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Physical habitat simulation and sedimentation

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ABSTRACT Stream channels provide habitat for aquatic species and for animals that use the banks of the stream. In the process of determining the instream flows needed to maintain desirable habitat conditions, two sedimentation factors are of importance. The first is a need to maintain a desirable channel shape and the second is to maintain desirable substrate by flushing fines through the system. The state of the art for channel maintenance is not satisfactory at this time because the various techniques available do not give reliable results. A flushing flow methodology is available and is presented.

INTRODUCTION

The inclusion of instream flows as an aspect of water management is enhanced by the use of models that develop a functional relation between the physical habitat and streamflow. The use of such models was described by Milhous (1984a, 1986a) and Nestler et al. (1988); the hydraulic simulations used with the models by Milhous (1984b); aspects of the channel geometry by Stalnaker et al. (1988); and the biology by Stalnaker (1979).

Stream channels provide habitat for aquatic animals, such as fish and aquatic benthic invertebrates. Associated with the channel are "near water" habitats important to amphibians, reptiles, birds, and mammals.

The channel description needed for physical habitat modeling is illustrated in Fig. 1. The physical habitat suitability of an area is a combination of physical attributes describing the area. The combination function, CF, can be expressed as

$$CF = F(f(v),\ g(d),\ h(s),\ k(dw),\ \text{etc.}) \qquad (1)$$

where F( ) is the overall function used to combine the various functions and f(v), g(d), etc.; these functions have values between 0.0 and 1.0. The physical habitat area is obtained using the equation:

$$WUA = \int_A CF * a\ da \qquad (2)$$

The integral is over the total wetted surface area A, CF is as described above for the area a, and WUA is the weighted usable area, which is to say the surface area weighted for its worth for a specific lifestage of an aquatic animal. Examples of the types of models developed to date are presented in Milhous (1988a).

Six attributes typically used are: (a) velocity, (b) depth, (c) substrate (i.e., size of the bed material), (d) cover, such as overhang vegetation or banks, and turbulence in the water, (e) the presence of fines in the bed material, and (f) water temperature.

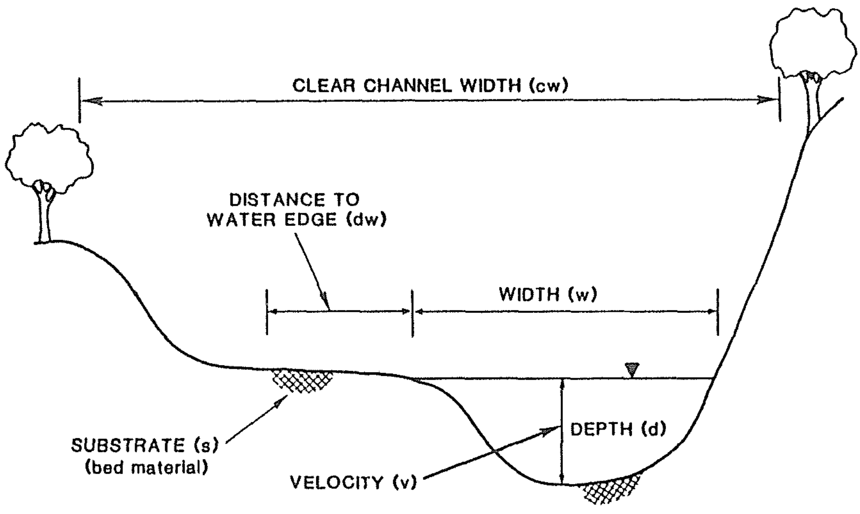

Fig. 1 Channel characteristics needed for physical habitat modeling.

In this paper, the attributes related to the channel and sediment are presented.

SEDIMENTATION - GENERAL

The morphology of a stream channel and the characteristics of the bed material have significant influence on the physical habitat available in the stream. Both channel shape and size distribution of the bed material can be modified by water management practices. One objective of an instream flow analysis is to determine the flows that will maintain a desirable channel and/or maintain desirable bed material.

The impact of water management on the stream depends on the type of streamflow modification and the characteristics of the stream. If the water is removed without the construction of a reservoir, most of the sediment remains in the stream. If a reservoir is constructed, the sediment transport capacity may be reduced, and the sediment load is almost certainly reduced.

In this paper two sediment considerations are discussed. The first is the maintenance of a desirable channel form and the second is the determination of flows needed to flush fines from coarse bed material.

CHANNEL MAINTENANCE FLOWS

A change in channel shape is likely with changes in sediment loads, streamflow, or the size of the sediment load. Milhous (1986b) reviewed techniques used to estimate flows needed to determine a channel maintenance flow. The 1986 review was added to in 1988 (Milhous 1988b). In the review below only width will be considered. The hydraulic geometry relations presented by Leopold et al. (1964) include the width equation:

$$w = a\,Q^{b} \tag{3}$$

where Q is a representative discharge for the stream, and w is the stream width at discharge Q. The terms a and b are coefficients. If the peak discharge is considered representative, the average value of b is 0.54 (Leopold et al. 1964).

