PREDICTION OF SEDIMENT TRANSPORT PROCESSES IN THE UPPER KINTA RIVER BASIN, MALAYSIA

Siti Adabiyah binti Sulaiman*
MEE21734

Supervisor: Prof. EGASHIRA Shinji**
Assoc. Prof. HARADA Daisuke***
Prof. SUGAHARA Masaru****

ABSTRACT

Understanding sediment transport processes and sediment supply from slopes is essential for river basin management. To specify sediment supply conditions from slopes, this study investigated the occurrence of landslides upstream of the Kinta Dam basin using slope stability analysis. The results showed that landslides occur mainly adjacent to river channels and roads, which affects the sediment supply to the river channel. Subsequently, the sediment transport process in the river basin was evaluated to investigate the effect of landslide on reservoir sedimentation. The computation was conducted for two cases: Case 1 was for the current drainage condition with sediment supplied from the landslide, and Case 2 was for the virtual drainage condition without landslides. The results showed that fine sediment generated from landslides was actively transported to the reservoir throughout the year, causing bed degradation where coarse sediment remained in the channel. Fine sediment transported from upstream accumulated in the dam with landslides, and the sediment yielded double in volume.

Keywords: landslide, sediment transport, reservoir sedimentation, basin scale model, Kinta Dam

INTRODUCTION

In a river basin, sediment is supplied upstream and transported downstream. Sediment may be deposited along the channel or accumulated in an impounded reach, such as a reservoir. Sediments are naturally supplied by geomorphic processes, such as rock weathering, landslides and debris flow. However, landslide occurrences in a river basin may be triggered by land use changes, such as the construction of roads in hilly areas. In Malaysia, roads are commonly constructed in hilly terrain by cutting out forests, and eventually, such actions create slopes with a gradient of more than 30°. Artificially created slopes are therefore susceptible to shallow landslides. In view of landslide risk to road users, the Public Works Department in Malaysia has examined the hazard and risk of landslide on federal highways using a statistical approach to classify the slope into five classes, i.e. very high, high, medium, low and very low. Landslide occurrence was investigated using the relationship between rainfall runoff and a slope stability model. The model simulates the infiltration of rainfall into the subsurface and surface layers of the soil and how it affects slope stability.

Sediments are generally transported via bed and suspended loads. Commonly studies have been conducted based on individual aspects of sediment transport, but not on the linkage at the drainage basin scale. The relationship between sediment transported from upstream to downstream of the river basin, aggradation, and degradation of bed variation is vital for river basin management.

***** Civil Engineer, Public Works Department, Malaysia.
** Adjunct Professor, GRIPS
*** Adjunct Associate Professor, GRIPS
**** Professor, GRIPS

In this study, numerical computation was used to study the sediment transport process together with the rainfall runoff process. The phenomenon of sediment transportation was then linked with the estimation of basin-scale reservoir sedimentation. Dams and reservoirs are important structures for water management. Dams are constructed for various uses, such as hydropower generation, flood control, and water supply for domestic and industrial applications. However, sediment deposition in a reservoir affects the storage capacity and eventually the design lifespan of the dam (Abedini et al., 2012). Therefore, predicting sediment deposition in reservoirs is critical for managing reservoir storage.

This study discusses sediment transport processes in drainage basins and the influence of sediment supply due to landslides on sediment transport processes using a slope stability model, a rainfall runoff model, and a sediment runoff process model. Focusing on reservoir sedimentation in drainage basin, the impact of sediment supply due to landslides on sediment transport processes is investigated based on the results obtained from numerical computations for two cases: a present drainage condition with sediment supplied from a landslide and a condition without sediment from landslides.

THEORY AND METHODOLOGY

i. Slope stability model

Figure 1 shows a schematic of the subsurface and surface flows formed along a slope in relation to rainfall. Subsurface flow occurs when it exceeds the critical moisture content, where surface flow occurs when subsurface flow exceeds the depth of the surface soil layer (Yamazaki et al., 2016).

