance in improving flash flood monitoring methods, especially for flash flood warnings, steps of research methods, results of data collection and analyses, and discussion of the findings. Several conclusions finally are presented.

2. RESEARCH SIGNIFICANCE

Understanding hydrology and hydraulic characteristics and processes will provide guidance to improve the current warning systems. Previous studies of hydrology and floods on the Mt. Merapi slope were isolated topics. Integrating them to understand the spatial distribution of threats and the frequency of floods is important for evaluating the flood monitoring system. The other important thing is that the geological factors give influence the flash flood occurrences and magnitudes such as the presence of ash and sand deposits.

This study identified that time lags on a steep slope in a range of several minutes to hours. Considering the hydraulics of overland flow runoff and flood, higher discharge gives higher flow depth, higher velocity, and shorter travel time. Understanding this phenomenon is expected to improve the flash flood warning system on Mt. Merapi slope.

3. METHODS

This research collects flash flood event data from previous studies, news, and interview with local institutions such as the Sabo Technical Center (STC) and the Disaster Management Agency (BPBD) of Sleman Regency, problems of flash flood warnings along the rivers on Mt. Merapi slope, digital elevation model (DEM) data, land cover geospatial data, river cross-section data, and river structure data. Heavy rainfall data (> 50 mm) are collected from the database of the Hydraulic Laboratory of the Civil and Environmental Engineering Department of UGM and also the STC, especially those that preceded the flash flood occurrences. Based on the availability of the data, two rivers were selected according to their importance namely Bebeng River and Boyong River. All rainfall data were measured using the standard flip bucket type and recorded electronically into loggers or telemetric systems. The flash flood data were recorded by the ultrasonic type (Bebeng River) as shown in Fig. 5, and the pressure gauge type (Boyong River).

The selected rivers were evaluated for further analysis. Rainfall data analyses of previous studies were evaluated, especially those of extreme cases and/or related to flash flood events. The results are then compared with the collected rainfall data of more than 50 mm/hr. Similarly, flood data analyses of previous studies were evaluated and then to be paired with the causing rainfall data. The next step was identifying the rainfall hyetograph and flood hydrograph shapes for time-lag evaluation. These time-lags are assumed to represent the time travel for run-off from the upstream river catchment area to the water surface measurement site.

The arrival of a flash flood is defined as an incoming flood front meeting a certain condition. This condition or critical condition is selected based on its potential to cause damage or an accident. This critical condition criterion was studied for Sempor Creek on the South slope of Mt. Merapi and Ciberang River in West Jawa Province [2,18].

In this study, the time lags were approximated based on the time of the peak rainfall intensity of rainfall events and the time of the following peak of stage hydrographs. The relation between peak flood water levels and time lags is to be discussed.

Time lags and total time for warning and evacuation need to be compared. This is because in terms of flood warnings when the evacuation time is less than the time lag, the precursory rainfall for a flash flood can be used for warning issuance for evacuation. However, when a time lag is less than the evacuation time, forecasting is needed. A new chart was developed to accompany the LRI vs. SRI chart. The flow chart of the research method is shown in Fig.2.