Other equations have been developed relating width to the streamflow and sediment load. The first is an empirical equation developed by Hey (1982) for gravel-bed streams in Great Britain:

$$P = 2.20\ Q^{0.54}\ Q_s^{-0.05} \tag{4}$$

where P is the wetted perimeter (meters), Q is the 1.5 years annual flood flow (m^3/sec), and Q_s is the bed-load (m^3/sec). For wide rivers, the wetted perimeter is nearly the same as the width.

The Hey equation is similar to equation (3) except for the small impact resulting from change in sediment load suggested by the power term of -0.05 on the sediment load. The Hey equation suggests that the river will widen as a result of a reduction in the sediment load.

Carson & Griffiths (1987) presented the Parker equation (Parker 1979) as follows:

$$Q_s = K\ Q^{0.23}\ D_{50}^{1.2}\ W^{0.77} \tag{5}$$

where Q is the dominant discharge (basically the same as the Q in the Hey equation), Q_s is the bed-load capacity, D_{50} is the mean bed particle size and W is the stream width. This equation can be rearranged to be

$$W = K^1\ Q_s^{1.3}\ Q^{-0.30}\ D_{50}^{-1.56} \tag{6}$$

The Parker equation suggests that a reduction in streamflow results in an increase in width; and a reduction in bed-load results in a decrease in width--the opposite of the Hey equation.

The three equations can be used to predict a new width given the present width. For example, the equation based on the hydraulic geometry equation used to predict the width that would result from a change in the reference discharge is

$$W = W_o \left(\frac{Q}{Q_o}\right)^{0.54} \tag{7}$$

Just how well does this approach work? Information on channel changes below dams was assembled by Williams & Wolman (1984) and was used to test equation (7) (Milhous 1988b). The result was that equation (7) did not predict even the direction of width change in 11 of 16 cases.

In the Missouri River, the pre-project width was about 710 m with a sediment load of about 155 million tonnes per year and an average annual peak discharge of 5200 m^3/sec. After construction of dams upstream, the width increased to 830 m with a reduction in sediment load to about 27 million tonnes per year and an average annual peak discharge of 1200 m^3/sec. The hydraulic geometry equation for width suggested that the width should have been reduced, but it actually increased.

Mellema & Wei (1986) gave the following explanation:

In the natural river prior to the construction of the dams, there was a balance over the years between erosion of the high banks and the building of new valley lands by sediment deposited during floods, resulting in a continual migration of river channel within the valley. Due to the balance between the erosion and deposition processes, there was no longterm net loss of high valley lands. Since closure of the dams, the operation of the reservoir system has eliminated both the floods and the sediment that were essential for the rebuilding process; however, the process of bank erosion continues. This has resulted in a continuing net loss of high valley lands that are not replaced elsewhere in the valley as in the era before the reservoirs. High valley lands are being converted to river channels and sandbar areas, while the width between high banks continues to widen. This process is transforming the present open river reaches into gradually widening areas of sand bars and channels, occupying increasing proportions of the valley width between the high bluffs.

Assuming that the slope and bed material size have not changed, expected ratios of widths based on the three width equations are as follows:

Hydraulic geometry (3)	0.45
Hey (4)	0.49
Parker (6)	0.16
Actual	1.67

The width ratios generated by all of the equations tend toward the inverse of the observed effects. (Note that the Hey equation is for gravel bed rivers; the Missouri has some gravel, but much more sand.)

At this time an acceptable approach to determining channel maintenance flows based on a width equation is not available; therefore, each stream must be taken individually and a site-specific study made to determine the channel maintenance flow. Such a study should include historical analysis, as suggested by Kondolf & Sale (1985).

One concept that needs to be included in a maintenance technique is the identification of thresholds at which the general form of the channel changes from one type to another. If one uses data from Williams (1978) on actual width changes along the Platte River and the expected width changes calculated by using the hydraulic geometry relation, the relation given in Fig. 2 results. The locations to the right of the break have lost most of the original dynamic multiple channels and those to the left are still braided, although the braiding has been reduced. The "threshold" is at a mean annual peak flow of 142 m^3/sec.

