IMPACT OF SEDIMENT SUPPLY CONDITION ON MORPHOLOGICAL CHANGE ALONG LOWER WEST RAPTI RIVER, NEPAL

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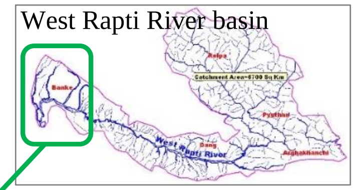
ABSTRACT

This study aims to evaluate the impact of sediment supply condition on morphological changes along the study reaches; the lower West Rapti River basin, Nepal. Two zones along the West Rapti River; Zone-1 and Zone-3 are selected as target areas. In Zone-1 and Zone-3, gravel and fine sand are dominant respectively, though these two zones are closely located. Two-dimensional numerical flow simulation with bed deformation are conducted in the target areas. In addition, in Zone-1, impact of finer sediment supply investigated with different sediment supply condition. The results of simulation are investigated in terms of rate of bed load and suspended sediment transport, temporal and spatial distribution of non-dimensional bed shear stress, change in bed elevation and sand bar behavior to understand the river bed aggradation and degradation area as well as channel change process along the study reach. As a result, in Zone-1, active bed deformations are simulated in case that finer materials are supplied additionally. In addition, characteristics of bed deformations are quite different between Zone-1 and Zone-3, which is caused due to the difference of material size in two Zones.

Keywords: Sediment supply, River morphology, Flow pattern, Bed deformation, Channel changing

INTRODUCTION

Lower plain part of Nepal has been working as a storage of sediment, transported by numerous rivers. In monsoon period, huge amount of sediment and drift wood produced by landslides and debris flows in mountain area are transported to lower areas. Due to low riverbed gradient, transported sediment gets deposited and riverbeds are continuously aggraded, thus reducing the conveyance capacity of river channel. In addition, bank erosion which is a serious issue in the plain area takes place actively. For this reason, river channel have different characteristics like braided, meandering and channel shifting. Such characteristics of rivers have been experienced as the main causes of flood hazard including inland inundation, loss of lives and properties, disruptions of livelihood and environmental degradation. In average, about 300 people lose their life each year due to floods and landslides in Nepal with property damage exceeding 626 million NPR on average (DWIDP, 2007).



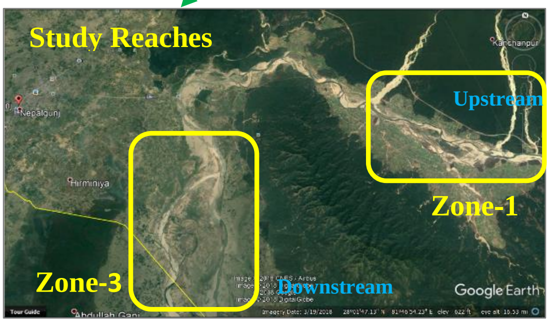


Figure 1. Location of the study area

Behind such sediment related disaster, the geographical features of Nepal like high mountains, steep slopes with young and fragile geology, steep river gradient and uneven intense precipitation are found responsible. Moreover, “In addition to these natural process, development activities and increasing population have caused further vulnerability and destabilization of land resources. This continuous human induced vulnerability stems from activities such as deforestation, cultivation of marginal land,

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road building in hills and mountains, and encroachment of flood plains. The water induced disaster, thus, have been occurring more frequently in recent times."(NWP, GoN, Nepal, 2006).

Lower plain area of West Rapti River basin also has been facing such type of sediment related disaster since years. To overcome form such types of problems, study of river morphology changing process is quite important. Thus this research is concerned on the study of impact of sediment supply condition on morphological change along lowermost part of West Rapti River basin; the study area as shown in Figure 1, in Nepal. West Rapti River is a Class II river covering 6,700 Km^2 basin area. It lies in southern-west part of the country. It is expected that important morphological parameters including channel aggradation and degradation area could be identified so that the human suffering and consequent socio-economic losses and environmental degradation can be reduced by applying proper countermeasures along the study reaches.

