

NUMERICAL MODELING OF BED MIXING AND TRANSPORT FOLLOWING DAM REMOVAL

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Abstract SRH-1D is used to investigate the sensitivity of numerical model predictions on the sediment transport following the removal of Matilija Dam in Ventura County, CA. The analysis is intended to demonstrate the model sensitivity to various methods of computing transport of sand-gravel mixtures.

Dam removal often results in the release of large amounts of fine material to a much coarser downstream channel. Two main processes are important to the prediction of the sediment process following dam removal: the mixing of the fine and coarse material in the river bed, and the mutual effect of fine and coarse sediment on their transport rates. The active layer concept is generally used to represent the thickness of the bed that is available for transport. The active layer concept assumes that there is complete mixing throughout it. The active layer methodology may not correctly represent the movement of fine material over the top of coarse material, before the coarse material is mobilized. The active layer concept may also not represent the infiltration of fine material into a coarse bed that was previously free of fines. The other process is the mutual effect of fine and coarse material on each other's transport rates. Fine material has been shown to increase the mobility of coarse material and the coarse material will trap some of the fine material.

There have been recent laboratory experiments by various researchers that analyze these interactions. Empirical relationships that describe the effect of fine material on the transport rate of coarse material have recently been developed and there has also been some work on describing the effect of coarse material on the transport rates of fine (Wilcock and Crowe, 2003). There has also been some initial work describing the infiltration of fine material into a coarse bed (Cui et al., 2008). However, few numerical models of practical systems that include these processes have been constructed and the practical effect of including these processes is not well understood. This paper describes the practical model implementation of sand and gravel interactions into a one-dimensional model (called SRH-1D).

DESCRIPTION OF SITE

Matilija Dam is located on Matilija Creek which forms the Ventura River after the confluence with North Fork Matilija Creek (Figure 1). The dam is located approximately 16 miles upstream from the Pacific Ocean in Ventura County, CA. The dam is approximately 120 feet high and almost completely full of sediment ranging in size from clays to boulder, with the majority of the sediment in the sand size class. The total sediment deposit behind the dam can generally be divided into three regions: the reservoir deposit, the delta, and the upstream channel (Table 1). The reservoir deposit is below the pool elevation and is primarily clay and silt with a total volume of 2.1 million yd³. Its maximum thickness is approximately 80 ft. The delta is located immediately upstream and a significant portion of the deposit is above the normal pool elevation.

It is composed of a mixture of silt, sand, gravel, and cobble and has a total volume of 2.8 million yd³ with a maximum thickness of approximately 40 feet. The upstream channel portion of the deposit is composed of primarily sand, gravel, cobbles and boulders with a volume of 1 million yd³ and a maximum thickness of about 20 feet.

The Ventura River has a slope of approximately 0.02 immediately downstream of the dam and this gradually decreases to about 0.006 about 1 mile upstream of the ocean (Figure 2). The bed material immediately downstream of the dam is composed of large boulders and cobbles. Boulders become generally less prevalent in the downstream direction and the bed is dominated by large cobbles.

Table 1 Grain size distribution and volume of impounded sediment.

Grain Diameter (mm)	% finer than		
	Reservoir	Delta	Upstream Channel
512	100.0	100.0	100.0
256	100.0	100.0	87.9
128	100.0	100.0	75.9
64	100.0	99.8	60.9
32	100.0	98.4	48.9
16	99.9	95.1	36.9
8	99.8	92.5	29.9
4	99.7	89.9	24.9
2	99.7	87.3	21.9
1	99.5	83.7	18.4
0.5	99.0	77.5	15.0
0.25	97.2	66.5	12.0
0.125	92.2	50.8	9.0
0.0625	82.8	33.2	6.0
0.031	70.9	21.9	4.0
0.016	57.3	14.5	2.0
0.008	43.1	9.7	1.0
0.004	30.1	5.3	0.0
0.002	18.0	0.0	0.0
Total Volume (yd³)	2,100,000	2,800,000	1,000,000

