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MATHEMATICAL MODELING OF FLUVIAL SEDIMENT DELIVERY, NEKA RIVER, IRAN

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Simulation of cross section changes and sediment delivery in a specified time is the most important subject in river engineering. The spatial variation in sediment delivery along a channel reach is caused by sediment deposition and erosion. Studies of sediment delivery and channel changes may be through physical modeling or mathematical modeling, or both. Mathematical modeling of erodible channels has advanced with the progress in physics of fluvial processes and computer techniques. In this research, the delivery of sediment (sand and gravel) in the Neka River was studied through mathematical modeling of spatial variations of sediment characteristics for the effects of 200, 100, 50, and 25 year floods. The simulation results are useful for identifying river reaches subject to potential erosion and deposition. The results show sediment delivery increases toward the downstream direction. The amount of sediment delivery for the 200-year flood is 152000 tons and decreases for lower return periods. The general pattern of sediment delivery shows that there is erosion from the channel boundary. The study illustrates how erosion and fill of the channel bed accompanied by significant changes in channel width may contribute significantly to sediment storage. Sediment yield can be better quantified by an erodible-boundary model, as opposed to an erodible-bed model.

INTRODUCTION

Alluvial rivers are self-regulating in that they adjust their characteristics in response to any change in the environment. These environmental changes may occur naturally, as in the case of climatic variation or changes in vegetative cover, or may be a result of such human activities as damming, diversion, sand and gravel mining, canalization, bank protection, and bridge and highway construction. Such changes distort the natural quasi-equilibrium of a river. In the process of restoring the equilibrium, the river will adjust to the new conditions by changing its slope, roughness, bed-material size, cross-sectional shape, or meandering pattern. River channel behavior often needs to be studied for its natural state and responses to the aforementioned human activities. Various models are available for sediment and water routing in natural and man made channels. The computer program FLUVIAL-12 is a mathematical model that is formulated and developed for water and sediment routing in natural and man-made channels (Chang, 1998).

The FLUVIAL-12 has undergone testing and calibration using many data sets. For instance, data from the inlet channel of San Elijo Lagoon in Southern California (Chang and Hill, 1977), San Diego River in Southern California (Chang, 1982), San Lorenzo River in Northern California (Chang, 1985), Santa Clara River in Southern California (Chang and Stow, 1989), Stony Creek in Northern California (Chang, 1994), Feather River in Northern California (Chang et al., 1996), and San Dieguito River (Chang, 2004).

In this research, the Neka River was studied. The purpose of the study was water routing, sediment routing, simulation of changes in channel width, bed profile, and changes due to curvature effects for a given flow period.

MATERIALS AND METHODS

Study Area

The study area is located at the eastern part of the province of Mazandaran in the north of Iran. Figure 1 shows the Neka River study area starting from Chaman Village and extending upstream for a distance of about 4 km.

Analytical Basis of the Fluvial Model

The FLUVIAL model has the following five major components: water routing, sediment routing, changes in channel width, changes in channel-bed profile, and changes in geometry due to curvature effects.

The water routing component has the following three major features: (1) numerical solution of the continuity and momentum equations for longitudinal flow by the Chen and Fread technique (Chang, 1998), (2) evaluation of flow resistance due to longitudinal and transverse flows, the longitudinal energy gradient is evaluated using the Manning formula and transverse energy gradient is evaluated from the Chang formula (Chang, 1984):

$$S'' = \left(\frac{2.86\sqrt{f} + 2.07f}{0.565 + \sqrt{f}} \right) \left(\frac{h_c}{r_c} \right)^2 F^2 \qquad (1)$$

where f is the Darcy Weisbach friction factor, h_c is the flow depth at channel centerline, r_c is the mean channel radius and F is the Froude number, and (3) upstream and downstream boundary conditions, that is the flood hydrograph and stage-discharge relation respectively.

