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Evaluating the effect of land development on sediment transport using a probability density function

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Abstract: An important problem in sedimentation analysis is the development of a channel section that preserves, as best as possible, the current sedimentation regime even though the flood frequency tendencies have been altered due to land development within the catchment. In order to accomplish this task, a methodology is needed that estimates sediment transport capacity for various channel configurations. Such a procedure is described which allows the computation of the total sediment transport capacity for each of several T-year return frequency runoff hydrographs. This information is used to obtain an approximate probability distribution for the total sediment transport capacity, and the mean and standard deviation of this distribution are computed.

Comparing the results for the catchment in its present state with a future developed state, using a selection of new channel parameters, indicates how to improve the channel to control changes in sedimentation due to development. The analysis procedure provides a basis for estimating a new channel configuration such that the new flow conditions retain, as best as possible, the existing condition sedimentation effects, and hence retain the natural sediment supply and transport trends even though runoff flow rates have changed due to land development within the catchment.

The results of Wilson Creek are typical of the several sites examined, see Table 3 below. The T = 2, T = 5, T = 25, and T = 100 year values for total sediment transport capacity, in kilotons, are 6.9, 39.4, 61.3, and 96.7 with a mean of 17.1 and standard deviation of 19.3. After development with no change in the channel the respective values increase to: 17.9, 84.6, 128.1, and 258.0 with a mean of 39.1 and standard deviation of 44.3. A new channel can be constructed which will reduce these sediment transport capacity values, after development, to 5.2, 41.0, 62.0, and 124.8 with a mean of 17.4 and standard deviation of 22.0.

Key words: Sedimentation, probability density function, synthetic study, development.

1 Introduction

An existing stable channel will have an associated set of sediment transport capacities S_T for each T-year flood design storm. These values can be regarded as the values of a random variable S_{tot} with $\mathrm{Prob}(S_{tot} \leqq S_T) = 1-1/T$, as is discussed below. Development in the catchment will increase these values if the channel is not redesigned. It would be best if the channel could be redesigned so that the new channel, after development, would have the *same* distribution of S_T values as the old channel before development, but it is generally not possible to preserve the entire distribution of values. As is shown below, it is possible to have the new mean value be equal to the old mean value, and is often possible to have the standard deviations the same as well. Even then there are differences between the distributions of sediment transport capacity before development, and after development with a new channel, which need to be taken into consideration.

2 Theoretical development

A regression equation which approximately relates the instantaneous sediment transport capacity dS/dt and discharge Q is given by the Brownlie equation [1]:

$$\frac{dS}{dT} = aQ^{b}. \tag{1}$$

Given this equation, the parameter values of a and b, and a T-year runoff hydrograph of values $Q_T(t)$ of Q, the total sediment transport capacity, S_T, is given by

$$S_T = \int_0^{\infty} aQ_T(t)^b \, dt. \tag{2}$$

Generally speaking, increasingly larger storms have the capacity to move increasingly larger amounts of sediment: the T-year storm having probability 1-1/T of being exceeded. This argument, which is only approximate as storms are not linearly ordered, nevertheless indicates that the number S_T is a reasonable estimate for the 1-1/T values for the random variable S_{tot} which gives the total amount of sediment transport capacity for a storm:

$$\mathrm{Prob}(S_{tot} \leq S_T) = 1 - 1/T. \tag{3}$$

See [3, page 271-275]. Writing F for the probability distribution function for S_{tot}, the above equation becomes

$$F(S_T) = 1 - 1/T. \tag{4}$$

Once F is determined, the expectation $E(S_{tot})$ of S_{tot} can be obtained by an integration by parts

$$E(S_{tot}) = \int_0^{\infty} t\,dF(t) = \int_0^{\infty} (1 - F(t))dt \tag{5}$$

and, similarly, the second moment is

$$E(S_{tot}^2) = \int_0^{\infty} t^2 dF(t) = \int_0^{\infty} 2t(1 - F(t))dt \tag{6}$$

from which the standard deviation for S_{tot} can also be computed. These equations are used to calculate the distribution function F and its mean and standard deviation. This information is then used as a target for the "future" condition (of land development) channel system in order to preserve the natural sediment supply and transport capacity tendencies. Such a sediment transport capacity "preservation" channel is generally termed an "equilibrium channel" [1].

To see the effects of future land development on the distribution of S_{tot}, an indirect approach is needed because the parameters a and b of equation (1) which would apply to the developed area cannot be obtained since there are no regression data.