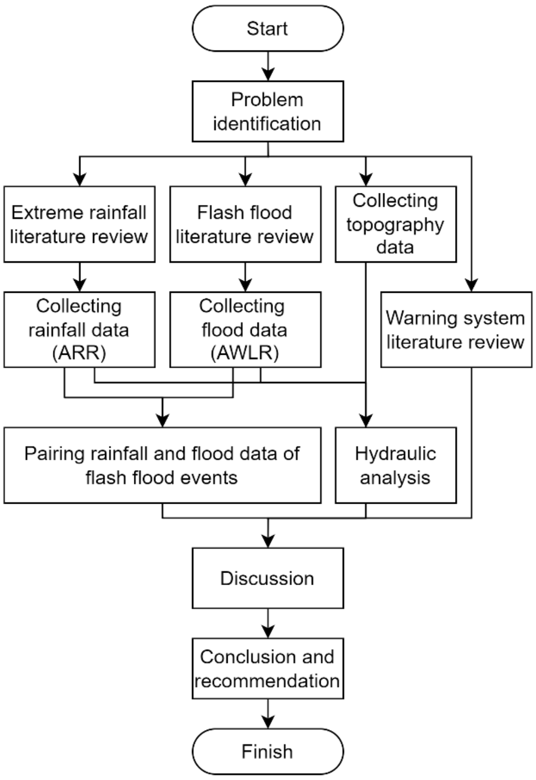

Fig.2 Flow chart of study method

4. RESULT AND DISCUSSION

Flash flood events in rivers on the Mt. Merapi slope during the last 20 years have caused significant losses. Data on flash flood events that caused damages from 2010 until 2021 were collected from online news. It shows that there were 19 heavy casualties such as bridges, small dams, water supply pipes, and house failures that caused several injuries and loss of lives along the Pabelan, Putih, Boyong, and Gendol Rivers during that period. as shown in Table 1. The flash flood events at the end of 2010 and the beginning of 2011 were related to the 2010 Mt. Merapi big eruption which supplied thick volcanic ash. Gonda, et.al [19] collected flash flood and debris event data and summed them up into a chart of river vs. the number of days with flash floods or debris flow occurrences between October 2010 and March 2012. Fig.3 shows the chart that has been modified by ordering the river names according to their angular position on the Mt. Merapi slope in a counterclockwise manner. It was reported that the debris flow occurrences are related to the presence of ash from Mt. Merapi eruption.

The rivers on Mt. Merapi slope can be grouped into two categories based on sectors of South-West, and South. If tributaries join the main rivers the river numbers are reduced to only ten namely Pabelan, Blongkeng, Putih, Batang, Bebeng (SW), Boyong, Kuning, Opak, Gendol, and Woro (S).

Comparing the number of days with SW and S groups, the SW group has 111 days and the S group has only 53 days with flash flood or debris flow occurrences within approximately one and a half years between October 2010 and March 2012. The SW slope of Mt. Merapi seems to have more frequent flash floods or debris flow occurrences.

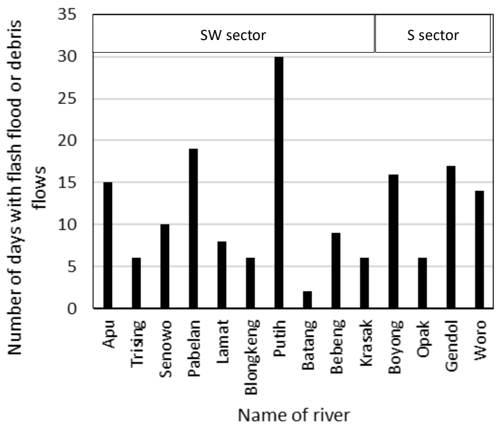

Fig.3 Number of days with flash flood events in several rivers on Mt Merapi slope between October 2010 and March 2012 (modified from [19])

4.1 Hydrology Characteristics

A study by Sujono, et. al. [20] concluded that the SW slope of Mt. Merapi has the highest number of heavy rainfall events as shown in Fig.4.

This finding is in line with the number of days with flash floods or debris flows on the Mt. Merapi SW slope mentioned before. As shown in Fig.1, the river alignments on the Mt. Merapi slope are nearly parallel. Therefore, the shapes of catchment areas are ribbon shapes that are long and thin.

For spatially uniform distributed rainfall, this type of catchment area shape introduces a lower peak hydrograph compared with that circular shape with a radial drainage pattern.

However, because the upper parts of the catchment areas are high and steep, they stimulate orographic rainfalls, therefore, higher-intensity rainfalls often occur in the upper parts of the river catchment areas. The steep slope drainage channels, then, create sudden flood bores.

