FLUSHING FLOWS

D.W. Reiser, M.P. Ramey
and T.A. Wesche

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Dudley W. Reiser, Michael P. Ramey, and Thomas A. Wesche

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I. INTRODUCTION AND BACKGROUND

The regulation of streamflow can both positively and negatively affect existing fishery habitats, fish populations, and channel characteristics. This occurs because, in most geograpical areas, natural precipitation and run-off patterns have produced well-defined periods of low and high streamflow. The regulation of such flows can disrupt the biological communities which have adapted to the natural flow regime. In the western U.S., it was quickly recognized that uncontrolled development of water could result in the elimination of aquatic communities and dramatically alter channel morphology. This was alarming, since many of the systems in jeopardy harbored significant sport and commercial fishery resources, such as the salmon fisheries of the Pacific Northwest.

As a consequence, fisheries biologists and hydrologists have begun investigating the relationships between fishery habitat and streamflow with the ultimate goal of being able to prescribe flows necessary for the maintenance and/or enhancement of fish populations. To this end, a wide variety of methodologies for assessing the "instream flow" needs of aquatic life have been developed and used. Descriptions of many of these can be found in Stalnaker and Arnette,[1] Wesche and Rechard,[2] Estes,[3] and EA Engineering, Science, and Technology, Inc.[4] The net effect is that the regulation of water development projects is now often designed with consideration for existing fishery resources.

An important concept overlooked during many instream flow studies is the dynamic nature of the river system being regulated. Bovee[5] noted that the instream flow investigator will ultimately be confronted with one of two problems related to channel dynamics: first, the determination of a flow regime that would prevent channel change and, second, the prediction of a new channel shape, should channel change be inevitable. From a biological perceptive, it is more desirable to accurately address the former than to risk the uncertain — and possibly catastrophic — consequences of the latter.

In regulated stream systems, an important option exists which can be used to maintain desired channel characteristics: the programed release of a predetermined discharge for a given duration. Such releases, termed "channel maintenance" or, more commonly, "flushing flows" (for the effect of removing [flushing] fine sediments from gravels), can be applied to meet a variety of interrelated management goals. In this chapter the basis for and the theory behind such flows are discussed and methods used for making flushing flow prescriptions are presented. The last part of the chapter is devoted to providing guidance in developing reliable flushing flow recommendations.

In general, the primary uses of flushing flows include maintenance of channel geometry and the qualitative and quantitative maintenance or enhancement of fishery habitat. Indeed, 76% of respondents to a recent survey reported by Reiser et al.[6] listed the removal of fine sediments from spawning gravels as a major purpose of flushing flow releases. In addition, 35% listed the removal of stored sediment from fish rearing habitats, while 37% cited channel maintenance as a major need. Given these results, it is not surprising that most of the flushing flow methods that have been developed (and discussed in this chapter) have focused on the maintenance of fish habitat.

While the need for flushing flow releases for channel maintenance has not received the attention that fish habitat maintenance has, the two are closely linked. Perhaps the primary difference between the two is more a matter of temporal and spatial variation than of physical process. The goal of a fish habitat maintenance flush is often a short-term improvement of habitat critical to a given life stage and/or species. Such a flow release can be either a routine annual event intended to coincide with the normal run-off period, or a one-time mitigative action to offset a perturbation resulting from an improper land-use activity (e.g., increased sediment load resulting from poor erosion control) or a natural catastrophic event such as a landslide or slump. In either case, the results of the flush can be measured immediately and evaluated with respect to the biological consequences of fine sediment deposition.[7-10] While results of studies assessing the impact of sediment on aquatic biota are at times inconclusive and contradictory, in general they have demonstrated inverse relationships between the accumulation of fine sediment in fish spawning and rearing habitat vs. fish survival and abundance.[11-14]

The concept of channel maintenance flows implies a longer time frame to determine success or failure, entails management of the entire active channel, and requires an understanding of the complex set of factors that influence channel morphology. For example, a fish habitat flushing flow may be termed a success if it reduces fine sediments in an important spawning area. However, a flow of the same magnitude and duration released in the same river may be inadequate for channel maintenance if flows are insufficient to flush fine sediments and plant materials from the edge of the stream. If such a situation persists over a period of years, riparian encroachment into the active channel might occur, resulting in a change in channel size and shape (Figure 1).

II. CHANNEL RESPONSE TO FLOW REGULATION

Before proceeding to the discussion of flushing flow methods, sediment transport mechanics, and the determination of flushing flow requirements, consideration should first be given to the complex of factors that result in deposition of sediments in regulated streams and those which control channel geometry and morphology.

A. Deposition of Sediments in Regulated Streams

In general, sediment movement in streams is dependent upon two factors: (1) the availability of sediment in the drainage, and (2) the sediment-transporting ability ("competency") of the stream. Either factor may limit sediment transport rates, and changes in both can occur in conjunction with water development projects and flow regulation.

With respect to flushing flows, it is stream competency which is most affected by streamflow regulation and is thus the cause of sediment deposition problems. This is because most developments alter the natural hydrograph of the system, reducing peak flows and decreasing the ability of the stream to transport sediment (Figure 2). O'Brien[15] noted that decreased competency can have direct and serious effects on the aquatic biota, including important fish populations (Figure 3). The net effect of the regulation of flows is that sediment input to the system may accumulate rather than being periodically removed ("flushed") during high flow events such as spring run-off.

The extent of sediment accumulation depends upon the type of project, its location, and its operational characteristics. For example, a "run-of-the-river", low-head hydroelectric project provides essentially no flow control. Although some ponding of sediments may occur immediately behind the dam, the natural hydrograph remains unaltered and normal high flows should continue to transport sediments. In contrast, large multipurpose impoundments afford almost complete control of the flow regime and releases may be regulated on a demand basis.

Along with flow control, water development projects affect the amount of sediment input into the downstream, controlled reach of stream. A benefit often cited with large reservoirs is that sediments will settle out in the impoundment and downstream releases will be much cleaner. This can have a definite biological advantage in that it is often possible to selectively withdraw the clean water from lower reservoir depths having colder water. Such withdrawals can result in the establishment of a tailwater salmonid fishery.

