Rainfall and Sediment-Driftwood Production and Runoff Model (RSR Model): Process-Based Modeling for Rainfall-Induced Multi-Hazard Events and Sediment Management in River Basins

In recent years, extreme rainfall events have manifested as "multi-hazards," where floods, landslides, debris flows, and driftwood transport interact in complex ways. These intertwined phenomena have led to frequent and severe water-related disasters worldwide, often involving massive quantities of sediment and driftwood. Large-scale landslides and debris flows in mountainous areas supply vast amounts of sediment and driftwood to river channels, causing rapid deposition and driftwood jams in downstream plains and significantly exacerbating inundation risks. Furthermore, long-term issues—such as prolonged turbidity caused by fine sediment runoff from collapsed slopes following heavy rains or earthquakes, and soil erosion on exposed slopes in river basins—have become critical global concerns. Addressing these phenomena requires a holistic scientific approach rather than isolated assessments. To meet these needs, ICHARM has been developing the Rainfall and Sediment-Driftwood Production and Runoff (RSR) model.

The primary strength of the RSR model lies in its integration of multi-hazard processes within a distributed rainfall-runoff framework. As shown in Figure 1, the RSR model consists of a distributed rainfall-runoff model (RRI) coupled with a unit river channel model, which handles riverbed elevation changes and sediment transport processes within the river channel network (Figure 2 (1)). In hillslope areas, the model incorporates components for landslide occurrence based on stability analysis, debris flow runout processes described by a point-mass system (Figure 2 (2)-①), and hillslope erosion caused by surface flow (Figure 2 (2)-②). Together, these components enable the model to simulate both short-term and long-term sediment production and transport processes throughout the entire catchment.

Additionally, a driftwood model has been developed to assess sediment-driftwood-flood hazards. Driftwood production is estimated based on the density of standing trees in mountain slope areas, where trees are recruited due to the erosion processes of landslides and debris flows. When debris flows reach a unit channel, driftwood is delivered along with sediment into the river network. To simulate the movement of numerous driftwood pieces during floods, the model describes their behavior as neutrally buoyant particles using advection and storage equations, while accounting for interactions with sediment erosion and deposition.

The RSR model has been applied to various spatio-temporal scales of sediment transport phenomena in many river basins globally. Among these applications, three case studies from Japanese river basins are presented to demonstrate the model's performance and highlight the importance of physical process-based analysis.

1. Abira River Basin (Hokkaido)[1)]: Figure 3 shows the hillslope erosion depth and the unit channels that directly received sediment delivery after a 39-day simulation. The model successfully reproduced observed suspended sediment discharge (Figure 4, upper). A comparison with a case excluding hillslope erosion confirmed that fine sediment supplied from upstream hillslopes significantly affects sediment flow conditions in downstream reaches (Figure 4, lower).

2. Uchi River Basin (Miyagi Prefecture)[2]: For the disaster caused by Typhoon Hagibis in 2019, the RSR model reproduced landslides and debris-flow impacts (Figure 5). By providing upstream boundary conditions to a 2D depth-integrated water and sediment transport model, the simulation accurately reproduced the deposition depth of inundated sediment in the plain area. The analysis revealed that large sediment volumes from mountainous areas led to rapid bed aggradation and braided channel formation in tributaries.
3. Akatani River Basin (Fukuoka Prefecture)[3]: In analyzing the disaster that occurred in the Akatani River during the 2017 Northern Kyushu Typhoon, the RSR model was coupled with a 2D model, similar to the previous case study. As shown in Figure 6, simulation results clearly demonstrate that accounting for driftwood transport is essential for accurately reproducing the actual inundation area. The analysis confirmed that the flooding was significantly influenced by backwater impacts induced by driftwood blocking bridges.

Built on fundamental physical principles, the RSR model offers exceptional flexibility in synchronizing varying spatial and temporal scales. This adaptability is crucial for addressing both short-term pulse events, such as flash floods, and long-term continuous processes involving basin-scale sediment transport and morphological evolution. The model is freely available via the iRIC software: https://i-ric.org/solvers/rri-on-iric/.

<Reference>

1) Menglu QIN, Daisuke HARADA and Shinji EGASHIRA: Prediction of Sediment Transport Process in River Basin Focusing on the Effect of Hillslope Erosion, Japanese Journal of JSCE, Volume 80 (2024) Issue 16, Article ID: 23-16088.DOI: https://doi.org/10.2208/jscejj.23-16088

2) Qin, M., Harada, D., and Egashira S.: Modeling of Water-Sediment Inundation Process Incorporating with a Rainfall-Sediment Runoff model, Proceedings of the 24th IAHR-APD Congress 14-17 October 2024, Wuhan, China

3) HARADA D. and EGASHIRA S. : Method to evaluate large wood behavior in terms of convection equation associated with sediment erosion and deposition, Earth Surface Dynamics 11 (6), 1183-1197, 2022.

