SEDIMENT TRANSPORT PROCESSES IN MOUNTAIN AREA OF KINUGAWA RIVER

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ABSTRACT

This study aims to develop a sediment transport model incorporated in Rainfall Run-off Inundation (RRI) Model. The sediment transport process model is able to analyze the sediment transport processes in Kawamata River Basin located in the upstream of Kinugawa River. Sediment transport rates, riverbed deformation and sediment size distributions are evaluated at four areas. The model is calibrated in RRI Model at Typhoon No.7 of September 2007. Then, the model was processed again with the prepared sediment parameters and inputs. Results obtained from the present model show that sediment armoring of riverbed and high concentration of suspended and wash load are predicted in upstream area. Fine sediment is transported and trapped behind Kawamata Dam. Bed load transport rate is high at peak discharges. Sedimentation processes in a channel are attributed to flood discharge, particle size of bed sediment, river shape and river slope.

Keywords: Sediment transport, sediment budget, river bed evolution, flow discharge, Kawamata River Basin

INTRODUCTION AND BACKGROUND

Kawamata River Basin is part of Kinu River Basin that flows to Tonegawa River which is the largest river in Japan. Water source from Kinunuma swamp and terminates in Kawamata Dam. The catchment area is approximately 179.40 sq.km. with water surface area of 259 hectares. The basin is characterized by high and steep topography. Valley widths are narrow and rivers are short giving a large ratio of peak flow discharge to basin area. Thus, massive sediment movement takes place often during heavy rains. As a result, there is a greater risk of sediment induced disasters. Sediment disasters causes damage to lives, properties and environment. In this regard, it is a necessity to give attention on the sediment transport processes on any river system.

The main objective of this study is to develop a model to analyze the sediment transport processes in Kawamata River basin. Usually, inundation analysis on rivers neglects the effect of sediment. Due to the fact that all rivers have sediments, it is necessary and helpful for designers to include the effects of sediment movements on river analysis. To develop such method, a 1-D sediment transport model is combined with the Rainfall Run-off Inundation model. The proposed method will be able to predict flood hydrograph at any point of channel network, sediment discharges such as bed load, suspended load and wash load, evaluate river bed deformation and sediment size distribution at any point of channel network if the rainfall condition is specified in the drainage basin

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METHODOLOGY AND THEORY

To predict sediment transport processes on a given drainage basin in the course of rainfall run-off, sediment models are incorporated in RRI Model. Figure 1 shows sequential activities of the study.

Rainfall Run-off Inundation (RRI) Model is a two-dimensional model capable of simulating rainfall run-off and flood inundation simultaneously (Sayama et al. 2012). The flow on the slope grid cells is calculated with the 2D diffusive wave model by the mass balance equation while the channel flow is calculated with the 1D diffusive wave model by the momentum equations described as follows:

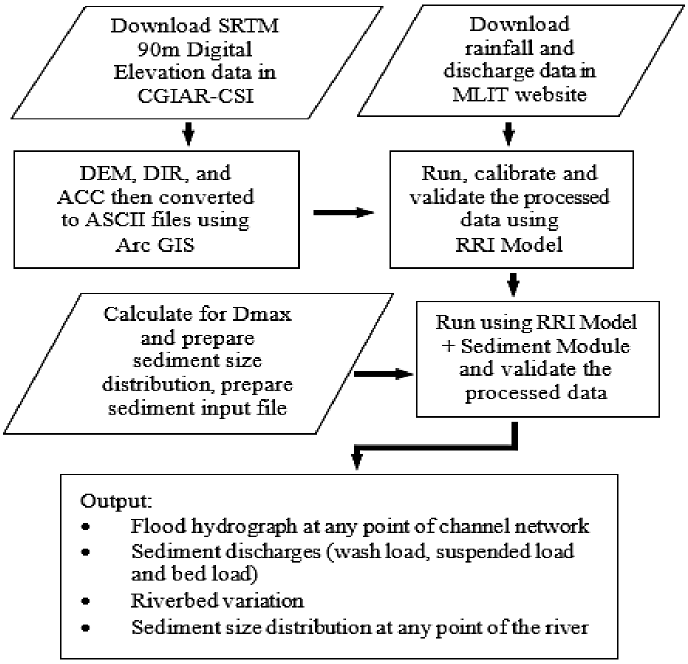

Figure 1 Sequential steps of the study

$$\frac{dh^{i,j}}{dt} + \frac{q_x^{i,j-1} - q_x^{i,j}}{\Delta x} + \frac{q_y^{i-1,j} - q_y^{i,j}}{\Delta y} = r^{i,j} - f^{i,j} \quad (1)$$