THEORY AND METHODOLOGY

The main objective of this study is to evaluate the morphological change in order to design suitable channel. To address the morphological changing characteristics along channel, depth integrated two dimensional (2D) governing equations for flow pattern as well as bed deformation analysis are employed in this study.

The depth integrated mass conservation equation for flow pattern in Cartesian coordinate system is described as:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(uh) + \frac{\partial}{\partial y}(vh) = 0 \quad (1)$$

The x and y components of momentum conservation equations for flow pattern in Cartesian coordinate system are described as:

$$x: \frac{\partial uh}{\partial t} + \frac{\partial uuh}{\partial x} + \frac{\partial uvh}{\partial y} = -gh\frac{\partial}{\partial x}(h + z_b) - \frac{\tau_x}{\rho} + \frac{1}{\rho}\{ (\frac{\partial}{\partial x}(h\sigma_{xx}) + \frac{\partial}{\partial y}(h\tau_{yx})\} \quad (2)$$

$$y: \frac{\partial vh}{\partial t} + \frac{\partial vuh}{\partial x} + \frac{\partial vvh}{\partial y} - gh\frac{\partial}{\partial y}(h + z_b) - \frac{\tau_y}{\rho} + \frac{1}{\rho}\{\frac{\partial}{\partial x}(h\tau_{xy}) + \frac{\partial}{\partial y}(h\sigma_{yy})\} \quad (3)$$

Where, h is the flow depth, t is the time, u and v are the component of depth averaged flow velocity along x and y direction respectively, g is the acceleration due to gravity, z_b is the bed elevation, ρ is the mass density of water, σ_{xx} σ_{yy}, τ_{xx} and τ_{yy} are the depth- averaged Reynold's stresses, τ_x and τ_y are the x and y component of bed shear stress (τ_b).

Following equation describes the mass conservation of suspended sediment:

$$\frac{\partial \bar{c}\mathrm{h}}{\partial t} + \frac{\partial r_1\overline{cu}\mathrm{h}}{\partial x} + \frac{\partial r_1\overline{cv}\mathrm{h}}{\partial y} = \frac{\partial}{\partial x}(\mathrm{h}\epsilon_x\frac{\partial \bar{c}}{\partial x}) + \frac{\partial}{\partial y}(\mathrm{h}\epsilon_y\frac{\partial \bar{c}}{\partial y}) + E_i - D_i \quad (4)$$

Where, $\bar{c}$ is the depth averaged sediment concentration, r_1 is the correction factor, ϵ_x and ϵ_y are the x and y component of dispersion coefficient respectively, E_i is the erosion rate and D_i is the deposition rate of suspended sediment in each grid.

Temporal change in bed variation are described by following mass conservation equation of bed sediment:

$$\frac{\partial Z_b}{\partial t} + \frac{1}{1-\lambda}\sum_i\left(\frac{\partial q_{bix}}{\partial x} + \frac{\partial q_{biy}}{\partial y} + E_i - D_i\right) = 0 \quad (5)$$

Where, Z_b is the bed elevation, λ is the porosity, q_{bix} and q_{biy} are the bed load transport rate along x and y direction in each grid respectively.

Bed load discharges were evaluated by following equation given by Ashida and Michiue.

$$q_{bk} = 17p_{mk}\tau_{*e}{}^{1.5}\left(1 - k_c\frac{\tau_{*ck}}{\tau_{*k}}\right)\left(1 - \sqrt{\left(k_c\frac{\tau_{*ck}}{\tau_{*k}}\right)}\right)\sqrt{S_g g d_k{}^3 r_b} \quad (6)$$

Where, k is the value of class size, τ_{*e} is the effective non-dimensional bed shear stress, k_c is the modification function of the effect of the local bed slope on the sediment transport, τ_{*c} and τ_* are the critical non-dimensional bed shear stress and non-dimensional bed shear stress respectively. S_g is the specific weight of bed material in fluid, d is grain size and r_b is the function of the exchange layer thickness.