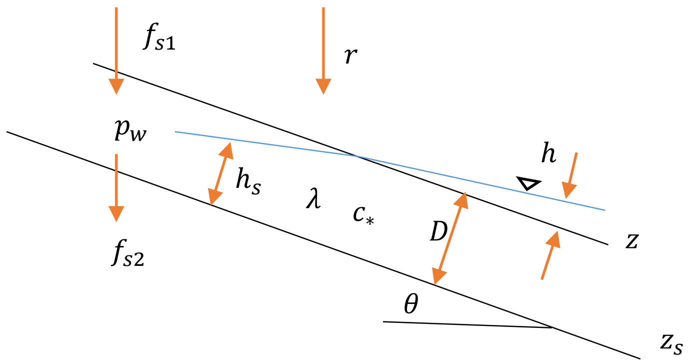

Figure 1. Schematic diagram of surface soil layer and water flow on a slope.

Where,
r : rainfall
p_w: moisture content of surface soil
h_s : subsurface flow depth
h : surface flow depth
θ : local maximum gradient
D : surface soil depth
λ : porosity of surface soil
c_* : sediment concentration of surface soil
f_{s1}: infiltration rate of surface layer
f_{s2}: infiltration rate from surface to lower layer

The condition for the occurrence of landslides is determined by a balance equation of forces acting on the control volume specified on an infinitely long slope. The forces consist of gravitational and resistance force. The resistance force was evaluated using cohesion and Coulomb shear stress, including the buoyancy force. The threshold condition resulting from the forces in relation to gradient θ is:

$$\tan\theta_c = \frac{\left\{\left(\frac{\sigma}{\rho}-\frac{h_s}{D}\right)c_* + \left(1-\frac{h_s}{D}\right)p_w\right\}\tan\phi + \frac{c}{\rho g D\cos\theta}}{\left(\frac{\sigma}{\rho}-\frac{h_s}{D}\right)c_* + \left(1-\frac{h_s}{D}\right)p_w\left(\frac{h_s+h}{D}\right)} \tag{1}$$

Where,
θ_c: critical gradient for an occurrence of landslide, σ : mass density of soil particles, ρ : mass density of water, ϕ : internal friction angle, c : cohesion, D : surface soil depth, c_* : sediment concentration of surface soil.

ii. Sediment transport processes model

The sediment transport process prediction is a combination of the rainfall runoff process model and the sediment transport model. In the rainfall runoff model, the flow per unit slope was calculated using the 2D diffusive wave model and Darcy's law. Furthermore, the flows in the unit channel were evaluated using 1D continuity equation and diffusive wave model (Sayama et al., 2012).

$$\frac{\partial h^{i,j}}{\partial t} + \frac{q_x^{i-1,j} - q_x^{i,j}}{\Delta x} + \frac{q_y^{i,j-1} - q_y^{i,j}}{\Delta y} = r^{i,j} - f^{i,j} \tag{2}$$

$$q_x = \begin{cases} -k_a h \frac{\partial H}{\partial x}, & (h \le d_a) \\ -\frac{1}{n}(h - d_a)^{\frac{5}{3}} \frac{\partial H}{\partial x} \frac{1}{i^{1/2}} - k_a h \frac{\partial H}{\partial x}, & (d_a < h) \end{cases} \tag{3}$$

$$q_y = \begin{cases} -k_a h \frac{\partial H}{\partial y}, & (h \le d_a) \\ -\frac{1}{n}(h - d_a)^{\frac{5}{3}} \frac{\partial H}{\partial y} \frac{1}{i^{1/2}} - k_a h \frac{\partial H}{\partial y}, & (d_a < h) \end{cases} \tag{4}$$

where $q_x^{i,j}$ and $q_y^{i,j}$ are the x and y components of the water flux in unit width at the grid cell at (i,j), k_a is the lateral saturated hydraulic conductivity, d_a is the soil depth multiplied by the effective porosity, and i is defined as $i = [(\partial H / \partial x)^2 + (\partial H / \partial y)^2]^{1/2}$.