Sediments are trapped if the regulated systems are closed or semi-closed with respect to upstream sources of sediment. Thus, the extent of sediment reduction is dependent upon the location of the project relative to the major sediment sources in the drainage. For projects

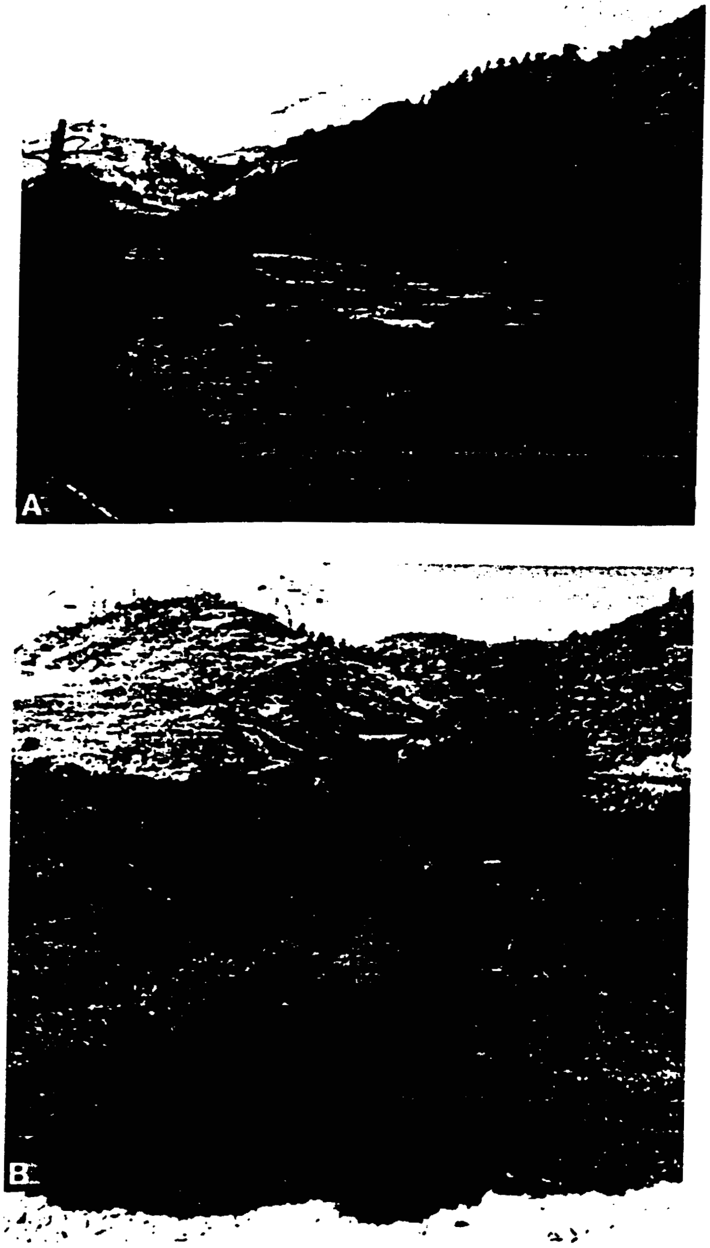


FIGURE 1. Response of a Wyoming steam to flow regulation. (A) Immediately upstream from transbasin diversion. (B) Immediately downstream from transbasin diversion after 85 years of regulation.

located below major sediment sources, relatively clear, sediment-free water would likely prevail throughout the controlled reach. This same water, however, now has greater potential for sediment transport and erosional cutting and channel degradation may occur. Colloquially, this water is often termed "hungry", in that it readily scours and erodes the stream channel. Barring man-induced sediment recruitment to the stream, this condition can result in serious

FIGURE 2. The accumulation of sediments in regulated streams occurs as a result of the reduction or elimination of peak flows, which reduces its competency and sediment transport ability. The photograph shows additional sediments added as a result of a catastrophic storm event.

problems of gravel transport out of the system. In fact, available spawning gravels in some streams have become severely limited due to this process.[16,17] In this case, it is the lack of sediment rather than its excess which creates a problem, and some extraneous input of gravel may actually benefit the aquatic resource (e.g., replenishment of spawning gravel).[16,18-22]

In contrast, projects located above major sediment sources would have little effect on reducing sediment recruitment to downstream segments. Coupled with the regulated flow regime, sediment input rates in this situation would likely exceed transport rates and sediment depositional problems are likely to occur with time. It is this condition which most often predicates the need for flow releases to flush sediments and maintain suitable habitat conditions and channel morphology.

In gravel-bed streams, which are typical of mountain systems, fine sediments may be deposited through an upper, poorly graded, coarse pavement layer into the underlying substrate material. Fine particles traveling in suspension are deposited in the pores of this pavement layer both by gravity settling and by sieving of the intragravel flow entering the stream bed. Einstein[23] found in laboratory experiments that once the fine sediment has been deposited in the gravel bed, minimal upward or horizontal movement of this material takes place. The findings of Beschta and Jackson[24] indicate that the depositional process tends to be selective, in that the particle size distribution of the deposited material is finer than that of the suspended load.

The amount of material that intrudes into the gravel bed is highly dependent upon the grain size distribution of the fine sediment and also that of the gravel bed. If the size of the fine material is small relative to that of the receiving gravels, the gravel pores tend to fill from the bottom to the top of the pavement layer. Beschta and Jackson[24] found that for larger suspended sediments, a filter layer can form within the gravel pavement which restricts the intrusion of additional fine material into the gravel stream bed. Einstein[23] found that the rate at which the fine sediment accumulates in the gravel layer depends upon the concentration

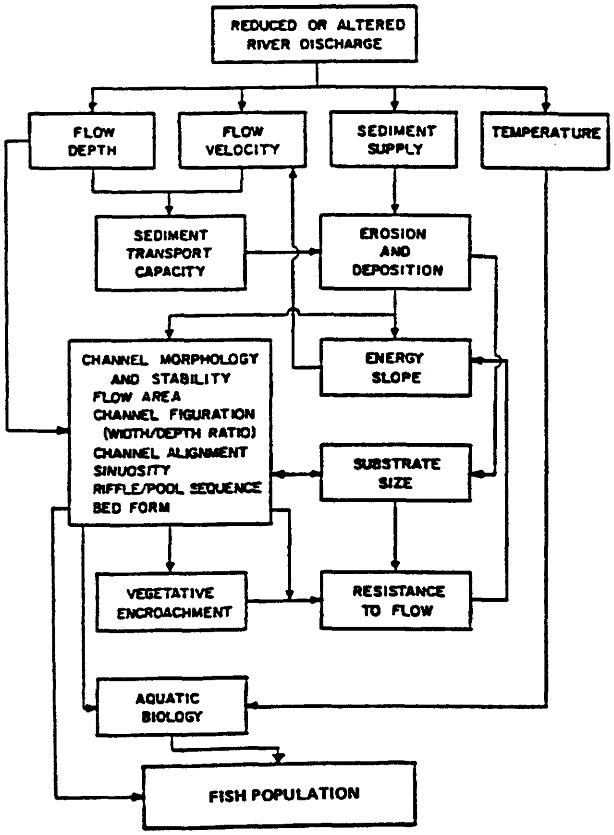


FIGURE 3. Effects of altered flow regimes on hydraulic parameters associated with biological components. (Modified from O'Brien, J. S., Hydraulic and Sediment Transport Investigation, Yampa River, Dinosaur National Monument, WRFSL Rep., 1984, 83-8.)

of the suspended load carried by the stream but is independent of the flow velocity or the amount of material already present within the pores of the gravel bed.

