Reservoir construction, river sedimentation and tributary sediment size

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Abstract The channel of the Trinity River in northern California (USA) has changed as a result of water storage in the basin and diversion from the basin. The changes include a 50% reduction in bankfull width, loss of a feathered edge along the channel, increased sand in the substrate, and sand waves over the substrate. Grass Valley Creek is tributary to the Trinity River and yields large quantities of sand and fine gravel. The sediment yield from Grass Valley Creek is 566 t km^{-2} with much of the load being sand. The Trinity River, prior to water development, could transport most of the sediment from Grass Valley Creek as suspended load, however, following water development the river could no longer move the sediment as suspended load, but had to transport much of the Grass Valley Creek sediment inflow as bed load. This is the cause of the increased sand content of the stream bed and the sand waves over the stream bed. Two other rivers (the Gunnison in western Colorado and the Rio Grande in New Mexico) have also had major reservoirs constructed upstream of tributaries with large sediment loads. The difference between these two rivers and the Trinity River is that the sediment loads were fines (silt and clay) which the rivers could still transport as suspended load.

INTRODUCTION

In a previous paper (Milhous, 1995a) three watersheds were compared to demonstrate the range of impacts storage reservoirs may have on the balance of tributary sediment and the ability of the river to transport the sediment. The three rivers illustrated three general situations.

(a) The first case is the situation where large quantities of sand and fine gravel are delivered by a tributary to a large river downstream of a major reservoir and diversion that reduced both annual flows and the peak flows. The example is the Trinity River in northern California. Significant changes in the channel and the bed material have occurred.

(b) The second situation is where a reservoir reduced the peak flows and sediment supply in a sand bed river with a downstream tributary that transports large quantities of very fine sediment to the river. The example is the Rio Grande below the Rio Puerco in central New Mexico. Reduction of relative sediment yield from the Rio Grande as compared to the yield from the Rio Puerco does not appear to have changed the characteristics of the bed material.

(c) The third case is where a number of tributaries discharge mixtures of sand and fine sediment to the main river in surges. The example is the lower Gunnison River in western Colorado. The major impact of reservoirs has been to reduce the capacity of the river to cleanse the bed material of the fines and sand, with the result that there are more fines and sand on, and within, the stream bed than in the most probable natural situation.

This paper deals only with the Trinity River case and will describe the results of more detailed investigations undertaken after the work described in the 1995 paper. The main concept is that the size composition of the sediment must be considered in any attempt to understand historic bed material changes caused by reservoirs, or to forecast the changes that may result from a future reservoir. In the absence of size information, a hydraulic engineer or hydrologist can do little other than guess at the impacts that streamflow changes will have on bed material characteristics.

THE TRINITY RIVER

The Trinity River, a tributary of the Klamath River located in northern California (USA), has large water storage and diversion facilities, constructed by the US Bureau of Reclamation (USBR), that divert a large portion of the natural streamflow from the Trinity River to the Sacramento Basin. The reservoirs and diversion have had a major impact on the Trinity River by changing flows, the physical characteristics of the channel morphology, and bed material. The reach considered in this paper is just downstream of Lewiston Dam.

The storage and diversion of water has changed the mean daily flows of the Trinity River at Lewiston during all parts of the year. The average daily flow has been increased in the summer in order to meet an "instream flow need" but it has been reduced to approximately 20% of the natural flow during winter storm and spring runoff periods. The Trinity River project has also caused a change in peak flows; the median annual peak daily flow in the Trinity River has been reduced from 408 $m^3 s^{-1}$ in the 49-year period (1912-1960) prior to construction of the project, to 34 $m^3 s^{-1}$ in the 35-year period (1961-1995) following construction of the project. These changes in streamflow have caused a 50% reduction in bankfull width, loss of a feathered edge along the channel, increased sand in the substrate, and sand waves over the substrate (Frederiksen, Kamine & Associates, 1980; Nelson *et al.*, 1987).

