INUNDATION PROCESSES OF FLOOD FLOW WITH SEDIMENT TRANSPORTATION IN THE AGNO RIVER MIDDLE STREAM, PHILIPPINES

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ABSTRACT

Typhoon Parma caused the worst flood disaster in the Agno River Basin in 2009, from October 8 to 9. This study aimed to estimate the flood and sediment inundation process in the Agno River Basin middle stream area, where 14 dike breaches have been reported and observed with wide inundation, in order to gain a better understanding of flood hazard characteristics in that area and to support the improvement of the Agno River Basin flood risk management. A method was proposed by adapting the rainfall and sediment runoff analysis for the entire river basin to obtain the upstream boundary conditions (inflow discharges of water flow, bed load sediment, and suspended sediment flow) for two-dimensional flow and bed variation analysis in the flood-prone area. The rainfall and outflow discharge of the Ambuklao dam, located at the upstream end of the plain area of the Agno River, from September 27 to October 11, 2009, were used for rainfall and sediment runoff analysis. The simulation results were validated by observing the grain size distributions of riverbed sediment and the inundation area. The findings shed light on the difference in flooding patterns between the alluvial fan area and meandering plain area: the former exhibits shallow and high-velocity flooding, whereas the latter exhibits widespread and retarded flow in the lower land, resulting in a wide and long duration of inundation. It also reveals that wide inundation flows carrying fine sediment produce wide sedimentation in the inundated area, which is typically overlooked in flood risk assessment.

Keywords: Flooding, Flood and sediment inundation, Rainfall and sediment runoff, Bed variation, Dike breach, Sediment sorting

INTRODUCTION

1. Background of the 2009 flooding in the Agno River basin

On October 8-9, 2009, Typhoon Parma caused the worst flooding in the Agno River basin, inundating the Province of Pangasinan and causing serious damage to agriculture, infrastructure, and loss of life (NDCC, 2009). The highest daily inflow and outflow discharges of the Ambuklao, Binga, and San Roque Dams were recorded on October 8. The San Roque Dam recorded a 5,360.71 m^3/s peak outflow discharge, which was attributed as the primary cause of the worst historical flooding in the Agno River basin; however, the specifics of the flooding and inundation mechanisms in the plain area have not yet been fully investigated. For example, during the disastrous 2009 floods, 14 dikes failed in the Agno River's middle stream area (Sunday Punch, 2009). Only three dike breaches located in the lower reach of the middle stream plain area were found because of the large inundation area (Rosales, Villasis, Santo Tomas, and Alcala towns, shown in , left); however, the upper reach of the middle stream plain area in Asingan and Tayug towns was reported to have many severe flooding events in its villages (Figure 1, right). Furthermore, the Agno River Basin's mountainous terrain is a high sediment production area with frequent landslides triggered by heavy rainfall, and landslides were also reported during the 2009 flood (NDCC, 2009). Nonetheless, no reports on sediment-related disasters in the plain area during floods or the sedimentation issues of the three dams along the upstream area (Figure) have been published.

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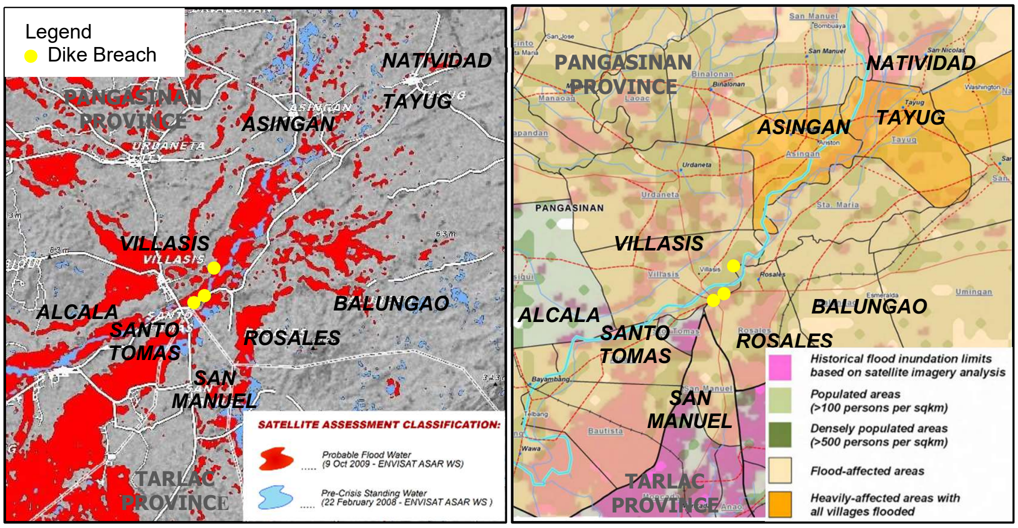