The equilibrium concentration of suspended load at reference level was evaluated using Lane and Kalinske's equation as following:

$$q_{su} = 5.55\left[\frac{1}{2}\frac{u_*}{w_f}exp\left(-\frac{w_f}{u_*}\right)\right]^{1.61} w_f r_b \quad (7)$$

Where, q_{su} is the upward flux of suspended load from riverbed, u_* is the shear velocity, w_f is the fall velocity of suspended sediment.
A numerical model solver Nays2DH, based on above depth integrated 2D governing equations, developed by Yasuyuki SHIMIZU and Hiroshi TAKEBAYASHI, 2014 for flow pattern and bed deformation was employed to address the morphological changing characteristics along channel. The solver is applied in International River Interface Cooperative (iRIC) web site with version 3.2.5, which gives an integrated river simulation environment. On the basis of observed sediment size, study area was divided in three Zones as Zone-1, Zone-2 and Zone-3, among which Zone-1 and Zone-3 were selected for the study purpose due to distinct properties of sediment particle found.

DATA AND COMPUTATIONAL CONDITIONS

USGS, HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) 3 arc-second resolution DEM data was used to generate the initial river topography (elevation data) after analyzing by GIS for both zone-1 and zone-3. The annual maximum discharge data measured at Kusum gauge station which is the nearest upstream station from the study area were used to calculate the peak steady flood discharge of Q_2=2000 m^3/s (2 year return period and danger level flood), Q_{10}=5600 m^3/s (10 year return period flood) and Q_{25}=7700 m^3/s (25 year return period flood and design discharge for structural countermeasures) for flow pattern and bed deformation. For bed deformation analysis in Zone-1, observed non-uniform sediment sorting data collected and analyzed by ICHARM expert team in 2017, representing actual stable morphological condition of study reach were used as Distribution-1(Figure 2.a and black curve in Figure c). Computational Case-1 is conducted with the Distribution-1. To evaluate the impact of sediment supply condition at upstream, another finer sediment supply condition was developed assuming the occurrence of landslide and debris flow at upstream mountainous area which produce lot of sediment including much finer particles as Distribution-2 (red curve in Figure 2.c). In computational Case-2, Distribution-2 is set as upstream boundary grids, and Distribution-1 is set as initial distribution except the most upstream grids.

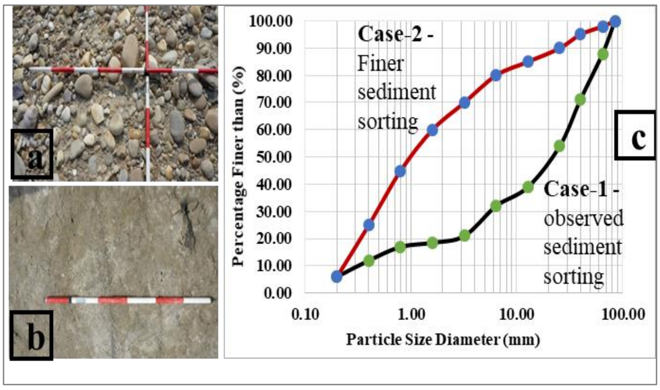

Figure 2. Observed sediment particle size and applied sediment supply conditions

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In Zone-3, as the observed sediment size found uniform with size 0.2 mm diameter as shown in Figure 2.b, same data is used for bed deformation.

After preparing necessary data, the initial condition and other necessary computational condition for flow pattern and bed deformation analysis with uniform as well as non-uniform sediment size, were prepared accordingly for setting up calculation conditions. Bed deformation simulation was performed for 5 days computation time period with steady flow condition considering the total length of erosion during monsoon period at mean flow discharge as following:

$$Q_p * T = (T_2 - T_1) * Q_m \tag{8}$$

Where, Q_p is peak flow discharge, T is peak flow computation time, T_1 is starting of mean flood during monsoon period, T_2 is end of mean flood during monsoon period, Q_m is mean flood during monsoon period.

RESULTS AND DISCUSSION

(A) Flow pattern analysis

Flow pattern analysis was conducted in both Zones to check the stability of numerical simulation. Steady flow of 2000 m^3/s for 1day computation time was applied for flow pattern simulation.