The change in channel width occurred primarily because of the changes in streamflow; but the loss of the feathered edge was probably caused by willow and alder growth on pre-1961 gravel-bars that could not be removed by the reduced flows but did trap sediment. This made it easier for more trees to grow, which in turn trapped more sediment, with the result the channel has a steep bank without the shallow side slopes that gave the pre-project feathered edges (Frederiksen, Kamine & Associates, 1980).

A large quantity of sediment is delivered to the Trinity River below Lewiston Dam by tributary streams. The reduction of flows below the dam has caused the deposition of sediment in and on the stream bed. A high percentage of the fines and sand are derived from the Shasta Bally batholith and transported to the Trinity River by Grass Valley Creek. The Shasta Bally batholith is weathering rapidly to sandy material that is easy to erode. Most of the Grass Valley watershed, but little of the remaining Trinity River watershed, is underlain by the batholith (Nelson *et al.*, 1987).

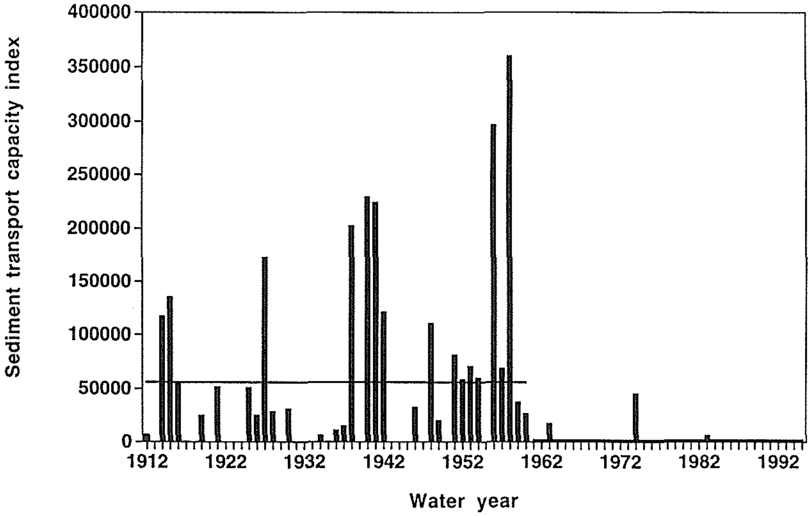

Fig. 1 Annual ability (STCI) of the Trinity River to transport sand 4 mm or smaller as suspended load.

IMPACT OF STORAGE AND DIVERSION OF WATER ON SEDIMENT MOVEMENT

The ability of the Trinity River to transport sand as suspended load has been reduced. The discharge required to transport 4 mm sand as suspended load is 190 $m^3 s^{-1}$. The long-term variation in the transport capacity index (STCI), which reflects the annual ability of the river to transport sand 4 mm or smaller, is presented in Fig. 1. (See following sections for details of how the 190 m^3s^{-1} and the sediment transport capacity

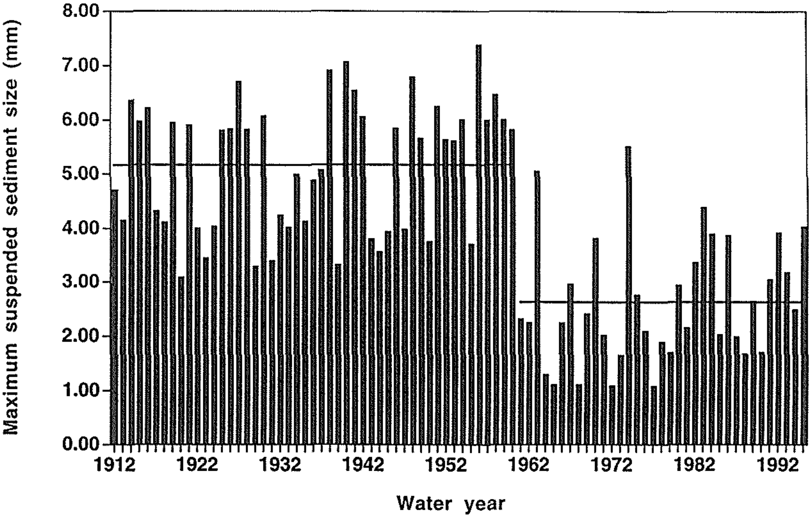

Fig. 2 The maximum size of the suspended load transported by the peak daily discharge on the Trinity River for each water year.