$$q_x = \begin{cases} -k_a h \dfrac{\partial H}{\partial x}, & (h \le d_a) \\ -\dfrac{1}{n}(h-d_a)^{5/3}\sqrt{\left|\dfrac{\partial H}{\partial x}\right|}\, gn\left(\dfrac{\partial H}{\partial x}\right) - k_a h \dfrac{\partial H}{\partial x}, & (d_a < h) \end{cases} \quad (2)$$

$$q_y = \begin{cases} -k_a h \dfrac{\partial H}{\partial y}, & (h \le d_a) \\ -\dfrac{1}{n}(h-d_a)^{5/3}\sqrt{\left|\dfrac{\partial H}{\partial y}\right|}\, sgn\left(\dfrac{\partial H}{\partial y}\right) - k_a h \dfrac{\partial H}{\partial y}, & (d_a < h) \end{cases} \quad (3)$$

where $q_x^{i,j}$, $q_y^{i,j}$: discharges from a grid cell at (i,j) in x and y directions, k_a: lateral saturated hydraulic conductivity and d_a: soil depth times the effective porosity.

In general, riverbed is composed of non-uniform sediment. Change in bed elevation is determined by analyzing the sediment inflow and outflow at any point. Temporal change in river bed elevation is described by:

$$\frac{\partial z_b}{\partial t} + \frac{1}{(1-\lambda)}\sum_i\left(\frac{\partial q_{bi}}{\partial x} + D_s - E_s + D_w - E_w\right) = 0 \quad (4)$$

Ashida and Michiue's bed load formula is employed, which is given by q_b.

$$q_b = \sum \mathrm{q}_{bi} \quad (5) \qquad q_{bi} = 17 p_i \tau_{*e}^{\frac{3}{2}}\left(1 - \frac{\tau_{*c}}{\tau_*}\right)\left(1 - \frac{u_{*ci}}{u_*}\right) \quad (6)$$

Mass conservation equation of suspended sediment within the flow body is described by:

$$\sum_i\left(\frac{\partial c_{si} h}{\partial t} + \frac{\partial \mathrm{r}_i u c_{si} h}{\partial x}\right) = \sum_i \frac{\partial}{\partial x}\left(h\varepsilon_x \frac{\partial c_{si}}{\partial x}\right) + E_s - D_s \quad (7)$$

where E_s is the erosion rate and D_s is the deposition rate of suspended sediment.

The erosion rate for suspended sediment is calculated from equation 8 where w_{oi} is the settling velocity and C_{aei} is calculated by Lane and Kalinske as:

$$\mathrm{E}_s = \sum_i \mathrm{E}_{si} = \sum_i w_{oi} C_{aei} \qquad (8) \qquad\qquad C_{aei} = 5.55 \left\{ \frac{1}{2} \frac{u_*}{w_{oi}} exp\left(-\frac{w_{oi}}{u_*} \right) \right\}^{1.61} r_b \qquad (9)$$

Deposition rate for suspended sediment is calculated by:

$$\mathrm{D}_s = \sum_i \mathrm{D}_{si} = \sum_i w_{oi} C_{sbi} \qquad (10) \qquad\qquad C_{sbi} = \frac{C_{si}\beta_{si}}{1 - exp(-\beta_{si})} \qquad (11)$$

where C_{sbi} is the concentration at reference level of size class i

Mass conservation equation of wash load and associated erosion – deposition rates are described as:

$$\sum_i \left(\frac{\partial c_{wi} h}{\partial t} + \frac{\partial \mathrm{r}_i u c_{wi} h}{\partial x} \right) = \sum_i \left\{ \frac{\partial}{\partial x} \left(h \varepsilon_x \frac{\partial c_{wi}}{\partial x} \right) \right\} + E_w - D_w \qquad (12)$$

Erosion and deposition rate of wash load can be calculated by equation 12 and 13 respectively.