The basic assumption we make is that, as a function of the velocity of flow V, [dS/dt]/Q will remain approximately the same when the area is developed; i.e. the instantaneous sediment transport capacity per unit cfs of discharge for a given velocity of flow will remain the same for the channel when that channel is demonstrating the same sediment transport capacity properties, for each storm, as when in the natural condition of land development. (For example, if the flow in the channel increases while transporting the same quantity of sediment per unit of flow (cfs), then erosion may occur.) It is recalled that the goal is to find a channel configuration that preserves the natural condition sediment transport capacity properties and, therefore, the issue of overall sediment supply to the channel system becomes secondary due to the preservation of the in-progress sedimentation effects.

Under a wide range of conditions for open channel flow the flow velocity V, due to a discharge Q, is approximated by the equation [2]

$$V = \alpha Q^{\beta} \tag{7}$$

where, intuitively, α is related to the slope and friction in the channel and β is related to the channel geometry. Knowing the values of α and β, and the values of a and b in the first equation, it is immediately apparent that, for "equilibrium channel" conditions,

$$\frac{dS}{dt}/Q = kV^{\ell} \tag{8}$$

where $\ell = (b-1)/\beta$ and $k = a(\alpha)^{-\ell}$. The total sediment transport capacity for a storm Q can be written

$$\int_0^{\infty} [kV(t)^{\ell}]\ Q(t)\ dt. \tag{9}$$

Under present conditions, equation (8), applied to a T-year discharge Q_T, reduces to equation (2).

For a T-year hydrograph reflecting future developed conditions, equations (3-6) and (9) allow the computation of the distribution of S_{tot} for different values of α and β. When α and β are chosen to have the values for the existing channel this computation shows how the volumes of sediment transport capacity would change, because of the increased discharge caused by development, if the channel were not improved.

For design purposes, α and β can be varied to show the effect on S_{tot} of improvements in the channel. For example, to mitigate the effects of development, one design criterion could be to keep the mean of the total sediment S_{tot} the same, so that in the long run the channel is neither filled or eroded. Other criteria could take into account in the standard deviation of S_{tot}, which give some idea of the expected amounts of variation in sediment transport capacity, resulting in filling or scouring in the channel.

3 Applications

3.1 Conceptual system

For discussion purposes, a hypothetical flow and sediment transport capacity regime is examined that is qualitatively similar to arid conditions in southern California. An actual case study is considered in Application B.

For this example problem, a triangular shaped runoff hydrograph is considered. Regardless of land development, a constant time duration of runoff is assumed. Consequently, runoff volume (for this example problem) is proportional to the peak discharge value, M. The runoff hydrographs are each taken to have a 6-hour duration, rising in a straight line from 0 to a maximum M at 3 hours and decreasing from M in a straight line to 0 at 6 hours. For existing conditions, the peak discharge M_T was taken to have 10-year value of $M_{10} = 2000$, and $M_{100} = 5000$. The 2 and 25-year values of 1050 and 2850 were obtained by taking log(T) and log (M_T) to be linearly related. The hydrograph for developed conditions was obtained in the same way by setting $M_{10} = 3500$ and $M_{100} = 6000$, and finding $M_2 = 2400$ and $M_{25} = 4350$.

The values of $\alpha = 1.9$ and $\beta = .40$ for equation (7) represent a typical channel, and the values a = .70 and b = 1.28 for equation (1) are taken from one of the channels in the actual case study below (corresponding to a trapezoidal concrete channel). Because the β parameter relates to the conveyance factor of the channel, changes in β follow directly from changes in the hydraulic radius, among other factors (Henderson, 1966).

3.2 The second application is an actual case study for the City of Yucaipa, California, Master Plan of Drainage study [5]

Three channels were studied in the referenced Master Plan of Drainage [5]: Gateway Creek, Oak Glen Creek, and Wilson Creek. Using cross-section data obtained from topographic maps, a typical cross-section was derived for each channel and α, β parameters developed for (7). The Brownlie equation fitted parameters of a and b were developed from the application [4]. Using a calibrated unit hydrograph method, runoff hydrographs for several return frequency events, for both undeveloped and developed conditions, were also prepared in [4]. Results from the computer analysis of the three creeks are summarized in Tables 2-4 in a fashion analogous to Table 1 and Application A.

In summary, in the conceptual example and in all the three case studies, the effect of development was to approximately double the total sediment transport capacity at all return frequencies. The effects of development could be mitigated in all the case studies by changing only the parameter α of the channel, while in the conceptual study if one wanted to preserve the probability distribution of the total sediment discharge, and not just the mean sediment transport capacity, it was necessary to change both α and β.