Figure 1. October 9, 2009 Flood Inundation Map. Left: UNOSAT, right: UNWFP

2. Objectives

This study aims to develop a method for evaluating the flooding process along the middle stream of the Agno River with sediment transportation using numerical simulations. This study focuses on the Agno River basin flood of 2009. A method proposed for rainfall and sediment runoff analysis were used to provide appropriate upstream boundary conditions during the flood duration for two-dimensional (2-D) flow and bed variation simulation to investigate the inundation processes of flood flow with sediment in the plain area. This study sought to clarify the various characteristics of flood hazards in the middle stream of the Agno River basin to provide scientific evidence for the development of a comprehensive flood risk management plan.

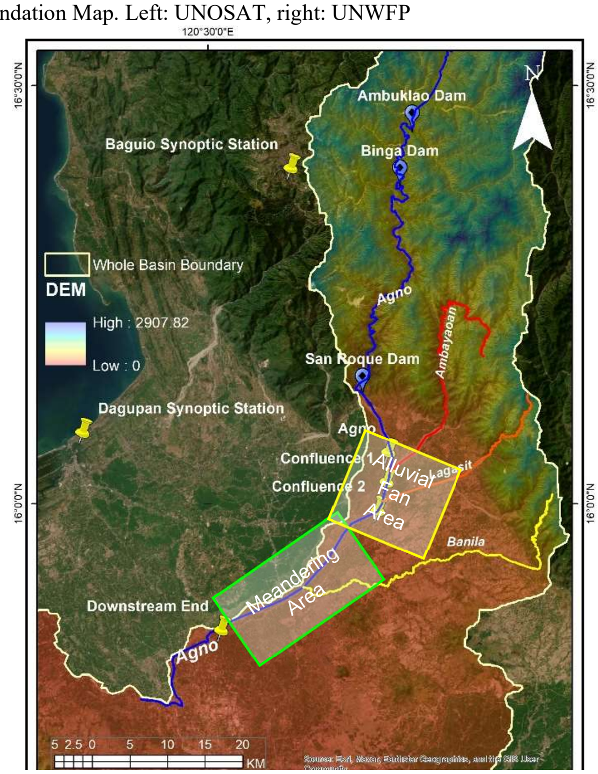

Figure 2. Study area for Rainfall and Sediment Runoff Analysis, and Domain Area for 2-D Flow and Sediment Inundation Analysis (in green box)

3. Study Area

Figure2 shows the Agno River Middle Stream, which consists of an alluvial fan and a meandering plain area. The riverbed slope of the alluvial fan area downstream of the San Roque Dam to the Tayug location ranged from 1/300 to 1/500, whereas the river section in the meandering plain area downstream of the Tayug location was less than 1/1000. At the same time, as shown in Figure 3, a significant sediment sorting phenomenon occurred from the San Roque location to the Don Teofilo Bridge; the river transitioned from a gravel river (D_{60} in San Roque is 50 mm) to a sandy river (D_{60} in Don Teofilo Bridge is 0.4 mm) at 32-km distance.

