礫石河床沖淤水流之數值模擬

Numerical Simulation of Sediment Flushing Flow in a Gravel-bed River

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摘　要

本研究針對礫石河床之沖淤水流進行數值模擬。本文採用礫石與泥砂二分區模式估算礫石與泥砂顆粒之臨界剪應力，並據以計算礫石與泥砂分區之輸運率。本研究所建立之數值模式將沖淤過程中礫石底床含砂量之改變對礫石與泥砂臨界剪應力之影響納入考慮，模擬結果顯示本研究所建立之模式較 Wilcock 模式更能反映真實沖淤狀況。本研究成果可做為河川棲地復育規劃之有效工具。

ABSTRACT

This study addresses the numerical simulation of sediment flushing flow in a gravel-bed river. The two-fraction model is used to estimate the critical shear stresses and thus the transport rates of gravel and sand fractions. The variation of critical shear stress with sand content is taken into consideration in this study. Simulation results indicate that the proposed model is more realistic than Wilcock model in modeling of sediment flushing process. The numerical model developed in this study may well serve as an efficient tool for habitat restoration planning.

1. INTRODUCTION

Because the water and sediment from the upstream are trapped at the reservoir, river channels immediately downstream of the reservoir typically experience a decrease in flood magnitude and sediment transport capacity. If the transport capacity of downstream channel is sufficiently reduced and fine sediments are continuously introduced from the reservoir or from downstream tributaries, the finer sediment may accumulate on the bed of the river. This process can result in the high content of finer sediment filled in the interstices of the gravel framework, and is regarded as one of the most detrimental factors of the degradation of the quality of incubation habitat. Controlled releases of reservoir water can be used to mimic the action of natural floods in removing accumulated fine sediments from the channel and loosening the gravel bed. Such flushing flows are frequently specified to restore or maintain aquatic habitat, especially for salmonids.

The goals of flushing release are removing the sands accumulated on the surface (surface flushing) and entraining the gravel to remove the sand in the subsurface (depth flushing). The rate of gravel transport increase with Q, typically more rapidly than that for sand, and a flushing flow can produce a net decrease of gravel in the channel if gravel supply is limited by reservoir trapping. Because gravel is an important component of fluvial habitat, gravel loss, or its replacement, represents an environmental cost of flushing flows that argues for a flushing Q that is as small as possible (*Wilcock et al., 1996*). To decide an appropriate flushing discharge Q that fits with all constrains, developing the model that can evaluate the sediment transport, gravel-sand interaction, and the level change of gravel bed is necessary.

The field data in this study was established by the observations during the reservoir trial release in Trinity River, California (*Wilcock et al., 1996*). The gravel and sand transport rates were derived from by regression according to the sampling data of sediment. To evaluate the effect of the proportion of sand to the sediment transport rate, the two-fraction model (*Wilcock, 1998*) is used to estimate the critical shear stresses of both sand and gravel. Then the quantity of sediment removal can be estimated by computer simulation, and compared with the result in the study of Wilcock.

2. THEORY

2.1 Two-Fraction Model

The transport rates of sand and gravel depend on f_s, the mass proportion of sand to the total mass of gravel and sand in the bed surface, not only through its influence on the amount of sand and gravel available for transport, but also through the inherent transportability of each fraction. Thus, the effect of f_s to sediment transport rates must be considered when one predicts the result of the sediment flushing flow. To express the relations between f_s and the capability of sediment transport, the two-fraction model [*Wilcock, 1998*] is used here to estimate the critical values of the bed shear stresses t_{cs} and t_{cg}, which produce incipient motion of sand and gravel, respectively. The strategy adopted by Wilcock in two-fraction model is to divide the sediment into only two size fractions, sand ($D_s < 2$ mm) and gravel ($D_g > 2$ mm), which allows sand and gravel to move at different rates.

The variation with f_s of t_{cs} and t_{cg} is constrained by the values in the limit of vanishing amounts of gravel ($f_s \rightarrow 1$) or sand ($f_s \rightarrow 0$). Values of t_{cs} for clean sand ($f_s = 1$) and clean gravel ($f_s = 0$) are known from empirical relations for narrowly sorted sediments, for which the dimensionless critical shear stress t_c^*, whose definition is $t_c/[(r_s - r)gD]$, is equal to ~0.04 for all sizes larger than ~0.5 mm.

As $f_s < 0.2$, the riverbed is made up of an interlocked framework of gravel grains and transport of the sand requires entrainment of the gravel grains. At this time, transport rates of sand and gravel are much the same as that for $f_s \rightarrow 0$. Thus, it may be expected that $t_{cs} \approx t_{cg}$ and $t^*_{cs} \approx t^*_{cg}\left(D_g/D_s\right)$.

