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Watershed Response from Design and Threshold Rainfalls Leading to Cascading Effects of Landslide

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ABSTRACT

Mountainous watersheds are prone to earthquakes and extreme precipitation events causing slope failures leading to landslides and landslide dams. These events negatively affect the river channels and the water storage capacity of streams and reservoirs. With the increasing water demand, sustainable development on water sufficiency has been receiving a lot of attention, and acquiring a comprehensive watershed runoff is necessary. The main objective of this research is to determine the watershed response in Antamok River using different designs and threshold rainfalls through hydrologic modeling. The hydrologic modeling process utilized the Hydrologic Engineering Center – Hydrologic Modelling System (HEC-HMS) software. The watershed response from the rainfall event that triggers landslide is quantified as 509.931 m^3/s which is, as expected based on the intensities far below the flows from the design storms which are as follows; 1645.744 m^3/s for 5-year, 2028.355 m^3/s for 10-year, 2511.654 m^3/s for 25-year, 2869.767 m^3/s for 50-year, and 3224.789 m^3/s for 100-year.

Keywords
landslide, reservoir, watershed, runoff, hydrologic modeling

Introduction

Common to mountainous watersheds, such as Antamok River Watershed, earthquakes, and intense rainfall events induce slope failures leading to landslide events damming the streams (Niu et al., 2012 and Takayama et al., 2021). Once the failure of the dam occurred, the primary affected will be those downstream (Fan et al., 2020). Moreover, these sediment movements result in partial or complete blockage once it reaches the river channel (Yang et al., 2020). On the recent issues on water storage capacity, reservoir siltation is one of the issues receiving increasing attention (Espa et al., 2019). Another threat to water resources is the negative impacts of flash floods which are an overwhelming natural risk (Niyazi et al., 2020). Asia has had a growing number of dam constructions over the past years due to rising energy and water demand (Zhang et al., 2020). These events have been shown to reduce watershed connectivity affecting the quality of water, flow patterns, and sediments (Zhai et al., 2010 and Zhang et al., 2020). Due to sedimentation, there has been an annual decrease by about 0.5% to 1.0% in the capacity of the global reservoir storage which poses a worldwide threat to the sustainability of reservoirs (Ren et al., 2021).

Intense rainfall are leading to the cascading effects of landslide (He et al., 2016 and Hu et al., 2016) which poses a serious threat from the severe flow of debris and flash flooding (Yang et al., 2020; Zhang et al., 2020; and Takayama et al., 2021). During flood season, the majority of sediment transport occurs (Guo et al., 2020). Hence, understanding sedimentation could improve river capacity and reduce the negative impacts on the neighboring ecology (Aziz et al., 2021). Rainfall and landslides are common in the Philippines with an average of twenty typhoons entering its area of responsibility (Ternate et al., 2017) which is given in a range of 965 to 4064 milliliters of rainfall (Cruz et al., 2019).

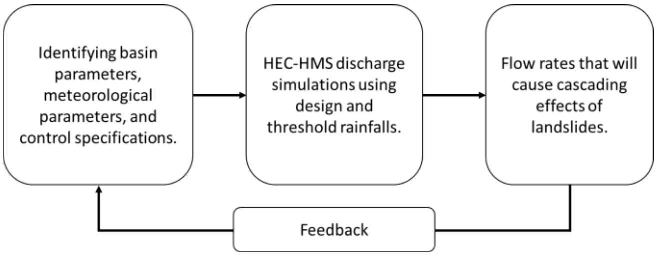

Figure 1: Research Paradigm of the Study

The Philippines has been a hotbed of disasters that leads to life loss, property damage, and economic loss (Alfredo Mahar et al., 2017). The growing negative effects of these disasters on both local and global socioeconomic systems pique increasing attention to the need for environmental management and disaster risk reduction (Cuaton & Su, 2020). In achieving this sustainable development, sufficient water availability is vital, and acquiring comprehensive watershed data is needed (Gumindoga et al., 2017). Assessing the watershed response remains the focus of the hydrologic sciences. In line with this, this paper quantified the runoffs in Antomok River using 5, 10, 25, 50, and 100-year return periods and the rainfall threshold leading to cascading effects of rainfall-triggered landslides that could potentially reduce the carrying capacities of rivers and reservoirs.

