京都大学防災研究所年報　第 52 号 B　平成 21 年 6 月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 52 B, 2009

Study on Early Warning System for Shallow Landslides in the Upper Citarum River catchment, Indonesia

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Synopsis

In this study we focus on water-induced landslides in the Upper Citarum River catchment aiming for development of a shallow landslides early warning system. The method combining two necessary components to identify shallow landslides potential: (i) a time-invariant spatial distribution of the land surface susceptible to slope instability, where the catchment area is characterized into stability classes according to the critical relative soil saturation, designed to portray the effect quasi-static of land surface factors on shallow landsliding, and (ii) the produced map is then linked with spatiotemporal varying hydrologic and soil strength properties to provide a time-varying estimate of slope movement susceptibility in response to rainwater. Coping with real-time satellite-derived rainfall products, the applicability of hydrological-slope stability model for real-time flood and landslide forecasting at the catchment scale could be explored.

Keywords: Shallow landslides, sediment, hydrology, slope stability, early warning, Citarum River.

1. Introduction

Geographical location of Indonesia causes most of the islands have experiencing with high rainfall and numerous active volcanoes. Having those characteristics, Indonesia is found to have high vulnerability to various natural disasters such as flood, various landslide types, droughts, earthquake, tsunami, and volcano eruption. Flood and landslides as the most widespread natural hazard cause casualties and millions of dollars in property damages almost annually. As the population increases and the social society become more complex, the economic and social cost of flood associated landslides will continue to rise unless there is a significant intervention and action. Indonesian Government has several policies and strategic plans for natural disasters preparedness and mitigation by promoting structural and non structural measures program.

The Upper Citarum River catchment, West Java is one of the persistently active landslides occurring in Indonesia. The flood triggering landslides are hit almost in every year and caused extensive damages. Hydrologic characteristics have been changed by land degradation (Agus *et al*., 2003), as a result, flood, debris flow and others landslide types are very frequent during the rainy season. The soils derived from volcanic tuff are easily erodible and prone to landslides. As suggested by field investigation, the type of landslide occurrence mainly is rapid shallow landslides (debris flow). According to the Geological Agency of Indonesia, since 1990 over 250 big landslides reported to have occurred there. Catchment erosion is also a serious problem in the upper river catchment where hillsides are steep. Shallow landsliding, as a form of mass movement, is one of the sources of hillslope erosion and catchment sediment yield. Therefore, there was an urgent need to devise countermeasure against frequent disasters. Herein, a new and innovative technology related disaster warning system as one of the most effective ways of nonstructural measures to minimize the damages caused by water-induced disasters could be introduced. As there is no operational integrated flood-landslides forecasting and warning system in place in the Upper Citarum River catchment, this study focuses on development a hybrid physically-based distributed hydrological and slope stability models as well as to explore its application using near real-time satellite-derived rainfall products for hydrological estimation and shallow landslide forecasting or warning system. This paper describes the preliminary results of this study on early warning system development.

2. Study Area

The Citarum River catchment is the largest river on the West Java Island. Total area of the Upper Citarum Catchment is around 2,283 km^2. The 269 kilometers Citarum River originates from Wayang Mountain with elevation of 2198 m above mean sea level south Bandung. In the first 25 km, the river follows a steep slope of 0.033 then flows onto the middle part of the basin with slope of 0.0033 starting at Bandung for another 169 km. In the lower parts, the river meanders across an alluvial plain for about 75 km before reaching the Java Sea. There are three cascading reservoirs in the Citarum river basin namely Saguling, Cirata and Jatiluhur. Those reservoirs are built not only for generating hydropower, water supply for irrigation, industrial and domestic but also uses to regulate and traps of sediment. Geomorphology of the catchment consists of volcanic cone, Tuff, Tuff Sand, Lapili, Breccia Aglomerat, Breccia and lahar, Breccia, Lava Andesit, Tuff Breccia lahar, and lava, Andesit and Dasit.

Based on the record of Meteorology and Geophysical Agency, the Citarum River catchment has an average monthly temperature of 22.8 to 26^{o}C, average annual rainfall of 1500 – 4000 mm, average monthly wind speed about 2 to 9 knot and average monthly evaporation rate between 120 mm to 150 mm. The population in the Upper Citarum catchment is rapidly growing with the urban area expanding around Bandung, the capital of West Java. In the upper Citarum River catchment, there are 12 river sub catchments which have very steep slopes flow into upstream of Citarum River. Flood and associated landslides are frequent during the rainy season. Figure 1 shows the whole Citarum catchment area and spatial distribution of the investigated landslides history according the data collected from the Geological Agency of Indonesia.