The shape of the gravel in a stream may also affect sediment deposition. Studies by Meehan and Swanston[25] indicated that at low-flow conditions, rounded gravels tend to accumulate more sediment than angular gravels, whereas the reverse is true at higher flows. The greater accumulation of sediments in the rounded gravels at low flows may be due to the lesser degree of turbulence at the gravel bed. At higher discharges a flow separation zone can develop behind angular gravels, causing greater sediment deposition.

The deposition and accumulation of sediments in regulated streams becomes a problem when it begins to affect the biotic community. This can occur as a slow, insidious process with the continuing deposition of small quantities of sediments (without subsequent transport) or be triggered as a rapid, almost catastrophic event, exemplified by a sudden slump or landslide. In either case, sediment is deposited in the stream in excess of ambient conditions, and its removal forms the underlying basis for a flushing flow.

The magnitude of a required flushing discharge will vary depending upon the area of consideration, i.e., spawning habitat (riffles), rearing habitat (pools), or channel maintenance. Reiser and Bjornn[26] noted that streamflow changes generally influence water velocities and the area of riffles more than pools. Kraft[27] and Wesche[28] both demonstrated that velocity vs. depth is the most dynamic parameter with respect to varying flows. Intuitively then, it

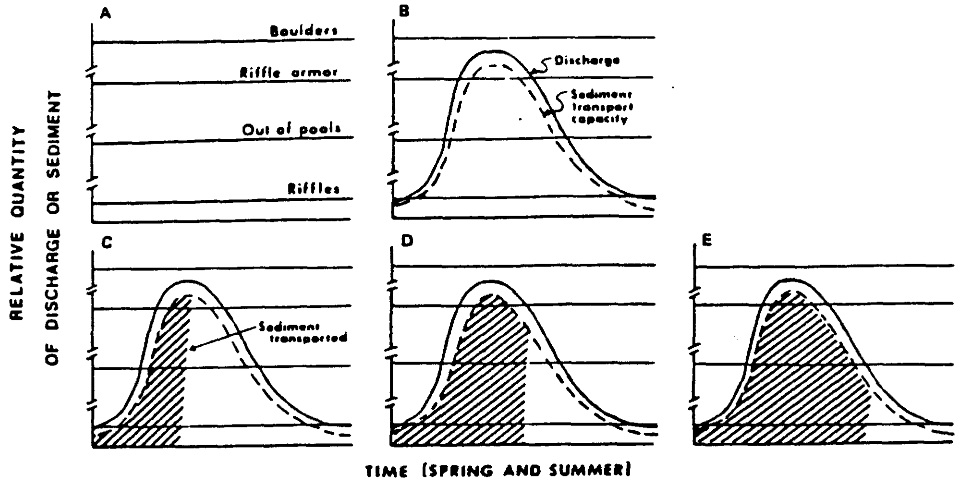
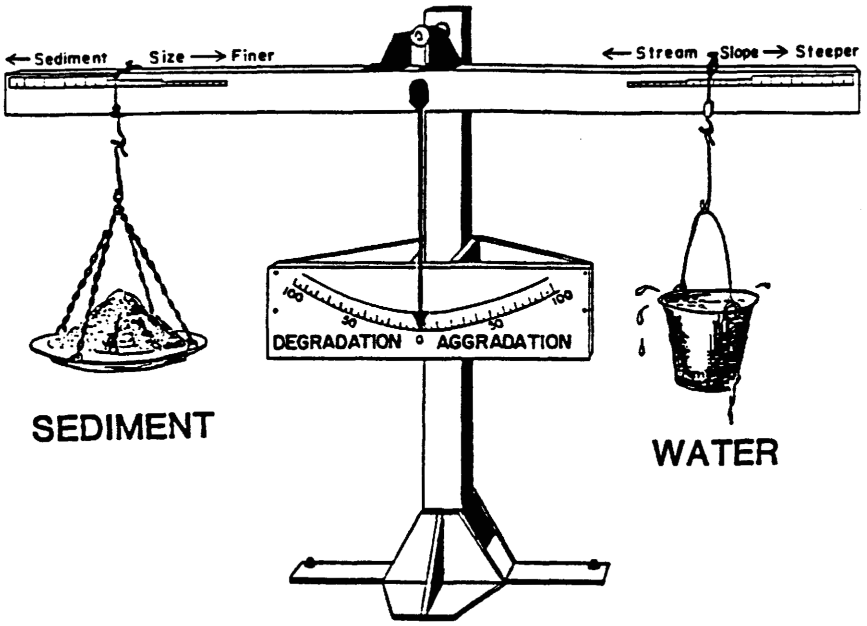


FIGURE 4. Relative discharges which transport sediment across riffles, out of pools, out of armored riffles, and out of substrate armored by boulders for a given section of stream. See text for explanation of A to E. (Modified from Bjornn, T. C., Brusven, M. A., Molnau, M. P., Milligan, J., Klamt, R., Chaco, E., and Schaye, C., Transport of Granitic Sediment in Streams and its Effects on Insects and Fish, Bull. No. 12, Forestry Wildlife Range Experiment Station, University of Idaho, Moscow, 1977.)

would be expected that higher flows would be required to remove surface sediments from pool vs. riffle areas; this is indeed the case. However, even higher flows are needed to flush fines from below an armored layer in a riffle (armor layer forms when finer material is held in place by coarse material). An excellent graphical presentation of the relative magnitude of these flows in an unregulated stream is provided in Figure 4, from Bjornn et al.[29] This figure displays the critical discharges needed for transporting coarse and fine sediments across riffles, out of pools, out of riffles after dislodging the armor layer, and out of the substrate after moving large boulders (Figure 4A). The amount of coarse and fine sediments capable of being transported through a given reach of stream is a function of flow (Figure 4B).