Methodology

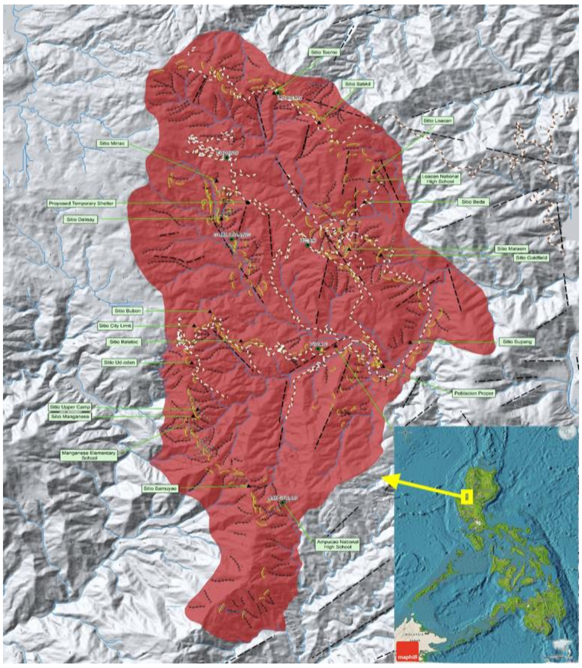

Figure 2: Antamok River, Itogon, Benguet

Description of the study area

The paper focused on Antamok River Watershed, Benguet, Philippines as the main study area. With this, all the information within its boundaries and adjacent locations was covered for the data gathering and collection. Benguet Province is a mountainous region receiving the highest 24-hours rainfall occurrences which tend to result in frequent rainfall-induced landslides (Nolasco-Javier & Kumar, 2018). Based on a recent study, Benguet has a site-specific rainfall threshold having an intensity-duration (ID) equation of $I = 16.659D^{-0.3309}$. This rainfall threshold implies that a landslide will be triggered in the study area with a rainfall of 140mm for a 24-hour duration (Caisip et al., 2022).

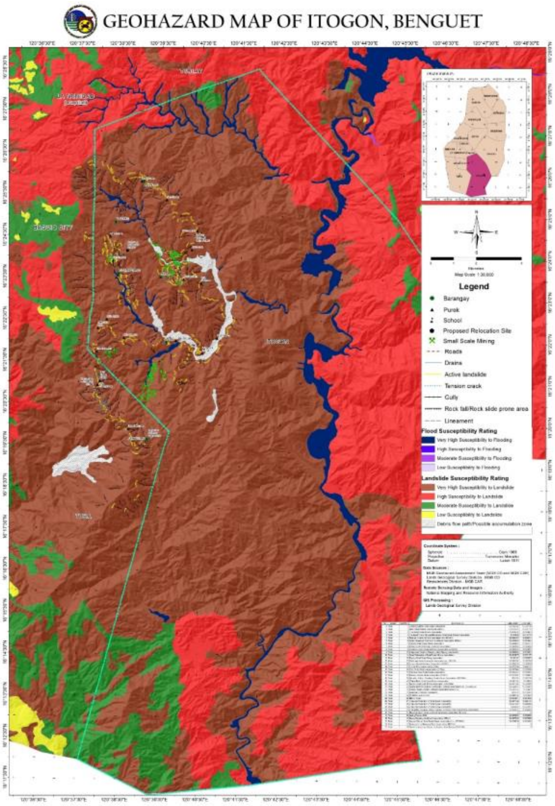

Figure 3: Geohazard Map of Itogon Benguet, from MGB Geohazard Assessment Team.

Figure 3 classifies polygons (areas of Itogon Benguet) into Low Susceptibility to Flood, Moderate Susceptibility to Flood, High Susceptibility to Flood, and Very High Susceptibility to Flood. Similarly, with a landslide (Low, Medium, High, and Very High). It can be perceived from the map that the majority of the study area has a very high susceptibility to landslide events.