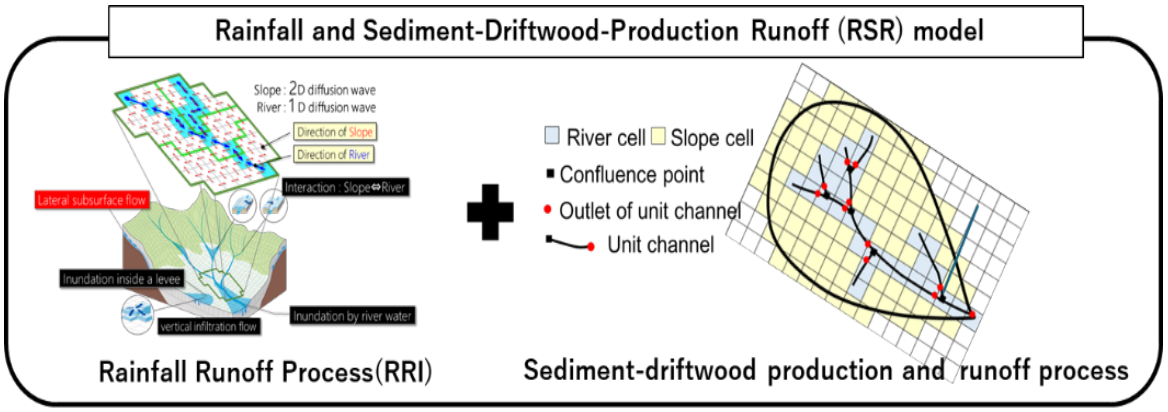
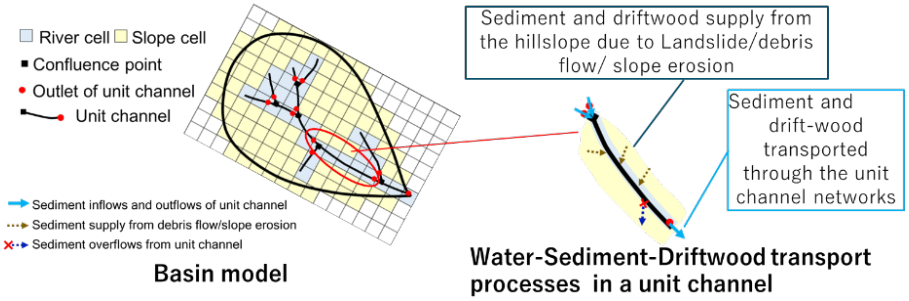


Figure 1 The structure of the Rainfall and Sediment-Driftwood-Production Runoff Model (RSR- Model)

（1）Sediment(drift woods) transport processes in channel networks（Unit channel model）



（2）Sediment and drift wood productions in mountain slope area

①Landslide and debris flow model (with drift wood production)　②Hillslope erosion model

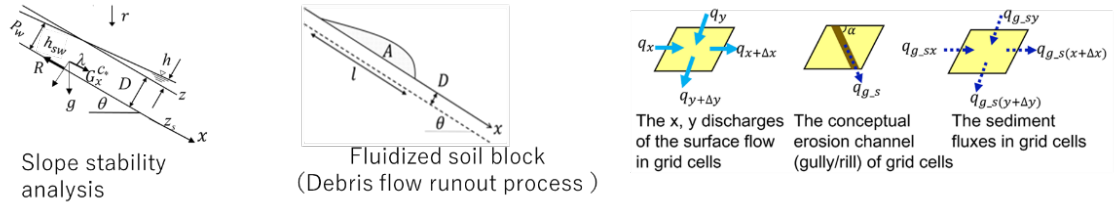


Figure2 Sub-models of the RSR Model

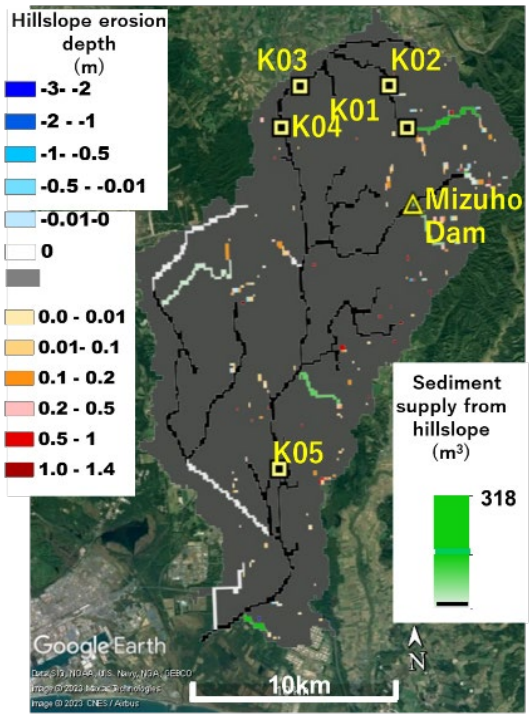


Figure 3 The simulation results of hillslope erosion depth and the distribution of direct sediment supply into unit channels

