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Sungkyunkwan University Environment and Remote Sensing Lab.

Applications of soil moisture for three-dimensional landslide thresholds

Seungcheol Oh[1], Jaehwan Jeong[2], Minha Choi[1,3*]

[1] School of Civil, Architectural Engineering & Landscape Architecture, Sungkyunkwan Univ., 2066 Seobu-ro, Jangan-gu, Suwon, Korea
[2] Center for Built Environment, Sungkyunkwan Univ., 2066 Seobu-ro, Jangan-gu, Suwon, Korea
[3] Dept. of Water Resources, Sungkyunkwan Univ., 2066 Seobu-ro, Jangan-gu, Suwon, Korea

INTRODUCTION

- Numerous studies have paid attention to the importance of hydrological variables (*e.g.*, precipitation, rainfall, groundwater, etc...).
- Above all, precipitation plays a key role since pore water pressure rise can lead to the reduction of slope stability (Campbell, 1975; Bogaard and Greco, 2016). Thus, many studies tried to determine the rainfall-driven threshold to figure out the landslide initiation conditions.
- Though rainfall-driven threshold (*e.g.*, Intensity-duration curve) is simple and straightforward, universal use has been constrained due to the site-specific features, such as hydraulic parameters, soil texture, and anthropogenic activities.
- Therefore, this study attempted to use soil moisture as additional variables for rainfall based thresholds.
- Daily precipitation from Global Precipitatio Measurement (GPM) IMERG Final-run and 3-hourly surface soil moisture from Global Land Data Assimilation System (GLDAS) L4 V2.1 were used to produce hydrological characteristics (*i.e.*, Antecedent Precipitation Index, 24-hr accumulated precipitation, antecedent soil moisture, daily-averaged soil moisture, and soil moisture increment).

STUDY AREA & DATASET

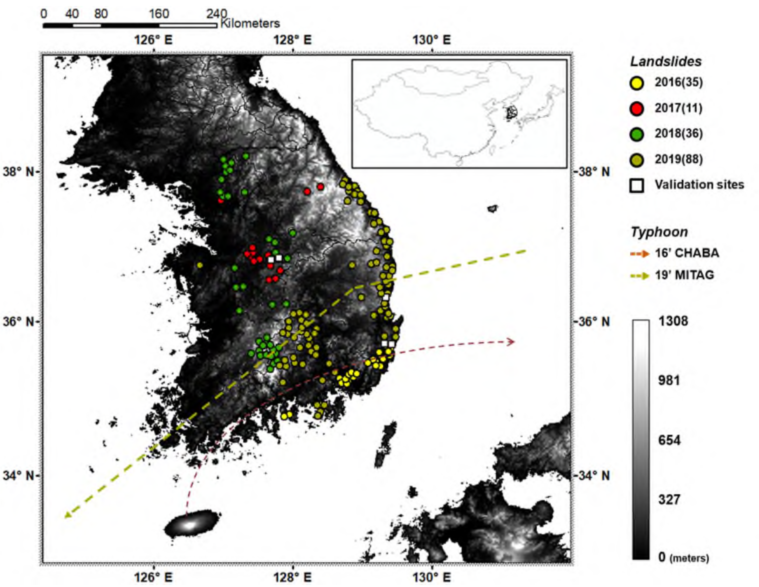

Fig. 1 Study area

- NASA GESDISC GLDAS L4 V2.1
- NASA, JAXA GPM-IMERG Final run

METHODOLOGY

Hydrological variables

$$API_{t+1} = \sum_{i=1}^{t} P_i k^{(t-i)} \quad (1)$$

$$\Delta SM = SM - SM_0 \quad (2)$$

- P is GPM-based 24-hr accumulated amount of precipitation. Antecedent Precipitation Index (API) was used for identifying the antecedent wetness conditions indirectly (Eq. 1). k is a decay factor, value of 0.84 (Li et al., 2021).
- SM is daily-averaged soil moisture. To observe the direct antecedent wetness conditions, Antecedent soil moisture (SM_0) was used (Eq. 2). Soil moisture increment (ΔSM) is a quantitative changes between soil moisture values. If the soil moisture increases compared to the previous day, ΔSM shows positive value.