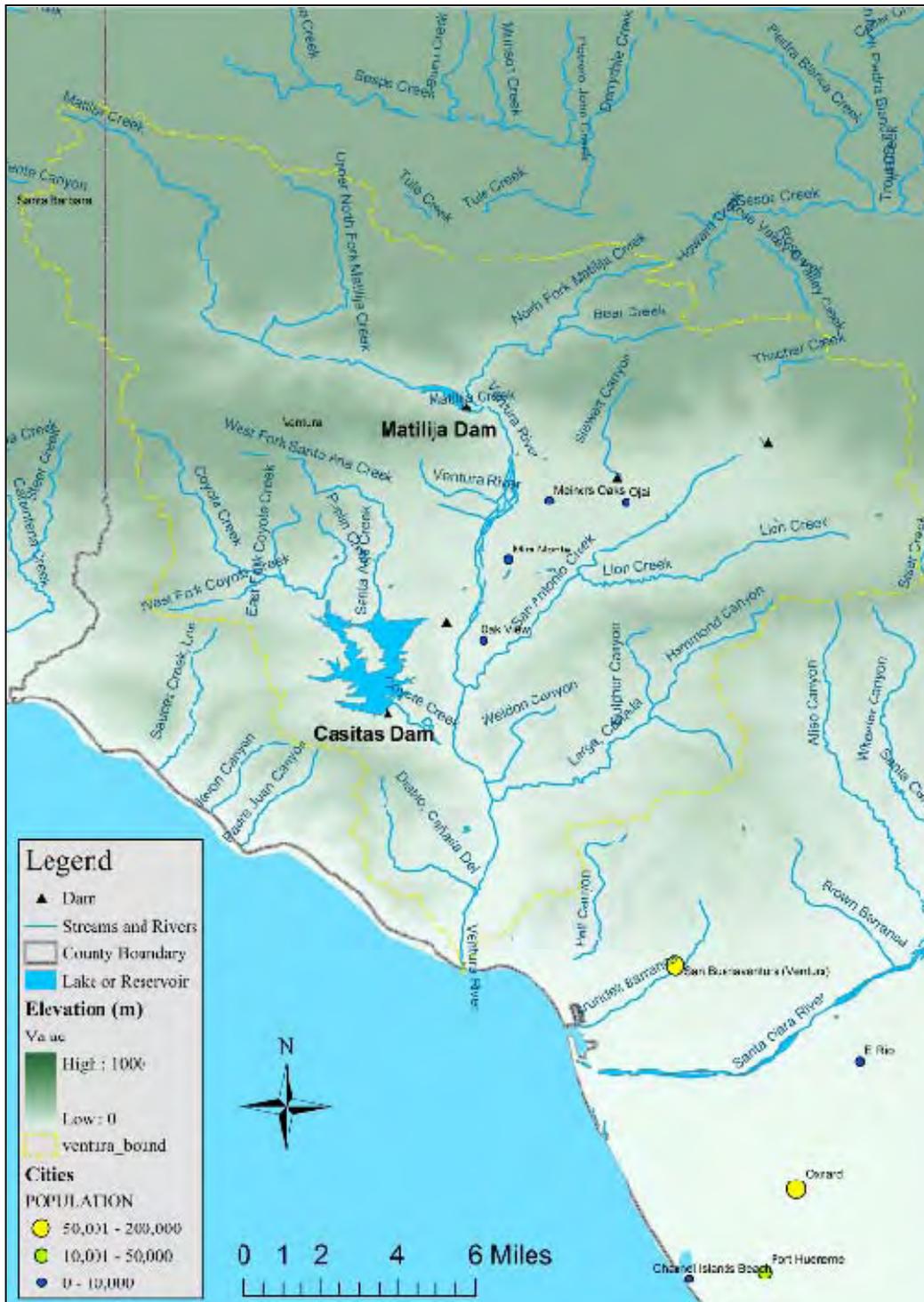


Figure 1 Ventura River Watershed.