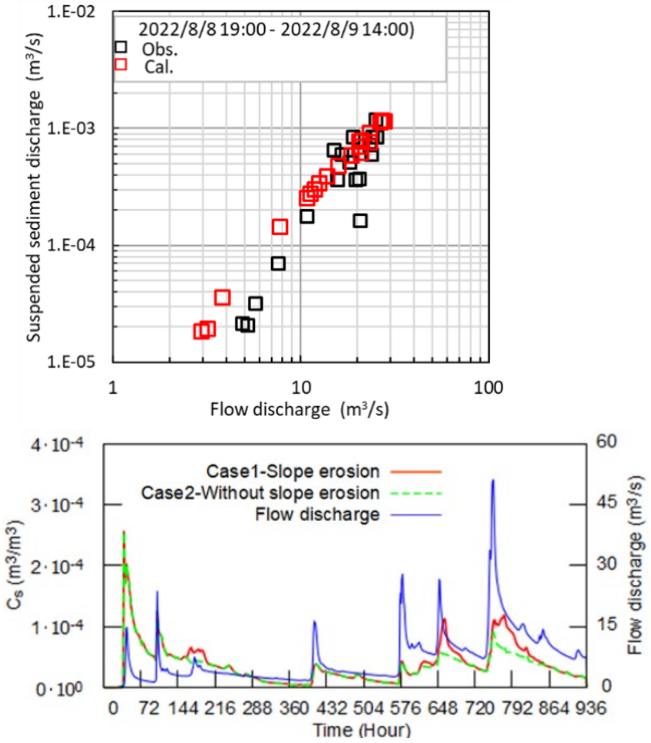


Figure 4 Comparison of suspended sediment flow and water flow discharge between calculation and observation at K05 (upper); The influence of fine sediment supply by hillslope erosion on the sediment concentration at K05 (lower).