Figure 4 further demonstrates three potential conditions of sediment transport in an unregulated stream. In Figure 4C, a condition of above-average discharge is presented. In this condition, flows are capable of mobilizing the armor layer on the riffles, and the fine sediment within the riffles can be transported downstream. As indicated, essentially all sediments have been transported out of the system before the flows begin to recede. Thus, little sediment would be redeposited at the lower flows. The condition illustrated in Figure 4D is representative of a stream that continues transporting fine sediments after the flows have declined below the level that mobilizes the armor layer on riffles. In this situation, the riffles would be refilled with sediment. Figure 4E depicts a stream that continues transporting fine sediments after flows have fallen below levels that remove fines from pools. In this case, the pools would be refilled with sediments. If no armor layer is present, sediments would be transported from riffle areas in all but the lowest flow conditions depicted.

The conditions displayed in Figure 4 are for an unregulated stream that exhibits characteristic run-off periods. In regulated systems, a much flatter hydrograph may result, with peaks in flow being of relatively short duration. Nevertheless, the same general patterns and principles apply, with the magnitude and duration of the required flushing flow depending upon the extent and characteristics of the sediment problem. Under some conditions, sufficient flushing may be achieved through a relatively rapid increase-decrease in flows. This would be the case if flushing were targeted at surficial fine sediments located immediately below a water development project. In contrast, the flushing of sediments within pools or



(SEDIMENT LOAD) × (SEDIMENT SIZE)

$\propto$

(STREAM SLOPE) × (STREAM DISCHARGE)

FIGURE 5. Relationship of discharge and sediment for a stable channel balance. (Modified from Lane. E. W., *Proc. Am. Soc. Civ. Eng.*, 81, 1, 1955.)

within armored riffle areas may require bed mobilization, which is achieved through a longer, higher-flow release. More information on the theory and mechanics of sediment transport is presented in Section III.C.

B. Channel Changes in Regulated Streams

A second, coincident effect of flow regulation is a modification in channel morphology and shape. This exceedingly complex process is governed by a closely interwoven and interactive set of climatological, geological, and biological characteristics. Bovee[5] noted that the prediction of a new channel shape to prevent channel change following flow regulation is a difficult problem which, according to Simons et al.,[30] is incapable of being predicted by theory alone. Kellerhals[31] suggested that the best way to predict new channel dimensions and shape is to look at a similar stream that has experienced the same type of impacts. Thus, the river manager faced with prescribing a flushing flow is likely to be unable to assess quantitatively the resulting channel response prior to the actual release of the flow. However, a fundamental understanding of channel dynamics will be useful in making such an assessment, and the following discussion is offered to aid in that understanding.

Climate, geology, soils, land use, and vegetation all combine to determine the hydrologic and sedimentologic regimen of rivers and their morphology.[32] River morphologies adjust to prevailing rates of water and sediment transport through them.[33] With time, rivers reach an equilibrium between energy and sediment load under the specific environmental conditions of a watershed (Figure 5). However, this equilibrium does not imply static conditions, and rivers are constantly adjusting to seasonal and annual changes in discharge and sediment load. Such adjustments are not always continuous, but occur in a complex manner after an extrinsic or intrinsic threshold is reached.[35] The state of equilibrium in channels has been defined variously as dynamic equilibrium, quasi-equilibrium, grade, regime, and steady-state.[36] Perturbations to this, such as floods or alterations in land-use activities, can accelerate change.[37] Likewise, long-term changes in climate, geology, soils, and vegetation will ultimately affect channel morphology and dynamics.

1. *Climate*

Schumm and Lichty[38] traced the adjustments of the Cimmarron River in southwestern Kansas and related them to climatic conditions. A period of channel widening was initiated by the maximum flood of record followed by a span of years with below-normal precipitation. Flood plain reconstruction occurred during a subsequent period of above-normal precipitation and floods of low-to-moderate peak discharge. This allowed vegetation to become established in the widened channel, which increased sediment deposition. Burkham[39] reported similar changes in the Gila River, Arizona which were triggered by floods in 1891 and between 1905 and 1917. Such events caused the width of the river to increase from 150 to 2,000 ft (45 to 600 m), its sinuosity to decrease from 1.2 to 1.0, and the slope to steepen by 20%. Within 45 years following the 1905 floods, bar growth and flood plain deposition had decreased the width and restored the channel, presumably a result of more normal precipitation regimes and increased riparian vegetation. Schumm[40] stated that differences among modern and paleochannels of the Murrembidgee River in Australia could be attributed to the effects of quaternary climate changes on the hydrologic regimen of the drainage basin. Love[41] outlined the development of the Chaco Arroyo in New Mexico during the past 140 years and concluded that downcutting of the Arroyo and its tributaries and later aggradation of the main channel over the long term were related to climatic change. Other comparisons supporting long-term climatic control of fluvial episodes are discussed by Knox.[42] In general, stable humid-zone streams are less sensitive to catastrophic events (floods, landslides) than are streams in semi-arid areas.[36,43]

2. *Geology and Soils*

As previously noted, the geology of a region has a direct effect on the extent of sediment available for transport and the amount and timing of discharge.[44,45] Schumm[35] stated that geomorphic and hydrologic features and processes of the drainage systems reflect processes in the run-off and sediment-source areas. Although difficult to document, the geologic history of an area is assumed to be a major factor determining current watershed conditions. Graf[46] noted that regional geologic materials may explain some of the observed variation in hydraulic geometry. After review of the long-term metamorphosis of the Mississippi and Murrembidgee River channels, Schumm[47] reported that paleohydrology and valley morphology appear to influence channel morphology, especially the pattern of modern rivers. Geological materials directly affect channel shape by their resistance to erosion and indirectly affect sediment loadings and characteristics through a weakening process.[48]

The type of soil in a watershed and its properties will also have a bearing on the mechanics of sediment transport and, therefore, channel slope. Channel-sediment characteristics have been found to have a measurable effect on geometry-discharge relations.[49-52] For streams of similar discharge characteristics, minimum channel widths generally occur if the median particle size of the bed material is very small (high silt/clay content).[53] Width tends to increase with median particle size, reaching a maximum when the bed material is a well-sorted, medium-to-coarse-grained sand. For median particle sizes greater than approximately 0.08 in. (2 mm), the coarse portion of the bed provides an armoring effect similar to that provided by silt and clay. This results in narrower, more stable channels than those that have sand beds. Stevens[54] argued that the amount of silt and clay in the banks determines the width of an alluvial channel and the composition of the bed is less important. More likely, the importance of perimeter sediment as a control of channel shape varies among rivers. The morphology of channels in equilibrium reflects their sediment load, which in turn is a product of their bed and bank materials.[36,47,55] Rivers can adjust their cross-sections to maintain a condition of sediment transport continuity without adjusting slope. The data of Andrews[56] from the East Fork River, Wyoming illustrate this phenomenon: the East Fork River maintains the sediment transport imposed by its tributary, Muddy Creek, entirely by adjusting its cross-section, particularly by increasing velocity. Richards[55] documented a similar adjustment in channel form occurring from sediment pollution by the china-clay industry in Cornwall, England.