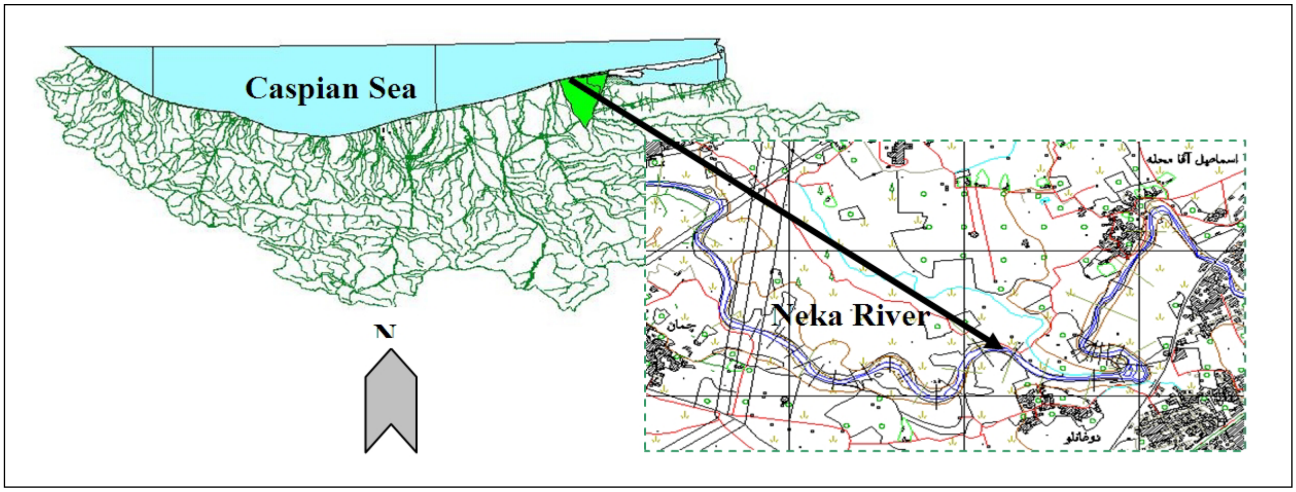

Figure 1. Catchment area of the Neka River.

The sediment routing component has the following major features: (1) computation of sediment transport capacity using a suitable formula for the physical conditions (2) determination of actual sediment discharge by making corrections for sorting and diffusion, the actual sediment rate is obtained by considering sediment material of all size fractions already in the flow as well as the exchange of sediment load with the bed using the method by Borah et al. (Chang, 1998), (3) upstream conditions for sediment inflow, and (4) numerical solution of the continuity equation for sediment. These features are evaluated at each time step; the results are used to determine the changes in channel configuration.

Changes in cross-sectional area, due to longitudinal and transverse imbalances in sediment discharge, are obtained based upon numerical solution of continuity equations for sediment in the respective directions. First, the continuity equation for sediment in the longitudinal direction is (Chang, 1998):

$$(1-\lambda)\frac{\partial A_b}{\partial t}+\frac{\partial Q_S}{\partial s}-q_s=0 \tag{2}$$

Where λ is the porosity of bed material, A_b is the cross sectional area of channel within some arbitrary frame, Qs is the bed-material discharge, and q_s is the lateral inflow rate of sediment per unit length. According to this equation, the time change of cross sectional area $\partial A_b / \partial t$ is related to the longitudinal gradient in sediment discharge $\partial Qs / \partial s$ and lateral sediment inflow q_s. The change in cross sectional area ΔA_b obtained in sediment routing represents the correction for a time increment Δt that needs to be applied to the bed and banks. With ΔA_b being the total correction, it is possible for both the bed and banks to have deposition or erosion; it is also possible to have deposition along the banks but erosion in the bed and vice versa. For a time increment, the amount of width change depends on the sediment rate, bank configuration and bank erodibility. After the banks are adjusted, the remaining correction for ΔA_b is applied to the bed. In the model, the allocation of scour and fill across a section during each time step is assumed to be a power function of the effective tractive force t_0 - t_c, i.e. (Chang, 1998):

$$\Delta Z=\frac{(\tau_0-\tau_C)^m}{\sum_B(\tau_0-\tau_C)^m\Delta y}\Delta A_b \tag{3}$$

where ΔZ is the local correction in channel-bed elevation, to (given by $\gamma\Delta S$) is the local tractive force, t_c is the critical tractive force, m is an exponent, y is the horizontal coordinate, and B is the channel width. The value of t_c is zero in the case of fill. Equation 3 may only be used in the absence of channel curvature. The change in bed area at a cross section in a curved reach is (Chang, 1998):

$$\frac{\partial z}{\partial t}+\frac{1}{1-\lambda}\frac{1}{r}\frac{\partial}{\partial r}(rq_s^{'})=0 \tag{4}$$

