PREDICTION OF SEDIMENT TRANSPORT PROCESSES IN NZOIA RIVER USING RAINFALL-RUNOFF MODEL

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ABSTRACT

This study proposes a method for predicting sediment transport processes on a basin scale using a hydrological model. A sediment transport module is introduced to Rainfall-Runoff-Inundation (RRI) model which calculates bed load and suspended load transport rates along the river channel. It also determines changes in river bed elevation and particle size distribution of bed material.

The model was applied to Nzoia River and used to calculate bed load and suspended load transport rates as well as bed elevation changes at three River Gauging Staff (RGS) stations along the main channel. Bed aggradation was observed to be continuous in the downstream RGS station with the particles becoming finer. However, in order to test the validity of the results obtained from this study, field data on the channel geometry and the particle size distribution of the bed material needs to be collected and compared to simulated results.

Keywords: Sediment transport, aggradation, Nzoia River, particle size distribution.

INTRODUCTION

Nzoia River basin is the largest basin draining into Lake Victoria from the Kenyan side. It has its sources in the forested highlands of Mt. Elgon, Cherengany Hills, Nandi Hills and Kakamega forest. The catchment area is approximately 12,900 km^2 and the main channel approximately 300 km long from its main source in the Chereng'anyi Hills to its mouth at Lake Victoria.

This study establishes a numerical modeling tool that evaluates the sediment transport processes along the Nzoia River and determines changes in both river bed elevation and particle size distribution of bed materials. The model allows for determination of these parameters at any point along the river channel.

By employing the numerical model we are able to determine the sediment transport rates at any point along the river for any given time period. This can be useful when studying the sediment transport processes in a river on a basin-scale level because it allows one to study how the processes vary across the basin for a given hydrological event.

METHODOLOGY

This study involved coding of a FORTRAN module for simulating sediment transport rates and adding it on to the existing RRI source code. RRI is a two dimensional model capable of simulating rainfall run-off and flood inundation simultaneously (Sayama, et al., 2012). Run-off discharges on land are estimated using the mass conservation equation (equation 1) as well as the diffusive wave approximation of the momentum conservation equations (equation 2 and equation 3)

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=r-f \tag{1}$$

$$q_x=-\frac{1}{n}h^{5/3}\sqrt{\left|\frac{\partial H}{\partial x}\right| sgn\left(\frac{\partial H}{\partial x}\right)};\ q_y=\frac{1}{n}h^{5/3}\sqrt{\left|\frac{\partial H}{\partial y}\right| sgn\left(\frac{\partial H}{\partial y}\right)} \qquad (2)\ \&\ (3)$$

In a river channel, gradually varied unsteady flow is considered. Discharge is calculated based on the one dimensional mass conservation and momentum conservation equations for channel flow.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{4}$$

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$$\frac{1}{g}\frac{\partial}{\partial t}\left(\frac{Q}{A}\right) = i_b - \frac{\partial h}{\partial x} - \frac{n^2 Q^2}{A^2 h^{4/3}} \tag{5}$$

Geometrical changes occur within a river reach whenever the sediment budget is altered. If sediment outflow rates are higher than the inflow rates, river bed degradation will be observed within the reach. On the other hand, if the outflow rates are lower than the inflow rates, river bed aggradation will be observed. This can be represented in the form of the mass conservation equation of bed sediment (equation 6)

$$\frac{\partial z_b}{\partial t} + \frac{1}{B(1-\lambda)}\sum_{i=1}^{Np}\left(\frac{\partial Bq_{bi}}{\partial x} + \frac{\partial Bq_{si}}{\partial x}\right) = 0 \tag{6}$$

if $\sum_{i=1}^{Np}\left(\frac{\partial Bq_{bi}}{\partial x} + \frac{\partial Bq_{si}}{\partial x}\right) > 0$ then degradation occurs in the river bed

if $\sum_{i=1}^{Np}\left(\frac{\partial Bq_{bi}}{\partial x} + \frac{\partial Bq_{si}}{\partial x}\right) < 0$ then aggradation of the river bed occurs