For Application B, the α parameter reduction factor is 0.69, 0.63, and 0.64 for Oak Glen, Wilson, and Gateway Creeks, respectively. Assuming friction factors to remain nearly constant, such a reduction in α is associated with approximately 58-percent reduction in bed slope, using Manning's equation. That is, the channel slope must be more than halved, requiring extensive drop structure installation.

4 Summary

A synthetic study of the sediment transport capacity of a channel due to the increased discharge caused by land development is implemented in a procedure which can be used to find design criteria for channel improvements to mitigate the effects of development. Because the existing condition sediment transport capacity properties demonstrate the natural

Table 1. Total sediment transport capacity in kilotons

	T=2	T=10	T=25	T=100	mean	sd
existing hydrology old channel ($\alpha = 1.9$, $\beta = .4$)	24.1	55.0	88.1	180.0	31.5	28.7
future hydrology old channel ($\alpha = 1.9$, $\beta = .4$)	71.3	114.9	150.6	227.3	70.6	43.7
future hydrology new channel ($\alpha = 0.6$, $\beta = .4$)	31.8	51.3	67.2	101.4	31.5	19.5
future hydrology new channel ($\alpha = \epsilon$, $\beta = 1.8$)	23.7	55.1	88.8	183.7	31.5	29.1

Notes:

$a = 0.700$, $b = 1.280$, $\epsilon = 1.2 \times 10^{-5}$, one kiloton = $2\text{x}10^6$ lbs, sd = standard deviation.

The main points to note from Table 1 are:

1) The second row shows the effect of development on the sediment transport capacity if the channel is not improved.

2) The third row shows that a new channel with $\alpha = 0.6$ and the same β will transport the same average total sediment, with a similar variation about this mean. But note also that the 2-year value is higher, and the 10-year value not too different, so that in the short term there would be scouring in the channel; equilibrium with the undeveloped long term average would only occur because very large (and infrequent) storms would move less sediment. The above analysis is applied similarly in the case of a decrease in peak discharge and/or volume. Such decreases may be associated with channel deposition and sedimentation.

3) The last row shows that it is possible to closely duplicate the current sediment transport capacity distribution after development, but only with a channel with essentially zero slope.

4) The tabulated sediment transport capacity quantities do not consider sediment supply limitations to the channel system. Consequently, large increases in sediment transport capacity, as predicted above, maybe be constrained by sediment supply. However, near natural condition sediment transport capacity, sediment supply is preserved.

Table 2. Oak Glen Creek total sediment transport capacity in kilotons

	T=2	T=10	T=25	T=100	mean	sd
existing hydrology old channel (α = 2.48, β =.22)	25.6	118.7	171.5	253.8	52.5	53.3
future hydrology old channel (α = 2.48, β = .22)	39.7	188.8	274.4	528.8	85.6	93.9
future hydrology new channel (α = 1.7, β = .22)	24.3	115.5	167.8	323.5	52.4	57.5

a = 0.70 b = 1.28

The main points to note from Table 2 are:

1) The second row shows that the effect of development on the existing channel is erosive, in general.

2) The third row shows that a new channel with α = 1.7 and the same β = 0.22 will approximately duplicate existing conditions.

Table 3. Wilson Creek total sediment transport capacity in kilotons

	T=2	T=10	T=25	T=100	mean	sd
existing hydrology old channel (α = 1.12, β = .30)	6.9	39.4	61.3	96.7	17.1	19.3
future hydrology old channel (α = 1.12, β = .30)	17.9	84.6	128.1	258.0	39.1	44.3
future hydrology new channel (α = 0.7, β = .30)	5.2	41.0	62.0	124.8	17.4	22.0

a = 0.15 b=1.47

Table 4. Gateway Creek total sediment transport capacity in kilotons

	T=2	T=10	T=25	T=100	mean	sd
existing hydrology old channel ($\alpha = .69$, $\beta = .32$)	0.6	5.3	8.4	14.5	2.2	2.8
future hydrology old channel ($\alpha = .69$, $\beta = .32$)	1.2	8.7	16.7	49.7	4.3	7.1
future hydrology new channel ($\alpha = .44$, $\beta = .32$)	0.6	4.4	8.5	24.8	2.2	3.6

$a = 0.49 \quad b = 1.484$

sediment supply and transport balances, another channel configuration may be evaluated that preserves the natural sediment transport capacity tendencies even though flow quantities of runoff have changed due to land development.

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