Sediment transport, in the presence of transverse flow, has a component in that direction. Sediment movement in the transverse direction contributes to the adjustment of transverse bed profile. Changes in channel-bed elevation at a point due to transverse sediment movement are computed using the transverse continuity equation for sediment (Chang, 1998):

$$\Delta z_K=\frac{\Delta t}{1-\lambda}\frac{2}{r_k}\frac{r_{k+1}q_{sk+1}^{'}-r_k q_{sk}^{'}}{r_{k+1}-r_{k-1}} \tag{5}$$

Written in finite difference form with a forward difference for qs’, this equation becomes:

$$\Delta z_K=\frac{\Delta t}{1-\lambda}\frac{2}{r_k}\frac{r_{k+1}q_{sk+1}^{'}-r_k q_{sk}^{'}}{r_{k+1}-r_{k-1}} \tag{6}$$

where k is the radial (transverse) coordinate index measured from the center of radius (Chang, 1998).

Input data

Input to the model includes features as follows:

1- Topographic maps

2- Digitized cross section data from the downstream end to the upstream end of the study reach

3- Inflow hydrographs with 25, 50, 100, and 200-year return periods. (Figure 2)

4- Downstream stage-discharge relationship. (Figure 3)

5- Size distributions of sediment samples along the study reach. Samples of bed sediment collected from the surface layer and the subsurface layer along the river reach. Sieve analyses were conducted to obtain the grain size distributions (Figure 4). The grain size distributions were used in the modeling study.

MODEL CALIBRATION

Major items that require calibration include the roughness coefficient, sediment transport equation, and bank erodibility factor.

Manning roughness coefficient

Roughness coefficients were selected in consideration of the field observations and attention to Chow tables. The coefficients are 0.04 for the main channel and 0.055 for floodways.

Sediment transport equation

A sediment transport formula is required in mathematical modeling of an alluvial stream. The rating curve for bed material load of study area was obtained. The model used three equations of

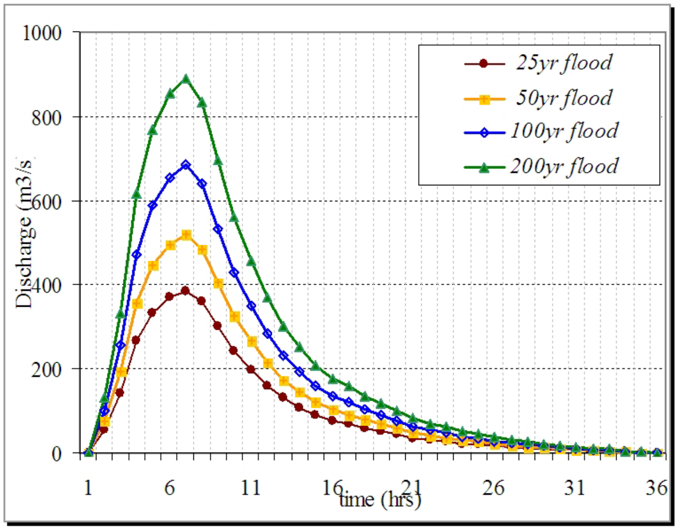

Figure 2. Flood hydrograph for the Neka River.

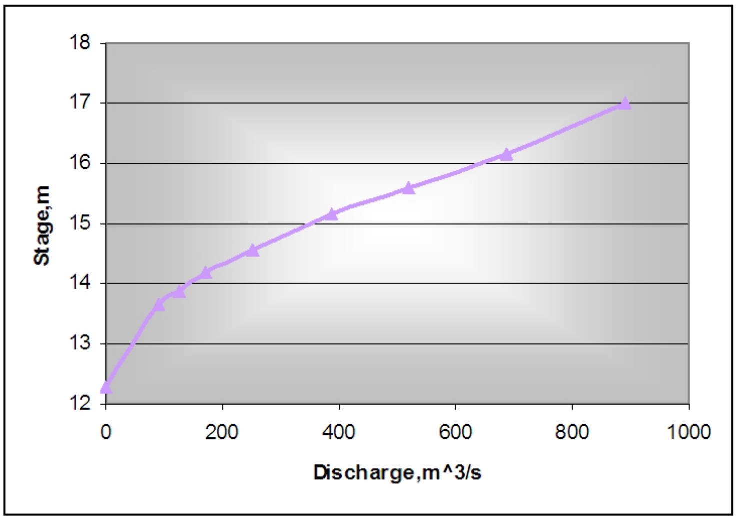

Figure 3. Flow rating curve for the Neka River.