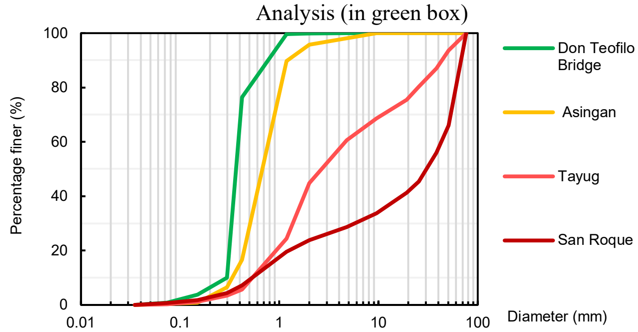

Figure 3. GSD 1989 Samples *(JICA, 1991)*

METHODOLOGIES

1. The structure of flooding and sediment inundation process analysis

Figure 4 depicts the structure of the proposed method for estimating flood and sediment inundation processes in the Agno River Basin's middle stream plain. The rainfall and sediment runoff model (RSR model; Qin *et al*., 2023) was used in the study area, shown in Figure 2, to obtain the upstream boundary conditions for the flood and sediment inundation process simulation by applying the 2-D flow and riverbed variation model (Nays 2DH model; Shimizu, 2011) in the plain area beginning 6 km downstream of Tayug town. Specifically, the upstream boundary conditions can be obtained using hydrographs of flow discharge, bedload discharge, and suspended sediment discharge for each grain size class.

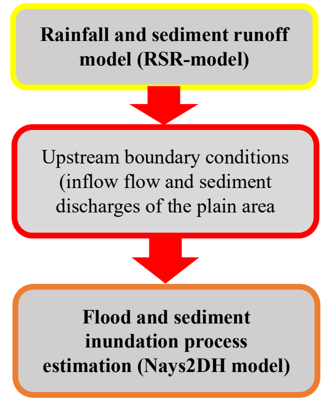

Figure 4. The Outline of the proposed method for flood and sediment inundation process analysis.

Figure 5 depicts the structure of the RSR model, which was coupled to the distributed rainfall-runoff model (Sayama, 2022) with a unit channel model for sediment runoff analysis (Egashira, Matsuki, 2000). The 2-D flow and bed variation computations are the same governing equations as those for the Nays2DH model. To estimate the sediment transport process, a bedload transport rate equation (Egashira *et al*., 1997; See Equation 3) capable of estimating the longitudinal sediment sorting process, and a suspended sediment erosion rate equation (Harada *et al*, 2022; Equation 5) proposed for treating very fine sediments, are adopted.

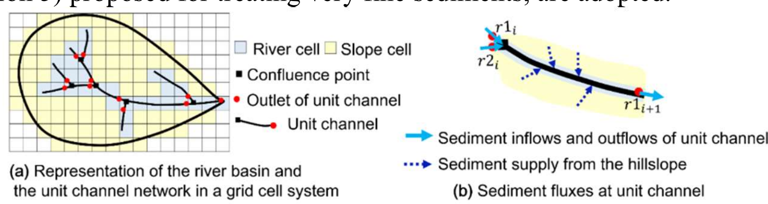

Figure 5. Unit Channel Principle for Rainfall-Sediment-Runoff Model (Qin *et al*., 2023)

2. Governing Equations

2.1 Rainfall and Sediment Runoff Analysis

In the rainfall-runoff analysis, the same methods proposed by Sayama (2022) were adopted. The surface flow was computed using diffusion wave approximation. For the lateral infiltration flow in mountainous areas Darcy's law was used, and vertical infiltration in plains was calculated using the Green-Ampt equation. The flow in the unit channels was based on the kinematic wave equation and was simplified by integrating and averaging the values in each unit channel, as proposed by Egashira and Matsuki (2000).

The mass conservation of riverbed sediment in unit channels:

$$\frac{\partial z_b}{\partial t} = \frac{1}{(1-\lambda)B(r1_{i+1})L(r1_{i+1})}\left\{\left(Q_{bj}(r1_i)\right) + Q_{bj}(r2_i) - Q_{bj}(r1_{i+1})\right\} + \frac{1}{(1-\lambda)}\sum_j\left(D_{sj}(r1_{t+1}) - E_{sj}(r1_{t+1})\right) \quad (1)$$

Where: z_b = riverbed elevation, λ = porosity of bed sediment, $B(r1_{i+1})$ = width of the unit channel, $L(r1_{i+1})$ = length of the unit channel, $Q_{bj}(r1_i), Q_{bj}(r2_i)$ = bed load discharges of size class – j sediment from $r1_i$ to $r2_i$ transported to the unit channel $r1_{i+1}$, $Q_{bj}(r1_{i+1})$ = is the bedload discharge of size class-j sediment flowing out from the unit channel (Equation 4), $D_{sj}(r1_{t+1})$ = deposition rate of size class-j suspended sediment (Equation 7), and $E_{sj}(r1_{t+1})$ = erosion rate of size class-j suspended sediment (Equation 5).

