Prediction of soil moisture and rainfall induced landslides: A comparison of several PBL parameters in the WRF model

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Abstract. Rainfall intensity thresholds only do not take advantage of the awareness of the slope's hydrological processes, so they appear to produce large false and missed alert rates, decreasing the credibility of early warning systems for landslides. This study analyzes this dilemma by modeling the behavior of slopes to precipitation, including the potential effect of soil moisture uncertainty given by numerical modeling. For the simulation of soil moisture during the study period and event rainfall thresholds of an extreme event used to describe the intensity of a rainfall event, the Weather Research and Forecasting (WRF) model is used. The three days simulation conducted during a landslide event in Samigaluh, Kulon Progo on 28 November 2018. The four Planetary Boundary Layer (PBL) parameters in the WRF model are compared to understand each character, i.e., Yonsei University (YSU), Mellor-Yamada-Janjic (MYJ), Shin-Hong (SH), and Bougeault-Lacarrère (BL). To evaluate the precipitation as simulated by WRF, we use observation data from rain gauge and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). In general, all parameters have an underestimation of precipitation. Each PBL parameter's response to rainfall is different. Both MYJ and SH schemes are closer to observation than others for day 1 and day 2 of simulation, daily precipitation. For all PBL schemes, increased soil moisture is seen, suggesting that the soil is wetter and more vulnerable to landslide events. As an early warning predictor of landslides in terms of rainfall parameters, the SH method is very useful in this analysis. For early warning of landslides, a short period (<6 hours) of precipitation with a high accumulation of precipitation would be very beneficial.

Keywords: soil moisture, rainfall, landslide, WRF model

1. Introduction

The factors that cause a landslide are often divided into two categories [1], i.e., external and internal factors. Rainfall, earthquakes, and man-made factors are examples of external factors. Stratum lithology, slope gradient, slope aspect, slope profile, and height difference are some of the internal factors to consider. Internal factors tend to be constant in some cases, while external factors change over time. We focused on meteorological aspects, particularly soil moisture and rainfall variables, for this study.

Extreme weather conditions have a detrimental effect on the slope region, resulting in catastrophic landslide threat impacts (Figure 1). Heavy rainfalls, where continuous rainfall over a long period can
cause an accumulation of underground water flow that causes landslides [2–4], is one of the triggers for landslides. In general, Java Island is one of the mountain range islands in Indonesia, where this condition has the potential to cause landslides if heavy rains occur.

As a result of heavy rains on 27 November 2018, 10 landslide events occurred in Samigaluh, Kulonprogo on 28 November 2018 [5,6]. At an altitude of about 500 meters, Samigaluh is situated on the breccias rock, limestones, and alluvium [7]. Some parts located in the hilly and transition zones in the Kulon Progo area are categorized as very dense soil / soft rock (SC) types [8]. In northern Kulon Progo, the prevailing hilly topography would further increase the vulnerability of landslides in the future.

Figure 1. A case of a landslide event in Samigaluh, Kulon Progo on November 28, 2018 [6].

The Weather Research Forecasting (WRF), as one of numerical model implementation, is one method that is mostly used to predict heavy rain and landslide [9,10]. One of the reasons for the WRF model is that, given the relatively simple operation of the WRF model [11,12], and it can be used as a preventive measure for potential natural disasters and does not require complex infrastructure [13]. In other words, the WRF model can be used for landslide early warning applications in Indonesia.

Previous research [10] has shown variations in the behavior of heavy rainfall before landslides with three different Planetary Boundary Layer (PBL) schemes using the Weather Research Forecasting (WRF) model, namely: Yonsei University (YSU), Sin-Hong (SH), and Bougeault and Lacarrere (BL). The cloud formation that produced rainfall began at 10:00 LT, based on their study, and reached a peak at 13:00 LT. This starting time of rainfall producing clouds could be an early predictor of landslides occurring at 18:00 LT [14].

In the previous study [10], the parameter analyzed was only rainfall, without taking the soil conditions underneath into account [9]. The role of soil conditions in landslides is very significant in other studies as well. Soil moisture is the parameter that can be obtained in the WRF model output. In this research, apart from rainfall, the potential for soil moisture in the event of landslides was also analyzed.