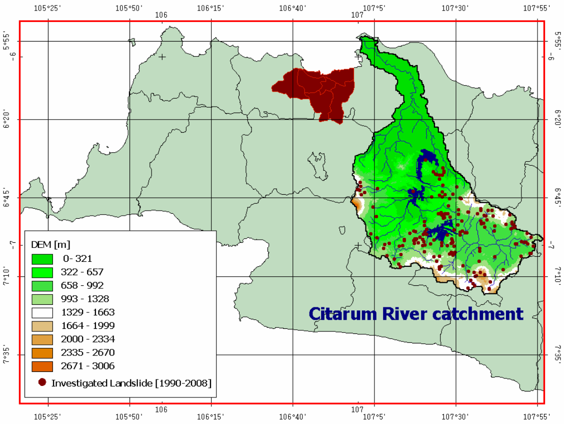


Fig.1 The map of Citarum River catchment and investigated landslide sites (1985-2008).

3. Past Landslide Events

Landsliding can be triggered by a variety of mechanism such as heavy rain, rapid runoff at hilly slopes, flash flood, erosion, rapid melting of volcanic debris during eruption, and earthquake. Two triggering thresholds that relate to different time scale need to be considered namely an antecedent rainfall threshold and a storm intensity duration threshold. These two thresholds can indicate a different level of potential hazards.

Landslide failures typically occur on steep slope and when rainfall infiltrates through a block of soil. The block of soil gradually saturates, pore water pressure increase and the shear strength decrease. Landslide problems can be caused also by land mismanagement, particularly in mountain, like upstream Citarum River catchment.

In areas burned by forest and brush fires, a lower threshold of precipitation may initiate landslides. Land-use zoning, professional inspections, and proper design can minimize many landslide, mudflow, and debris flow problems. A complete prediction of the shallow landslides process would include assessments of “where”, “when”, and “how big”. There are some factors which usually controlling landslides namely, rainfall, earthquake, volcanic eruption, vegetation, geological condition, and morphology.

The characteristics of landslides in Indonesia can be categorized into first is slow movement, creeping and no causalities but large damaged area and second is rapid movement with rock, earth, and debris flows with causalities and large numbers of damaged. From data collection, there is several landslides disaster induced by heavy rainfall in the Upper Citarum River catchment.

1. Landslide disaster in West Java at Cikalong Wetan, Bandung District on 16 September 2003 that caused at least 13 peoples feared dead and 7 homes have been swept away by the landslide.
2. Landslide disaster in West Java at Cililin, Walahir village on 21st of April 2004 that caused at least 15 peoples dead, 43 houses collapsed and heavy damaged, 60 Ha of paddy fields and more than 70 goats have been swept away by the landslides. This landslide mainly is due to very steep slope, high weathering products, land-use changed and high intensity of rainfall.
3. Landslide disaster in West Java at Leuwigajah, Cimahi on 21 February 2005 that caused at least 123 peoples are dead and 70 homes have been flattened by the landslide.
4. Landslide disaster in West Java at Rongga, Bandung District on 3 March 2005 that caused at least 2 peoples dead and a car overturned and dragged along the river.
5. Landslide disaster in West Java at Cikembang Village, on 16 March 2008 that caused at least 2 people dead and 48 homes were damaged by debris flow.

4. Rainfall thresholds

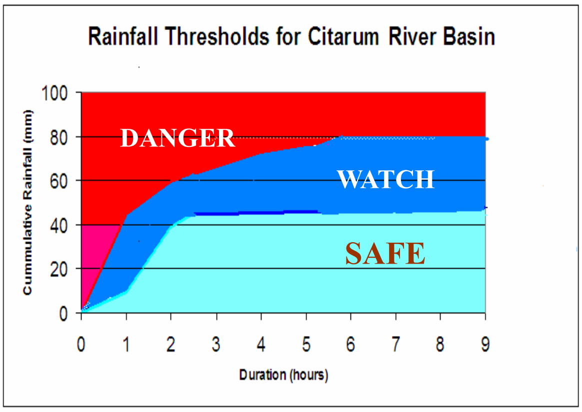


Fig. 2 Rainfall thresholds-triggered landslides for the Citarum River catchment.