In the sediment module, this equation has been discretized as follows:

$$\frac{\partial z_b^{i,j}}{\partial t} + \frac{1}{B(1-\lambda)}\sum_{n=1}^{Np}\left(\frac{Bq_{bn}^{i+1,j+1} - Bq_{bn}^{i,j}}{\Delta x} + \frac{Bq_{sn}^{i+1,j+1} - Bq_{sn}^{i,j}}{\Delta x}\right) = 0 \tag{7}$$

where $q_{bn}^{i,j}$, $q_{sn}^{i,j}$- are bed load and suspended load transport rates from a grid cell at (i,j)

Bed load transport rate (q_{bn}) at each grid cell is estimated based on Ashida and Michue's formula (1972). While suspended load transport rate (q_{sn}) is obtained by employing the following integration:

$$q_s = \int_a^H c(z)\, u(z)\, dz \tag{8}$$

in which $u(z)$ is the velocity profile predicted using logarithmic velocity law and; $c(z)$ is the sediment concentration profile predicted using Rouse's profile with the reference concentration proposed by Garcia & Parker (1991).

Changes in sediment sizes of bed material resulting from movement of bed material is simulated based on the mass conservation equation for a grain size d_i in the surface layer (equation 9)

$$\frac{\partial p_i}{\partial t} = -\frac{1}{(1-\lambda)\delta}\left\{\frac{\partial q_{bi}}{\partial x} + \frac{\partial q_{si}}{\partial x}\right\} - \frac{\partial z}{\partial t}\frac{f_i}{\delta} \tag{9}$$

where:

$p_i - \mathit{fraction\ of\ particle\ size\ class\ } d_i \mathit{\ and\ satisfies\ the\ equation} \sum_{i=1}^{Np} p_i = 1$

$\delta -$ thickness of first layer (exchange layer)

$f_i = p_{i2}, \left(\frac{\partial z}{\partial t} \le 0\right);\ f_i = p_i, \left(\frac{\partial z}{\partial t} > 0\right)$

DATA

Figure 1 shows the Digital Elevation Map (DEM) which together with Flow Direction Map (DIR) and Flow Accumulation Map (ACC) were downloaded and masked for the Nzoia river watershed. These files were then converted to ASCII text files and the DEM file corrected for errors. Soil distribution map was downloaded from FAO website and masked for the Nzoia river watershed as well. Based on the sand, silt and clay composition of each of the soil types, they were further reclassified based on soil texture and then converted to ASCII text file.

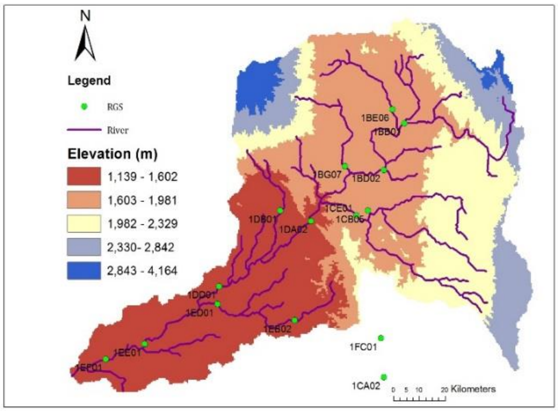

Figure 1: DEM for Nzoia Basin

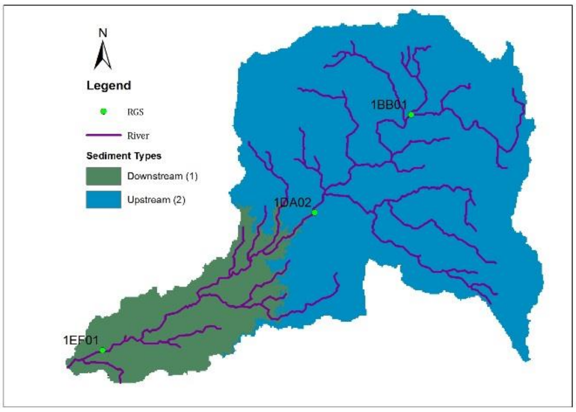

Figure 2: Bed material distribution map

Figure 2 shows the bed material distribution map which was created by dividing the catchment into two areas (i.e. upstream and downstream) and converted to ASCII text file as well. Figure 3 shows the sediment particle distribution graphs for each of these areas which were obtained by estimation with attention focused on the difference of sediment mobility in upstream and downstream reaches. Both the map and the graphs were used as input in the sediment module.

