Method for predicting sediment runoff processes and channel changes in West Rapti River, Nepal

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ABSTRACT

Present study aims to develop a model to evaluate sediment transport processes in drainage basins as well as to evaluate influences of river channel changes on flooding process. A sediment transport process model which is combined with a rainfall runoff model is proposed, taking the mechanisms of bed load, suspended load, wash load and associated bed variations into consideration. The model is applied to the sediment transport processes in West Rapti river basin. The predicted results suggest that sediment transport rates, armoring processes and bed evolutions are predicted well with flood hydrographs at several specified points. In the downstream reach of West Rapti river, a relationship between the channel change and the flood flow is investigated by means of a depth integrated 2D model in order to obtain preliminary results on the influences of channel changes on inundation process.

Keywords: Sediment transport process, Rainfall runoff, River morphology, Bed deformation

INTRODUCTION

West Rapti River basin is one of the class II river basin having catchment area of around 6,700 km^2. The river channel slope of the upstream area is about 12 %, due to high slope of river and topography, this basin is more prone to sediment disaster. In the downstream reach, the bed slope is about 0.1 %. The average annual rainfall, mean discharge and maximum discharge of the basin are 1500 mm, 136 m3/sec and 3000m^3/sec respectively. The flow of sediment on river is destructing the agricultural land of downstream. Due to bed aggradation and bank erosion the river channel changes into braided and at the same time enhances lateral shifting, such channel changes are the main problems and features of the river West Rapti. Thousands of hectares of agricultural land, infrastructures such as irrigation systems, bridges, road network, and hydropower systems are damaged due to floods which occur mainly during monsoon season. The vulnerability is being amplified in the area due to lack of awareness, unplanned settlement, increasing unemployment, encroachment of river land and living with poverty. The study mainly deals about the prediction of sediment runoff processes in the river basin and the influences of channel changes on inundation using 2D depth integration method.

METHODOLOGY

i. Method to predict sediment transport processes in West rapti River

In order to predict sediment transportation at any points in the drainage basin, we try to combine a rainfall- runoff model and a sediment transport process model. The rainfall-runoff model proposed by Sayama et al. (2012) is employed. In this model, rainfall-runoff over the mountainous slopes is evaluated by means of the 2-D diffusive wave approximation, and river channel flow is predicted by the 1-D diffusive wave equations described as follows.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \quad (1)$$

$$\frac{1}{g}\frac{\partial}{\partial t}\left(\frac{Q}{A}\right) = i_b - \frac{\partial h}{\partial x} - \frac{n^2 Q^2}{A^2 h^{4/3}} \quad (2)$$

Where, A is the cross-sectional area of flow body, Q is the flow discharge, q is the lateral inflow in unit length, i_b is the river bed slope and n is manning's roughness coefficient

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It is necessary to know the behaviors of sediment in the area of different terrain slope to understand the sediment transport mechanism and associated channel changes

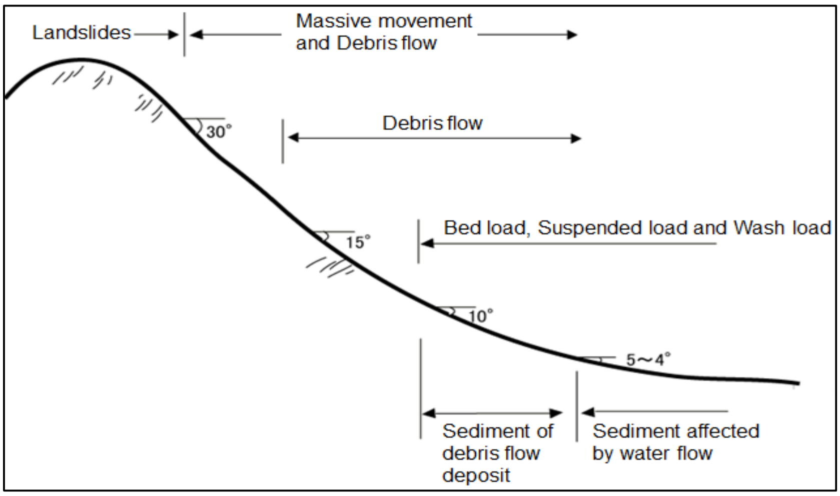

Figure 1: Sediment transport in drainage basin

According to Egasira (2015), sediment transport form such as landslide, debris flow, sediment movement as bed load, suspended load and wash load are shown in figure 1. Figure 1 suggests that areas having terrain slope higher than 30^0 and within 30^0 to 15^0, are susceptible to landslide and debris flow respectively. Sediment transport takes place in the form of bed load, suspended load and wash load in the regions where the terrain slope ranges from 10^0 to 15^0 (Egashira, 2015). The average slope of the river channel is about 8^0 which means channel changes are influencing by bed load, suspended load and wash load.