Three-dimensional thresholds

- Three-dimensional landslide threshold appears in a planar form (Eq. 3)(Fig. 2).

$$f_{thr}(x, y, z): ax + by + cz + d = 0 \quad (3)$$

- If the variable is located above the plane at a certain point in time (Eq. 4), it is considered a state in which a landslide can occur.

$$f(Var_x, Var_y, Var_z) > f_{thr} \quad (4)$$

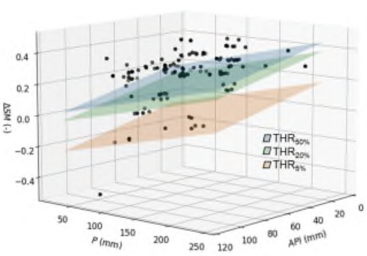

Fig. 2 Examples of three-dimensional threshold

RESULT & DISCUSSION

Two-dimensional analysis of corresponding variables

- First, for the analysis of landslide initation conditions, the correspondence between factors was analyzed in two-dimensions (Fig. 3). Left-hand side shows the overall positive correlation between API and SM_0. Since the external forces required for the initiation vary depending on the initial conditions (Zuoan et al., 2006), identifying these forces is necessary. Noted that 10 landslides occurred even at a low level of SM_0. Although high intensity precipitation can cause landslides even under relatively low SM, it is difficult to see P of less than 50 mm act as an external forces to destroy slope stability.
- Macroscopically, the increasing SM to P appears as logistic, positive correlations (right-hand side). The distribution of SM varies from 0.3 to 1.0, while that of P varies from 18 mm to 250 mm. Considering the outliers, P of 40 mm and 0.3 of SM were adopted as minimum requirements.

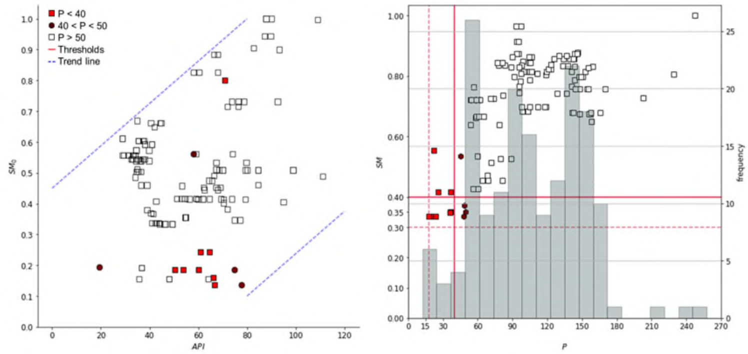

Fig. 3 Two-dimensional correspondence of variables. Scatterplots of (a) API with SM0 supplemented by P (b) P with SM

Determine three-dimensional landslide thresholds

- Fig.4 shows the least square regression based three-dimensional threshold. API, P and △SM were used as variables. Probability density function was used for conservative determination: 1) to prevent too many false alarms 2) to exclude the effects of outliers. In addition, thresholds obtained in Fig. 3 were used additionally (grey-colored plane).

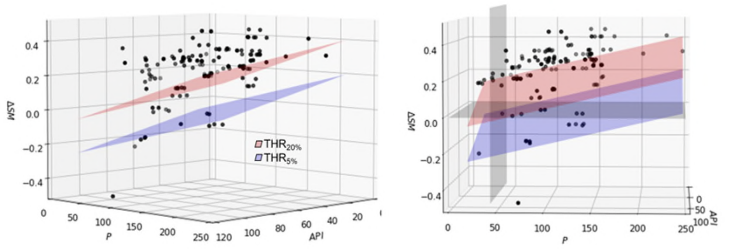

Fig. 4 Three-dimensional landslide threshold. API, P, and SM for x-, y-, and z-axis

Validation of suggested thresholds

- To validate the detecting capability of thresholds for landslide prediction and to determine the frequency of false alarms, time series analysis was performed (Fig. 5).
- The landslide that occurred in July 2017 was failed to detect, but that in August 2018 was successfully detected. However, in the case of the previous landslide, it is judged to be an outliers that occurred in P of less than 40 mm.
- There were 25 false alarms solely based on P threshold, while 22 (16) of false alarms occurred from $THR_{5\%}$ ($THR_{20\%}$), respectively. The false alarm showed a significant decrease when the three-dimensional threshold was used simultaneously.

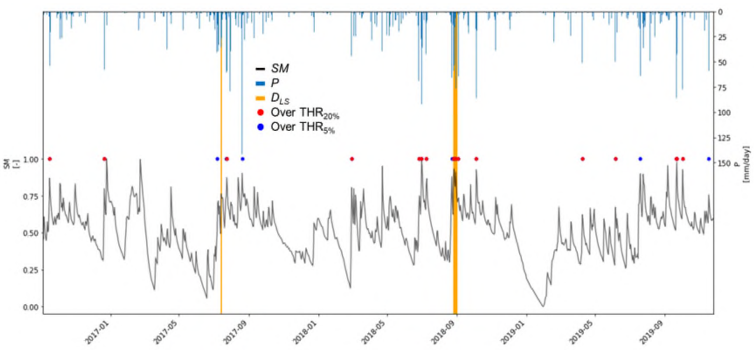

Fig. 5. Time-series analysis for validation of three-dimensional threshold

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