3. Land Use

Land-use activities such as logging, farming, and mining can cause changes in river channel morphology by increasing sediment yield and run-off, with sediment yield generally affected more than run-off.[36] Trimble[57] reported channel aggradation as an effect of forest removal and intensified cropping. Harris[58] studied sediment yield and run-off changes in response to logging. White and Wells[59] found that watershed devegetation by a forest fire produced a complex channel response related to variations in amounts and source areas of sediments. Channels in the system aggraded immediately after the fire in response to summer precipitation. As coarse sediment supplies from the hillslopes declined in the fall and run-off events became fewer and of a lower magnitude, the channels began scouring. During the following summer, channel aggradation again occurred in response to revegetation. With dormancy of riparian vegetation in the fall, increased erosion of stream banks occurred and channel scouring again dominated. Urbanization also can cause a cyclic variation in sediment yield, with extremely high yields during the construction phase but markedly reduced yields when urban development is complete.[60]

4. Streamflow and Flow Regulation

The relationship of stream discharge to channel morphology has also been researched. Much of this work has been focused on development and analysis of empirically derived power function equations which relate discharge to variables defining the morphology of a channel.[34,49,61-67] Schumm[40] outlined several qualitative models of channel metamorphosis, which were calibrated with empirical data. O'Brien[15] developed a qualitative model, shown in Figure 2, to illustrate the effect of altered flow regime on hydraulic and biological parameters. However, no comprehensive, quantitative process-response model of channel adjustment exists. Richards[36] states that this is because of the multivariate and indeterminate nature of river equilibrium. Also, environmental changes commonly alter discharge and sediment yield simultaneously, but to different and varying degrees, often with secondary responses.[68]

There is disagreement as to what discharge levels are responsible for the shape of a channel in equilibrium. Researchers[69-71] have identified "effective" discharges in rivers as the increment of discharge which transports the largest fraction of the annual sediment load over a period of years, and thus the flow to which the channel adjusts. However, Harvey et al.[33] stated that the identification of one discharge as that to which channel systems adjust seems to be an oversimplification. Pickup and Warner[72] identified a range of discharges to which different channel properties adjust. Carlston[73] found that meander geometry can adjust to frequent discharges of less-than-bank-full flow, whereas Andrews[74] showed that the morphology of straight reaches responded to average annual bank-full discharges.

Responses of fluvial systems to various forms of flow regulation have likewise been documented. In general, the channelization of a stream reach leads to destabilization that may be propagated upstream and downstream for long distances.[37] Barnard and Melhorn[75] described the response of Big Pine Creek Ditch, Indiana to channelization. After its channelization in 1963 to improve drainage, the channel began a long-term adjustment toward the prechannelized state by (1) increasing sinuosity and initiation of new point bars and meanders accompanying lateral channel migration, (2) reestablishment of pool-riffle sequences through scour and silting, (3) bank erosion and slumping, (4) a decrease in gradient, and (5) reductions in channel drainage capacity which increased flood frequency. Bray and Kellerhals[76] reviewed data on morphological effects of 11 Canadian interbasin diversions and found that receiving channel responses resulted in major degradation, channel widening, bank erosion and slumping, increased silt loads, and channel incision, Some posssible effects on the contributing channels were a decrease in channel size and capacity, aggradation at the confluences of tributaries, and a reduction in channel slope.

Reduced channel capacity is a common adjustment of rivers subjected to regulation. Williams[77] documented the reduction in channel size of the North Platte and Platte Rivers in Nebraska in response to decreases in water discharge caused by dams. Average annual peak flows dropped to 10 to 20% of their preregulation period values. As a result, between the late 1800s and 1962, channel width on the Platte River near Grand Island, Nebraska decreased from 3400 to 870 ft (1000 to 265 m). Bray and Kellerhals[76] reported reduced channel capacity in the Peace River, Canada, below the Bennett Dam, as a result of an estimated 105,000 to 210,000 ft^3/sec (3000 to 6000 m^3/s) reduction in spring flows. In addition, because the supply of sediment from the tributaries is unchanged, the river is aggrading at major confluences and deltas are being built into the Peace River channel. Gregory and Park[78] documented a 54% reduction in channel capacity on the River Tone, England, downstream from the Clatworthy Reservoir. This reduction persisted for 6.8 mi (11 km), up to the point where the contributing watershed area was at least four times that of the area draining the reservoir. Petts[79] reported reduced channel capacity on the River Derwent below the Ladybower Reservoir, England. Huang[80] examined the changes in channel geometry and capacity due to dams on seven alluvial Kansas streams. He concluded that the stream below a dam tends to form a relatively narrower and deeper channel as a result of channel degradation and increased channel roughness. Channel capacity, he noted, tended to increase at sections near the dam, as a result of degradation from reduced sediment loads, and to decrease at sections near and beyond "the point of incipient degradation further below."

5. *Case Studies*

Because many of the responses of a river system cannot be predicted from theory alone, an important means for evaluating river response to man's activities such as water development is by documented case studies. Case studies can serve as a basis for the development of dynamic modeling techniques and can provide insight into river responses for certain activities under specific conditions. In general, this approach requires information regarding (1) the historical condition of the channel, (2) the influence of the regulation on the hydrologic and sediment regimes of the river reach, (3) the present condition of the channel, and (4) additional factors that may influence channel condition, such as land-use changes or recent floods. The major limitation in most cases will be the availability of accurate historic data. One such study is currently (1988) being conducted by the Wyoming Water Research Center on regulated streams in the Central Rocky Mountain region of the U.S. The goal of the study is to provide guidance to water managers regarding the response of various channel types to flow depletion and augmentation resulting from transbasin diversion. The hypothesis to be tested is that the overall channel response to flow alteration (expressed in terms of width, depth, and conveyance capacity of lower-order, higher-elevation streams) occurs at differing rates, both temporally and spatially, and depends upon the magnitude of hydrograph modification, the type of geologic control, and channel stability. These latter variables may be further modified by gradient, sinuosity, channel aggradation and degradation processes, and the composition of the streamside vegetation. Through studies such as this, insight can be gained regarding the rate of response of channel types, and more quantitative information will be available upon which decisions regarding the need for and magnitude of flushing flow releases can be made.