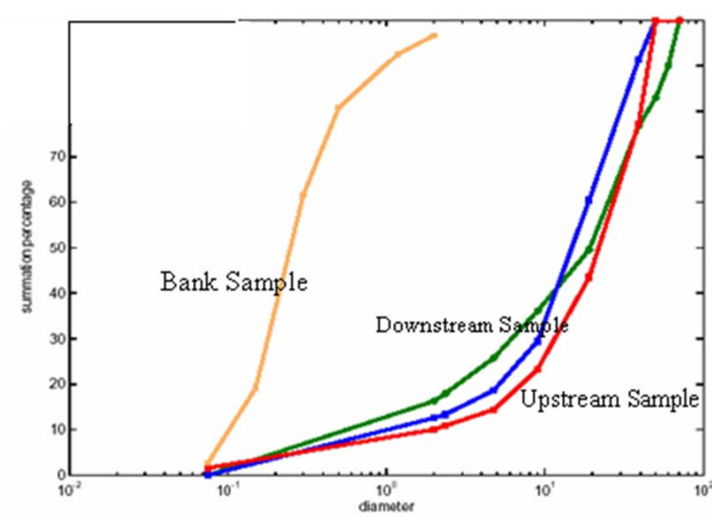

Figure 4. Distribution of bed and bank material for the Neka River.

sediment transport, Engelund-Hansen, Yang, and Ackers-White. The sediment discharge versus water discharge relation was computed using these formulas and is shown in Figure 5. From this figure, it is easy to see that the results produced by the Engelund-Hansen formula are closest to the measurement data.

Bank erodibility factor

The bank erodibility factor (BEF) affects the changes in channel width and lateral migration of the channel. This factor needs to be selected to reflect the variation in bank material. The BEF introduced as an index for the erosion of bank material and the four bank types reflecting the variation in erodibility classified as follows (Chang 1998):

(1) Non-erodible banks.

(2) Erosion-resistant banks, characterized by highly cohesive material or substantial vegetation, or both.

(3) Moderately erodible banks having medium bank cohesion.

(4) Easily erodible banks with noncohesive material.

Values of the BEF vary from zero for the first type to one for the last type of bank. By size distribution and curve of bank material for the Neka River (Figure 4), inspection of the river, and the erodibility of banks, the maximum value of the BEF (value = 1) was used.

SIMULATION RESULTS

Spatial variations in sediment delivery

Sediment delivery is the cumulative amount of sediment that has passed a certain point for a specified amount of time. The spatial variation in sediment delivery along a channel reach is caused by sediment deposition and erosion. Deposition signifies that sediment is stored in the channel, resulting in aggradations at the cross-section and a reduced sediment delivery downstream. Erosion results in channel degradation and increased sediment delivery. A uniform sediment delivery indicates a balance between erosion and deposition. The spatial variation of sediment delivery during the 25, 50, 100, and 200-yr return periods are shown in Figure 6. The spatial pattern of sediment delivery is similar for all floods. The spatial pattern of sediment delivery shows a sharp rise in the river from kilometer 4.3 to 3.1. This trend is related to the increase in river flow due to a low area of cross section and therefore an increase in erosion from the channel boundary. In river kilometer 2.8, due to higher cross section, river flow is low and aggradation is occurring. From kilometer 2.8 to 2.6, the increase in sediment delivery is rapid. From this point to the downstream end of the reach, the increase in delivery is slow. The amount of sediment delivery in at the Chaman village for a 200-yr flood is 152000 tons.

Changes in Channel Geometry

Channel geometry changes occur due to scour and fill, which is by no means uniformly distributed across the channel width. Scour of the bed may be accompanied by scour or fill of the over bank area, or vice versa. Such complex adjustments in channel morphology directly affect the hydraulics of flow and sediment transport. It must therefore be emphasized that fluvial simulation must be based on an erodible boundary model instead of an erodible bed model.