Velocity field distribution and comparison of flow pattern with google image

Figure 3.a shows the simulated result of depth averaged two-dimensional velocity field in Zone-1. The obtained spatially distributed velocity field is well recognizable. The red color represents the velocity more than 3 m/s along Zone-1. Comparing the flow pattern obtained by model with google image of same time period, flow path of main channel and braided small channel found well matched. Red ellipses in Figures 3 (a) and (b) are showing the quite matching of sand bar island in between flow path in model and google image. Similar matching of flow pattern result was found also in Zone -3. In this respect, flow pattern in study reach obtained from numerical simulation has found well matched with the actual river channel.

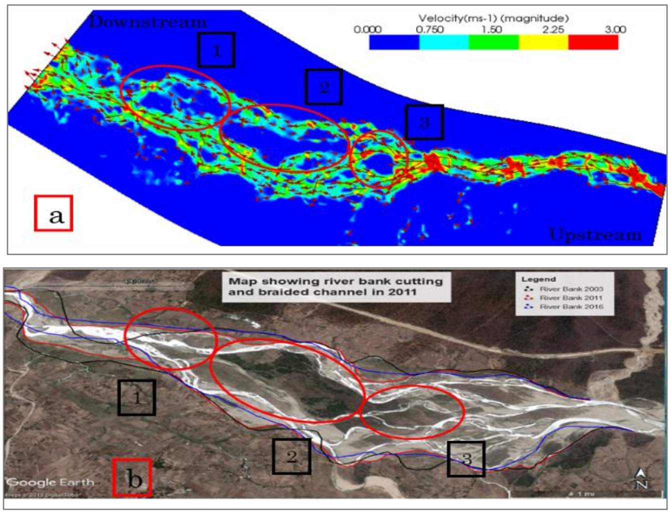

Figure 3. Distribution of velocity field and comparison flow pattern by model and google image

(B) Bed deformation analysis and impact of sediment supply condition

Under bed deformation analysis, impacts of finer sediment supply condition (Case-2) were observed over the observed sediment supply condition (Case-1) in terms of temporal and spatial distribution of non- dimensional bed shear stress, change in bed elevation and sediment transport rate along the channel with respect to Q_2, Q_{10} and Q_{25} steady flow condition. On the basis of these channel changing tendency along the channel were figured out. The model results are presented as following:

Temporal and spatial distribution of non-dimensional bed shear stress

Sediment flow characteristics depends on the distribution of bed shear stress. Both bed load and suspended load influenced by bed shear stress distribution. Figure 4 shows the temporal and spatial distribution of bed shear stress along Zone-1 and Zone-3.

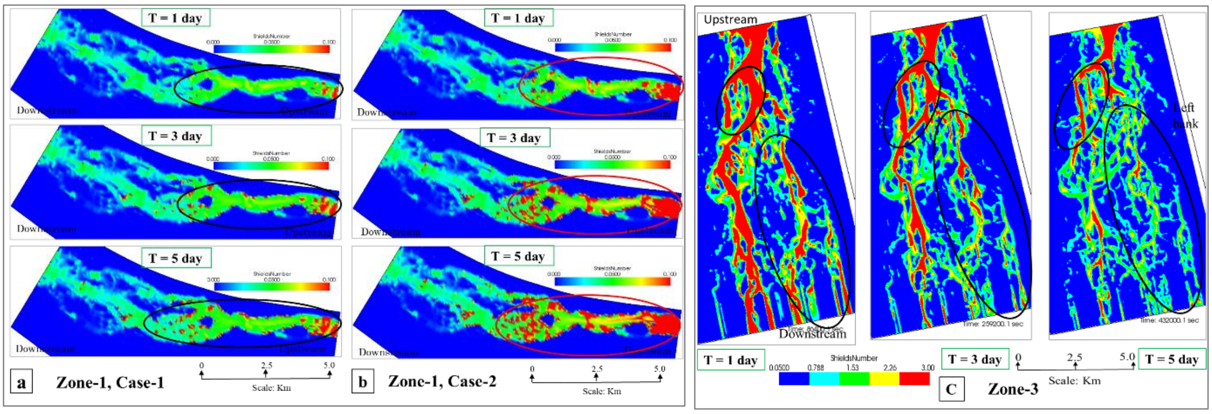

*Figure **4**. Temporal and spatial distribution of non- dimensional bed shear stress at Q_{25}=7700 m^3/s*