index were determined.) Prior to construction of the project, the Trinity River had considerable capacity to transport sand of 4 mm or less. The average value of STCI (dimensionless) was 56300 prior to the project, but was reduced to 2040 by the project. During the period 1912-1960, 78% of the years had an annual STCI greater than 0, with the longest run of zeros being 3 years. In contrast, from 1961-1995 only 11% of the years had a non-zero STCI and the longest run of zeros was 11 years. Under natural conditions the zero capacity would occur when the sediment yield from Grass Valley Creek was also low, but the reservoirs have destroyed that natural linkage.

To illustrate further the impact of the project on the ability of the river to transport sand, the maximum size of the sediment transported in the river at the annual maximum daily discharge is shown in Fig. 2 (calculation logic and procedure explained in a following section). The impact of the project on the ability to transport sediment was to reduce the maximum size transported as suspended load by the peak daily flow of the river from an average of 5.2 mm to 2.6 mm. Table 1 summarizes the changes in the sizes of sediment the river transports as suspended load caused by the project. Grass Valley Creek is tributary to the Trinity River and yields large quantities of sand and fine gravel. The average annual sediment yield from Grass Valley Creek was 27 900 t (1979-1995). Under natural conditions most of the sediment from Grass Valley Creek would pass downstream as suspended or wash load.

The d_{50} and d_{90} sizes of the suspended load and bed material sampled by the US Geological Survey are given in Table 2. Comparing Table 1 with Table 2 shows that the range of sediment sizes in Grass Valley Creek includes the range in which reduction of the maximum particle size of the wash and suspended load could affect the bed material. A very rough estimate of the size of the total sediment yield from Grass Valley is a d_{50} of 0.42 mm and a d_{90} of 1.3 mm. Much of the sediment from Grass Valley Creek is still transported as wash and suspended load but there is enough sediment larger than 1.1 mm to expect a change in bed material and this did in fact occur. The sediment load from the other tributaries probably has a d_{50} of about 0.02-0.04 mm, which is much smaller than that of Grass Valley Creek.

Table 1 Maximum values for the size of the suspended load in the Trinity River for the period prior to construction of the Trinity River storage and diversion facilities and following completion of the facilities. Streamflow data used were from the records of the US Geological Survey.

	1912-1960	1961-1995
Median	5.6 mm	2.2 mm
Average	5.2 mm	2.6 mm
Maximum	7.4 mm	5.5 mm
Minimum	3.1 mm	1.1 mm

Table 2 The size of sediment load and bed material samples from Grass Valley Creek. d_{50} is the size at which 50% of the particles are smaller and d_{90} is the size at which 90% are smaller than. Data from the records of the US Geological Survey.

	Suspended load (mm):		Bed load (mm):		Bed materials (mm)	
	d_{50}	d_{90}	d_{50}	d_{90}	d_{50}	d_{90}
Median	0.21	0.80	1.39	3.71	3.3	27.0
Average	0.29	0.84	1.41	3.78	15.7	31.9
Maximum	0.76	2.20	2.75	8.00	82.1	117.0
Minimum		0.062	0.50	1.92	0.3	1.0

SIZES OF SEDIMENT TRANSPORTED

The maximum sizes of the sediment transported as bed, suspended, and wash load have been calculated by developing a model of the hydraulics of the stream, using the model to calculate a "substrate movement parameter" (ß), and then using ß to calculate the maximum size of sediment particles that the stream will transport at each cross section, and deciding on a maximum size representative of the whole reach of river (Milhous, 1997). The equation for the substrate movement parameter is:

$$\beta = \frac{RS_e}{d_{50a}(G_s - 1)} \tag{1}$$

where ß is the substrate movement parameter, R is the hydraulic radius, S_e is the energy slope, d_{50a} is the median size of the bed surface material (armour), and G_s is the specific gravity of the bed material. The substrate movement parameter is the dimensionless shear stress calculated using the median size of the bed surface material (the armour).