Changes in channel geometry are shown by the changes simulated in bed profile and cross sections (Figures 7 and 8). Water surface and channel bed changes are shown during the 200-yr

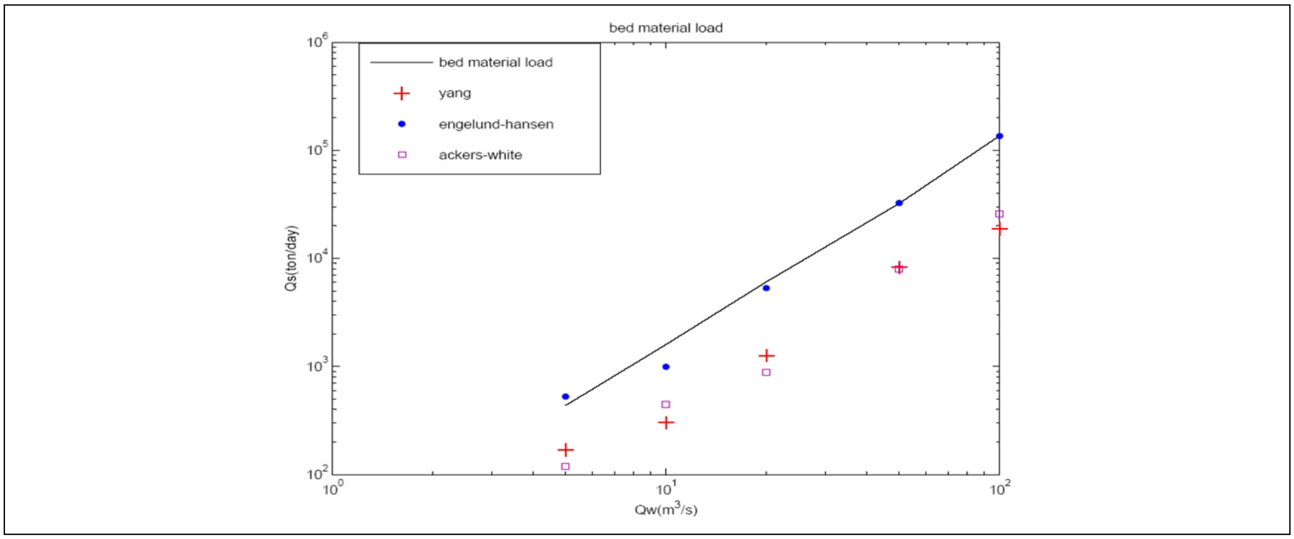

Figure 5. Comparison of methods for predicted sediment concentration.

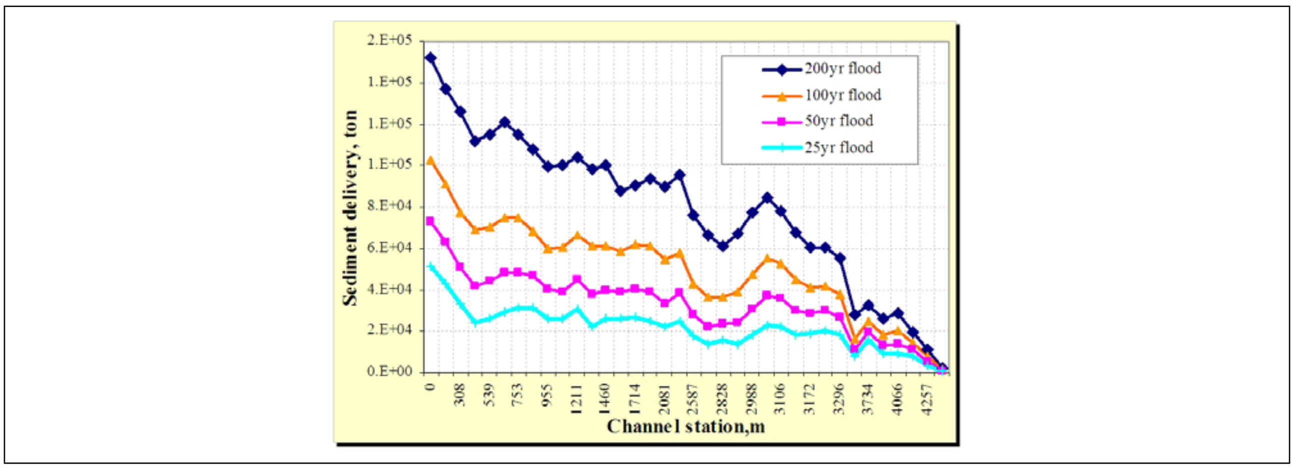

Figure 6. Time and spatial variations in sediment delivery for the Neka River.

flood. Figure 7 shows the modeled water surface and channel thalweg profiles. The 200-yr modeling run shows that channel bed aggradation is predicted at most cross sections, and degradation at some locations.