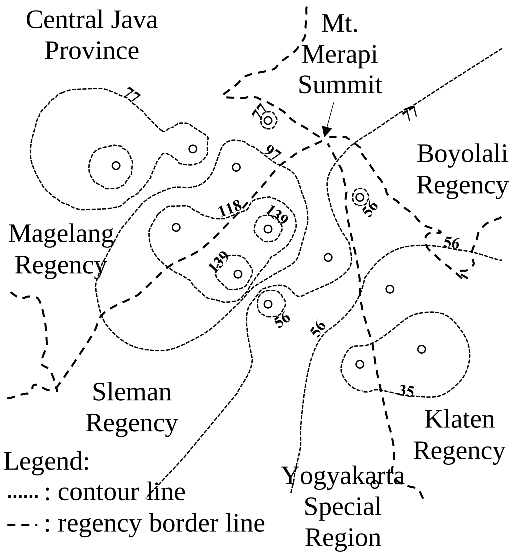

Fig.4 Contours of numbers of heavy rainfall events on Mt. Merapi slope (sketched from [20])

4.2 Flash Flood Hydraulics

Flood monitoring stations at several locations on the Mt. Merapi slope have been installed for decades. However, the continuity of records is low. An automatic water level recorder (AWLR) of ultrasonic type was installed at Kopen north side of Krasak Bridge (See Fig.1) by the Sabo Technical Center (STC), the Ministry of Public Works and Housing (MPWH) as shown in Fig.5, and another one of pressure type at Gemawang, Boyong River by the Hydraulic Laboratory (HL), Universitas Gadjah Mada (UGM). The existence of sabo dams along both the Bebeng and Boyong Rivers as well as the shape and roughness of the river bed has reduced the flow velocity along the upstream reach of the rivers. Most river valleys are in V or U shapes therefore, flash floods rarely cause inundation or overflow into agriculture and inhabitant areas except those on the valley. However, the danger is threatening bridges, bank failures, and the people who work along the river bed such as sand miners.

The selected important rivers, namely Bebeng and Boyong River upstream ends are under the new lahar deposit created by the 2019-2022 sequence eruptions [21,22]. Along those rivers, there are a series of sabo dams and consolidation dams to capture sediment carried by debris flows and reduce the sediment flows reaching the vulnerable river structures or bridges. Based on visual observation, design drawings, and tables [23], along the Bebeng River from the upper end until the national road bridge connecting Yogyakarta and Magelang, there are 28 series of sabo and consolidation dams. Along Boyong River from the upper end until the Yogyakarta City north border, there are 65 series of sabo and consolidation dams.

Fig.5 The acoustic sensor of the Kopen AWLR Station

A typical set of sabo and consolidation dams has a drop structure of 4 to 10 m high. Therefore, the original averaged longitudinal slope and averaged longitudinal slope reduced by drop structures are as follows.

Table 1 Longitudinal slope of the river beds

Rivers	Original Slope	Reduced Slope
Bebeng	0.031479	0.018604
Boyong	0.029545	0.015635

The presence of sabo and consolidation dams reduce the flow velocity and bore propagation in case of flash floods. Considering the 10-year return period flood peak discharge of Bebeng River of 25 m^3/s, by assuming the bed roughness coefficient of n-Manning of 0.025, and 30 m average widths, the original slope gives an approximate velocity of 0.735 m/s. The reduced slope gives an approximate velocity of 0.625 m/s, therefore the approximate velocity has been reduced by 15.02%. As for Boyong River, the presence of sabo dams gives an 18.06% reduction in flow velocity.

Travel time of debris flow along Boyong River has been estimated [24]. The velocity, V (Km/hour), of debris flows, was approximated using the following equation.

$$V = 72\left(\frac{H}{L}\right)^{0.6} \tag{1}$$

Where H is the elevation difference (m), and L is the river reach length (Km). The equation gives a much larger velocity than the normal flow approximation. For a 0.0315 slope, it gives a velocity of 2.511 m/s. Based on the equation the velocity and travel times of debris flow along reaches between two sabo dams and between the Mt. Merapi summit were estimated. The results show that the travel time from the Mt. Merapi summit to the sabo dam BOD1 at Pulowatu (13.46 Km from the summit) is 44.55 minutes.

