Numerical Analysis of Riverbed Adjustment Processes in Response to Massive Landslide Sediment Input: A Case Study of Laishe River, Taiwan

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Introduction

Following Typhoon Morakot in 2009, the Laishe River in Pingtung County experienced massive upstream landslides, resulting in severe bed aggradation. Fifteen years post-event (2024), while the landslide areas have largely recovered, significant volumes of sediment remain deposited within the river channels. The trajectory of riverbed morphology recovery following extreme sedimentation events still needs further study. This study applies the SiMHiS (Storm Induced Multi-Hazards Information Simulator) model (Fujita et al., 2019; Yamanoi, 2017) to explore the hydrological response and sediment dynamics induced by Typhoon Morakot as well as the recovery trends and spatial variations in riverbed elevation across upstream and downstream reaches in the following hypothetical rainfalls.

Method

This study employed the SiMHiS model to simulate rainfall-runoff, sediment supply, and sediment transport processes across two phases: the Typhoon Morakot event (Phase 1) and a subsequent hypothetical rainfall sequence (Phase 2). The numerical simulation spanned approximately 3,712 hours.

In Phase 1, we reconstructed the hydrology and landslide induction of Typhoon Morakot. The event featured a cumulative rainfall of 2,414 mm. The landslide volume derived from DoD (DEM of Difference) calculations was introduced into the model.

In Phase 2, we simulated a hypothetical sequence of 24-hour 100 design storms separated by 12-hour dry intervals. The design storms included return periods of 2, 5, 10, and 20 years. This phase aimed to investigate the long-term morphological evolution following the massive deposition from Phase 1.

Two sediment input scenarios were evaluated in Phase 2: In scenario 1, no further sediment from slopes was introduced after the Morakot event. In scenario 2, sediment from gradually recovering landslide areas was incorporated, calculated using the RUSLE model. The hyetograph of rainfall and input of slope sediment used in scenarios 2 displayed in Figure 1.

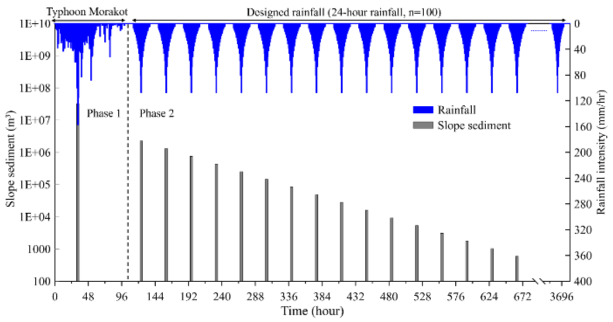

Figure 1 The hyetograph of rainfall and input of slope sediment used in scenarios 2.

Distinct grain size distributions were applied: median grain sizes (D_m) were 60.8 mm for the Morakot landslide material (S1) and 35.4 mm for slope sediments for post-Morakot slope erosion sediment, and 399.3 mm for the initial channel bed to the coarse bed material characteristic that existed prior to Typhoon Morakot.

To facilitate the comparison of riverbed evolution across different channel reaches, a dimensionless elevation change index, ΔE_i^*, was defined:

$$\Delta E_i^* = \frac{\mathrm{Max}\Delta E_i - \Delta E_i}{\mathrm{Max}\,\Delta E_i} \quad (1)$$

where $\mathrm{Max}\Delta E_i$ is the maximum aggradation depth during the simulation, and ΔE_i is the elevation change at a specific time step. The value of $\Delta E_i^* = 1$ indicates full recovery to the initial bed elevation.

Result and discussion

The simulation of hydrological response and sediment dynamics induced by Typhoon Morakot revealed that deposition occurred primarily along the main channels, whereas erosion dominated the upstream tributaries. Notably, deposition was more pronounced in the upstream reaches of the main channel compared to downstream sections, a pattern consistent with trends observed in the DoD analysis. In the main channels, the total deposition volume simulated by the model showed excellent agreement with the volume calculated from DoD analysis, yielding a relative error of only 1.8%.

In the subsequent simulation (Phase 2), upstream channels demonstrated greater initial deposition followed by a rapid recovery of riverbed elevation (Figure 2). In contrast, the downstream channel exhibited a lower magnitude of deposition with a delayed peak yet showed a significantly slower recovery rate.

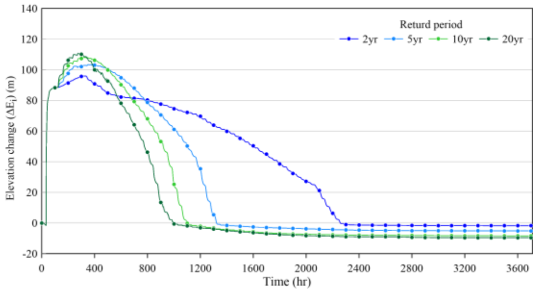

Figure 2 The elevation change of the upstream channel L9 in scenario 1.

We compared the average variation of riverbed elevation under the four rainfall settings. The final ΔE_i^* in scenario 1 for the 2, 5, 10, and 20-year return periods were 0.32, 0.95, 0.99, and 0.97, respectively. In scenario 2, these values were 0.32, 0.92, 0.98, and 0.84, respectively (Figure 3). Notably, recovery patterns were not linearly correlated with rainfall intensity.

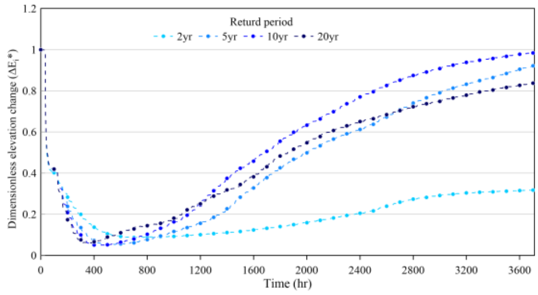

Figure 3 The change of average ΔE* of channel L1 to L9 in scenario 2 in four rainfall intensity.

The higher discharge in 20-year events mobilizes not only fine sediment from slopes but also coarser grains from the initial channel bed. The selective transport and subsequent redeposition of these coarser materials likely hinder transport efficiency and slow the degradation process. Conversely, the final ΔE_i^* remains low in the 2-year rainfall setting, which may be attributed to insufficient stream power (a transport-limited condition) under this rainfall setting.

Conclusion

The SiMHiS model successfully reproduced the spatial pattern of main channel deposition following heavy landslide input induced by Typhoon Morakot. Long-term evolution analysis indicates that upstream channels exhibit faster recovery rates despite higher initial deposition. Crucially, recovery patterns were not linearly correlated with rainfall intensity; moderate rainfall intensities (5–10 year return periods) were identified as the most effective drivers for riverbed recovery under current sediment conditions.

Reference

1.Fujita, M., Yamanoi, K., & Suzuki, G. (2019). Method for predicting debris-flow occurrence based on a rainfall and sediment runoff model. 7th International Conference on Debris-Flow Hazards Mitigation, Golden, USA.

2.Yamanoi, K. (2017) 土砂生産・土砂供給過程を考慮した土砂流出モデルの開発とその応用に関する研究, Thesis presented to Kyoto University.