2. Data and Methods
To simulate the local scale flow with PBL characteristics over the Kulon Progo area (denoted by “x” in Figure 2), the Advanced Research WRF (ARW) v. 4.1.2, 3D non-hydrostatic atmospheric mesoscale model is used in the present study. This analysis is a continuation of the previous study [10], with implementing a new PBL scenario. The Mellor-Yamada-Janjic (MYJ) scheme [15,16], which reflects local diffusion, is the PBL scheme considering the WRF model. So, there are two local schemes (MYJ [15,16] and BL [17]), one non-local scheme (YSU [18]), and one local and non-local scheme (SH [19]) in this study (Table 1). It is expected that the addition of this PBL scheme would increase the understanding of the role of local scale diffusion in cloud growth potential.
Table 1. Configuration of the WRF model.

| Description                  | Option                                      |
|------------------------------|---------------------------------------------|
| Dynamics                     | Non-hydrostatic                             |
| Input Data                   | Global Forecast System (GFS)                |
| Input Interval               | 6 h                                         |
| Grid size                    | D1: (123 x 48) x 34, D2: (109 x 76) x 34, D3: (97 x 91) x 34 |
| Resolution                   | D1: 9 x 9 km, D2: 3 x 3 km, D3: 1 x 1 km   |
| Map projection               | Mercator                                    |
| Integrated time step         | 30 s                                        |
| PBL schemes                  | YSU, MYJ, SH, and BL                        |
| Surface parameterization     | Noah land surface scheme                    |
| Microphysics                 | WRF Single Moment 6-class (WSM-6)           |
| Short wave radiation         | Rapid Radiative Transfer Model Global (RRTMG) scheme |
| Long wave radiation          | Rapid Radiative Transfer Model Global (RRTMG) scheme |
| Cumulus parameterization     | A new Tiedtke scheme (only for domain 1)    |

For high resolution model simulations, the WRF model is designed with three nested grids (9, 3 and 1 km) (Figure 2) and 34 vertical levels. The outer domain (D01) covers a larger region with a 9 km resolution and 123 x 48 grids. The second inner domain (D02) has a 3 km resolution with 109 x 76 grids, and the innermost domain (D03) has a 1 km resolution with 97 x 91 grids. The model is run using 0.25° x 0.25° six-hourly data from Global Forecast System (GFS) for the initial and boundary conditions.

Figure 2. Model domain study are used following Nuryanto et al. (2020) [10]. Study area are denoted by “x”.

The physical model options used are the new Tiedtke scheme [20,21] for convective parameterization for only D01, WRF single moment 6-class (WSM6) [22] for cloud microphysics, the Noah land surface model [23,24] for surface physics, Rapid radiative Transfer Model [25] for both long-wave and short-
wave radiation. The observational rainfall dataset used to compare with the WRF output are obtained from BPP Samigaluh rain gauge station, the nearest station located within the study area (denoted by “*” symbol, see Figure 3), that available in the Database Center of the Indonesian Agency for Meteorological Climatology and Geophysics (BMKG). Besides that, we use daily precipitation datasets from satellite observation is also used for model evaluations, i.e., the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) [26].

Besides comparing the model output with rainfall station data, a comparison is also made spatially with CHIRPS. A comparative analysis of the model output between the PBL schemes was also carried out to see the tendency of each scheme to the variables of rainfall and soil moisture. Comparisons were made both spatially and temporally. Temporal comparison is made by taking one of the points in the Samigaluh area.

3. Results and Discussions

An intercomparison of performance of various PBL parameterization schemes in simulating the diurnal variation of rainfall (mm) and satellite observation at daily intervals at the Samigaluh station is presented. A comparison of the spatial rainfall trends between the satellite and the deepest WRF domain (D03) model on 27 November 2018, is shown in Figure 3. It can be shown that the four PBL schemes have variations in rainfall patterns. In the northern part of Kulon Progo, the maximum precipitation in the model appears to be. On the other hand, the subdistrict of Samigaluh, which has undergone landslides, shows that the region has a reasonably high level of rainfall. In the four schemes, this is clear.

Figure 3. Comparison of rainfall simulation of WRF model using four PBL schemes with CHIRPS in 27 November 2018.

A very striking distinction from the four PBL schemes is that, relative to other schemes, the MYJ system appears to be higher in its northern border regions. This trend is quite similar to the BL method, which is both systems that reflect local circumstances. In the BL system, the rainfall patterns appear to be close to both the YSU and SH systems, with a minor variation in the area of the northern boundary where lower rainfall is given by the BL scheme.
Compared with the WRF model output data at the same site, Figure 4 shows the time series of daily rainfall at the observed Samigaluh station location (asterisks in Figure 3). Generally, it seems to illustrate that the WRF model appears to be inferior to the observational evidence. However, the MYJ and SH schemes seemed to be better on the two simulation days than the YSU and BL schemes. This also illustrates a disparity between MYJ and BL in answer to the local scheme, where MYJ has higher rainfall than BL. This also shows a difference in the response to the local scheme between MYJ and BL, where MYJ has higher rainfall than BL at the observation point.

![Rainfall distribution](image)

**Figure 4.** Daily rainfall distribution of four PBL schemes with observation station (*) as denoted in Figure 3.

For each PBL scheme, Figure 5 shows the ratio of soil moisture. Soil moisture appears to have a similar pattern at a depth of 10-200 cm. At the same time, there is a difference in the value of the soil moisture at the top layer (0 - 10 cm). This difference indicates that the falling rainfall will first affect the top layer soil moisture conditions. The same value is seen at the location of the observation point in Samigaluh. There is, however, a great contrast between each scheme at some other point.