Recomputing the travel time and extending the location to 27.5 Km from the summit (near the North border of Yogyakarta City) based on Google Earth data, gives a travel time from the summit to BOD1 of 47.9 minutes and to the Yogyakarta City border of 162.3 minutes (2 hours 42.3 minutes). As for Bebeng River, the approximate travel time from the summit to the Krasak Bridge, which is 18.4 Km downstream of the summit, is of 81.7 minutes (1 hour 21.7 minutes).

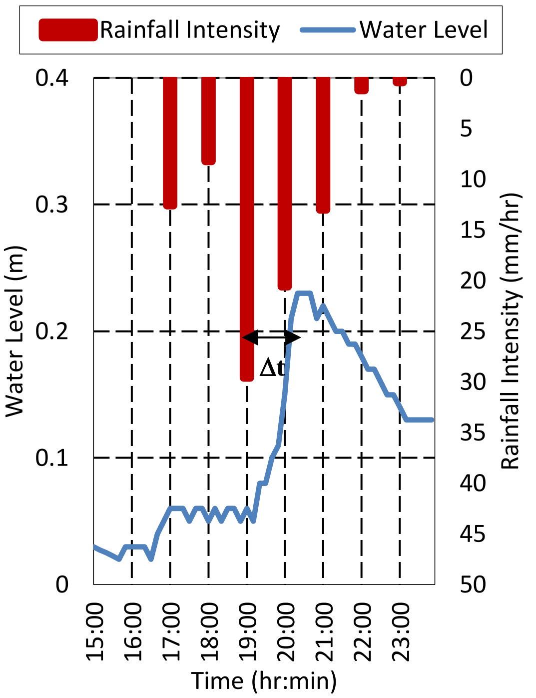

Fig.6 Flood hydrograph at AWLR Kopen Sta., rainfall hyetograph of Stabelan ARR Sta., and lag time on 4th January 2015

Analysis of the lag time, Δt, between the measured start time of the precursor rainfall and that of the peak water level hydrograph was done to estimate the travel time of flash floods. For the Bebeng river, the rainfall data were measured at Sta. Stabelan, Sta. Ngandong, Kemput, or Angin-angin, or a combination of any two stations, depending upon the availability of the data and distance to the upstream catchment area. The method approximated the lag time as shown in Fig. 6 and 7.

Based on pairs of rainfall and water level records, two relations between the lag time of incoming flood and the local maximum of water level related to the causing rainfall series were established for Kopen and Gemawang AWLR Stations as shown in Fig. 9 and 10.

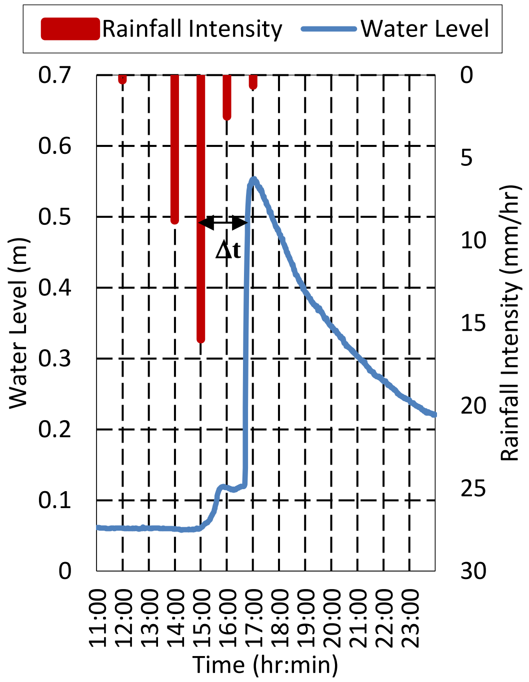

Fig.7 Flood hydrograph at AWLR Gemawang Sta., rainfall hyetograph of BE-D4 ARR Sta., and lag time on 25th February 2020