III. EXISTING FLUSHING FLOW METHODOLOGIES

Prior to establishing the magnitude and duration of a flushing flow, the objectives of the flow must be clearly defined. As discussed earlier, flushing flows may be prescribed for channel maintenance, for the removal of fine sediments from important riffle and pool areas, or for the surficial removal of fines from a channel.

At this time, there are no existing standard methodologies for the determination of flushing flow requirements. There is general agreement that more research is necessary in this field prior to the establishment of a single, reliable technique. Too little is understood about the physical processes of sediment transport in gravel bed rivers and their relationship to the supply of water and sediment.

Until standard methods are developed, evaluations will require an approach tailored to the specific needs and characteristics of each stream and project. This may entail the use of several different office techniques to derive an initial flow estimate, followed by detailed field studies to refine and finalize recommendations.

The most reliable method for establishing required flushing flow rates is to observe the study stream at various flow levels. Field observations such as sampling and tagging of bed material and/or measurement of sediment transport rates should be made to determine the effectiveness of flushing flows. Unfortunately, it is often difficult to control the flow on many streams and equally difficult to make useful measurements. However, where feasible, they provide the best results of all methods.

A number of methods have been suggested for the establishment of flushing flow requirements. Table 1 identifies 16 methods and briefly describes the basis and applicability of each. These methods have been individually discussed by Reiser et al.[6] The methods generally fall into three basic categories:

- Hydrologic event methods
- Channel morphology methods
- Sediment transport mechanics methods

A. Hydrologic Event Methods

Hydrologic event methods utilize streamflow records to develop a statistical correlation between a hydrologic parameter and the observed flow at which adequate flushing is achieved. Some of these methods are based on flood frequency analysis and specify a flow equivalent to a flood with a specific return period (e.g., a 2-year flood). Other methods use flow duration analysis and specify a flow with a specific exceedence probability (e.g., the flow that is exceeded 5% of the time).

A sequence of natural flow events determines the shape of an alluvial channel. Although the process is dynamic, many river and stream channels maintain a stable shape. The dominant discharge, defined as the equivalent steady discharge to produce the same dimensions as the sequence of natural events, has been found to be approximately the same as the bank-full discharge for many natural channels. In addition, the bank-full discharge appears to be approximately the same as the frequency of occurrence of the flow which transports the most sediment ("effective discharge").[30] For gravel-bed channels, the channel-forming discharge is approximately equal to the 1.5-year flood event. Since the channel-forming process is closely linked to the sequence of flows in the channel, there is some basis for

Table 1
SUMMARY OF METHODOLOGIES FOR ASSESSING FLUSHING FLOWS

Methodology	Type	Basis	Method considers flow				Comments	Ref.
			Magnitude	Timing	Duration	Effectiveness		
Tennant (Montana) method	Office (field studies recommended but not detailed)	200% average annual flow	X				Requires extensive flow records; site photographs recommended	81, 82
Northern Great Plains Resource Program method	Office	Average annual flow	X				Requires extensive flow records; method not developed primarily for flushing flows (see text)	83
Dominant discharge/channel morphology method	Office	Dominant discharge (1.5-year frequency peak flow)	X	X	X(24 h)		Requires extensive flow records (9 years); suggests a gradual rising and receding of the flushing flow	84
Estes and Orsborn method	Office	2-year average annual peak flood event — QF2P; 3-d average around QF2P; 7-d average around QF2P	X		X (instantaneous) 3d; 7d)		Requires extensive flow records; flow synthesis techniques are discussed; suggests field studies for flow verification	3, 85
Hoppe method	Office	17th percentile on flow duration curve (Q17)	X		X (48 h)		Requires extensive flow records; empirically developed for the Fryingpan River, CO — Q17 may be specific to that system	86, 87
Bed material transport method	Field	Threshold discharge for transport; determined using bedload tracers	X		X		Restricted to clear water systems with good visibility; several test flows required; office techniques not described	88

Table 1 (continued)
SUMMARY OF METHODOLOGIES FOR ASSESSING FLUSHING FLOWS

			Method considers flow					
Methodology	**Type**	**Basis**	**Magnitude**	**Timing**	**Duration**	**Effectiveness**	**Comments**	**Ref.**
Instream flow incremental methodology	Office/field	Indirect approach: point at which weighted usable area (on spawning curve) begins to decrease	X				Several assumptions must be made using this approach (see text); presently does not directly address flushing flows (the CIFASG* is reviewing approaches for integrating this)	5, 89
Wesche method	Field	Bank-full discharge (empirically determined) uses drainage basin similarities for estimating unmeasured systems	X	X	X (3 d)	X	Approach developed on high mountain streams in Wyoming; applicability to other systems uncertain; requires flow measurements during high flow events	90
Beschta and Jackson method	Office	Flow/drainage area ratio (estimated at 13.7 cfs/mi^2); 5th percentile on flow duration curve Q5	X				Developed in small coastal streams of Oregon; approach may not be applicable on other systems; flow records required	24
Effective discharge	Field/office	Effective discharge/bank-full discharge	X	X	X (48 h)	X	Developed on Yampa River in Colorado/Utah; extensive field measurements required; sediment discharge relationships based on field and laboratory studies; approach included a physical model of the system; requires extensive flow records	15