To know when shallow landslides are likely to occur, an antecedent rainfall and storm intensity duration thresholds needs to be developed. Observed landslides data from 2003 to 2005 and rainfall data monitoring are used as references to develop rainfall thresholds in the Upper Citarum River catchment. Observations of daily rainfall at the closest stations to landslide locations are selected. The rainfall distribution patterns of Bandung Hourly Automatic Rainfall Station are used for disaggregating the daily rainfall data of the selected rainfall stations. The plots of the relationships between rainfall durations and cumulative rainfalls at each date of landslides occurred can be constructed and analyzed for developing rainfall thresholds and the results can be seen in Figure 2. This rainfall intensity duration thresholds can be used to indicate different levels of potential hazards. A lower threshold identified a rainfall level below which significant shallow landslides hazards are considered unlikely, and above which shallow landslides are likely. An upper threshold represents a rainfall level above which abundant landslide large enough to destroy infrastructures.

5. Landslide Susceptibility

The second step is creating a susceptibility map based on geology, soil, slope, land use and rainfall information. The susceptibility maps were created through an iterative process from two kinds of information. Firstly is quasi-static map which consist of land use map, geology map, slope map, distribution of soil movement and landslide image. Secondly is dynamic map which consist of rainfall map, earthquake, or eruption of volcano. By analyses of GIS, those maps can be superimposed so that the resultant maps of relative susceptibility represent the best estimate generated from available inventory data can be produced.

Time-Invariant Shallow Landslide Susceptibility Map Using Factor of Safety

Engineering geologists often use the relationship between shear stress (the component of stress that operates in the down-slope direction, τ) and shear strength (the properties that resist shear stress, i.e., cohesion + normal stress (S)) to carry out a slope stability analysis. The ratio of shear strength to shear stress is called the factor of safety (*FS*). For modeling shallow landslides the simplified case of a planar failure on an infinite slope is generally accepted and the *FS* is calculated by Equation 1 (Montgomery and Dietrich, 1994). When this ratio is greater than 1, shear strength is greater than shear stress and the slope is considered stable. When this ratio is close to 1, shear strength is nearly equal to shear stress and the slope is unstable.

$$FS = \frac{C + \cos\theta\left[1 - r_w\right]\tan\phi}{\sin\theta};\begin{cases} C = \dfrac{C_r + C_s}{H\rho_s g} \\ r_w = \dfrac{h_w \rho_w}{H\rho_s} \end{cases} \qquad (1)$$

in which C_r and C_s is the effective root and soil cohesion; ϕ is the effective angle of internal of soil; H is the soil depth; h_w is the saturated depth; θ is the slope angle; ρ_s is the mass density of soil at field moisture; ρ_w is the weight density of water. Most of are can be spatially variable but it is assumed that only m ($=h_w/H$) is time-varying, therefore, the factor of *FS* is a function of m. Assuming that the value of every term in Equation 1, except for m, is known or can be estimated for each local area/grid, a critical relative saturated depth for a grid m^c can be determined, where $m^c_i = FS_i^{-1}(1)$ (see Figure 3 and Equation 2).

$$m^c = \frac{h^c_w}{H} = \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right) + \frac{C_r + C_s}{H\rho_w g\cos\theta\tan\phi} \qquad (2)$$

Based upon the concept of critical soil saturation, three slope stability classes can be defined:

1. Theoretically always stable which is expressed by

$$\tan\theta < \tan\phi\left(1 - \frac{\rho_w}{\rho_s}\right) + \frac{C_r + C_s}{H\rho_s g\cos\theta} \qquad (3)$$

2. Theoretically always unstable, is expressed by

$$\tan\theta \geq \tan\phi + \frac{C_r + C_s}{H\rho_s g\cos\theta} \qquad (4)$$

3. Potentially stable or unstable, predicted by Equation (1)

Land surfaces theoretically always stable are those predicted to be stable even when saturated as well as slope elements theoretically always unstable are those predicted to be unstable even when dry condition.