$$\mathrm{E}_w = -(1-\lambda) f_i \frac{\partial z_b}{\partial t} \qquad (13) \qquad\qquad \mathrm{D}_w = \sum_i \mathrm{D}_{wi} = \sum_i w_{oi} C_{wi} \qquad (14)$$

Sediment transport rate and associated channel change are influenced by sediment size of bed surface. The fraction of size class d_i is described in terms of mass conservation equation of size class d_i for bed surface layer. This is given by:

$$\frac{\partial p_i}{\partial t} = \frac{1}{1-\lambda} \left(\frac{\partial q_{bi}}{\partial x} + E_{si} - D_{si} + E_{wi} - D_{wi} \right) - \frac{\partial z_b}{\partial t} \frac{f_i}{\delta} \qquad (15)$$

DATA

The targeted rain is the 07 September 2007 flood event, hourly rainfall datas are downloaded in MLIT website in four gauging station located within the drainage basin, then, datas are converted to data file. Discharge datas in Kawamata Station are downloaded to compare with the simulated results of RRI model.

Download 3 arc second (90m) SRTM DEMs from the website of CGIAR-CSI for Japan. Topographic file for Kawamata drainage basin such as Digital Elevation Model (Figure 1 DEM), Flow Direction (Figure 2 DIR) and Flow Accumulation (Figure 3 ACC) were prepared using ArcGIS, then converted to ASCII file.

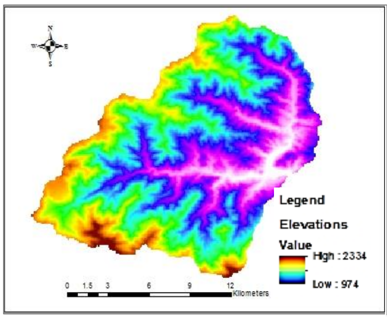

Figure 1 DEM

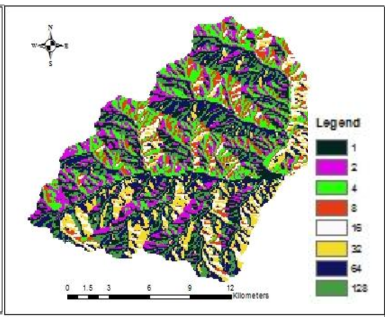

Figure 2 DIR

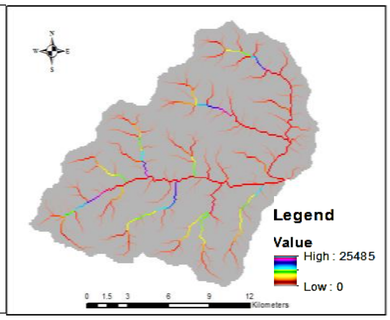

Figure 3 ACC

For the preparation of sediment inputs for RRI, maximum size of sediments are calculated at different points along the reach.Analysis of sediment size distribution was divided into three zones as shown in Figure 4. Using the log plot in Figure 4, distribution of particle sizes was calculated and represented according to JIS A 1204 and used as sediment input. Sediment models were introduced into the RRI source codes for the evaluation of sediment transport processes in a channel and referred as *sed_input.txt*.

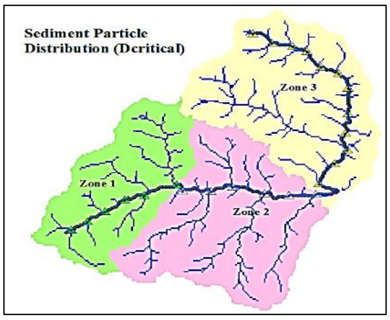

Fig. 4 Particle Distribution

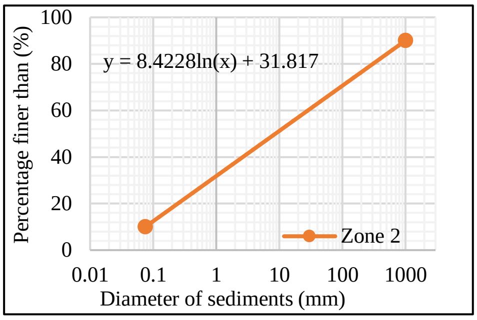

Fig. 5 Log Plot of Dcritical

RESULTS AND DISCUSSION

In this study, RRI model was run several times to determine the parameters that gives the best possible results. The model was calibrated for the flooding event of September 2007 (Figure 4) and showed a Nash Sutcliffe Efficiency (NSE) of 0.856.