U.S. Forest Service channel maintenance flow method	Office	Bank-full discharge/dominant discharge (1.5-year recurrence interval)	X	X	X (3 d)	X	Developed on streams in northern Wyoming; extensive flow records required; method considers a wide range of flows, not only peak flows	91
Incipient motion methodology (Meyer-Peter/Muller-based)	Field/office	Predicting discharge which causes incipient motion of particle; employs Meyer-Peter/Muller transport formula	X	X	X (3 d)		Used on streams in southeastern Wyoming; Meyer-Peter/Muller formula can provide widely varying results; assumptions used in this technique should be evaluated on a site-specific basis; technique probably suitable for implementation-type studies	92
Incipient motion methodology (Shields entrainment function)	Office	Predicting discharge for incipient motion of particle; based on a Shields entrainment function	X		X (variable)		Method based on Shields parameter of 0.03; other values can also be used which would change relationships developed; technique provides an estimate of needed flow as a function of grain size, stream width, and channel slope	6
Sediment transport models (see text)	Office/field	Sediment-discharge relationships/transport capacity	X				Model output can be highly variable; proper and careful selection and use of models is critical	

Table 1 (continued)
SUMMARY OF METHODOLOGIES FOR ASSESSING FLUSHING FLOWS

Methodology	Type	Basis	Method considers flow				Comments	Ref.
			Magnitude	Timing	Duration	Effectiveness		
Critical velocity method	Office/field	Relating critical velocities to transport 0.5 to 1.5 in. gravel to stream discharge	X		X		Used on streams in Sierra Nevada of California; uses both field and office (flow records) data; employs Froude number to assist in determining maximum flushing discharge	93
Physical process method	Office/field	Adaptation of Shields parameter	X		X		Method uses Shields parameter for determining surficial and depth flushing requirements; used on Williams Fork River, CO	94

• CIFASG, Cooperative Instream Flow and Aquatic Sciences Group.

the development of flushing flow methods that use functions of the natural flow sequence. Their applicability, however, would most likely be regional.

B. Channel Morphology Methods

Channel morphology methods identify a channel-shape parameter such as the bank-full depth to establish an adequate flushing flow release. The morphology of alluvial rivers and streams is determined by the interaction between a number of geologic and hydrologic variables. These interactions are not fully understood. However, many investigators have noted that alluvial rivers and streams develop a hydraulic geometry which is dependent upon the relationship between water discharge and sediment discharge. Generally, these relationships can be applied to channels within one region. The regime theory, developed for irrigation canals in India, formed the basis of hydraulic geometry relationships for rivers and canals.[95] Generalized hydraulic geometry relationships were developed by Leopold and Maddock[61] for different types of rivers and different regions of the U.S. using extensive data from the U.S. Geological Survey. More recently, Parker[96,97] developed a set of dimensionless regime equations for gravel bed channels with mobile stream beds and stable banks. Hydraulic geometry relationships have been developed using the bank-full discharge as a variable. It seems feasible, however, that similar relationships for a specific region could be established for the critical discharge at which the gravel bed of a stream mobilizes. Parker[97] also developed a relationship between the bed shear at bank-full conditions (τ_{BF}) and the critical shear stress (τ_C) for bed mobilization in gravel-bed streams. The equation is of the form

$$\tau_{BF} - \tau_c = 0.2\,\tau_c \tag{1}$$

where τ_{BF} = shear stress at bank full condition and τ_C = critical shear stress for bed mobilization.

Equation 1 may be rearranged as

$$\tau_c = 0.83\,\tau_{BF} \tag{2}$$

This indicates that the bed will mobilize when the flow depth is slightly greater than 80% of the bank-full depth.

C. Sediment Transport Mechanics Methods

The present state of the art of sediment transport mechanics, particularly with regard to gravel-bed rivers, has not developed to a point where a single reliable method is available to accurately estimate the flushing flow required to achieve a specific objective. The high variability in hydraulic conditions in natural streams and rivers, the difficulty in collecting meaningful data, and the complexity of the physical processes have all contributed to the development of numerous empirical methods, which often predict dramatically different results. Consequently, it is common to apply several different methods to evaluate a problem and then rely on judgment to reconcile differences. The intent of this section is to briefly address the physical processes involved in sediment transport and to summarize some tools that are available to evaluate flushing flow requirements.

The removal of fine sediments from stream gravels requires that the entire stream bed be mobilized. In laboratory studies, Beschta and Jackson[24] found that fine sediments could be flushed from 1.5-cm gravels to a depth of approximately 1 cm. These results agree with those of O'Brien,[15] who found that fines could be cleared from a cobble channel bed to a depth of approximately 0.5 to 1.0 cm of the average cobble diameter. However, both investigators indicated that further flushing of fines requires mobilization of the stream bed.

Most sediment transport relationships rely upon a "threshold of motion" concept — the idea that a certain minimum flow is required to mobilize the stream bed before significant sediment transport occurs.

1. Threshold of Movement

The initiation of motion of sediment particles has been studied by numerous investigators since the 18th century. The research into the threshold conditions has centered around one of two hydraulic properties of the flow: the critical mean velocity or the critical tractive (shear) stress.

Lane[34] reported permissible canal-design velocities which he obtained from a 1936 Russian design code. The permissible design velocities, presented below, are based on a flow depth of 1 m:

Particle diameter (mm)	5	10	15	25	40	75	100	150	200
Mean velocity (m/s)	0.8	1.0	1.2	1.4	1.8	2.4	2.7	3.3	3.9

Lane[34] also published the following correction factors for flow depths less than or greater than 1 m:

Depth (m)	0.3	0.6	1.0	1.5	2.0	2.5	3.0
Correction factor	0.80	0.90	1.00	1.10	1.15	1.20	1.25

Neil[98] developed a mean velocity criterion for scour of coarse uniform bed materials. From his flume experiments, Neil fitted the equation

$$\rho V^2/\gamma_s' D = 2(D/d)^{-1/3} \tag{3}$$

where V = mean channel velocity, ρ = fluid density, γ_s' = submerged specific weight of sediment grains, D = grain diameter, and d = flow depth. Neil's relationship incorporated a depth correction factor similar to the Russian data reported by Lane.[34] A depth correction factor is necessary because it is the near-bed velocity that controls the threshold of motion of the sediment particles: for a given mean velocity, the velocity near the bed varies with the flow depth.