As $f_s > 0.4$, the gravel framework is replaced by the sand matrix with interbedded gravel clasts. Gravel entrainment is no longer influenced by adjacent gravel clasts and depends primarily on local exposure by sand scour. A minimum $t^*_c \approx 0.01$ has been observed for the entrainment of individual instrumented grains as they were progressively elevated reletive to the remainder of the bed. At this time, transport rates of gravel and sand should be much the same as that for $f_s \rightarrow 1$. Thus, values of the dimensionless critical shear stress t^*_{cg} and t^*_{cs} as $f_s >\sim 0.4$ and $f_s <\sim 0.2$ can be determined (see Table 1).

Table 1. Approximation values of dimensionless critical shear stress at the limit of sand content.

	Clean gravel ($f_s = 0$)	Clean sand ($f_s = 1$)
t^*_{cg}	0.04	0.01
t^*_{cs}	0.04(D_g/D_s)	0.04

In order to make the two-fraction model more applicable in solving the flushing problems, we illustrate the variety of t_{cs} and t_{cg} between sand content f_s graphically according to the two-fraction model (see Figure 1.). Obtained from the sampling data, $D_{i,50}$ is used to represent the diameters of sand D_s and gravel D_g, and which are 1.5 mm and 36 mm, respectively. Thus, we can get values of the corresponding t_{cs} and t_{cg} from different f_s by Figure 1.

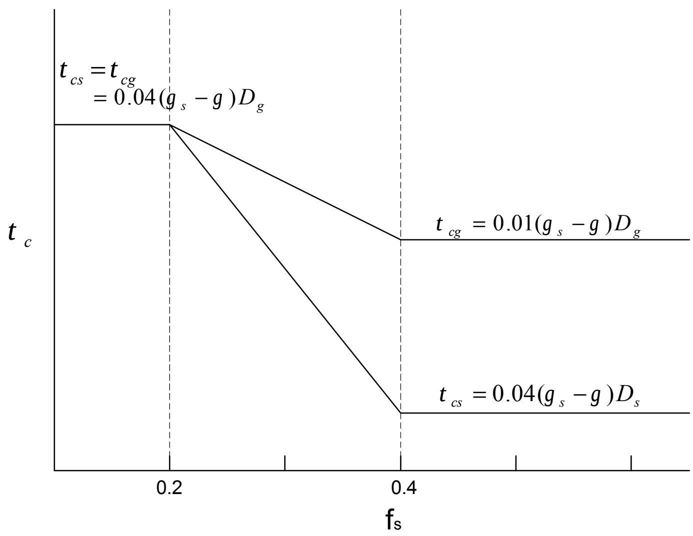

FIGURE 1. The relation between sediment critical shear stress t_{cs}, t_{cg}, and sand content f_s.

2.2 Sediment Transport Rate

The sediment transport rates are often developed through long-time field observations. During the trial release in Trinity River, *Wilcock* [1996] took samples of sediment in the riverbed to determine the equations of transport rates by regression.

The gravel transport rates are well matched by the *Parker* [1979] transport relation, which is a power approximation of the Einstein relation at low shear stresses. In the unit of Figure 2, the relation is

$$q_{bg} = \frac{t_0^{1.5}}{17.8}\left(1 - 0.85\frac{t_{rg}}{t_0}\right)^{4.5} \tag{1}$$

where q_{bg} is the gravel transport rate per unit width; t_0 is the bed shear stress resulted by water discharge and t_{rg} is the reference shear stress that produces a small reference transport rate and serves as a surrogate for the critical shear stress t_{cg}. The value of t_{rg} is taken to be 22.5 Pa by Wilcock, which fitted to the gravel trap observations in Trinity River during trial releases.

Since the value of t_{rg} is 22.5 Pa, we can get the value of t_{cg} = 19.2 by the relation, $t_r^* = 1.172 t_c^*$, [*Parker, 1979*]. Then, through Figure 1, we can get that, as t_{cg} is 19.2 Pa, the corresponding f_s is 0.234 and the value of t_{cs} is 17.9 Pa. By regression for the sampling data, in the unit of Figure 2, the transport rate for sand is

$$q_{bs} = 0.0171(t_0 - t_{cs})^{0.8732} \tag{2}$$

where q_{bs} is sand transport rate per unit width and t_{cs} is the critical shear stress for sand.