Lateral migration of channel bends are also predicted by the model. Bank erosion changes the channel curvature and the movement of sediment through a bend. Figure 8 shows the erosion in a concave bank and aggradation in a convex bank.

Variation in bed material diameter

In the process of erosion, finer sediments are more easily removed from the channel boundary and coarser sediments are usually left behind. Spatial variations of grain size in the 200-yr flood are shown in Figure 9. There is a natural decrease in sediment size in the downstream direction, caused by a decrease in gradient and stream power. Increase and decrease in D_{50} is for erosion and aggradation, respectively. The maximum D_{50} is 30.86 mm for the 200-yr flood.

Temporal characteristics of sediment yield

If Y is the yield for a particular flood and P is the probability of the flood occurrence in one year, then PY represents the contribution to the stream mean annual yield $\overline{Y}$ from this flood. However, the variable Y is continuous; its value has a probability density so that only a finite interval of Y has

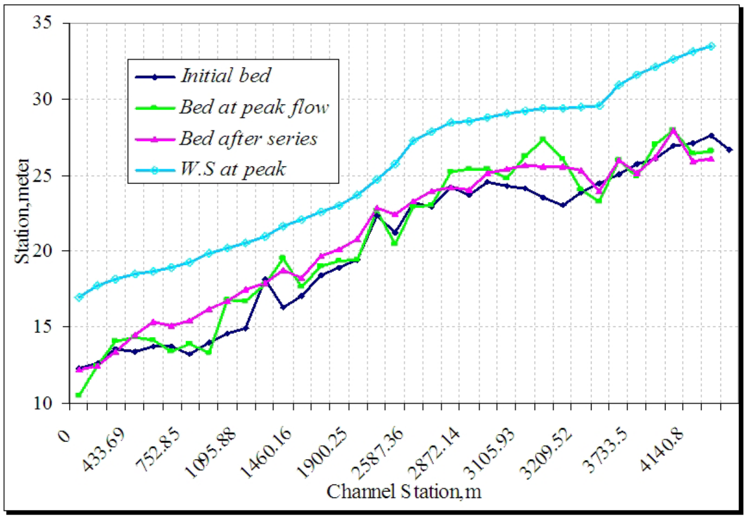

Figure 7. Water surface and bed profile changes during the 200-yr flood.

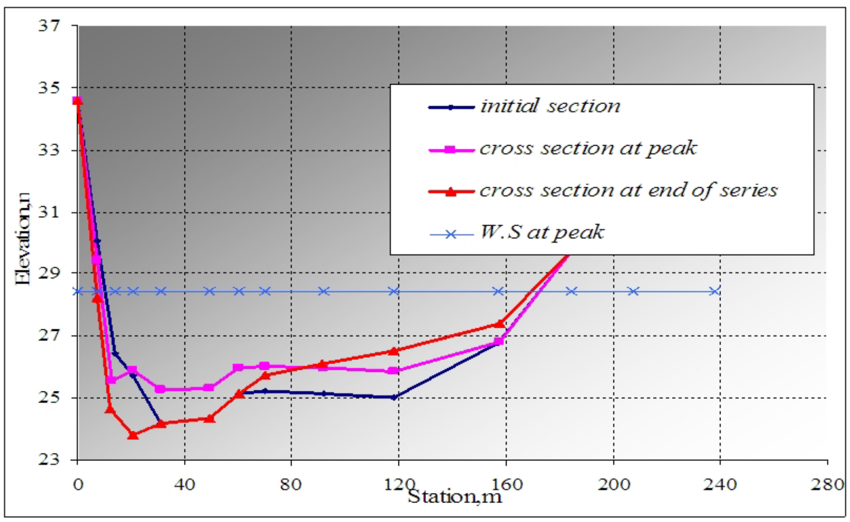

Figure 8. Changes in cross section at river kilometer 1.1 during 200-yr flood.