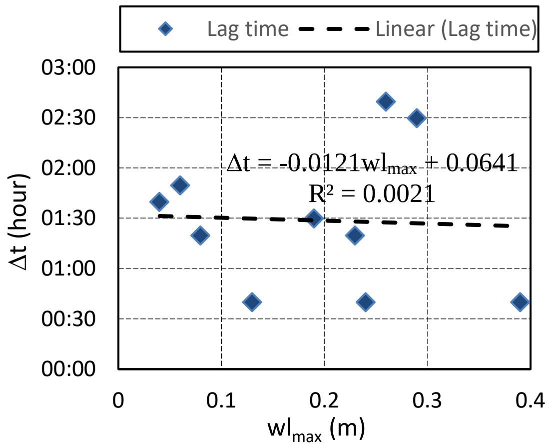

Fig.8 Lag time vs. peak flood water level at Kopen Sta. of Bebeng River (18.4 Km from the summit)

Fig. 8 and 9 show that the lag time is weakly related to the water level's local peak. The averaged values of the lag time for each river compared with the approximate results based on Eqn.1 are shown in Table 2.

Table 2 Comparison between calculated and measured lag times

Rivers	Eqn. 1	Measurement
Bebeng	1 hr. 21.7 min.	1 hr. 29 min.
Boyong	2 hr. 42.3 min.	1 hr. 56 min.

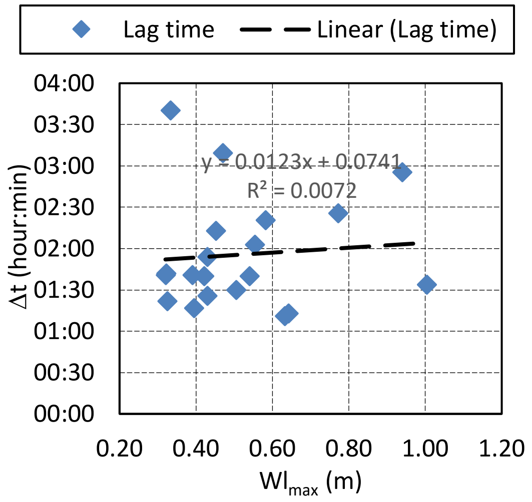

Fig.9 Lag time vs. peak flood water level at Gemawang Sta. of Boyong River (27.5 Km from the summit)

For the case of Bebeng River, the difference is less than ten minutes, however, for that of Boyong River, the difference is significantly large. Probably for the case of Boyong River, there is a relatively longer mild slope reach (from Pulowatu to Gemawang).

4.3 Flash Flood Monitoring

In Mt. Merapi slope, most flash flood events are with debris, therefore, currently, monitoring flash floods for giving a warning uses the method for monitoring debris flows [5] based on LRI vs. SRI charts as shown in Fig.10 below. Rainfall events are plotted in the chart and they can be separated into causing rainfall and non-causing rainfall zones by a critical line or curve. Based on this critical line or curve, warning and evacuation lines were commonly determined by trial.

These lines are used as indicators for issuing necessary messages when monitoring a rainfall event by plotting the progress of LRI and SRI values for each incoming rainfall data crossing those curves. However, because the distance between curves which represents a distance of a combination of LRI and SRI, temporal information is commonly written at each rainfall progress. This way gives a little help to estimate the availability of time from a flood precursor (crossing one of the lines) to the arrival time of the flood front. Because of this, it is necessary to have an additional chart to monitor the progress of rainfall in a chart with a time axis as shown by the lower chart in Fig.10 below [25].