The governing equations for the sediment transport process constitute the mass conservation equations of the bed load formula and mass conservation of suspended load. The mass conservation equation of bed sediment in unit channels (Figure 2) can be described as follows (Egashira et al., 2008):

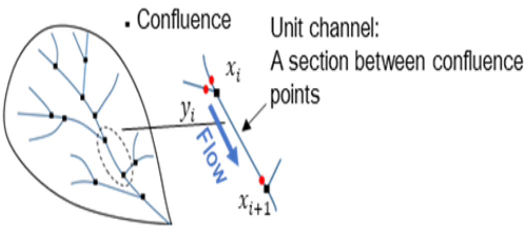

Figure 2. Concept of unit channel.

$$(1-\lambda)\frac{\partial Z_{b(x(i+1))}}{\partial t} = \frac{1}{B_{(x(i+1))}L_{(x(i+1))}}\left\{\sum_j Q_{bj(xi)} + Q_{bj(yi)} - Q_{bj(x(i+1))}\right\} + \sum_j \left(D_{sj(x(i+1))} - E_{sj(x(i+1))}\right) \tag{5}$$

where,

λ: porosity of bed sediment, Z_b: river bed elevation, $B_{(x(i+1))}$: unit channel width, $L_{(x(i+1))}$: unit channel length, $Q_{bj(xi)}$, $Q_{bj(yi)}$: bed load discharges of size class-j sediment from xi and yi transported to the unit channel, $Q_{bj(x(i+1))}$: bed load discharge of size class-j sediment flowing out from the unit channel, $D_{sj(x(i+1))}$: deposition rate of size class-j suspended sediment, $E_{sj(x(i+1))}$: erosion rate of size class-j suspended sediment. In addition, the mass conservation equation of suspended sediment is simplified as follows:

$$\frac{\partial c_{j(x(i+1))}h_{(x(i+1))}}{\partial t} = \frac{1}{B_{(x(i+1))}L_{(x(i+1))}}\left\{\sum_j Q_{sj(xi)} + Q_{sj(yi)} - Q_{sj(x(i+1))}\right\} - D_{sj(x(i+1))} + E_{sj(x(i+1))} \tag{6}$$

where,

c_j: sediment concentration of size class-j, h: flow depth of unit channel, $Q_{sj(xi)}$, $Q_{sj(yi)}$: suspended load discharges of size class-j sediment from xi and yi transported to the unit channel, $Q_{sj(x(i+1))}$: suspended load discharge of size class-j sediment flowing out from the unit channel.

DATA

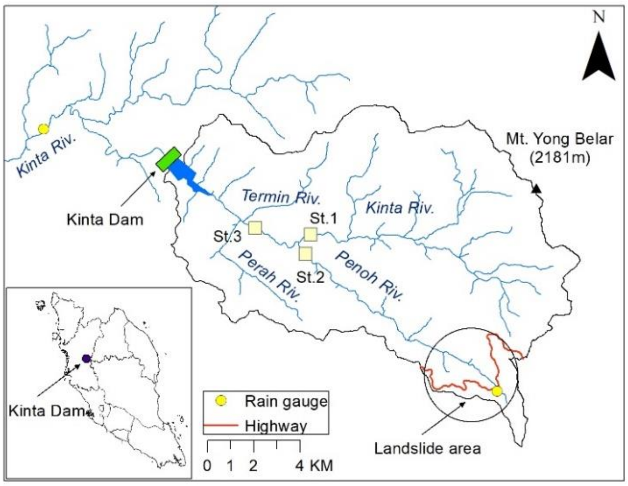

Figure 3. The location of the Kinta Dam basin.