Modeling

The hydrologic modeling process utilized the Hydrologic Engineering Center – Hydrologic Modelling System (HEC-HMS) software. The IfSAR (Interferometric Synthetic Aperture Radar) spatial data which includes both DTM (digital terrain model) and DSM (digital surface model) were acquired. (DENR-NAMRIA, 2013) which offers three-dimensional elevation data with a high solution of 5-m spatial data. These data were incorporated into the GIS software where the preprocessing was performed using the HEC-GeoHMS extension. After Hydrologic Parameters Estimation, the basin model was incorporated into HEC-HMS followed by Hydrologic Modelling System Processes. For this study, the following model was used for the corresponding methods (Azam et al., 2017). SCS was used for the Loss Method. Clark was used for Transform Method. The recession was used for Baseflow Method, and Muskingum-Cunge was used for Route Method.

Simulation

For the watershed response, the rainfall data were incorporated into the meteorological model which is considered one of the primary inputs. Under the meteorological model, frequency storm was selected for the precipitation with a storm duration of one (1) day, an intensity duration of one (1) hour, and an intensity position of 75 percent. For each set-up, the meteorological data using the RIDF for 5, 10, 25, 50, and 100-year return periods and the rainfall threshold were used. The Rainfall Intensity-Duration Frequency (RIDF) curves for 5, 10, 25, 50, and 100-year return periods for the watershed of Antamok River were gathered through coordination with the Hydro-Meteorology Division of Philippine Atmospheric, Geophysical and Astronomical Services and Administration (PAGASA).

The location of the landslides was identified through the use of the data provided by the Department of Public Work and Highways (DPWH), Mines and Geosciences Bureau (MGB), and the National Disaster Risk Reduction and Management Council's (NDRRMC) archive of landslides in Benguet province. Control specification, another main component, will dictate the start time, the end time, and the time interval of the simulation. The time steps were set to 15 mins. The same time frame and time interval for all the cases and for both control specification and time-series data were used. After entering all the required data, under compute, six (6) simulation runs were created. These runs simulated the model and compute the watershed response or the discharge using the six (6) meteorological models. The model was used for the different designs and threshold rainfall to get the runoff that will cause cascading effects of landslides.

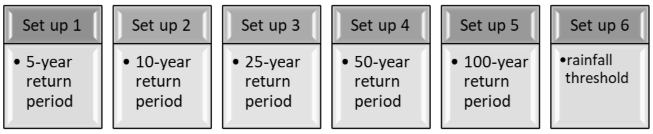

Figure 4: Different simulation set-ups

Results and Discussions

Hydrologic modeling

The basin was developed using ArcGIS software, HEC-GeoHMS Preprocessing. It uses SCS Curve number for Loss, Clark Unit Hydrograph for Transform, Recession for Baseflow, Muskingum-Cunge for Routing, and outlet coordinates are 16º23'2.57'' N and 120º43'20.30'' E.

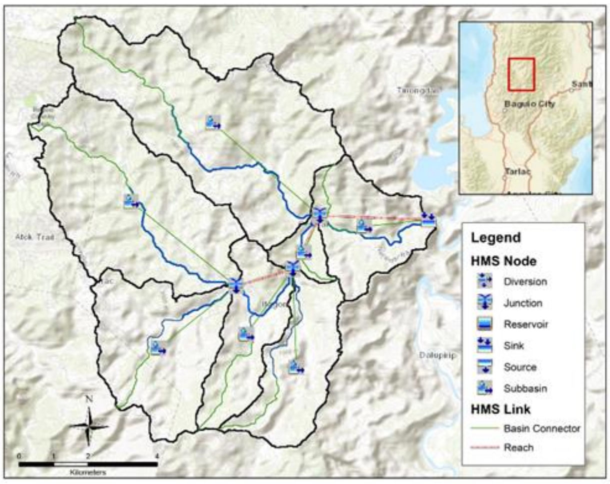

Figure 5: Delineated HEC-HMS watershed boundary for Itogon, Benguet

HMS simulation

The basin model contains nine (9) subbasins, four (4) reaches, four (4) junctions, and one (1) outlet. The control specification was set for 1.5 days which start and end dates being September 1, 2018, and September 2, 2018, 00:00 and 12:00, respectively, and 15 minutes time intervals. Both basin model and control specifications are constant for the six (6) runs.