In Fig.10 upper chart, when a snake-line reaches point t_5, the critical curve crossing indicates that the flash flood will occur. A warning message certainly must be issued. However, there are two possible conditions for a certain location downstream, the minimum time necessary for evacuation (ET) is less or more than the travel time or lag time (LT) for the flash flood to arrive. In the first case, the evacuation would be successful, however, in the second case, the flood would arrive before the evacuation completes.

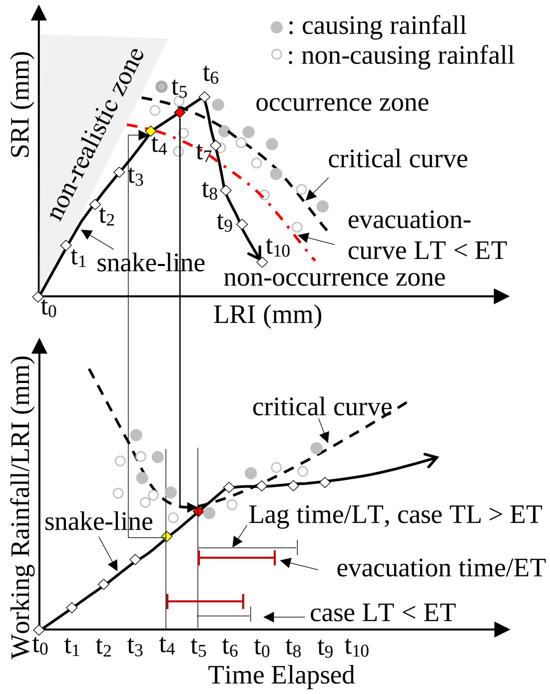

Fig.10 The relation between the LRI vs. SRI and Time Elapsed vs. Working Rainfall/LRI charts

As shown in the lower chart in Fig.10, in the case that LT is greater than ET, an evacuation message can be delivered when the snake-line crosses the critical curve, however, in case of LT is less than ET, the evacuation message needs to be issued before the snake-line crossing the critical curve. The latest time to issue the evacuation message needs to be forecasted since the snake line might or might not cross the critical line. The forecast of crossing can be done by extending the last snake-line until crossing the critical curve, say, at a point FP. Therefore, the latest time to issue an evacuation message is FP – (ET – LT). This point can be projected in the upper chart of Fig.10 at point t_4, and it will locate an evacuation curve. In the last case, the uncertainty is much higher than that in the first case.

Another method in the forecasting of flash floods is demonstrated by [26]. It used an entropy model and GIS that generates a detailed flash flood map, however, it does not relate to warning of an incoming flash event. A flash flood warning method was developed by [27] using a deep learning method with a long short-term memory-based approach. It used time series of precipitation data before the flash flood event and the maximum daily precipitation, curve number, and slope as predictor parameters. It gives a reliable flash flood warning 1 day ahead. This is not suitable for the problems on Mt. Merapi slope.

5. CONCLUSIONs\S

The South-West Mt. Merapi slope has higher rainfall intensity than the other slope sides. This has caused the rivers flowing on the South-West slope to experience more flash flood events. In recent years new volcanic material is ejected and deposited on the South-West slope just below the summit. Therefore, the risk of flash floods with volcanic material on the South-West slope is increasing.

Flash flood propagation in the river reaches on Mt. Merapi slope can be approximated by a simple formula implemented stepwise that gives a similar result to the measured one for the shorter upstream reach. Based on pairs of precursor rainfall and the related local peak water level data, it is unlikely that the local peak water level influences the time lag for those two AWLR Sta. locations.

The development of a flash flood monitoring system needs to include flood propagation time in considering the issuance of warning messages. The relation between rainfall intensity and the time lags of several vulnerable sites along the rivers need to be further studied especially the effect of the spatial distribution of the rainfall intensity. The critical line identifying the combination of a working rainfall and time elapsed since the beginning of an individual series of rainfall starts to cause flash floods at a certain location along the river needs to be further studied.

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