Figure 4.a shows the result of observed sediment supply condition (Case-1), in which bed shear stress found to be increasing spatially and temporally in 1day, 3days and 5 days. Difference of bed shear stress concentration inside black ellipse in Figure 4.a and red ellipse in Figure 4.b shows the impact of finer sediment supply (Case-2) over observed sediment supply condition (Case-1) where temporal and spatial amplifying of bed shear stress found significant. Low concentration of bed shear stress along downstream of Zone-1 indicates the stable condition of channel along this part. Similarly, Figure 4.c

shows the temporal and spatial distribution of bed shear stress in Zone-3, where value of bed shear stress found much higher than in Zone-1. Temporal decreasing of bed shear stress in Zone-3 indicates the widening and evolution of channel with respect to time of sediment flow which causes change in bed elevation and in turn, channel change. Result with flow discharge Q_2=2000 m^3/s and Q_{10}=5600 m^3/s has also showed the same trend of temporal and spatial bed shear stress distribution along Zone-1 and Zone-3, but the concentration value found relatively low in comparison of Q_{25}= 7700 m^3/s.

Temporal and spatial change in bed elevation and behavior of sand bar

Meso scale bed forms influence the channel morphology significantly. Bed elevation change is related with the formation, deformation and migration of sand bar along the channel. Figure 5 shows the temporal and spatial change in bed elevation along Zone-1 and Zone-3 at Q_{25} = 7700 m^3/s steady flow condition. Black color ellipse in Figure 4.a are showing increasing variation in bed elevation under

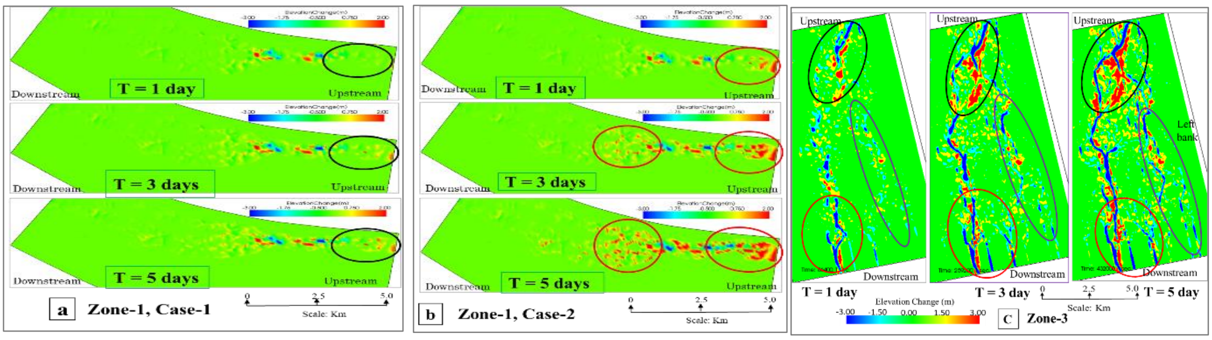

*Figure **5**. Temporal and spatial change in bed elevation at Q_{25}=7700 m^3/s*

observed sediment supply condition (Case-1) whereas red color ellipse in Figure 5.b are showing the amplifying condition of bed elevation change due to finer sediment supply (Case-2) along Zone-1. The maximum deposition and scouring along the channel in day 5 has been found to be 3.78 m and 3.38 m in Case-1, whereas 3.66 m and 7.38 m in case-2 respectively. In Zone-3, as showed in Figure 5.c, at upstream and downstream part marked by black and red color ellipse, sand bar formation, deformation and migration process found to be increased temporally and channel change occurred towards upstream right bank and left bank. Upstream and downstream part found more active than middle reach.