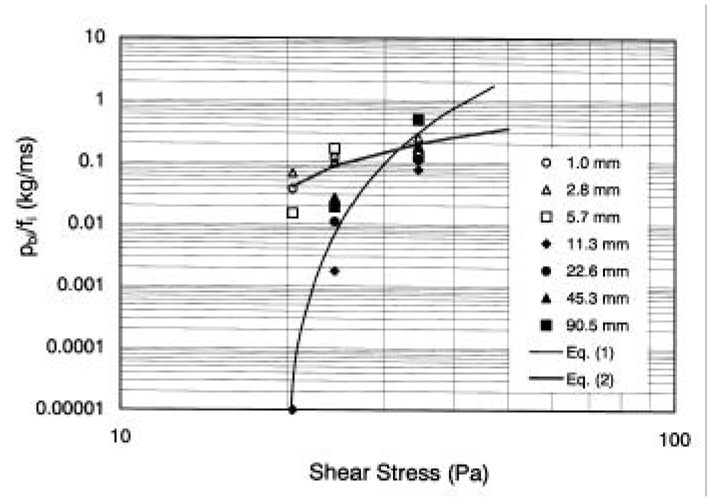

FIGURE 2. Fractional transport rates as a function of bed shear stress.

2.3 Sand Supply from Bed Subsurface

An expression for the upward supply of sand from the subsurface is needed to account for subsurface flushing during a release. The rate of upward entrainment depends on the relative concentration of sand in the surface and subsurface and the frequency of gravel entrainment from the bed surface, which determines the frequency with which subsurface fine grains are subjected to the flow. The net rate with which sand is removed from the subsurface may be expressed as

$$\frac{dMu}{dt} = 0.5\left(\frac{f_{ss} - f_s}{f_{ss}}\right) M_{ss}\left(\frac{1}{t_{ex}}\right) \tag{3}$$

where f_{ss} is the proportion of sand in the subsurface, M_{ss} is the mass of sand in the subsurface, M_u is mass of sand supply from subsurface, and t_{ex} is the exchange time defined as the duration producing minimum satisfactory entrainment. A reservoir release of 164 cms for 5 days in Trinity River produced nearly complete entrainment of the bed surface. Thus, t_{ex} (in days) of any other discharge can be determined for the same transport volume as

$$t_{ex} = 5\left(\frac{q_{bg,164}}{q_{bg,Q}}\right) \tag{4}$$

where q_{bg} and $q_{bg,Q}$ are the gravel transport associated with $Q = 164$ cms and a value of water discharge *Q*, respectively. Values of t_{ex} vary inversely with *Q*, so that the larger entrainment rates associated with higher discharges produce smaller t_{ex}, and a more rapid dM_u / dt.

2.4 Thickness of Surface and Subsurface Layers

A surface layer thickness is 0.075 m ($\approx D_{90}$ of the bed framework gravel), which was assumed by Wilcock for the volume of fine sediment on the bed surface that could be flushed with no gravel entrainment. The bed thickness that could be flushed with active gravel entrainment was taken to be 0.15 m, which is slightly larger than the limit of gravel scour of $1.7D_{90}$, estimated from local observations of gravel entrainment [*Wilcock et al., 1996*], implying that sand removal can proceed to a depth slightly greater than the depth of gravel entrainment [*Beschta and Jackson, 1979; Diplas and Parker, 1985*]. Thus the subsurface layer thickness is 0.075m, which is the gravel entrainment thickness minus the surface layer thickness. The mechanism of sand removal in the subsurface layer is upward supply to the surface layer, and a fine content of 25% is assumed for the subsurface layer, based on the observation in bulk samples taken at Trinity River.

3. CASE STUDY

3.1 Study Site

The Trinity River drains 7640 km^2 of steep, dissected terrain in the Klamath Mountains of northwestern California (see Figure 2). Runoff from the uppermost 1860 km^2 of the basin was impounded by Trinity Dam (and its reregulating reservoir, Lewiston Dam) beginning in 1961, as part of the U.S. Bureau of Reclamation Central Valley project. Floods have been virtually eliminated on the Trinity River in the reach directly below the reservoir. Flow regulation has reduced the mean annual flood from 525 to 73 cms and the2-year flood from 484 to 30 cms, based on the continuous discharge record from 1911 at the U.S. Geological Survey (USGS) gage at Lewiston (Figure 3). Concurrent with the reduction of sediment transport capacity in the main stem, sediment yields from tributary watersheds increased as a result of road construction and timber harvest. Most notable among these tributaries is Grass Valley Creek, which flows into the Trinity River about 13 km downstream of Lewiston Dam (Figure 3). Grass Valley Greek weathers to produce decomposed granitic soils that are readily eroded and produce large yields of sediment finer than 8 mm. Little transport of bed material occurs at $Q < 85$ cms, and essentially no transport of materials coarser than 1 mm occurs at the typical postdam in-stream minimum flows of 4 cms (1961-1978) and 8.5 cms (1978 to present).