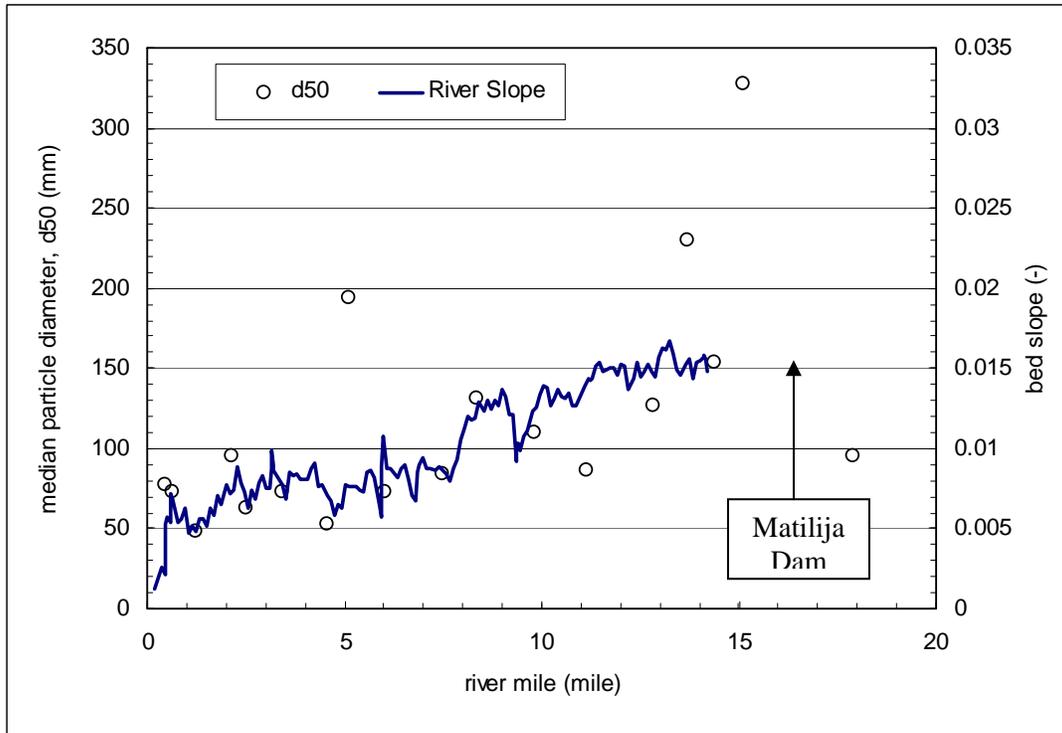


Figure 2 Ventura river slope and median bed material size.

METHODS

A one-dimensional model sediment transport model, SRH-1D (Huang and Greimann, 2010), is used to simulate the sediment transport following the removal of Matilija Dam. SRH-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. It is able to compute water surface profiles in single channels, dendritic, and looped network channels. It has both steady and unsteady flow models, steady and unsteady sediment models. SRH-1D uses standard step method to solve the energy equation for steady gradually varied flows. SRH-1D uses a staggered grid scheme to solve the de St Venant equations for unsteady rapid varied flows. Two methods of sediment transport are used in SRH-1D. For a long term simulation, the unsteady term of the sediment transport continuity equation are ignored, and the non-equilibrium sediment transport method of Han (1980) is used. For a short term simulations, the governing equation for sediment transport is the convection-diffusion equation with a source term arising from sediment erosion/deposition. This equation is solved with an implicit finite-volume method and with the Lax-Wendroff TVD scheme for the convective term and the central difference scheme for the diffusion term. Internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates are simulated. The notation of an active layer, which allows selective erosion, provides an appropriate framework to simulate the bed armoring. Non-cohesive sediment transport equations and cohesive sediment physical processes are applied to calculate the sediment deposition and erosion. The most recent version can be downloaded at: www.usbr.gov/pmts/sediment.

Several sediment transport formulae are available. The base transport formula in this analysis for comparison is the Wilcock and Crowe (2003) bed load formula. The Wilcock and Crowe (2003) formula is similar to the Parker (1990) in form:

$$\frac{q_{bi} g (s-1)}{p_i (\tau_b / \rho)^{1.5}} = 14 f(\phi_i) \quad (1)$$

where q_s = volumetric sediment transport rate per unit width; τ_b = total bed shear stress, d_{50} = the median diameter; g = acceleration of gravity; γ = specific weight of water; and s = relative specific density of sediment (ρ_s / ρ). The parameter ϕ_i is a measure of the shear stress relative to the reference shear stress:

$$\phi_i = \theta_i / (\xi_i \theta_c) \quad (2)$$

where θ_c is the reference Shield's number; and θ_i = Shield's parameter of the sediment size class i computed as:

$$\theta_i = \tau_g / (\gamma (s-1) d_i) \quad (3)$$

where τ_g is the grain shear stress. The grain shear stress is computed based upon the velocity and representative grain diameter:

$$\frac{U}{\sqrt{\tau_g / \rho}} = 2.5 \ln \left(\frac{12.27 R'}{k_s} \right) \quad (4)$$

where U is the cross sectional average velocity, R' is the hydraulic radius due to grain shear stress ($\tau_g = \gamma R' S_f$). The roughness height, k_s , used to compute the grain shear stress is $k_s = 2d_{65}$.

The function f is computed as:

$$f(\phi) = \begin{cases} (1 - 0.894 / \sqrt{\phi})^{4.5} & , \phi \geq 1.35 \\ 0.000143 \phi^{7.5} & , \phi < 1.35 \end{cases} \quad (5)$$

The function has the behavior that as ϕ_i becomes large, $f(\phi_i)$ approaches 1. The parameter, ϕ , is defined similar to the Parker equation:

$$\phi_i = \theta_i / (\xi_i \theta_c) \quad (6)$$

Wilcock and Crowe formulated an expression for the reference shear stress that was dependent upon the fraction of sand within the bed. Gaeuman et al. (2009) modified that expression so that it was dependent upon the geometric standard deviation of the sediment particle size distribution, σ_{sg} :

$$\theta_c = 0.021 + 0.015 \left[1 + \exp(10.1 \sigma_{sg} - 14.14) \right]^{-1} \quad (7)$$

The hiding function is:

$$\xi = (d_i / d_m)^{-\alpha} \quad (8)$$

where d_m is the geometric mean diameter. Notice that the geometric mean diameter is used in the above equation and not the median. The original paper mistakenly stated that the median should be used. The parameter α was specified as:

$$\alpha = 1 - 0.67[1 + \exp(1.5 - d_i / d_m)]^{-1} \quad (9)$$

where d_m is the mean particle diameter in the bed. The above equation has the behavior of approaching 0.33 for large d_i/d_m and approaching 0.88 for small d_i/d_m .

In SRH-1D, the following equations are used to compute θ_c and α :

$$\begin{aligned} \theta_c &= \theta_{c0} + 0.015[1 + \exp(10.1\sigma_{sg} - 14.14)]^{-1} \\ \alpha &= 1 - (1 - \alpha_0)[1 + \exp(1.5 - d_i / d_m)]^{-1} \end{aligned} \quad (10)$$

where if $\theta_c = 0.021$ and $\alpha_0 = 0.33$, the Wilcock and Crowe (2003) relation is recovered. The user can specify the value of θ_{c0} and α_0 .

Bed load equations like Parker and Wilcock and Crowe ignore the suspended load transport and in systems where both suspended and bed load are a concern, they should be paired with an equation that would predict the suspended load. The Engelund-Hansen formula can be rewritten in the form:

$$\frac{q_{si}g(s-1)}{(\tau_b/\rho)^{1.5}} = p_i \frac{0.05V^2}{g(s-1)d_i} \quad (11)$$

which is similar in form to the Parker and Wilcock and Crowe formulas. The similar forms suggest that a transport equation for sand in a gravel system could be obtained by combining the Parker or Wilcock formulas with the Engelund-Hansen formula as follows:

$$\frac{q_{si}g(s-1)}{(\tau_b/\rho)^{1.5}} = p_i \max\left[C, \frac{0.05V^2}{g(s-1)d_i}\right] f(\phi_i) \quad (12)$$

with $C = 14$ for Wilcock and Crowe methods. The function f is given in equation **Error! Reference source not found.**. The above method is used to compute the sand load, while the standard methods for Wilcock and Crowe are used for the gravel and larger sizes.

Other model input included flow rates, sediment loads, channel roughness, initial channel geometry, and initial bed material. In addition, several computational parameters were required, including the active layer thickness and non-equilibrium adjustment factors.