Spatial distribution of sediment transport rate and characteristics of study reaches

In Figure 6, red and black bold curve and dot curve shows the bed load and suspended sediment transport rate in observed sediment supply condition (Case-1) and in finer sediment supply condition (Case-2) respectively. Under this condition, result found shows the sediment transport rate of suspended and bed load in upstream part relatively higher than downstream part of the study reach. It also revealed that in upper part suspended load is dominated. Increased rate of both types of sediment transport in Case-2 shows the impact of finer sediment supply found to be increased from 0.98 m^3/s in Case-1 to 1.8 m^3/s in Case-2 at 0 km and suspended sediment transport rate from 1.76 m^3/s to 6.8 m^3/s at 0 Km respectively. However, the decreasing trend of both types of sediment transport rate found to be similar from upstream to downstream along the channel.

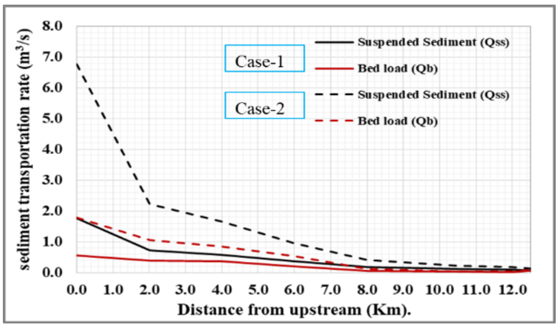

Figure 6. Longitudinal profile of sediment transport rate along Zone-1

Figure 7 illustrates the longitudinal profile of sediment transport rate in zone-3. Red curve and blue curve represent the bed load and suspended load transport rate respectively. The area has found highly suspended sediment dominated as the suspended sediment transport rate is much higher than bed load transport rate. The maximum bed load transport rate found to be 0.98 m^3/s at 0 Km whereas maximum suspended sediment transport rate found to be 7.0 m^3/s at 1.8 km from upstream. The trend of bed load transport rate is almost constant while suspended sediment transport rate found varying. Comparing Zone-1 and Zone-3, Zone-3 found much more active in sediment transport.

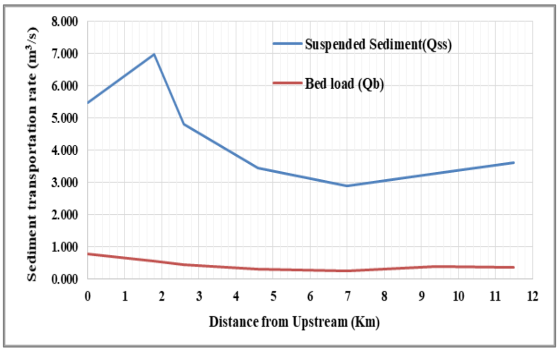

Figure 7. Longitudinal profile of sediment transport rate along Zone-3

Vulnerable locations and active tendency of channel changing along the study reach

In Zone-1, all the results found, like high concentration of distribution of bed shear stress, active change in bed elevation and higher sediment transport rate revealed that the upstream part is morphologically more active than downstream part. Both banks and middle area before braided at this part found more vulnerable. However, due to concentration of flow in one channel, it is easier to predict morphological characteristics and to apply suitable countermeasure in Zone-1.

On the other hand, Zone-3 found much more vulnerable in comparison to Zone-1 due to active channel changing characteristics. As the river bed variation including sand bar formation, deformation and migration process found more active, upstream and downstream parts are relatively more vulnerable than middle reach. Level of vulnerability found to be increased along with the increase in flow strength and finer sediment supply condition.

CONCLUSIONS

Although, the river morpho-dynamics are very complex and challenging without sufficient relevant data along West Rapti river basin, the temporal and spatial distribution of morphological features are reproduced using 2D numerical model. The flow pattern obtained from model truly represent the natural flow pattern. Results obtained from bed deformation clearly showed the reproduced bed shear stress, bed elevation change and sediment transport rate along the study reach. From the study, it is revealed that increasing discharge and finer sediment supply condition caused by landslide and debris flow in upstream area accelerate the river morphological changing process. All the morphological parameters like velocity field, non-dimensional bed shear stress, bed elevation variation, suspended as well as bed load transport rate were found to be significantly influenced spatially and temporally along with the increasing discharge and sediment supply condition.

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