The equations used to calculate the maximum size of the wash ($d_{\max wl}$), suspended ($d_{\max sl}$), and bed load ($d_{\max bl}$) are:

$$d_{\max wl} = \frac{RS_e}{0.56(G_S - 1)} \tag{2}$$

$$d_{\max sl} = \frac{RS_e}{0.28(G_S - 1)} \tag{3}$$

$$d_{\max bl} = \left[\frac{RS_e}{0.018(G_S - 1)}\right]^{2.85} (d_{50a}^{-1.85}) \tag{4}$$

The equation for the maximum size of the bed load should be used when only when ß is less than 0.035. The maximum size of the wash load is one half of the maximum size of the suspended load. The wash load is that portion of the sediment load which has a 100% probability of moving down the stream. The maximum size of the suspended load represents a particle which is just removed from the stream bed and moved downstream in suspension. The relationships for the maximum size of the sediment load in the Trinity River are shown in Fig. 3. The cross section data used in the hydraulic simulation are from Barta *et al.* (1993) and were obtained after channel adjustment to post-construction flows.

THE SEDIMENT TRANSPORT CAPACITY INDEX

The use of a sediment transport capacity index (STCI) is helpful in investigating impacts of water projects and water management on the ability of a river to move sediment (Milhous, 1995b). The equation for STCI is:

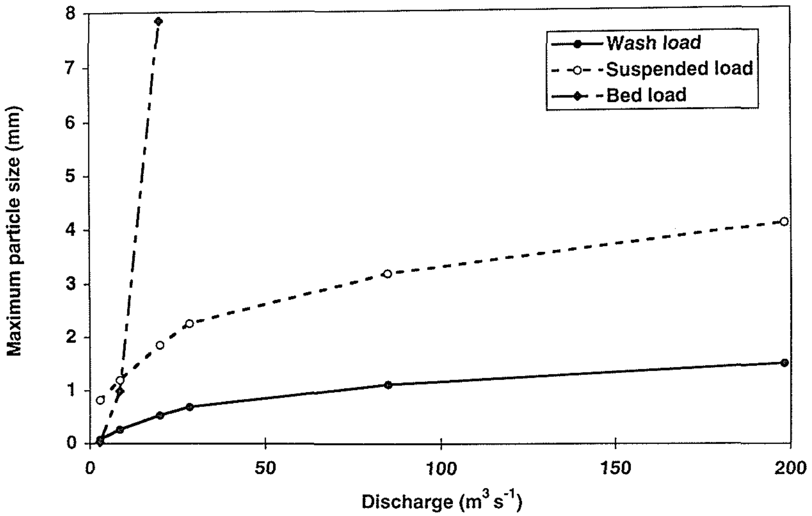

Fig. 3 Maximum size of wash, suspended, and bed load in the Poker Bar reach of the Trinity River near Lewiston, California.

$$\mathrm{STCI} = \sum \left[\frac{\left(Q * (Q - QCRT)^{b}\right)}{\left(QREF^{b+1}\right)} \right] \qquad (5)$$

where: Q is the daily discharge, $QCRT$ is a critical discharge, $QREF$ is a reference discharge, and b is the power term in the sediment concentration *vs* discharge equation. The summation is over the period of interest, which in this application is a water year. The critical discharge used for Fig. 1 is the discharge required to just transport 4 mm sand as suspended load. The value of 190 m^3 s^{-1} was obtained from Fig. 3.

APPLICATION TO A 1990 SEDIMENT YIELD EVENT

Figure 4 illustrates the impact of the reservoirs and diversion on the substrate during a storm in 1990. The gravelly substrate appears to have been covered by a sand wave during the runoff event from 15 May (day 227) to 7 June 1990 (day 250). The d_{90} of the sand wave was 5.4 mm and the d_{50} was 2.47 mm. In Fig. 2 it was shown the impact of the project has been to reduce the maximum size of the sediment transported in suspension. This reduction in maximum size could be the reason for the sand wave.