GSMap satellite rainfall for the year 2008 was obtained with assistance of ICHARM and converted to a data (.DAT) file.

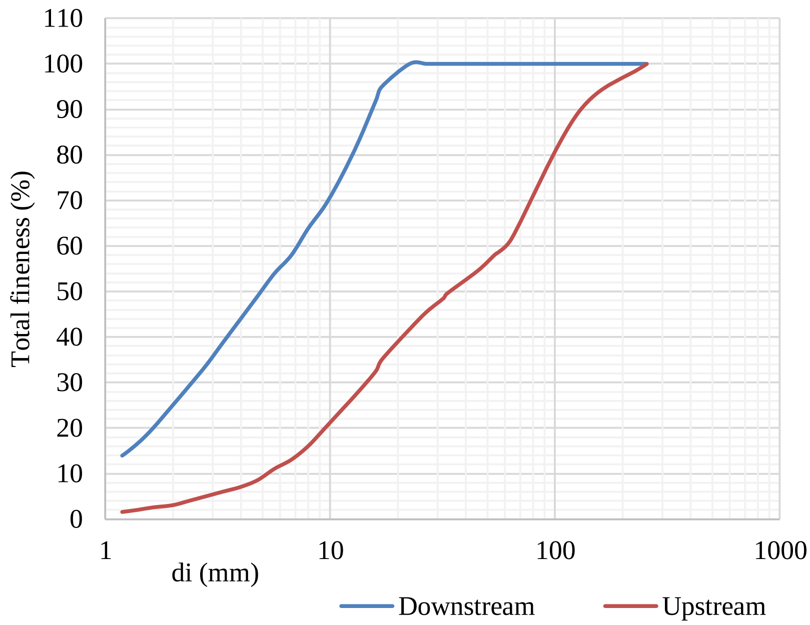

Figure 3: Particle size distribution for bed material

RESULTS AND DISCUSSION

To simulate sediment transport processes, the model was first calibrated and validated. The simulated river water levels were compared to observed water levels at downstream RGS station 1EF01. A Nash Sutcliffe Efficiency value of 0.79337 was achieved for calibration; and 0.66207 for validation, which were satisfactory. In analyzing the sediment transport, three RGS stations along the main river channel were focused on i.e. 1BB01 (upstream), 1DA02 (midstream) and 1EF01 (downstream). Three outputs were analyzed at each of these stations i.e. bed load and suspended load transport rates; variations in the river bed elevations; and variations in the distribution of particle sizes in the bed material. Based on the outputs the following observations were recorded:

i. Sediment Discharges:

Sediment transport rates are mainly affected by the flow discharge, channel geometry and sediment sizes. Sediment hydraulics suggest that sediment discharge increases with flow discharge. Also, an increase in river bed slope results in higher sediment discharge.

Figure 4 shows the relation between bed load transport rates (Q_{sb} (up) – upstream; Q_{sb} (mid) – midstream & Q_{sb} (down) – downstream) and flow discharge (Q_r) at the three RGS stations. We observe the bed load transport rates are highest at the midstream station because the bed slope at this point is steeper than that at upstream and downstream stations. Lowest bed load transport rates are observed in the downstream station despite it having finer bed material because of the reduced bed slope.

Figure 5 shows the relation between suspended load transport rates (Q_{ss} (up) – upstream; Q_{ss} (mid) – midstream & Q_{ss} (down) – downstream) and river flow discharge (Q_r). Comparing suspended sediment transport rate and bed load transport rate, we find that suspended sediment is much higher than bed load. This shows the river is suspended sediment dominated at all three stations.

Upstream station has higher suspended sediment transport rates when compared to the other stations. This is an indication that the suspended sediment concentration is much higher upstream than the other stations.

ii. Bed Elevation Variations

Bed elevation changes in the upstream and the midstream stations keep varying from aggradation to degradation indicating shifting in the sediment balance from negative to positive over the simulated time period. However, during the low flow period in December, both stations have bed aggradation occurring indicating higher sediment inflow rates during this period.

Figure 6 shows changes in sediment transport rates (Q_s) and changes in river bed elevation (z_b) over the simulated time period at the downstream station. Bed aggradation is noticed throughout the simulated time period. This indicates the sediment inflow rates were always higher than the outflow rates.