The location of the Kinta Dam basin is illustrated in Figure 3. It is in the state of Perak, Malaysia, and drains an area of 150 km^2. The study area was separated into two regions. The first was upstream of the Kinta Dam, where a slope stability analysis was performed. The parameters employed in the stability analysis were as follows:

Area	9 km^2
Grid	10 m × 10 m
Soil depth	1 m
Sediment concentration	0.6
Porosity	0.4
Cohesion	5 kN/m^2
Critical water content	0.1

The second was the Kinta Dam basin. We used 450 m grid topography data for sediment transport analysis. The simulation was performed for data collected in 2013, and the flow discharge was calculated using the Rainfall Runoff Inundation (RRI) model followed by sediment transport analysis. The simulation was carried out by calibrating the calculated volume of sediment in the dam with the recorded sediment deposited in the Kinta Dam. Additionally, the sediment concentration between the two rivers, Kinta and Penoh River, was also used for calibration. The data were based on the Global Environment Centre (GEC) 2020 report.

RESULTS AND DISCUSSION

Figures 4 and 5 represent the calculated discharge at 3 km downstream of the landslide location and the accumulated number of unstable meshes resulting from stability computation for landslides in the target area, respectively. The number of unstable meshes for landslides was based on an area of 100 m^2 and did not represent the actual number. Figure 4 suggests that rainfall accumulated in the surface soil layer until 0400h on January 24. It discharged rapidly after 1600h and reached a peak discharge at 0400h on January 25. When the rainfall stopped, the discharge decreased. The simulated peak discharge was approximately 7.5 m^3/s. Figure 5 illustrates that the number of unstable meshes increased after 1600h on January 24 and stabilized after 0800h January 25. Figure 6 shows the spatial distribution of unstable meshes for shallow landslides. This suggests that the meshes for shallow landslides were located along the road and adjacent to the river channel.

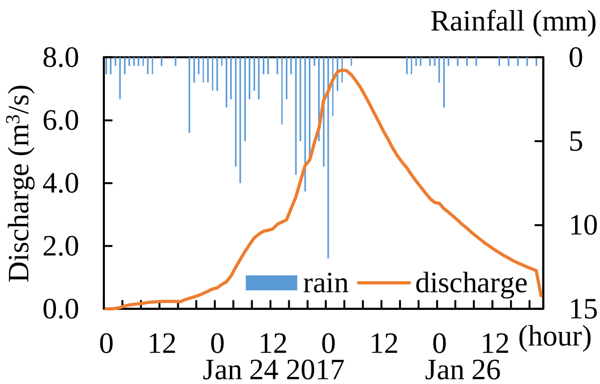

Figure 5. Target rainfall and discharge on 23 -26 Jan.

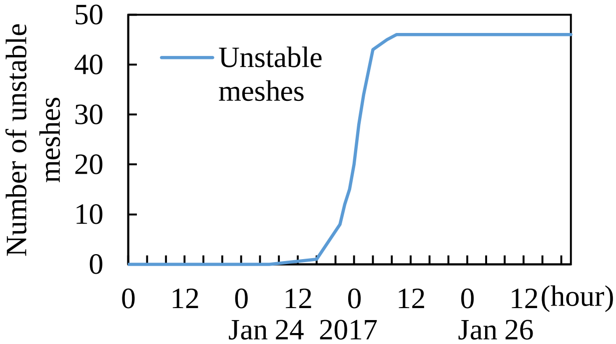

Figure 4. Temporal change in cumulative number of meshes with landslide.

This location indicates the man-made slopes created from area profiling for road construction. The gradient ranged from 41 to 60°. The occurrence of landslides in this target area caused sediment deposition in the river channel as the slope inclined towards the river.

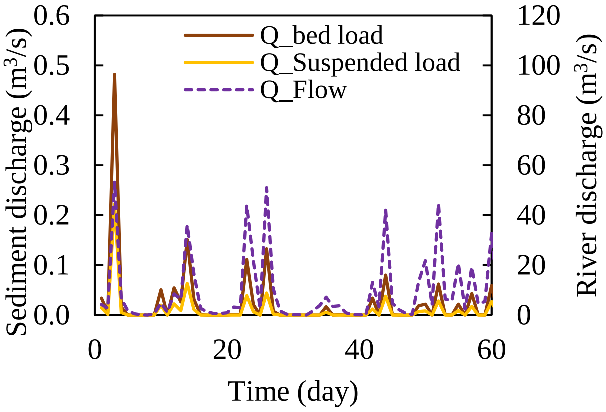

Figure 7. Flow and sediment discharge in St.3 Confluence.