The calculated maximum size of the sediment moved as suspended load is shown in Fig. 5. Also shown in Fig. 5 is the size of sediment that may have moved in suspension with natural (adjusted) flows. The diagram suggests that the sand wave would have moved as suspended load under natural flow conditions. The diagram also shows the coupling of the Grass Valley flows with the ability of the Trinity River to transport most of the sediment from Grass Valley Creek as suspended load. The conclusion from Figs 4 and 5 is that much of the sediment from Grass Valley Creek would be suspended load under natural conditions but must now be bed load.

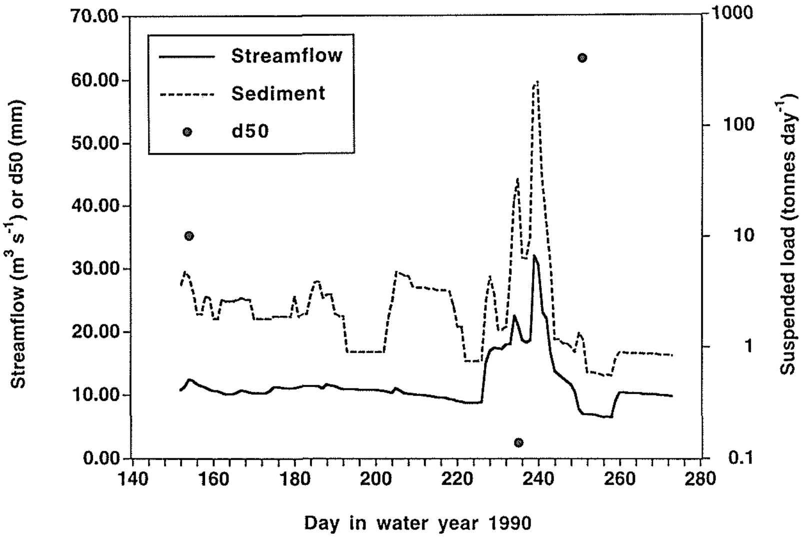

Fig. 4 The discharge, sediment load, and median (d_{50}) size of the bed material for the Trinity River below Limekiln Gulch near Douglas City, California, Water Year 1990. Data from the records of the US Geological Survey.

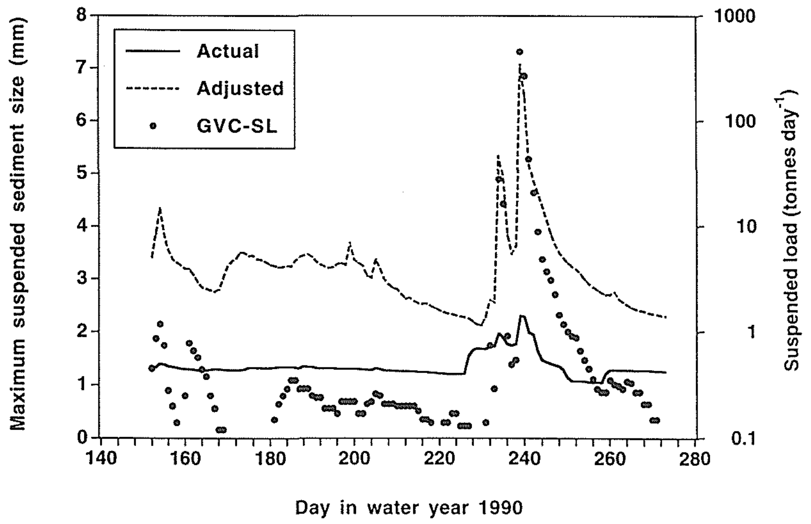

Fig. 5 The maximum size of sediment that could be transported by the May-June 1990 runoff event and during the same period if the reservoirs had not reduced the streamflow. GVC-S is the suspended sediment load from Grass Valley Creek.

CONCLUSION

The Trinity River had a change in bed material because the change in flows caused a change in the state of sediment movement from suspended load to bed load. The situation in the Trinity River is different from that in the Rio Grande and the Gunnison River because these are rivers where the size of the sediment transported to the river is small relative to the ability of the river to transport the material. Another conclusion is that the size of the sediment delivered by tributaries will have a profound impact on the changes that will occur in a river as a result of changes in its flows.

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