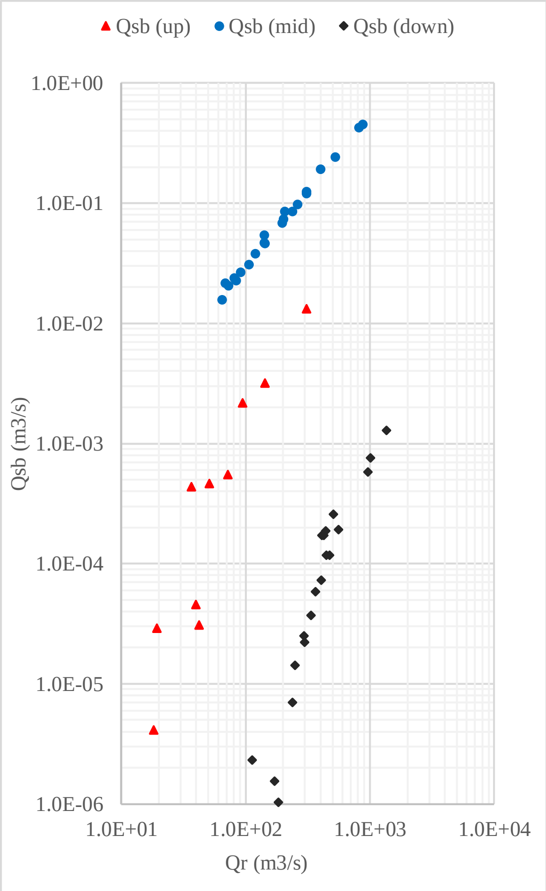

Figure 4: Bed load transport rates

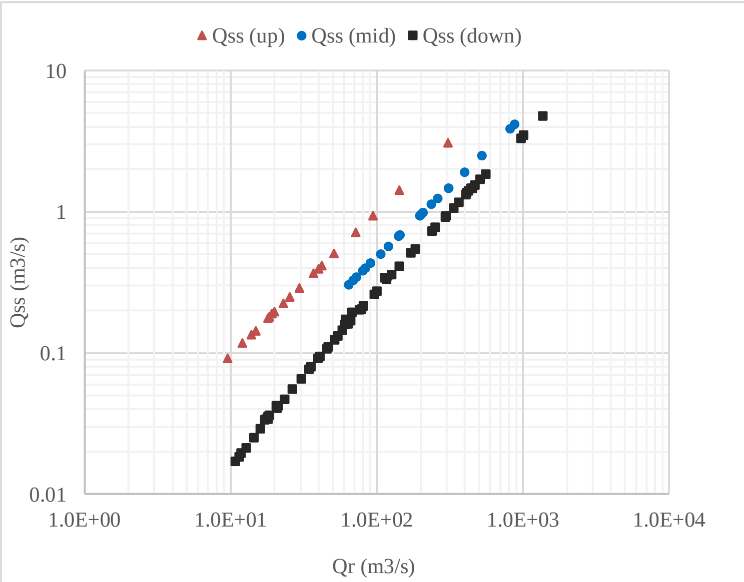

Figure 5: Suspended sediment transport rates

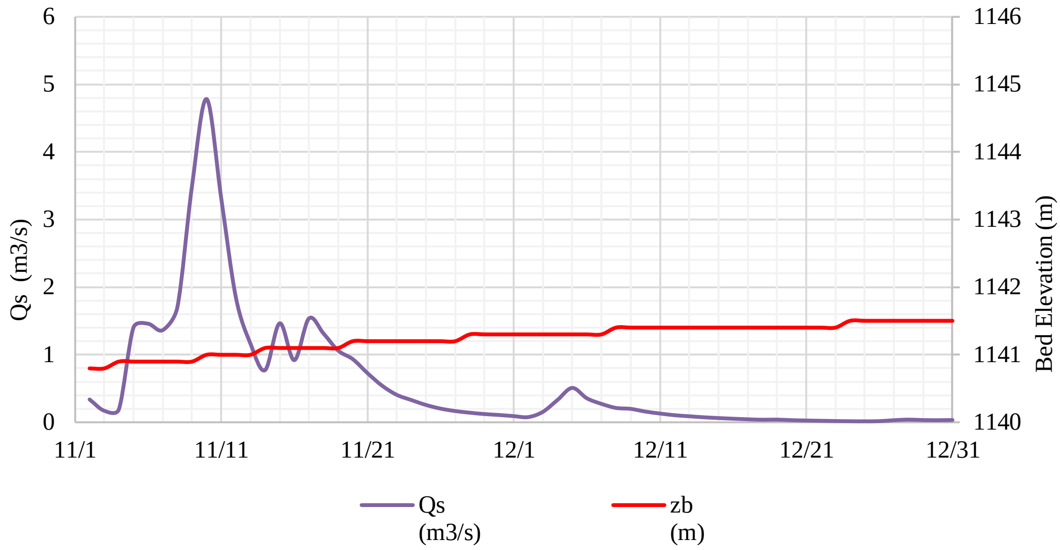

Figure 6: Graph of Water Discharge and River bed Variation with Time at 1EF01

iii. Mean Sediment Diameter (d_m)

For this study, the upstream (1BB01) and the midstream (1DA02) stations had a much coarser sediment used as input with a mean sediment size of 42.82. For the downstream station (1EF01) a finer sediment was used with a mean sediment size of 7.50.

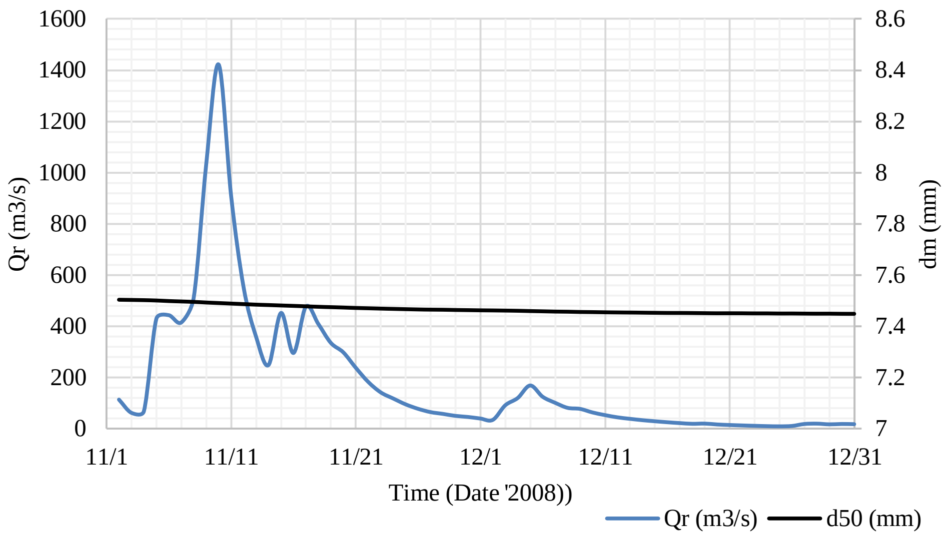

Figure 7: Graph of Water Discharge and Variations in Mean sediment size at 1EF01

Figure 7 shows the river flow discharge (Q_r) and changes in mean sediment size (d_m or d_{50}) over the simulated time period at the downstream station. In all three stations, negligible changes were noticed in the mean sediment size.

Generally, it is recognized that sediment coarsening takes place in the upstream and a fining occurs in the downstream. The changes in particle distribution noticed were negligible due to the short time period adopted for the study.

CONCLUSION

By employing the sediment budget equation, the model is able to analyze variations in the river bed's elevation at all points in a river system for a given hydrological event. This can be useful in trying to analyze the points along the river that are at risk of both degradation and aggradation. In this study we noticed that the downstream point (IEF01) is undergoing constant river bed aggradation which is reducing the Nzoia River's flow capacity. This means that with time, overtopping of the dykes will occur and therefore dredging will need to be done to mitigate this.

Apart from variations in the bed elevation and the sediment discharges, the module determines changes in the mean diameter size of the bed material which provides information on whether bed material is becoming finer or coarser. This gives a broader picture of processes within the bed material such as armoring that may be occurring or deposition of fine sediments from upstream.

This study has clearly shown that it is possibly to predict sediment movement along a river network by including the sediment module into the Rainfall-Runoff Inundation model. It is also able to predict river bed changes at any point along the river. However, the sediment module used in this analysis only considered river bed material movement. Introduction of wash-load component into the module would greatly improve its accuracy.

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