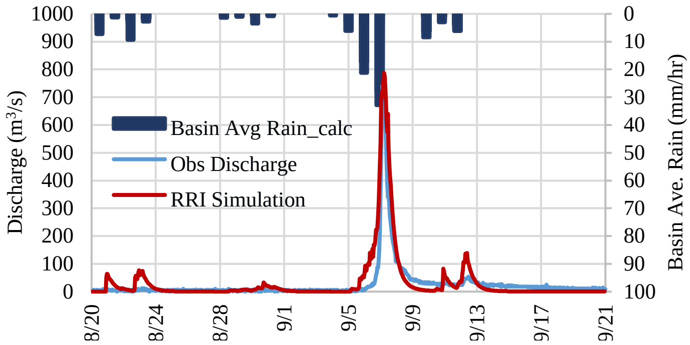

Fig. 6 RRI Model Calibration (Sept. 2007)

Using the calibrated parameters, RRI with sediment models was run again. The results for sediment transport processes are evaluated at three zones along the river reach and another one at Kawamata station. For this discussion, results are describe at Zone 1 (upstream) and Kawamata Station (downstream).

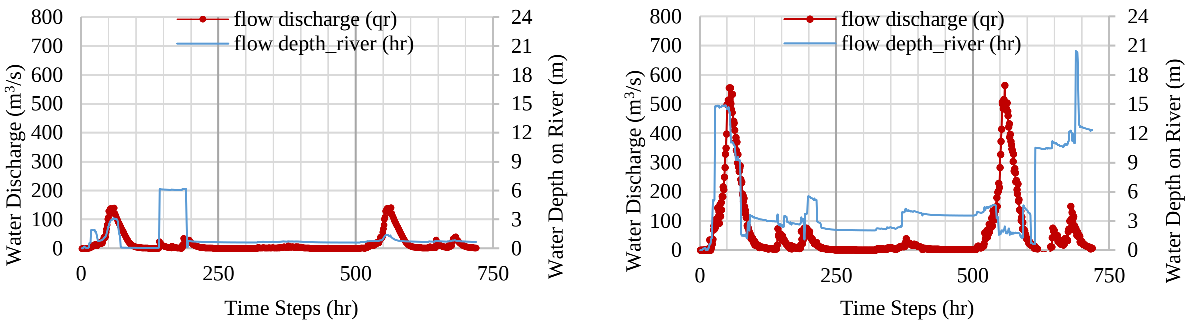

Fig. 7&8 Temporal Changes of qr and hr in Upstream & Downstream

Figure 7 and 8 shows the relationship between flow discharges and flow depths in upstream and downstream area. It can be observed that at period of peak discharge, flow depth start to increase and goes down as discharge decreases. In upstream area, flow depth becomes zero at end of flooding event while in downstream area, it can be noticed that flow depth remains constant after the flooding event due. This is due to the lowered riverbed elevation of Kawamata Lake.

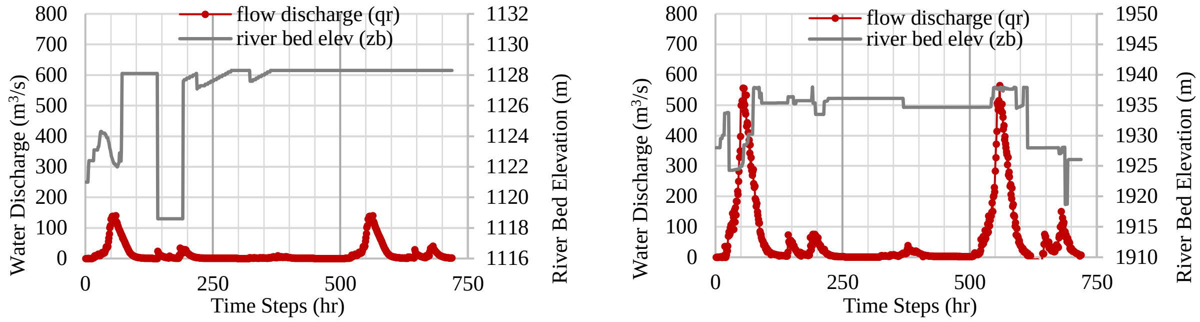

Fig. 9&10 Temporal Changes of qr and zb in Upstream & Downstream

Figure 9 & 10 shows the relationship between the flow discharges and riverbed elevations in upstream and downstream area. In upstream area, at onset of peak discharge, there is lower sediment inflow than outflow rates. It was determined that at high flow discharges, degradation occurs because of low sediment inflow rate. In downstream area, sediments are trapped behind the dam, aggradation is evident. This is the point when critical bed shear stress is very low, hence, sediments settles down.