RESULTS

This is an initial summary of the results and a more complete sensitivity analysis will be documented in the final paper submission. The non-dimensional critical shear stress was varied between 0.02 and 0.04 and results are shown in Figure 3. Increasing the critical shear stress to 0.04 had little effect on the simulation. Decreasing the critical shear stress to 0.02 actually increased the deposition at some locations. This is counter intuitive, but it is primarily because decreasing the critical shear stress in the reaches above the dam increased the sediment input in

the Ventura River by increasing the amount of sediment eroded from the area upstream of Matilija Dam.

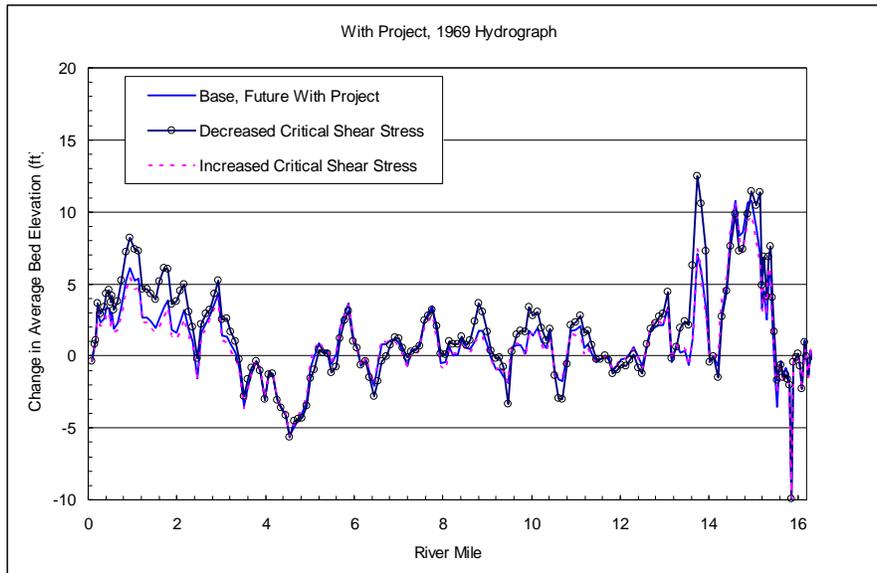


Figure 3 Comparison between various value of the reference shear stress in the Wilcock and Crowe (2003) formula.

The Parker transport formula (Parker, 1990) was used instead of the Wilcock-Crowe (2003) bedload formula to compute bedload. The result to the calculation is shown in Figure 4. The simulation using the Parker Formula generally predicted greater extremes in the erosion and deposition. However, the trends in erosion and deposition were the same.

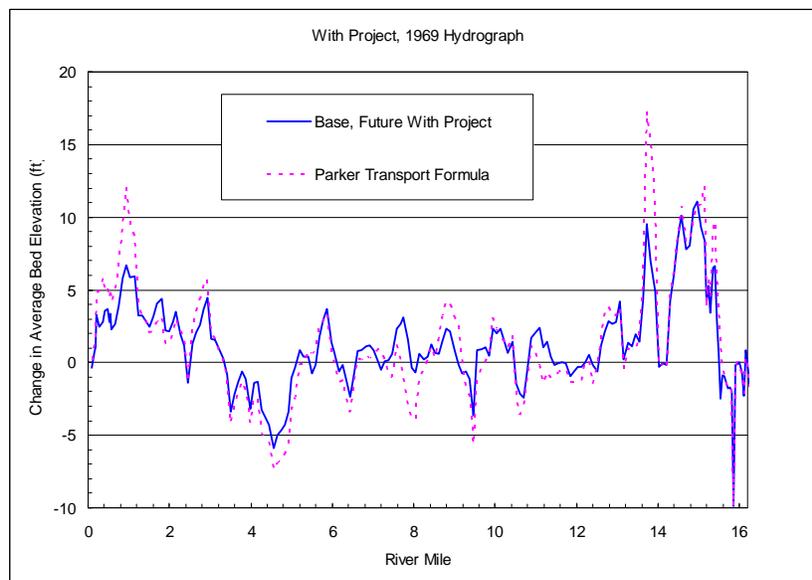


Figure 4 Comparison between Wilcock and Crowe (2003) formula and Parker (1990) formula.

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