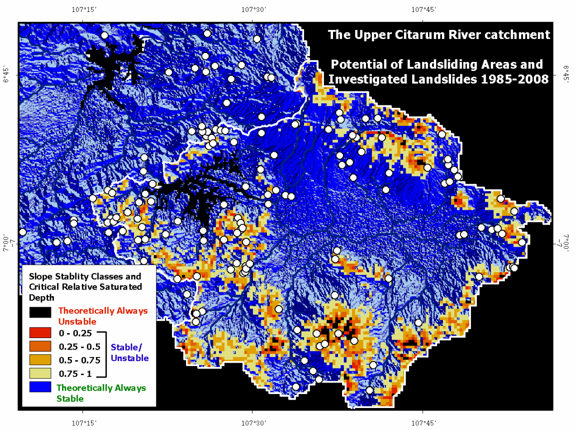


Fig. 3 Landslide susceptibility map based on static land surface factors compared to the spatial distribution of investigated landslides (1985-2008).

Applied the model to the past landslides historical data, the time-invariant landsliding susceptibility map shows good agreement in covering the spatial patterns of investigated landslide history (1985-2008).

Assessing Dynamic Map of Shallow Landslide Susceptibility Using Hydrological and Slope Stability Models

On shallow landslide occurrence, soil moisture plays an important control; increased soil water content increases the shear stress or decreases the shear strength of the soil mass. Therefore, an accurate estimation of rainfall on slopes and calculation of the dynamic sub-surface water flows are the important factors in prediction of landslide susceptibility. The combined physically-based distributed hydrological model (including soil erosion and sediment transport) and slope stability model has been developed by authors. The hydrological model considers three principal water flux pathways within a catchment: subsurface flow through unsaturated flow (capillary pore), subsurface flow through saturated flow (non-capillary pore), and surface overland flow. The soil water amount calculated with its model is then used for slope stability analysis. Herein, the factors of safety, which represents the ratio of shear strength to shear stress of soil mass, are used to characterize slope stability. Slopes having safety factors smaller than one are considered unstable.

The National Oceanic and Atmospheric Administration (NOAA), USA, provided global precipitation data at very high spatial and temporal resolution. NOAA-QPC Morphing Technique (QMORPH) rainfall estimates are available within 3 hours of real time and available on a grid with a spacing of 8 km. These data are then used in combination with the global coverage data sets of land surface characteristics (e.g., land use, DEM) from hydroSHEDS (http://hydrosheds.cr.usgs.gov/).

In this study, the integrated application of the QMORPH-based satellite precipitation estimation and a hybrid hydrological-geotechnical modeling system is addressed. In addition, the goal is establishing shallow landslides and sediment disasters early warning systems based on real time satellite data.

A physically-based distributed hydrological and erosion-sediment transport model has been developed to determine the dynamic of soil moisture, runoff hydrograph and sedimentation graph (Apip *et al*, 2008). This model was used as tool to predict m^c at any locations inside study site (Figure 4). As further stage, the failure condition for each grid square can be written in terms of the time-varying relative saturated depth: for $m_i \le m_i^c$, the slope is safe; and for $m_i > m_i^c$, the slope is unsafe.

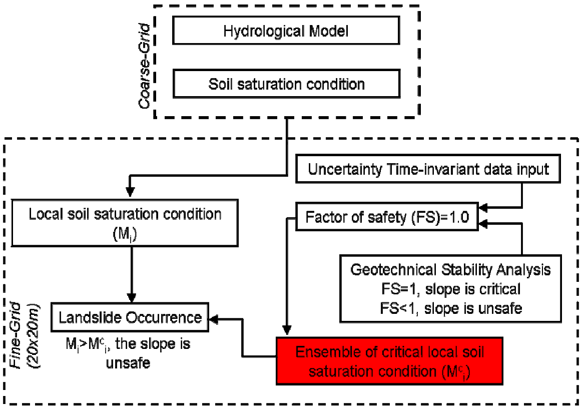


Fig. 4 Methodology for spatiotemporal dynamics of landslide potential prediction.

The application of the system for a past shallow landslides shows that the model successfully predict the effect of the rainfall movement and intensity on spatiotemporal dynamics of hydrological variables-triggered shallow landslides (Figure 5). The warning could be issued several hours before timing of landsliding initiation. In addition, the performance of the hydrological model shows good agreement in reproducing observed streamflow discharge at the catchment outlet (Figure 6). These results show that the potential exists for application of the system in improving the lead-time of disseminating shallow landslide disaster warning.