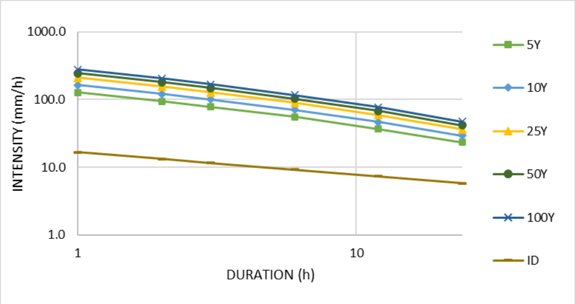

Figure 6: Equivalent Average Intensity (in mm/hr) of Computed Extreme Values for 5Y, 10Y, 25Y, 50Y, and 100Y Return Periods and the ID Threshold.

The meteorological model component uses frequency storm with one (1) day storm duration, one (1) hour intensity duration, and 75% intensity position. Rainfall depth for 1 hour, 2 hours, 3 hours, 6 hours, 12 hours, and 24 hours durations were entered using RIDF 5-year return period for the 1st run, 10-year return period for the 2nd run, 25-year return period for the 3rd run, 50-year return period for the 4th run, 100-year return period for the 5th run, and the ID threshold rainfall amount for the 6th run. This leads to having six (6) different meteorological models and simulation runs. In obtaining a steeper receding limb, the ratio to peak could be adjusted. The possible values for Ratio to Peak are between 0.0001 and 1 (MAPUA-DOST Framer Project and HEC-HMS Manual). These values were supported by the Disaster Risk and Exposure Assessment for Mitigation (DREAM) Project and Light Detection and Ranging Technology – Philippines (Phil-LiDAR) surveys and flood mapping on various rivers in the Philippines. The Ratio to Peak was adjusted to 0.010 and the recession limb goes back to its baseflow. This value is within the recommended range and similar to Pandana River, 0.017, and Ilang-Ilang River, 0.015 which are of similar properties.

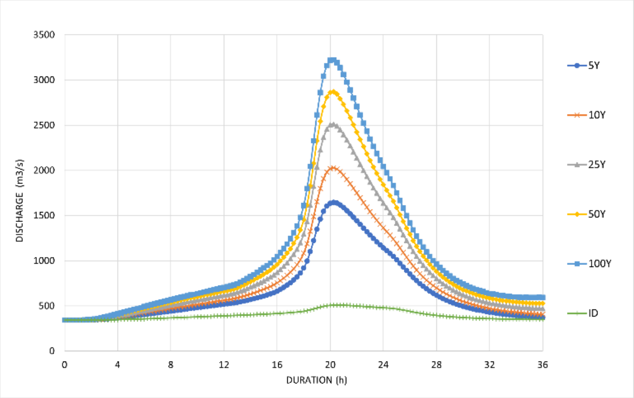

Figure 7: Watershed response from different designs and threshold rainfalls. HMS Simulation Output: Time-Series of Total Flow of Outlet.

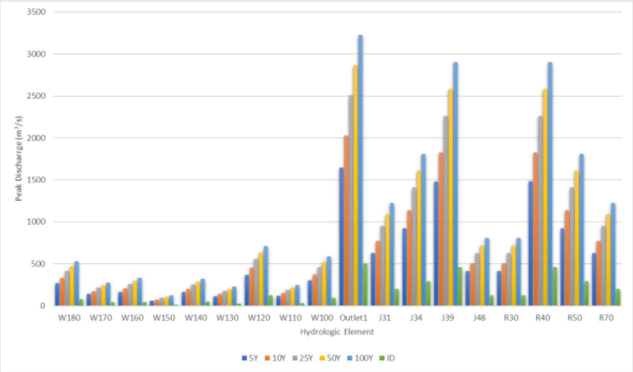

Figure 8: Watershed response from different designs and threshold rainfalls. HMS Simulation Output: Peak Discharge of the Hydrologic Elements.