Sediment transport process in channel networks is evaluated by means of 1-D sediment transport model. Related equations, which are described as follows.

$$\frac{\partial z}{\partial t} = -\frac{1}{(1-\lambda)BL}\sum_{i=1}^{iN}\left\{\frac{(\partial qb_i\})}{\partial x}\right\} + D_{si} - E_{si} + D_{wi} - E_{wi} \tag{3}$$

The critical conditions when the bed load initiate to move are critical bed shear stress, non-dimensional critical bed shear stress, and critical shear velocity. Non- dimensional equations are formulated to evaluate the bed load transport. Meyer-Peter & Muller formula (1948) and Einstein Bed-load function (1942, 1950) are some representative equations for this bed load transport evaluation. Among the several equations, the Ashida Michue formula (1972) is adopted for this study. Ashida and Michue evaluated the sediment volume of bed load layer using the following Bagnold's ideas. The bed load transport can be evaluated by the equation (4).

$$q_{bi} = 17 p_i \tau_{*e}^{3/2}\left(1 - \frac{\tau_{*c}}{\tau_*}\right)\left(1 - \frac{u_{*ci}}{u_*}\right) \tag{4}$$

where, q_{bi} is the bedload transport of sediment in class i, τ_{*e}: non-dimensional effective bed shear stress, τ_{*c}: non-dimensional critical bed shear stress for initiating sediment movement, τ_*: non-dimensional bed shear stress , u_{*ci}: critical shear velocity of size class i, u_*: non-dimensional friction velocity

The terms used in the equations can be solved by using the process mentioned in the textbook of Egashira (2015). It is not so easy to quantify the bed sediment in the river channel. Recently few methods have been developed by using local cells and hydrophone, which is mainly in steep channel, while Acoustic Doppler Current Profiler (ADCP) in relatively mild slope.

The erosion of the suspended sediment can be evaluated as the product of equilibrium concentration of suspended sediment and settling velocity of the suspended sediment. Concentration of sediment can be calculated by the equation of Lane and Kalinske as following equation (5).

$$C_{aei} = 5.55\left(\frac{1}{2}\frac{u_*}{w_{0i}} exp\left(-\frac{w_{0i}}{u_*}\right)\right)^{1.61} r_b \tag{5}$$

Where, w_{oi} is the settling velocity of suspended sediment for each sediment class size, and c_{aei} : equilibrium concentration of suspended sediment r_b: Saturation ratio of bed sediment (r_b=0, if no sediment case and r_b=1, if there is sufficient sediment)

The deposition of the suspended sediment can be evaluated as the product of equilibrium of suspended sediment at reference level and settling velocity of the suspended sediment. The concentration of suspended sediment at the reference level can be calculated by using equation (6).

$$C_{sbi} = \frac{C_{si}\beta_{si}}{1-\exp(-\beta_{si})} \tag{6}$$

Where: c_{sbi} is the concentration of suspended sediment at the reference level of size class i. C_{si} is the depth averaged concentration of suspended sediment of size class i, β_{si} is the dispersion coefficient in vertical direction.

As settling velocity of sediment is the governing factor for erosion and deposition rate that can be evaluated by using Ruby's formula as the equation 7.

$$\omega_0 = -\frac{6v}{d_m} + \sqrt{(\frac{6v}{d_m})^2 + \frac{2}{3}\left(\frac{\sigma}{\rho}-1\right)gd_m} \tag{7}$$

Where: υ is the kinematic viscosity of water (υ= 0.001 cm^2/sec), d_m is mean diameter class size of sediment size, σ is mass density of sediment particles (2650 kg/m^3), ρ is the mass density of water (1000 kg/m^3), g is the acceleration due to gravity (9.81 m^2/sec)

Generally the sediment finer than 0.1 mm diameter is considered as the wash load. Deposition rate and erosion rate of wash load mentioned in the equation 3 can be evaluated by using equation (8) and equation (9) respectively.

$$D_w = \sum D_{wi} = \sum w_{0i}C_{wi} \tag{8}$$

$$E_{wi} = -(1-\lambda)p_w\frac{\partial zb}{\partial t}\left(\frac{\partial z}{\partial t} \leq 0\right),\ E_w = 0\left(\frac{\partial z}{dt} > 0\right) \tag{9}$$

Where: w_{0i} is fall velocity of wash load and C_w is the Sediment concentration of wash load, $(\partial zb)/\partial t$ is lowering rate of bed elevation, λ is Porosity and p_w is the concentration of size class i.