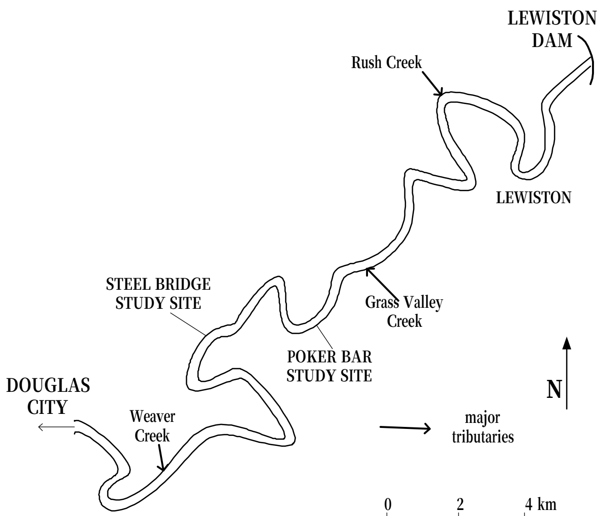

FIGURE 3. Location map of the Trinity River downstream of Trinity River and Lewiston Dams.

Flow and transport observations were made along two reaches, Poker Bar and Steelbridge, located 15 km and 20 km downstream of Lewiston Dam, respectively. At Poker Bar the channel is ~35 m wide and rectangular in section. The river banks are nearly vertical and composed of fine material deposited along the margins of the much wider active channel that existed before the Trinity and Lewiston Dams were closed in 1963. Extremely low discharge following dam closure permitted vegetation to become established within the former active channel and the banks have apparently been built during occasional tributary floods carrying high concentrations of fine sediment. By filling coarse pore spaces the fine material limits habitat for aquatic invertebrates and juvenile fish and is thought to limit salmonid spawning success by blocking fry emergence from the bed [*Wilcock et al. 1996*].

3.2 Simulation Case

To compare with the flushing results, the spatial conditions adopted in this study is the same as that in Wilcock's study, and the equation, regression for data recorded during observation, to estimate t_0 from discharge Q is

$$t_0 = 0.1664Q + 7.2148 \tag{5}$$

where t_0 is in Pa and Q is in cms.

The study reach is 7 km long and divided into seven subreaches, given different initial sand contents in the surface and 0.25 in the subsurface. The sand flushing simulation is based on sediment mass conservation within the surface layer of the riverbed. At each time step (1 minute), in each subreach section, the sediment content in the surface layer is the sum of sediment inflow from the immediately upstream section and the sediment supply from subsurface minus the sediment outflow in this section. The sediment transport volumes of sand and gravel are estimated by (2) and (1), respectively, and the volume of sand supply is estimated by (3). Among constrains of sediment flushing flow, two are effective sand flushing and minimization of gravel downstream loss, which induces the topographic change of riverbed. Thus, the water release of 130 cms is the appropriate discharge. The simulation result is shown in Figure 4, compared with that of Wilcock shown in Figure 5.

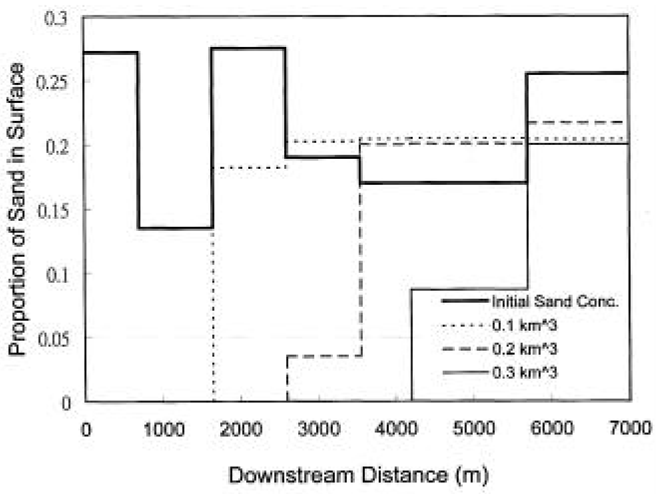

FIGURE 4. The flushing result of three different release volumes in this study.