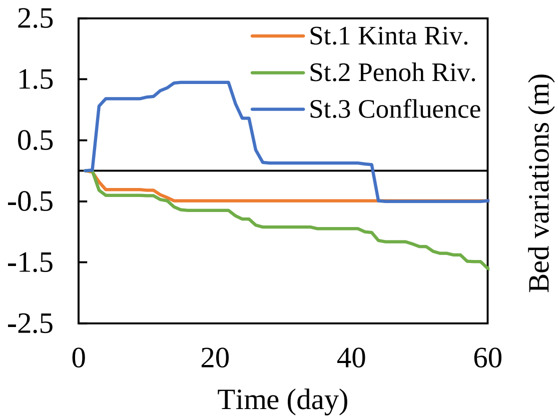

Figure 9. Temporal change of bed variations for 3 locations.

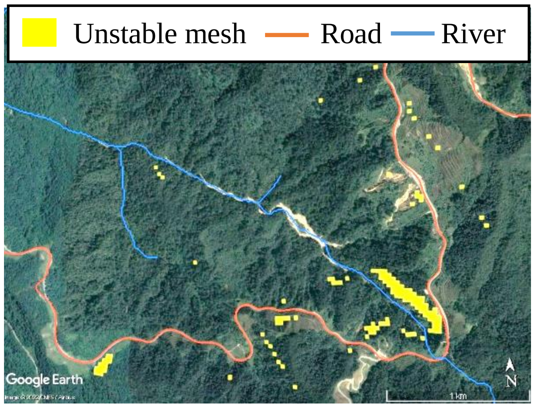

Figure 6. Spatial distribution of meshes with landslide.

Figure 7 indicates the temporal flow change and sediment discharge calculated by the model at Station 3 Confluence. During the first peak discharge, the sediment transport was higher than that at the following peaks. This implies that the transportation of fine particles originating from the slope was very active at the beginning and subsequently decreased as finer particles moved out. In addition, the results showed that sediment was transported mainly via bed load rather than suspended load, which was induced by a steep bed slope and shallow flow depth.

Figure 8 shows the temporal changes in bed variation for the three locations in the Kinta Dam Basin. It was predicted that the bed was eroded in Kinta and Penoh River, as channels consisting of fine particles are easily transported. Fine sediment carried from the two rivers was deposited at the confluence, as shown in the early stage, and experiences erosion in later stages as sediment inflow was reduced. Figure 9 shows the temporal grain size distribution of the river bed materials at the three locations. This shows that the grain distribution shifted from fine to coarse sediments in all three locations. This is proportional to the erosion process that occurs in the channel. Fine sediment was transported and the coarse sediment was retained.

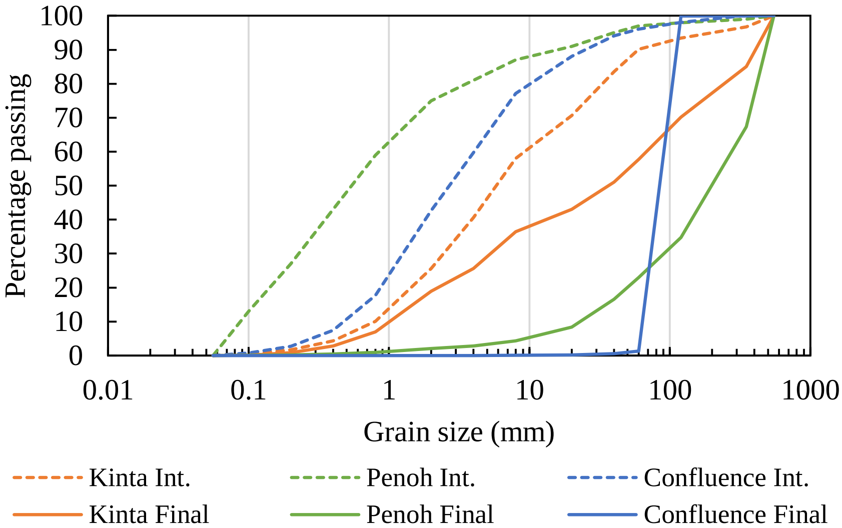

Figure 8. Grain size distribution in 3 locations.