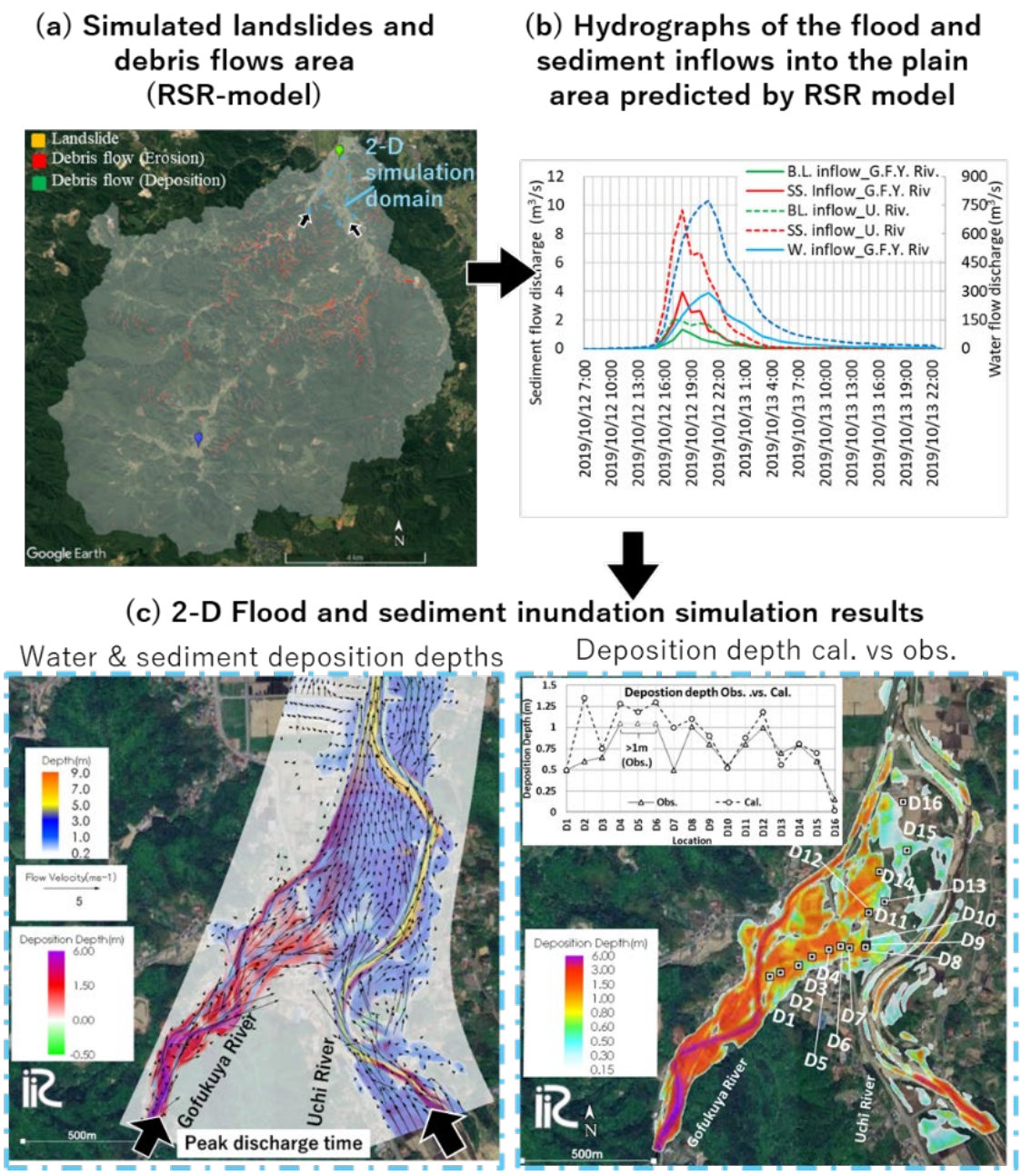


Figure 5 Application on rainfall induced multi-hazards disaster -from landslides-debris flows to flood and sediment inundation in-

(Uchi-kawa River Basin, Marumori Town, Typhoon Hagibis, 2019)

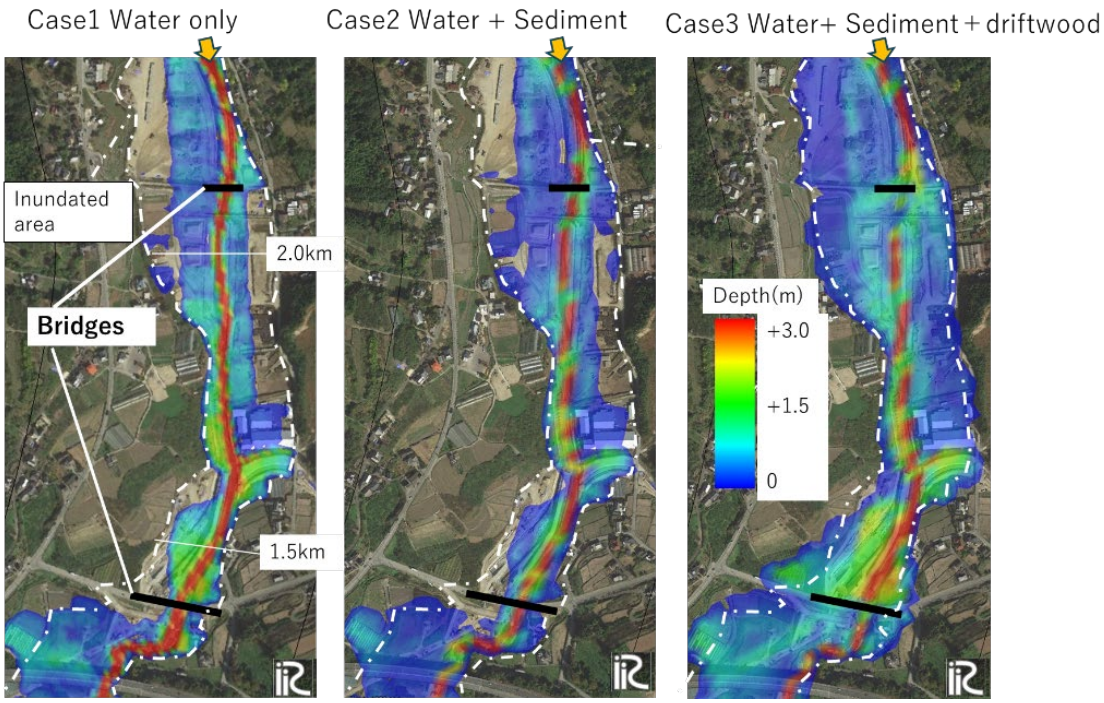


Figure 6 Application on rainfall induced multi-hazards disaster -sediment-driftwood-floods- (Akatani River, Nothern Kyusyu Typhoon, 2017)