The simplified convection equation for suspended sediment concentration in unit channels:

$$\frac{\partial hc_{sj}(r1_{t+1})}{\partial t} = \frac{1}{B(r1_{i+1})L(r1_{i+1})}\{c_{sj}(r1_i)Q(r1_i) + c_{sj}(r2_i)Q(r2_i) + \sum_n Q_{psj}^n(r1_{t+1}) - c_{sj}(r1_{t+1})Q(r1_{t+1})\} - D_{sj}(r1_{t+1}) - E_{sj}(r1_{t+1}) \quad (2)$$

where c_{sj} is the average concentration of the size class-j suspended sediment in the flow, $\sum_n Q_{psj}^n(r1_{t+1})$ is the total size class-j sediment discharge supplied from the adjacent hillslope area on both sides of the $r1_{t+1}$ unit channel, n is the total number of lateral inflow inlets of each unit channel, and Q_{psj}^{n} is the discharge of lateral sediment inflow; however, the lateral inflow of the sediment was not considered in this study.

2.2. Bed and Suspended Sediment Equations

Bed load transportation rate equation:

$$q_{b^*} = \frac{4}{15}\left(K_1K_2/\sqrt{f^d + f_f}\right)\tau_*^{\frac{5}{2}} \tag{3}$$

where q_{b^*} = non-dimensional bedload transport rate, τ_* = non-dimensional bed shear stress, and K_1K_2, f_d and f_f are specified theoretically, non-dimensional bed shear stress τ_* can be calculated by

$$\tau_* = u_*^2/(\sigma/\rho - 1)gd = h_t \sin\theta\,/(\sigma/\rho - 1)d \tag{4}$$

where: $u_* = \sqrt{gh\sin\theta}$, g= acceleration due to gravity, d= sediment size, $K_1 = \frac{1}{\cos\theta}\frac{1}{\tan\varphi - \tan\theta}$, $K_2 = \frac{1}{c_s}\left(1 - \frac{h_s}{h_t}\right)^{\frac{1}{2}}$, $f_d = k_d(1 - e^2)\left(\frac{\sigma}{\rho}\right)\bar{c}_s^{\frac{1}{3}}$, $f_f = k_f(1 - \bar{c}_s)^{\frac{5}{3}}\left(\frac{\sigma}{\rho}\right)\bar{c}_s^{\frac{-2}{3}}$, $\frac{h_s}{h_t} = \frac{1}{\left(\frac{\sigma}{\rho}-1\right)\bar{c}_s}\frac{\tan\theta}{\tan\varphi_s - \tan\theta}$; $k_d = 0.0828$, $k_f = 0.16$, φ_s = internal friction angle, θ = bed slope, σ = mass density of soil particles, ρ = mass density of soil particles, h_t = flow depth.

The equation of suspended sediment erosion rate is:

$$E_j = F_{bj}W_e\bar{c}_s \tag{5}$$

where $\bar{c}_s$ is the sediment concentration in the bedload layer, F_{bj} is the fraction of the size class j, W_e = Entrainment velocity, which were evaluated based on the principle of density stratified flow as

$$W_e = K_e u/R_{t*} \tag{6}$$

where K_e = 0.0015, u = flow velocity, $R_{i*} = \Delta\rho g h/\rho u^2$ And $\bar{c}_s$ can be obtained from the relationship $\frac{\Delta\rho}{\rho} = \left(\frac{\sigma}{\rho} - 1\right)\bar{c}_s$.

The Deposition rate is obtained by the equation as below:

$$D_j = cw_{0j} \tag{7}$$

where c_j = flow depth-averaged suspended sediment concentration of size class j and w_{0j} = setting velocity of particle size i.