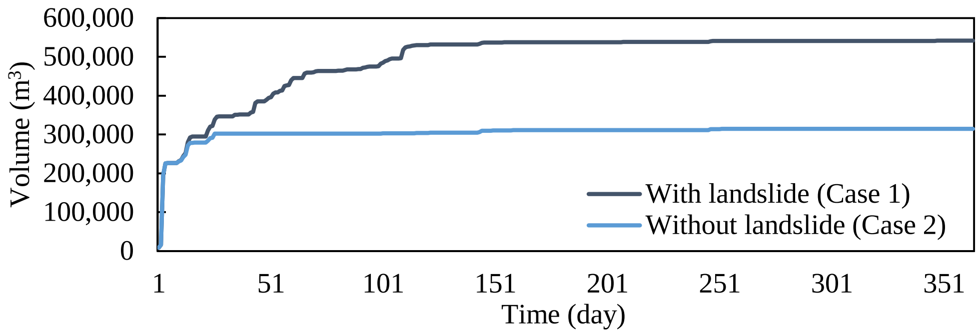

Figure 10. Temporal change of sediment deposited in Kinta dam for 2 cases.

Figure 10 shows the temporal change in the accumulated sediment runoff volume computed in the Kinta Dam for the two cases. The first case simulated the present condition with sediment supplied from a landslide, while the second case assumed that all the slopes in the basin were intact and did not supply sediment to the channel. Both cases showed that the sediment accumulated gradually at the beginning and staggered at a later stage. The influence of landslides on sediment runoff could be observed from this result. The fine sediments supply from the landslide increased the runoff volume twofold. With this trend, the reservoir storage capacity would be reduced twice faster than the design lifespan.

CONCLUSION AND RECOMMENDATION

This study proposed a modification of the rainfall-sediment runoff model by incorporating the sediment supply due to landslides, which enabled us to evaluate the impact of landslides on sediment transport processes. The model showed that the Kinta Dam basin mainly consisted of fine sediment particles rather than coarser particles as attributes of sediment eroded from landslides. With a steep bed slope, fine sediment was transported downstream and accumulated in the dam. Therefore, any upstream landslide would increase the supply to the channel and quickly decrease the dam capacity. Additionally, as the study suggests that roads increase the potential hazard of landslides, the author recommends that integrated river basin management should include road managers to reduce the impact of landslides on river basins.

ACKNOWLEDGEMENTS

The author would like to thank Professor Shinji Egashira and Associate Professor Daisuke Harada for their continuous support and excellent supervision during this research. Further gratitude to the International Centre for Water Hazard and Risk Management (ICHARM) for the golden opportunity to complete the master’s program at this institution.

REFERENCES

Abedini, M., Said, M.A.M, Ahmad, F.2012. Effectiveness of check dam to control soil erosion in a tropical catchment (The Ulu Kinta Basin). *Catena*, 63-70.

Egashira, S., Itoh, T., Horie, K., Nishimoto, N. 2008. A method to predict sediment transport process in drainage basin with dams. *River, Coastal and Estuarine Morphodynamics: RCEM 2007-Dohmen-Jansses & Hulscher (eds)*, 1193-1201.

Sayama T., Ozawa G., Kawakami T, Nabesaka S., Fukami K. (2012) Rainfall-Runoff-Inundation analysis of the 2010 Pakistan flood in the Kabul River basin. *Hydrological Science Journal*, 57(2), 298-312.

Yamazaki, Y., Egashira, S., Iwami, Y. 2016. Method to Develop Critical Rainfall Conditions for Occurences of Sediment-Induced Disasters and to Identify Areas Prone to Landslides. *Journal of Disaster Research*, 11 (6): 1103-1111.