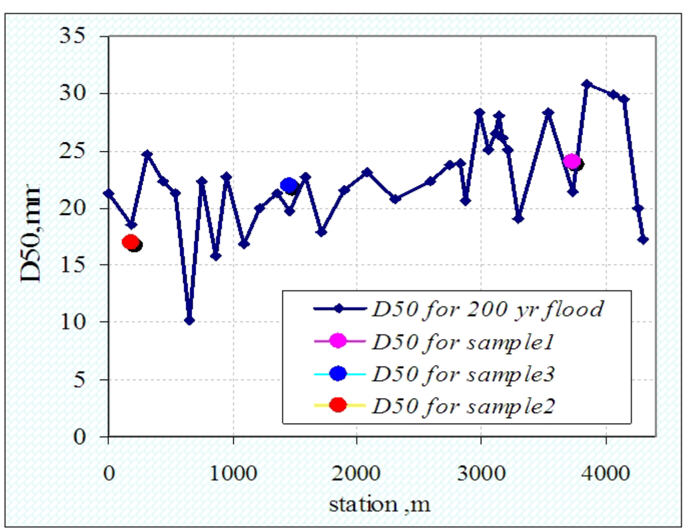

Figure 9. Changes in median grain size during the 200-yr flood.

a finite probability. The mean annual yield contributed from floods of all frequencies is therefore (Chang and Stow, 1989):

$$\bar{Y} = \int Y dP \tag{7}$$

The variable Y is shown as a function of P in Figure 10 for the downstream end of the Neka River reach. The probabilities of occurrence in one year for the 200, 100, 50, 25, and 10-year floods are 0.005, 0.01, 0.02, 0.04, and 0.1, respectively. The curve was derived by plotting the four calculated data points on a yield-probability chart and then fitting a continuous curve by eye. The integral in the above equation is represented by the area under the Y versus P curve in the figure. Integration of curve gives an estimate of the mean annual sand delivery. Variation in mean annual yield among this station suggests sediment storage and depletion. Table 1 summarizes sediment deliveries for different flood events.

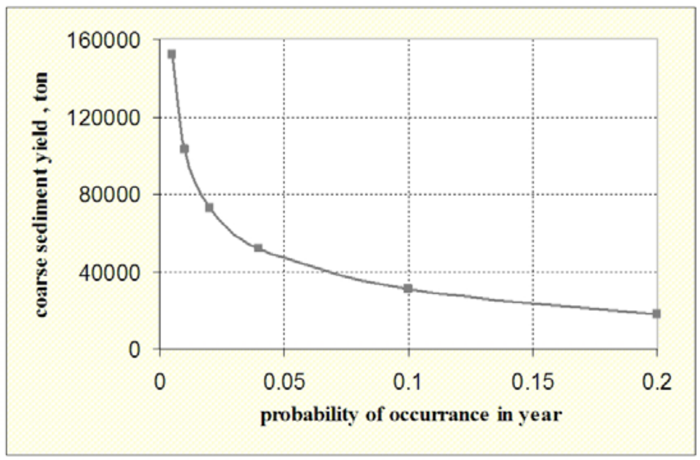

Figure 10. Yield-probability relationship for the Neka River at the downstream end.

Table 1. Summary of sediment deliveries by different flood events.

Yield by Flood Event, ton						Mean annual yield, tons/year
200Year	100Year	50Year	25Year	10Year	5Year	
152000	103000	73100	51600	30800	17800	8886

CONCLUSIONS

The computer program FLUVIAL-12 was selected for the Neka River study. The combined effects of flow hydraulics, sediment transport and river channel changes are simulated for a given flow period. River channel changes simulated by the model include channel bed fill and scour (or aggradation and degradation), width variation, and changes induced by the curvature effects. The result shows:

- The models were run using a number of different sediment transport equations. The Engelund-Hansen equation was selected because the results most closely agreed with measurements.

- The amount of sediment delivery in the downstream reach of the Neka River is about 152000 tons for the 200-year flood. In comparison to the sediment yield measured during the 25-year flood series, 495700 tons, this amount is small. In other return periods sediment removal from the channel reach is attributed primarily to the long-term flood series.

- Most cross sections show erosion and aggradation in bank and bed, respectively.

- Most of the river cross sections cannot pass the high flow, and flood control including modification and construction of levees will be needed.

- Comparing the samples of D_{50}, in samples 1 and 3 the median grain size decreases for aggradation, and increases in sample 2 for erosion.

- The simulation results are useful for obtaining mean annual yields for different river locations. The mean annual yield for the downstream reach of the Neka River is 8886 ton/year.

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