COMPUTATION CONDITIONS

For rainfall and sediment runoff analysis, 100 x 100m Digital Elevation Model (DEM) data, a Land Use map from Global HydroSheds data, and Ground Rainfall Data from Baguio and Dagupan Synoptic Stations (Figure 2) were used. The model was calibrated using the inflow discharge of the Ambuklao Dam and the outflow discharge of the San Roque Dam was given based on the observed data (Figure 6). For the flood and sediment flow inundation process analysis in the plain area used Nays2DH, the

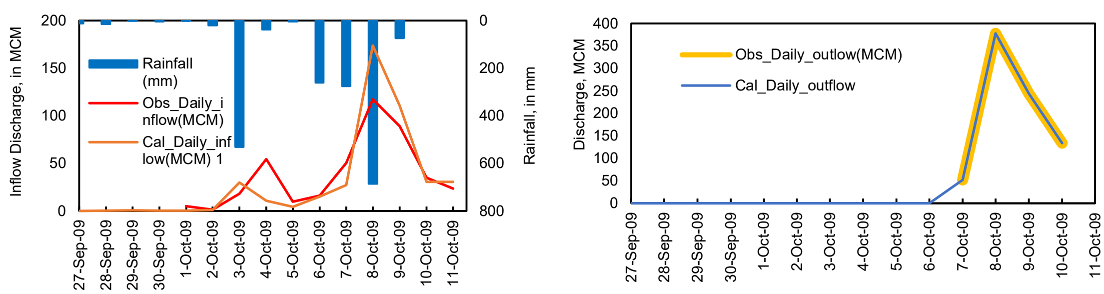

Figure 6. Calibration of Ambuklao Inflow Discharge (left) and San Roque Outflow Discharge (right)

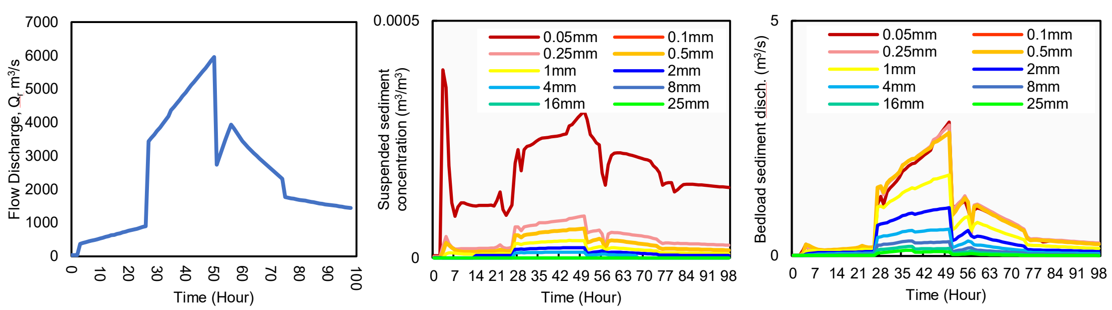

Figure 7. Upstream Boundary Conditions - Flow Discharge, Bedload Sediment Discharge, Suspended Sediment Discharge

domain area was set to 19 km long longitudinally and 8 km wide horizontally, and the resolution was 40 m in the flow direction and 30 m in the cross-sectional direction. The Upstream Boundary Conditions (Figure 7) were derived by the simulation results of rainfall and sediment runoff analysis. The Manning's roughness values of the river channel and plain area are 0.03 and 0.05, respectively. The initial grain size distributions (GSD) for all unit channel riverbed materials for the RSR analysis, sediment of the riverbed (GSD1 Nays2DH), and plain area (GSD2 Nays2DH) for the 2-D flood and sediment inundation simulation are shown in Figure 8.

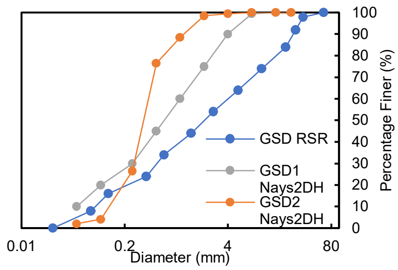

Figure 8. Initial GSD for RSR Analysis and 2-D flood and sediment inundation simulation

RESULTS AND DISCUSSION

1. Rainfall and Sediment-Runoff Analysis

According to the rainfall and sediment runoff analysis results, the calculated San Roque GSD was close, the Tayug GSD deviated slightly, and Sanchez and Carmen yielded results far from the 1989 samples (Figure 9). The inundation map yielded from the RSR Model (Figure 10) showed more inundation at the alluvial fan (yellow box) compared with the UNOSAT map but was generally consistent with the UNWFP map. In the Meandering plain area (in green box), the left bank-side plain area is in better agreement with the UNOSAT Map; however, the inundation is underestimated in the right bank-side plain area, particularly around Villasis.