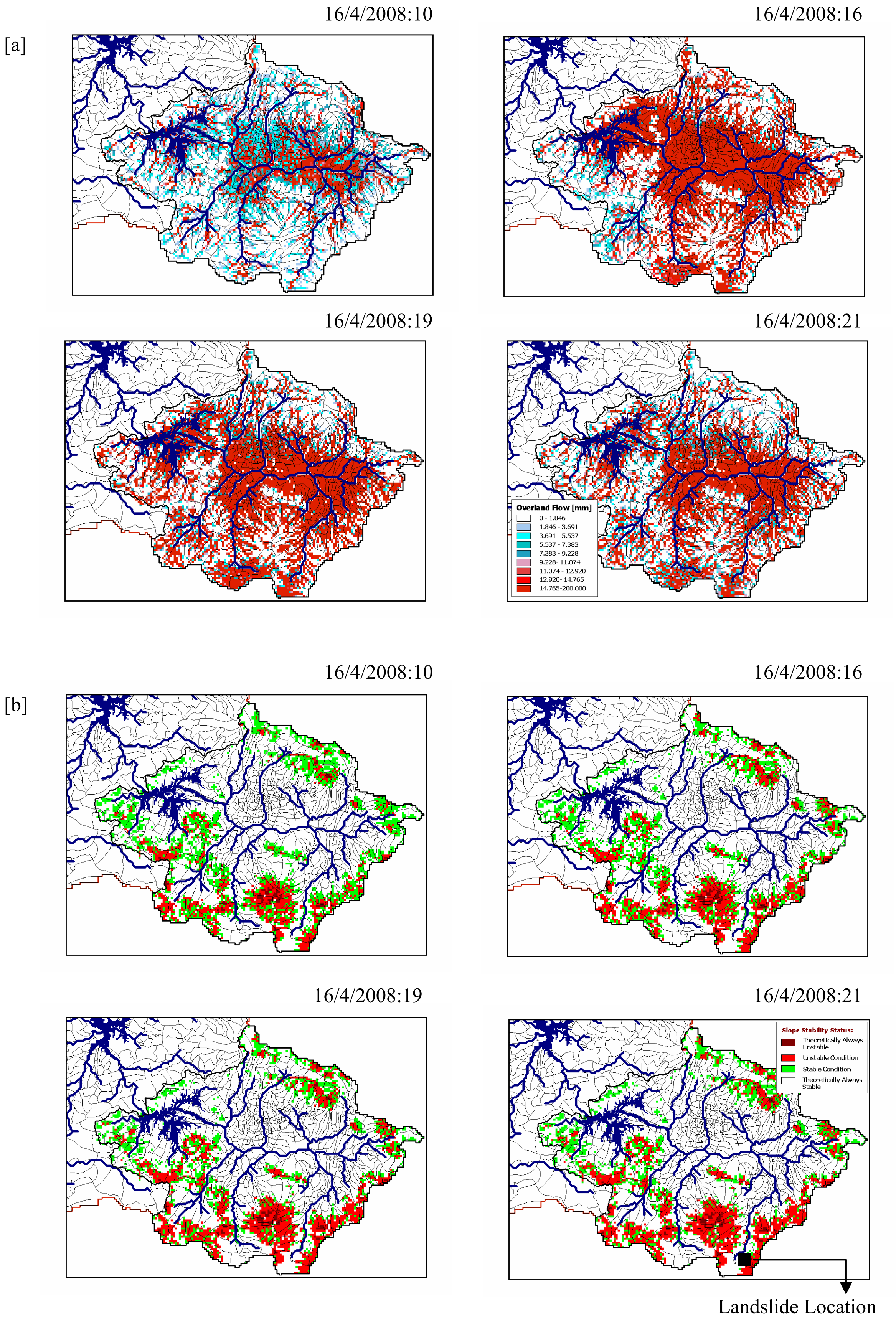
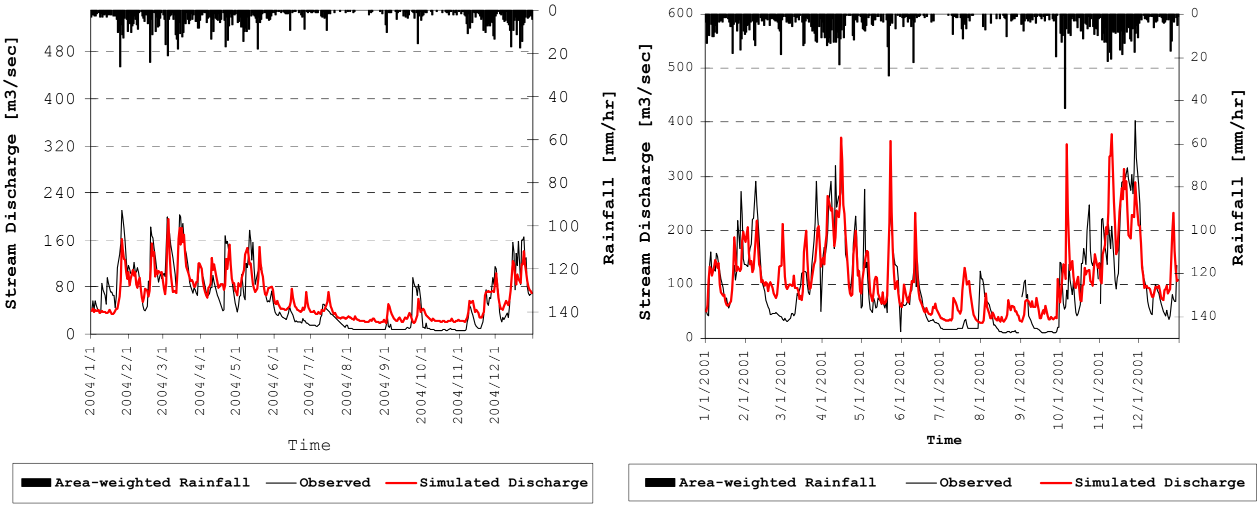