Bed materials discharges as bed load by the local hydraulics, while the suspended sediment transport is mainly the function of particle size distribution and wash load as the concentration of sediment. The temporal change of particle size distribution can be evaluated by the equation 10.

$$\frac{\partial p_i}{\partial t} = \frac{1}{1-\lambda}\left(\frac{\partial q_{bi}}{\partial x} + E_{si} - D_{si} + E_{si} - D_{wi}\right) - \frac{\partial z_b}{\partial t}\frac{f_i}{\delta} \tag{10}$$

Where: pi is the particle size, δ is the bed layer thickness and fi is the fraction of the particle size

ii. Method to evaluate influence of river bed variation on flooding process

The 1D model can analyze the general changes of flow and river bed from a macroscopic view, but cannot simulate the local sediment movement in detail. Then the two dimensional (2D) models are developed to simulate the refine local riverbed deformation and sediment deposition process in vertical and horizontal [Zhang *et al*., 2014]. In this model, the main assumption is non-dimensional shear stress plays main role to evaluate the sediment transport rate. Ashida Michiue's equation is used to calculate the bed load discharge in the direction of bed load. And for the calculation of suspended sediment, user can select either lane and Kalinske's equation or Itakura's and kishi's equation.

To evaluate the influences of river bed variation on flooding process, the 2-D model proposed by Takebayashi et.al (2011) is employed, which is as follows.

The continuity equation of water flow is given as equation (11).

$$\frac{\partial \mathrm{h}}{\partial \mathrm{t}} + \frac{\partial}{\partial x}(uh) + \frac{\partial}{\partial y}(vh) = 0 \tag{11}$$

The momentum conservation equations are as equation 12 and equation 13.

$$\frac{\partial}{\partial t}(hu)+\frac{\partial}{\partial x}(huu)+\frac{\partial}{\partial y}(huv)=-gh\frac{\partial}{\partial x}(h+Z_b)-\frac{\tau_x}{\rho}+\frac{\partial}{\partial x}(h\sigma_{xx})+\frac{\partial}{\partial y}(h\tau_{yx}) \quad (12)$$

$$\frac{\partial}{\partial t}(hv)+\frac{\partial}{\partial x}(hvu)+\frac{\partial}{\partial y}(hvv)=-gh\frac{\partial}{\partial y}(h+Z_b)-\frac{\tau_y}{\rho}+\frac{\partial}{\partial y}(h\sigma_{yy})+\frac{\partial}{\partial y}(h\tau_{xy}) \quad (13)$$

Sediment transport model is composed of mass conservation equation of bed sediment, the mass conservation of each sediment size class and the mass conservation equation of sediment inflow body. In addition, the bed load formula, and erosion / deposition formulas for suspended sediment are employed. The mass conservation equation of suspended sediment for each grain size is as follow.

$$\frac{\partial c_i h}{\partial t}+\frac{\partial r_1 u c_i h}{\partial x}+\frac{\partial r_1 v c_i h}{\partial y}=\frac{\partial}{\partial x}\left(h \in_x \frac{\partial c_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(h \in_y \frac{\partial c_i}{\partial y}\right)+E_i-D_i \quad (14)$$

The mass conservation equation of bed sediment is as follow.

$$\frac{\partial z}{\partial t}=-\frac{1}{(1-\lambda)}\sum_{i=1}^{iN}\left(\frac{\partial q_{bix}}{\partial x}+\frac{\partial q_{biy}}{\partial y}+E_i-D_i\right) \quad (15)$$

The formulas for the bed load, erosion and deposition of suspended sediment are discussed in equations (4), (5) and (6) respectively.

For this study, the different steps were carried out as methodology as figure 2. The governing equations (Mass conservation equation of water flow, momentum conservation equation of sediment transport, Mass conservation equation of sediment, Bed load equation) are employed for the study. Input data for both the RRSI and depth integrated 2D analysis are prepared. RRI Model including sediment model with governing equations and depth integrated 2D analysis are the main models used for this study considering several governing equations.