In comparison to the characterization of precipitation events alone, soil moisture measurements provide a direct indicator of the infiltration, storage, and exfiltration processes [27]. Wicki *et al.* [27] addressed the representativeness of point scale soil moisture measurements for landslide activity on a regional scale. However, the actual landslide triggering mechanism, which is the localized rise in pore water pressure and decrease in matric suction, is still discussed in more detail.
Figure 5. Comparison of soil moisture simulation of WRF model each four PBL schemes in 27 Nov 2018.

A graph of accumulated rainfall against rainfall intensity on 27 November 2018, can be seen in Figure 6. It can be shown that the four PBL systems have different rainfall values. The SH scheme is the strongest answer, and then the MYJ scheme. This implies that compared to others, the SH system appears to have a reasonably high rainfall response. A similar pattern between YSU and BL schemes is also seen in the graph.

Figure 6. Comparison of the rainfall intensity – cumulative rainfall of each PBL schemes in 27 November 2018.
If a rainfall intensity threshold of 10 mm/hour is implemented, all schemes will be achieved. However, only the MYJ and SH schemes can be used as indicators if the threshold for rainfall intensity is 15 mm/hour. In addition, if the threshold is 20 mm / hour, then the extreme event is only eligible for the SH scheme.

Similarly, if the accumulated rainfall of 20 mm / day is taken as the threshold, then all schemes might agree. However, if 40 mm/day of cumulative rainfall is taken, it will be fulfilled only by the MYJ and SH schemes. Additionally, only the SH scheme can be used as a measure of severe events if the threshold of 45 mm/day accumulated rainfall is taken. The MYJ and SH schemes can be used as measures since the values 40 and 45 have a very small difference, and extreme events can be measured by accumulated precipitation of 40 mm/day.

In the four PBL schemes on 27 November 2018, Figure 7 shows the relation of the plot of rainfall intensity with rainfall accumulation. It can be shown that the BL scheme has a shorter rainfall intensity period of 1 mm/hour. It is heavy enough to reach 8 mm/hour, despite its short length. Unlike the BL scheme, the average rainfall intensity tends not to be too high in the YSU scheme, but there was a time when there was very heavy rain that exceeded 12 mm/hour.

In addition, there is a small difference in the pattern each time based on the function of higher rainfall intensity, namely the MYJ and SH schemes. But the MYJ scheme usually has a longer duration than the SH scheme. While it has a long duration, the MYJ scheme's cumulative rainfall is still lower than the SH scheme. This shows that heavy rain will still make a significant contribution to every day's rainfall accumulation.

Figure 7. Plot rainfall intensity and cumulative for each PBL schemes in 27 November 2018.
In general, it can be seen that at noon (13:00 LT), the time for the early warning of heavy rain that could potentially landslide begins. The long duration (≥6 hours) existed in the YSU and MYJ schemes, vice versa in the BL and SH schemes. This long period of rainfall is of no benefit in risk mitigation for early warning purposes. On the other hand, for early warning of landslides, a short period (<6 hours) of rainfall with a high rainfall accumulation would be very useful. However, it does not appear necessary because the anticipated scenario for the next 6 hours does not show an alarm phase exceeding. Hence, it does not detect an imminent alarm level as the previous study in Italy [28][27].

The SH scheme is very useful to use as an early warning predictor of landslides in terms of rainfall parameters since it is reinforced by heavy rainfall that tends to have a shorter period. It is not possible to generalize that it can be extended to another time or place. It should be remembered that this relates to the 28 November 2018 case analysis of landslides. Further research is required to identify and plan other landslides.

A time series plot of the soil moisture fraction at the position of Samigaluh is shown in Figure 8. In general, while there are minor variations, the temporal distribution of soil moisture values can be shown to have a similar pattern. The simple trend is that there was a surge in soil moisture at that location on 27 November 2018, 13:00 - 19:00 LT. Compared to the other two schemes, the MYJ and SH schemes again tend to be dominant in value.

4. Conclusions
Based on the results of WRF simulation for 73 hours from 26 – 29 November 2018, it shows the considerable soil moisture amounts during a landslide event in Samigaluh, Kulon Progo 28 November 2018. In order to understand each character, the four PBL parameters in the WRF model are compared, i.e., YSU, MYJ, SH, and BL. All parameters have, in general, an underestimation of precipitation. The response of any PBL parameter to rainfall is different. Both MYJ and SH schemes for day one and day two of simulation, daily precipitation, are closer to observation than others. Increased soil moisture is seen in all PBL schemes, indicating that the soil is wetter and more vulnerable to landslide events. The SH method is very useful in this study as an early warning indicator of landslides in terms of rainfall.
parameters. Although a short duration (<6 hours) of precipitation with a high accumulation of precipitation does not detect an imminent alarm level, it will be very useful for early warning of landslides.

5. References

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