Fig. 5 Spatiotemporal dynamics of (a) the saturated excess overland flow and (b) slope stability condition for Cikembang's landslide in response to CMORPH satellite-based rainfall estimates on March 2008.



[a] [b]

Fig. 6 Hydrological model performance for (a) calibration (NSE=0.752) and (b) validation (NSE=0.617) periods. Streamflow discharges are evaluated at the catchment outlet.

6. Predictions of Shallow Landslide, Debris Flow, and Sediment Yield

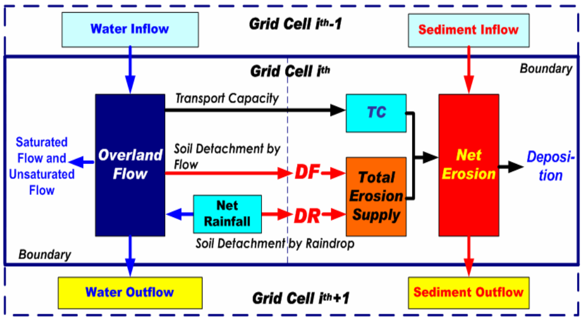


Fig. 7 Schematic diagram of the physically-based distributed sediment runoff model within a grid-cell scale.

As first stage of the model development, physically- based distributed sediment runoff model has been developed to determine hydrologic and sediment yield components generated from any temporally-spatially varied rainfall event or continuous rainfall data input (Apip *et al*, 2008). The modeling approach is deterministic, physically-based, empirical, spatially distributed and dynamical in time. Dynamic spatial of water movements, erosion patterns and sediment rates can be predicted at any location inside the catchment as well. The concept of physically-based distributed sediment runoff modeling is shown in Figure 7. A sediment transport algorithm is newly added to the rainfall runoff model. Sediment runoff simulation can be divided in two parallel phases: runoff generation and soil detachment.

Splash and flow erosion models as well as sediment transport models are incorporated to the distributed rainfall-runoff model (Morgan *et al*, 1998). It includes multiple sources of soil erosion, namely soil detachment by raindrop (*DR*) and hydraulic detachment or deposition driven by overland flow (*DF*). Soil detachment processes at interrill and rill are implicitly simulated as raindrop splash and flow detachment respectively. The erosion and deposition rates are calculated as a function of the hydraulic properties of the flow, the physical properties of the soil and the surface characteristic. The detachment by raindrop *DR* is a function of the energy imparted to the soil surface by the individual drops. The basic assumption of this model is that the sediment is transported and yielded when overland flow occurs. The transport capacity of overland flow also has to be specified to simulate sediment transport processes.

Integrating this model with the shallow landslide information (spatial water, sediment, and rock movements) will allow for making prediction system on sediment yields, landslide susceptibility map, and real-time forecasting (see Figure 8).