An equation given by Leopold et al. (1964) dividing single channels from braided channels follows:

$$Q = 4.73 \times 10^{-5} S^{-2.27} \qquad (8)$$

The slope of the Platte River is generally 0.0011. Where this slope is used, the threshold is a mean annual peak discharge of

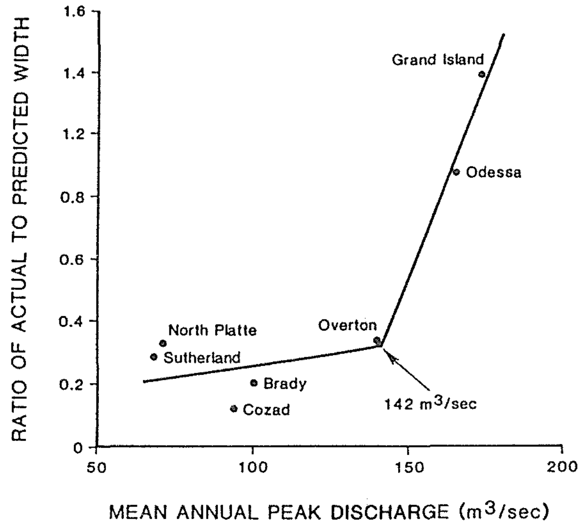

Fig. 2 Ratio of the actual to predicted width at the Platte River in Nebraska versus mean annual peak flow.

250 m^3/sec. The development of two different estimates that differ by about 70% for the threshold discharge needed to maintain braided channels suggests the need for additional research.

FLUSHING FLOWS

There are two general riverine conditions under which deposition of fines occurs in spawning gravel. The first condition is where the fine sediment is found predominantly in the voids between the gravels, as the fines are small enough that they are deposited within the bed material. In the second condition, the fine sediment is large enough to be deposited among the gravel particles forming the surface. Each of these conditions requires a different approach to evaluating spawning gravel flushing flow needs.

A stream substrate movement parameter, β, can be defined as

$$\beta = RS/G_s - 1)D_{50} \qquad (9)$$

where R is the hydraulic radius, S is the energy slope, G_s is the specific gravity of the bed material (substrate), and D_{50} is the median size of the bed surface material (armour layer). The term "movement parameter" is used to emphasize that the objective is to move the bed materials just enough to flush away the fines.

Research by the author in Oak Creek, Oregon, indicates that if the sheer stress (force per unit area) applied to the streambed is just large enough to move a small portion of the larger particles in the surface layer, fines deposited in and among the armour particles will be flushed from the bed. For fines deposited deeper in the voids, the bed material below the armour material will also have to be moved, and this will require a much higher sheer stress. In the fall of 1971, a runoff event with the characteristics needed to cause surface flushing of fines from Oak

Creek occurred. The movement parameter for the peak flow of the event was 0.02. On this basis, it appears that in order to obtain surface flushing of fines, the movement parameter should be at least 0.02, and to be on the safe side, 0.021. The assumption is that the Oak Creek results can be generalized to other rivers.

The movement parameter must be sufficiently high to move the bed material below the surface layer in order to remove fines from within the voids. Values of β between 0.017 and 0.076 for initiating movement of the bed material (substrate) are common in the literature. The lower values are probably for absolute stability and the higher values for general movement. The Oak Creek study indicates that 50% of the bed particles will move when the movement parameter is 0.047. If 30% of the armour material is moved, adequate flushing of fines is probable. At 30% movement probability, the movement parameter is estimated to be 0.035. The author recommends this value for deep flushing of gravel voids until additional research is done.

Table 1 An example of computing suitable spawning area as a function of the flows present during spawning and during the flushing event in a reach of the Salmon River, New York

Spawning flow (m^3/sec)	Weighted usable area (m^2/1000 m)				
	5.66*	9.91	21.2	42.5	85.0
0.71	0	41	41	41	41
1.42	0	86	107	108	108
2.83	0	173	394	436	436
5.66	0	286	1228	1412	1412
9.91	0	140	2062	2427	2427
14.20	0	30	1633	2238	2238
21.20	0	5	1034	2070	2136
28.30	0	0	295	1263	1593
42.50	0	0	17	551	1166
56.60	0	0	0	184	714
85.00	0	0	0	8	69

*flushing flows in m^3/sec

An example of the use of this concept in computing the suitable area for spawning is given in Table 1. For all flows <9.9 m^3/sec, none of the spawning gravel voids would be flushed and the stream reach spawning suitability would be zero due to fines filling the voids. The low level of suitable spawning habitat occurs in combination with the lower flushing flows because not all of the available spawning gravels are flushed of fines at flows <14 m^3/sec. For flows >14 m^3/sec, gravel voids are flushed but some gravel areas available for spawning are not suitable because the velocities and/or depths are too high for the fish to use. Optimum spawning conditions occur when flushing flow events are 42-85 m^3/sec, and spawning flows are 9.9 m^3/sec in this example.

CONCLUSION

The major conclusion is that current techniques are far from ready for application of any specific analytical channel maintenance methodology to instream flow management, but are closer to providing a quantitative flushing flow methodology.

Three specific conclusions are:

(a) Approaches to selecting a channel maintenance flow based on the simple hydraulic geometry relation will not work if there is any significant change in either sediment load or streamflow.

(b) The more complex approaches based on width changes give uncertain results and should be investigated further.

(c) Flushing flows can be determined based on considerations of physical habitats and physical processes.

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