Watershed response

Discharges from 5-year, 10-year, 25-year, 50-year, and 100-year rain events follow the same trend with a longer return period higher than the other. While the flow from the rainfall triggering landslide was way lower than the designed rain events. This can be verified from the Intensity Comparisons of the different design and threshold rainfalls which follows the same relationship. The lowest flow was caused by the derived rainfall threshold could be due to the soil type of the study area, Bakakeng clay, and Halsema clay loam, which have low permeability, hence, lower intensity of rainfall is needed for a landslide to occur (Abancó et al., 2020). Additionally, according to studies (Khan et al., 2017 and Khan et al., 2019), the exposure of these clay soil types to wet-dry cycles many repeated times may reduce the shear strength and the presence of cracks might alter the hydraulic conductivity which will make them prone to landsliding. Moreover, the intense mining activities and urbanization of the area also influence the slope susceptibility which could easily trigger landslides with lower rainfall intensity (Nolasco-Javier & Kumar, 2018).

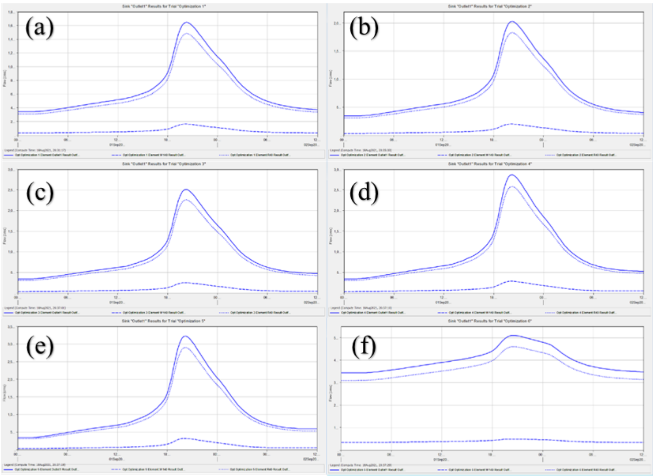

Figure 9: Hydrograph of the Outlet (a) using 5-year design rain, (b) using 10-year design rain, (c) using 25-year design rain, (d) using 50-year design rain, (e) using 100-year design rain, (f) using ID threshold for Benguet.

Conclusions and Recommendations

In water management, hydrology models are vital tools as they can calculate streamflow and assess future trends under different climate change scenarios (Zhang et al., 2020). Utilizing the commonly used design rainfalls in hydrological studies and water resources engineering design, together with the intensity-duration rainfall threshold of $I = 16.659D^{-0.3309}$, six set-ups were simulated in determining runoffs at 16º23’02.6” N, 120º43’20.3’E on Antamok River Watershed, Benguet, Philippines.

The generated runoffs are as follows; 1645.744 m^3/s for the 5-year return period, 2028.355 m^3/s for the 10-year return period, 2511.654 m^3/s for the 25-year return period, 2869.767 m^3/s for 50-year return period, and 3224.789 m^3/s for the 100-year return period. The watershed response from a rainfall event that triggers a landslide is quantified as 509.931 m^3/s which is, as expected based on the intensities, far below the flows from design storms. These could be caused by the low permeability of the soil type of the study area (Abancó et al., 2020). When clay type of soil is exposed to a repeated cycle of wet-dry, shear strength may be lowered and cracks might appear altering the hydraulic conductivity making them susceptible to landsliding. (Khan et al., 2017 and Khan et al., 2019). Finally, rapid urbanization and mining activities also impact the slope susceptibility causing a lower intensity of rainfall to easily trigger landslides (Nolasco-Javier & Kumar, 2018).

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