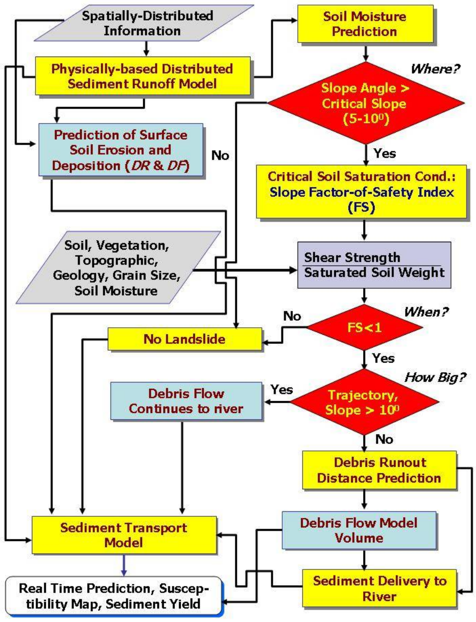


Fig. 8 Hydrologic-shallow landslide-debris flow conceptual model.

7. Real-Time Early Warning System

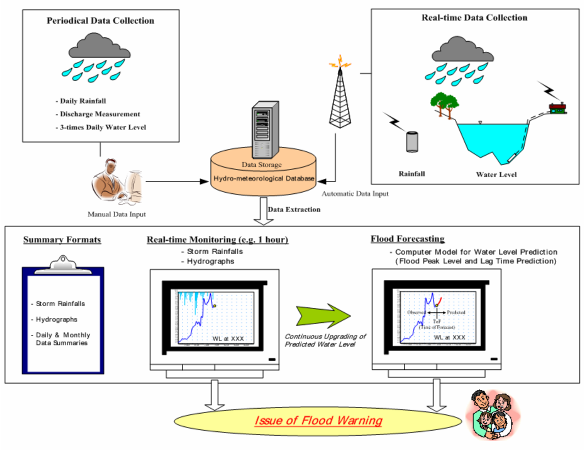


Fig. 9 The activities required for the flood associated landslides forecasting and warning.

The general procedures and activities required for the flood and shallow landslide forecasting and warning operations can be seen in Figure 9. All activities should be undertaken promptly utilizing the most up-to-date and reliable data and information. The Citarum River Flood and Shallow Landslide Forecasting and Warning System (FDFWS) should comprise a computerized database system for the storage/retrieval of hydrometeorological data, the computerized shallow landslide forecasting procedure and ground movement data. The latter will be linked to the database storage system only to the extent that it will access data in continuous real-time which is being transferred from the established hydro-meteorological network of rainfall, water level monitoring sites and ground movement monitoring sites.

Conclusions

1. Debris flow and landslides always occur every year in the Upper Citarum River catchment. The upper Citarum River basin has high susceptibility of debris flow-landslides.
2. The satellite-based rainfall products are capable of detecting a particular rainfall event within the Upper Citarum River catchment. Distributed hydrological model can reproduce the hydrograph well.
3. The spatial distribution of investigated landslides history is capable represented by slope stability model
4. Integrated distributed hydrological-slope stability models and near real-time satellite-derived rainfall estimates represents the effect of the rainfall movement and intensity on spatiotemporal dynamics of hydrological variables triggering shallow landslides.
5. More accurate (quantitatively) and high-resolution data are necessary for reasonable flood and landslide predictions.
6. With real-time satellite-derived rainfall products, the hydrological-slope stability model could be examined for applicability of real-time flood and landslide forecasting at the catchment scale.

Acknowledgment

This study was supported by the MEXT Coordination Fund for Promotion of Science and Technology, Japan Science and Technology Agency (PI: Prof. Kaoru Takara, DPRI, Kyoto Univ.).

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インドネシア・チタラム川上流域の表層崩壊早期警戒システムに関する研究

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要　旨

表層崩壊早期警戒システムの開発のためインドネシア・チタラム川上流域の水誘因の斜面災害の研究を行った。適用した手法においては表層崩壊可能性を同定するために必要な以下の二つの要素を統合している。（1）斜面不安定性に影響を及ぼす斜面表層の空間分布（時間不変）：ここでは表層崩壊に対する斜面表層要素の準静的効果を明瞭にするために相対土壌飽和度臨界値に従って流域を安定性階級ごとに分類を行なった。（2）作成されたマップは降雨に対する斜面流動鋭敏性の時間変動を推定するために時空間変動する水文学的そして土壌強度特性に関連づけられる。衛星から得られる実時間降雨情報を用いて，流域レベルで実時間洪水と土砂災害予報のための水文学的斜面安定モデルの適用性を検討する事が可能である。

キーワード: 表層崩壊，土砂，水文学，斜面安定性，早期警戒システム，チタラム川