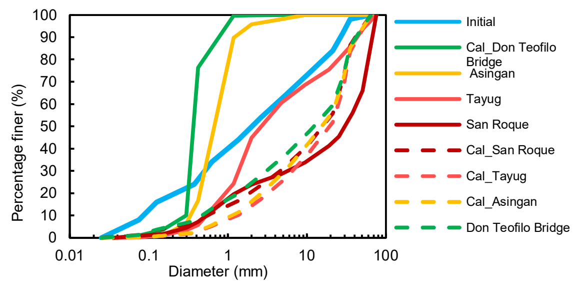

Figure 9. Observed GSDs, initial GSD and simulated GSDs from RSR

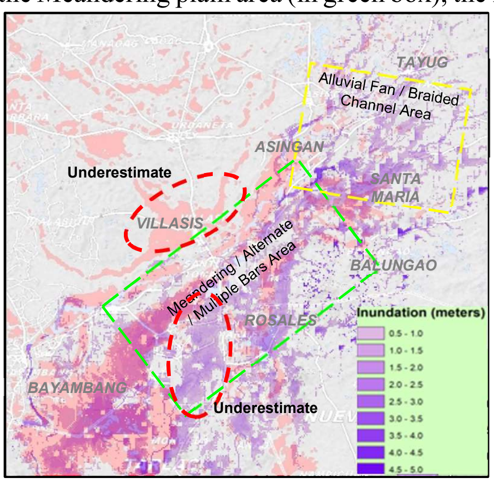

Figure 10. Inundation area and depth simulated by RSR-model 10/9/2009 Flood

2. Flow and Sediment Inundation Process.

Figure 11 depicts the spatial distributions of inundation depth and flow influx calculated by Nays2DH at the peak flow discharge of 6,000 m^3/s (Figure 7). The simulated inundation area agreed better with the UNOSAT map (Figure 1, left), especially near Villasis in the right bank- side plain area, which was well predicted. Furthermore, near the three identified dike breach locations, the flow concentration and high flow velocity were estimated. However, the relationship between inundation depth and the flow flux distribution in the plain area revealed that the large inundated zone downstream of the left bank-side plain area is influenced not only by the flow from the two dike breaches in the left bank, but also largely influenced by the wide overflow water from the downstream side where the river channel becomes very narrow. Similarly, the wide overflow along the right bank-side channel from the Asingan to the Don Teofilo Bridge is responsible for the right bank-side inundation area. The inundation flows carried mostly suspended sediment (Figure 12, left), resulting in a large sediment deposition on the plain area, as shown in the right side graph of Figure 12.