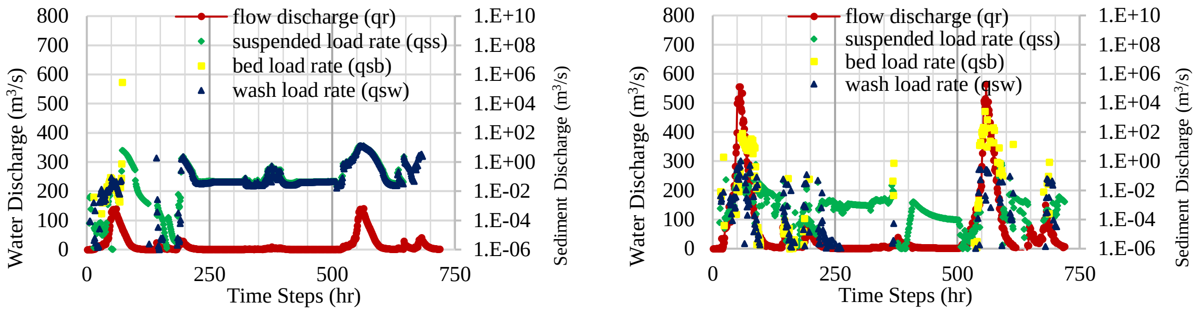

Fig. 11&12 Temporal Changes of qr and qsb/qss/qsw in Upstream & Downstream

Figure 11 & 12 shows the relationship between the flow discharges and sediment discharges in upstream and downstream area. In upstream area, large sediments start to move at time of peak discharge and settle again at time of low flow. It implies that large particles are not being moved by the flow and main means of transportation was through suspension. In downstream area, Bed load transport rate is high at point of peak discharges. Suspended load and wash load dominates in this zone and prominent throughout the flooding event.

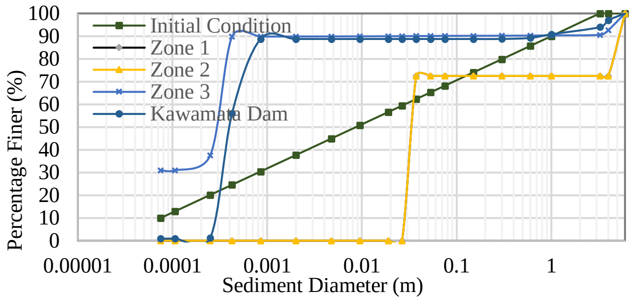

Fig. 13 Temporal Changes of Particle Size Distribution in Zone 1, Zone 2, Zone 3 & Kawamata Dam

Figure 13 shows the temporal changes of particle size distribution in four locations. Based from the results of simulation, upstream part has coarser materials because bed shear stress is high at this area. After flooding events, larger particles remain and finer particles are being transported in downstream area. It can be noted that suspended load and wash load dominates in the lake.

CONCLUSIONS

A method to evaluate sediment transport processes in drainage basins is proposed. This model is developed by combining sediment transport models with rainfall run-off model and is applied to predict the sediment processes in Kawamata Dam drainage basin. The model is able to provide interesting results on sediment transport rates and river bed evolution. However, there are several unsolved problems as follows:

i. The topographic map or DEM employed in study must give information nearly to the actual river channel because it has huge effect to the initial river bed slope.
ii. Long term simulation (example, 10 years or more) is recommended, to settle down the initial sediment discharges that would give a better result of sediment transport processes.
iii. A model that include the estimation of sediment production in the slope will improve the understanding on sediment movement.

This developments are recommended to help designers to create a better sediment management strategies that will extend reservoir life and benefit downstream areas.

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