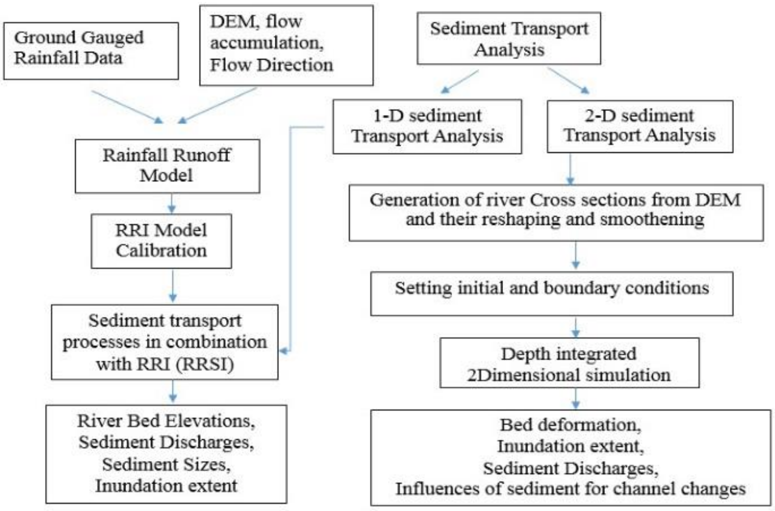

Figure 2: Methodology of the study

DATA

The main data used for this study are hydroshed 15 arc sec DEM downloaded from USGS website and flow direction and flow accumulation were prepared and the files were converted on the Ascii files for the model purposes. The figure 3 shows the drainage basin for the 1D sediment analysis. Ground gauged data, observed discharge, sediment particle distribution are the other data for the RRSI model.

The far downstream circled area shown in figure 3 is chosen for the purpose of depth integration 2D analysis. For this purpose the cross sectional grid

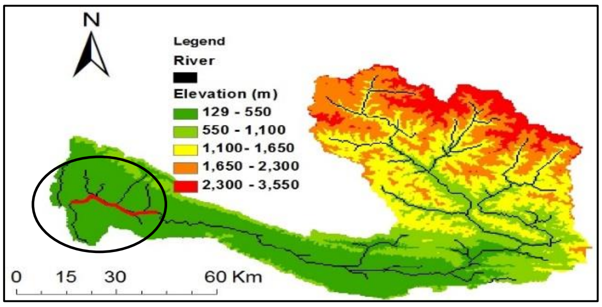

Figure 3: Study area

are prepared from the 3 arc sec hydro set data from USGS. And the initial and boundary conditions are set as listed below. Cross sectional Grid are prepared from the 3 arc hydro set data.(average grid size 90m×90m), average channel width is 800m, channel bed slope is 0.001,flow discharge is1000 m^3/sec up to 10 days and then real hydro graph, Manning's roughness coefficient is 0.027and average flow depth is 4.5m up to 10 days then 0.25m to 4.5m.

RESULTS AND DISCUSSION

Actual simulation period starts from the 18th of July to 16th September but the artificial flood event is added from 7th July to 17th July, which is same extent to the big flood of simulation period. To evaluate the channel changes and bed deformations of the west Rapti river basin, the RRI model with sediment transport process is used.

The depth integrated 2D analysis is also used for the evaluation of the bed deformation and inundation extent. The results obtained from the model are arranged and discussed here in separate headings.

To compare the inundation area from the RRI model and water indices, the MODIS/Terra surface reflectance 8-days L3 product (MOD09A1) image during flood period (2003-08-05 to 2003-08-12) is used. The Inundation area from the RRI output and the water index from MLSWI is compared.

For the analysis of the result from RRSI, the total basin is divided in the seven regions based on the calculated critical diameter of sediment particles as shown in figure 5. River flow discharge, bed elevation, Sediment discharge and particle size distributions of those regions are evaluated but results of region 1 are only presented here.

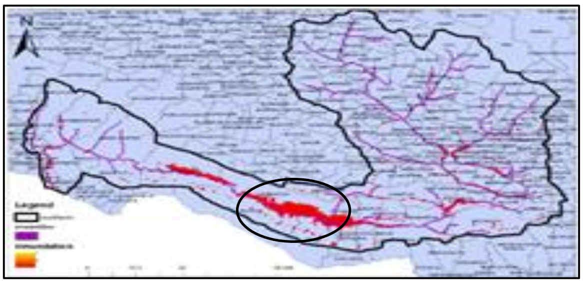

Figure 4: Inundation from RRI output

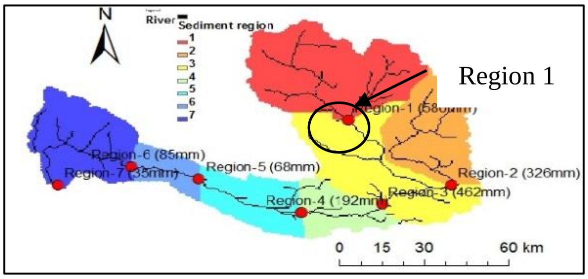

Figure 5: Sediment Analysis locations

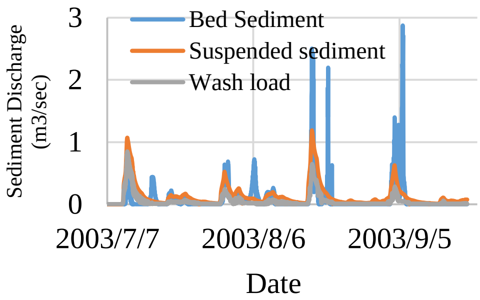

Figure 6: sediment transport in region1

a. Sediment Discharges:

The model calculated the sediment transport value in every location of the River. The sediment transport data is presented only for upstream locations Region 1 as given in figure 6. The sediment transport rate in every location is different so it is proved that the sediment transport rate depends on the river discharge, river slope and river geometry itself.

b. Bed Elevation Variations

It is clearly seen that the bed level change depends on the sediment transport rate with respect to time. In the upstream area the bed level is degrading and in the downstream area the bed level is aggrading. It is quite similar to the practical situation of the river. The bed elevation variations of region 1 is presented here in figure (7).

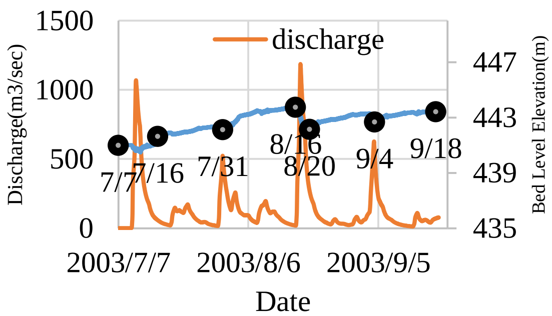

Figure 7: Bed elevation variations

c. Sediment particle size distribution

The result from the RRSI, it is seen that the particle size of the sediment are changing with respect to time as natural s shape. The sediment particle at specific location mainly depends on the bed level changes, erosion and deposition and fraction of the particles. The particle size distribution of region R1 is shown in figure (8).

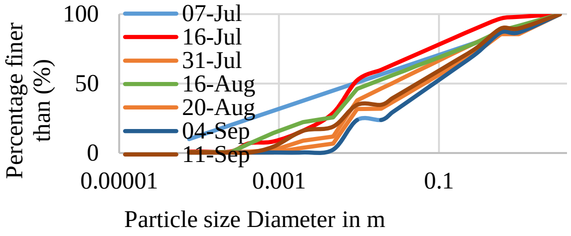

Figure 8: Particle size distribution in region 1

d. Depth Integrated 2D Analysis methods

The information get from the model output such as bed deformations, inundation extent and sediment transport rate are very important factors for the sustainable river management. Two type of simulations are used for this study, rigid bed simulation and the moveable bed simulation with uniform sediment size. For rigid bed analysis with water flow, there is no any bed deformations. The result of bed deformations from moveable bed analysis of 2 day and 10 day are presented in figure 9 and figure 10 respectively shows the. It is clearly seen that the bed deformation are present there and inundation range is increasing in the flood plain also

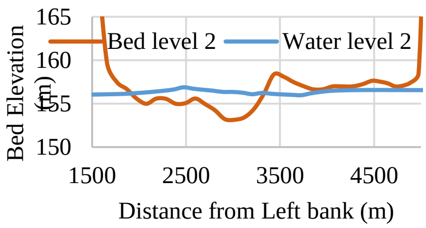

Figure 9: Channel section after 2 day

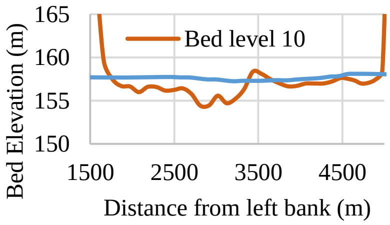

Figure 10: Channel section after 10 day

CONCLUSIONS

The present study proposes a method which combines the rainfall runoff model and sediment transport model for predicting the sediment transport processes in drainage basins. The proposed method is able to predict bed load transport, suspended load transport, wash load transport, sediment particle size distribution and the river bed variations together with a rainfall runoff process, and provides reasonable results.

The influence of a channel change on inundation process is investigated by means of a preliminary result obtained from a numerical simulation using the depth integrated 2-D model. The result suggests an importance of river bed variation on the inundation process.

The outputs from this method can be used for the proper river basin management. It is necessary to pay attention about contribution of sediment from landslide and debris flow. The bed aggradation is occurring in the downstream of river due to deposition of fine sediments, so either the height of embankment should be considered to reduce inundation problems or upstream basin management to reduce sediment flow.

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