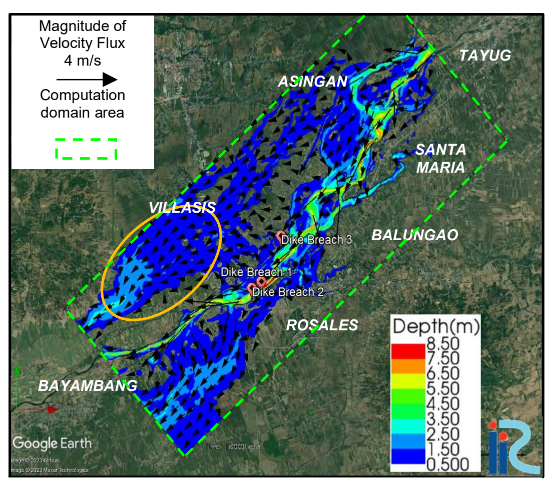

Figure 11. The calculated inundation depth and flow flux distribution

3. Discussion

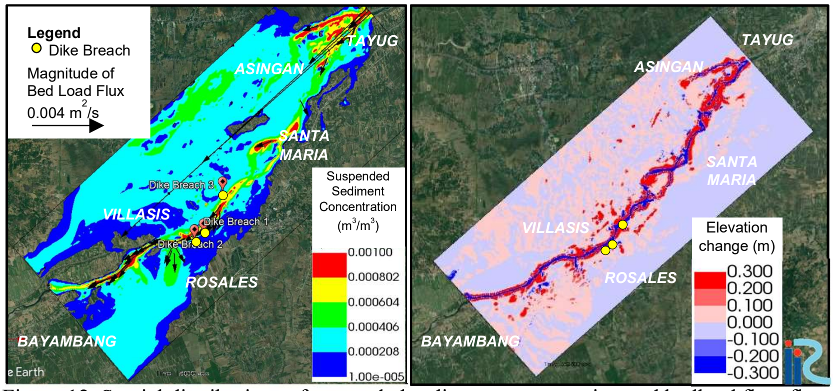

Figure 12. Spatial distributions of suspended sediment concentration and bedload flow flux during the peak discharge (L), the elevation change at the end of computation (R)

According to the validation results of the RSR-model, it is reasonable to conclude that the model can handle the rainfall and sediment runoff analysis, and inundation prediction in the alluvial fan area. However, the model shows a limitation for those estimations in the lower area where the river slope and plain area slope are milder than 1/1000. This was mainly caused by the momentum equation of the flow in the rainfall runoff analysis adopting the diffusion wave approximation for the plains area. However, the Nays2DH model used a 2-D dynamic wave equation, so the predicted inundation area matched the observation better, and the given upstream boundary conditions from the RSR model were validated accordingly. Therefore, the proposed method for estimating flow and sediment inundation processes in a plain area is valid. However, to adapt the results of this study to flood risk management, more detailed data on the site are required to validate the results and conduct further discussions.

CONCLUSIONS

This study proposes a method for obtaining the upstream boundary conditions for 2-D flow and bed variation computation in plain areas from river basin scale rainfall and sediment runoff analysis to estimate the large flood and sediment inundation of the Agno River Basin middle stream area in 2009. The findings shed light on the various patterns of flooding in the alluvial fan area and downstream in the meandering plain area. In contrast, shallow and high flow velocity flooding flows dominate in alluvial fan areas, whereas in the meandering plain area, a widely spread slow flooding flow accumulates as deep inundation zones. Furthermore, it demonstrates that the wide inundation flows in the meandering plain area can be transported over a long distance and carry fine sediment, resulting in not only wide water inundation but also wide sediment deposition. This implies that flood risk assessments must account for various flooding patterns as well as sediment inundation.

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REFERENCES

Egashira, S., & Matsuki, K. (2000). A Method for Predicting Sediment Runoff caused by Erosion of Stream Channel Bed (Abstract). *Dobuku Gankai Ronbunshuu*, 735-740.

Egashira, S., Miyamoto, K., & Ito, K. (1997). Bed Load Rate in View of Two Phase Flow Dynamics. *Annual Journal of Hydraulic Engineering JSCE, 41*, 789-794.

Harada, D., Egashira, S., Ahmed, T., & Ito, H. (2022). Entrainment of bed sediment composed of very fine material. . *Earth Surface Process and Landforms*, 1-11.

JICA. (1991, December). Study of Agno River Basin Control Final Report Volume III. Japan International Cooperation Agency.

NDCC. (2009). *Final Report on Tropical Storm "Ondoy" (Ketsana) and Typhoon "Pepeng" (Parma) September 24-27 and September 30-October 10, 2009.* Quezon City, Philippines: National Disaster Coordinanting Council.

Qin, M., Harada, D., & Egashira, S. (2023). Influences of hillslope erosion on basin-scale sediment process. *40th IAHR World Congress Vienna - Austria*, 10.

Sayama, T. (2022, December 7). Rainfall-Runoff-Inundation (RRI) Model ver. 1.4.2.7.

Shimizu, Y. (2011). Nays2D Flood Solver Manual.

Sunday Punch. (November 2009). *Agno River Flood Control Dike now fully repaired.* Pangasinan, Philippines.