4. RESULTS AND DISCUSSION

The result of 30-days flushing is shown as the f_s change with time on Figure 6. Because of the assumption that there is no sand inflow at section 1, the sand content in section 1 is reduced suddenly and flushed sand is accumulated gradually at downstream sections. Based on two-fraction model, the critical shear stress of sediment is the same within the range of $f_s = 0 \sim 0.2$ and decrease with increasing f_s within the range of $f_s = 0.2 \sim 0.4$ Thus, at the beginning, f_s of sections with high sand content ($f_s > 0.2$) reduce abruptly because of low critical shear stress, which makes sand flushed out easily. The sand flushed from sections with high f_s is accumulated in the surfaces of sections with low sand content ($f_s < 0.2$), so f_s of sections with low sand content increases at the beginning. When f_s reaches the value of 0.2, it is very hard to reduce sand content in the pores of gravel framework by flushing except that the sand content of immediately upstream section is almost zero, which makes no sand inflow from the upstream section, and as this occurs, f_s reduces from 0.2 to 0 abruptly. As shown on Figure 6, it shows the phenomenon clearly that the capability of sediment transport depends on the proportion of sand in the bed surface as $f_s > 0.2$, but as $f_s < 0.2$, the time that framework gravels are closed interlocked, sand removal depends on whether or not sand is supplied from upstream.

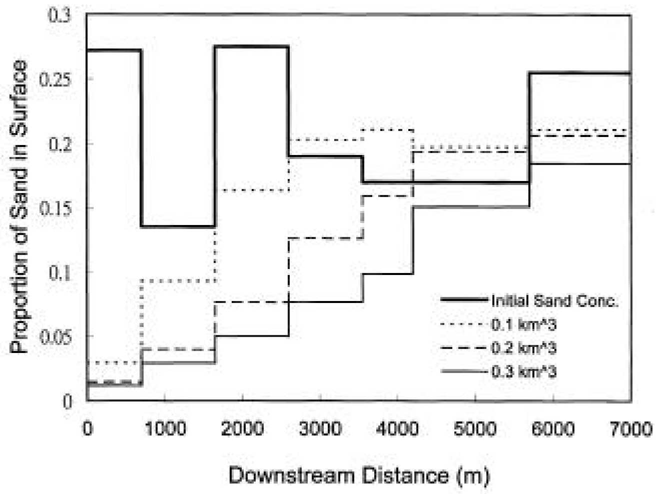

FIGURE 5. The flushing result of three different release volumes by Wilcock model.

We can compare the result in this study with that of Wilcock's study, which used three different reservoir release volumes, 0.1, 0.2, and 0.3 km^3, and get flushing results by simulation (see Figure 5). The conditions of simulation in these two studies are much the same, and the difference is that the effect of sand proportion to the capability of sediment transport is considered in this study, which is must be taken into account as dealing with sediment flushing problems. Compared these two simulations, apparently, a better result is shown in this study (see Figures 4 and 5) especially for those of larger reservoir release volumes due to longer durations of flushing, which makes more and more sections with zero sand inflow.

5. CONCLUSION

By knowing transport rates for sand and gravel in the Trinity Riv er through field observations and relations between sand content and sediment transport capability, we can predict a flushing result through computer simulation. However, in many flushing problems, the field observations, including river topography, sediment content in the whole reach, and so on, must be made in detail, which can reduce uncertainties in the research of flushing problems. Figure 1 derived from the two-fraction model provides a good means for application to flushing problems not only due to its consideration of the interaction between sand and gravel, but also its easier way for measuring than that of complete size distribution. So the primary goal of this study is to propose an ideal method, based on some simple assumptions, to deal with problems of sediment flushing flow. And the method presented in this research will be helpful for the future work of planning for flushing release.

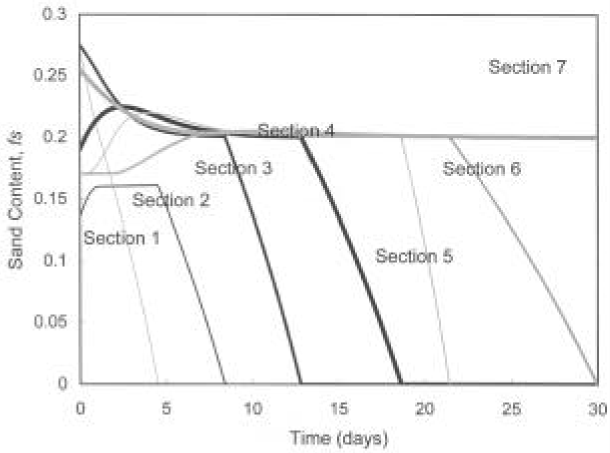

FIGURE 6. The result of 30-days flushing with the water release of 130cms.

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