The "critical tractive stress" approach has received more attention by investigators than the limiting velocity approach. Shields[99] was the first to be credited with the critical tractive stress approach to the investigation of the initiation of motion of sediment particles. The forces acting on a sediment particle are equated with the forces acting to keep the particle at rest. Following this approach, the controlling equation takes the form

$$\tau_c = k(\gamma_s - \gamma)d_s \tag{4}$$

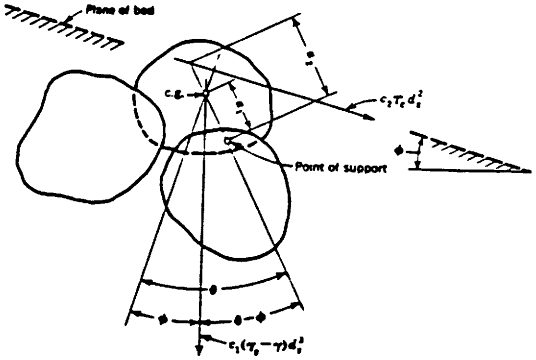
for forces acting to keep particle at rest, and

$$\tau_o = \gamma RS \tag{5}$$

for forces acting to move the particle, where τ_c = critical shear at incipient motion, τ_o = shear stress acting on channel bed, γ_s,γ = specific weights of sediment and fluid, R = hydraulic radius, S = energy slope, d_s = particle size, and k = dimensionless shear stress.

Solving Equations 4 and 5 for k yields

$$k = RS/(d_s[\gamma_s/\gamma - 1]) \tag{6}$$



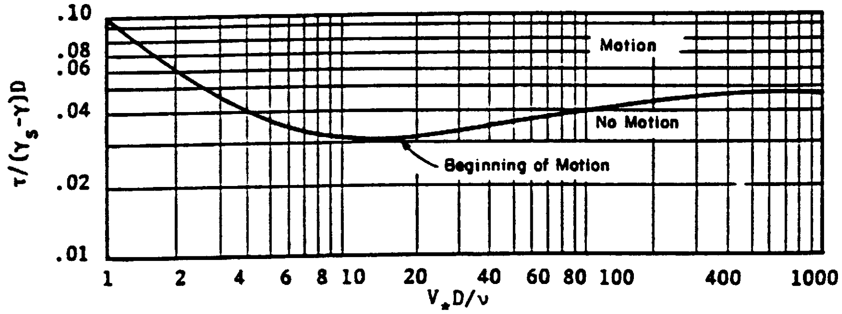


FIGURE 6. Shields relationship for beginning of motion. (Modified from Gessler, J., in *River Mechanics*, Shen, H. W., Ed., Water Resources Publications, Fort Collins, CO, 1971.)

The constant K in Equation 6 is the dimensionless shear stress at incipient motion and is commonly referred to as the Shields parameter. For hydrodynamically rough surfaces, such as a gravel-bed stream, Shields found that k remains constant at a value of 0.06. Shields obtained his results by measuring the bed load at various values of $\tau/(\gamma_s - \gamma)d$, with all values of τ being at least twice the critical value (τ_c). He then extrapolated his findings to a point of zero bed load. Thereby, he avoided the problem of defining the exact point where motion of the bed begins. Gessler[100] noted that Shields did not differentiate between losses due to bed form and those due to grain roughness and that he thus overestimated the Shields parameter at incipient motion by as much as 10%. The diagram shown in Figure 6 has been adjusted to reflect this correction.

The investigations that led to the development of the Shields diagram were based on the use of materials of uniform grain. By contrast, the pavement layer of a gravel-bed stream or river is composed of poorly sorted nonuniform materials. The characteristics of this pavement layer have been studied by several investigators.[100-105]

There is a complication in defining the point at which bed motion begins. Although the method used by Shields provides an objective means to evaluate bed motion it does not clearly define the exact point at which bed motion commences. More subjective methods of observing individual particles in the bed tend to support lower values of the critical Shields stress. Gessler[106] determined that an individual particle has a 5% probability of movement at a Shields parameter of 0.024 and about a 50% probability at a Shields parameter of 0.047.

The nonuniformity of grain sizes in gravel-bed streams also has the effect of reducing the effective Shields parameter.[104,105,107] This has been attributed to increased turbulence intensities at the bed associated with its largest particles. As a result, the most widely cited value of the Shields parameter applicable to mobilization of gravel-bed streams is approx-

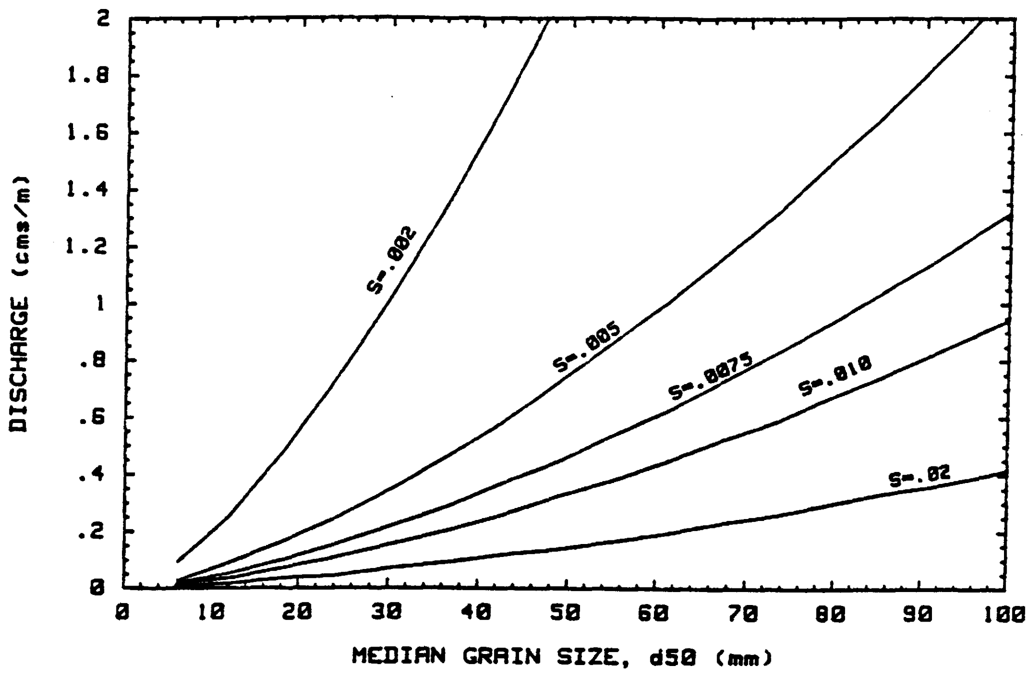


FIGURE 7. Critical unit discharges for bed mobilization as a function of grain size and channel slope. Relationships derived from a Shields entrainment function. (Modified from Reiser, D. W., Ramey, M. P., and Lambert, T. R., Review of Flushing Flow Requirements in Regulated Streams, Department of Engineering Research, Pacific Gas and Electric Company, San Ramon, CA, 1985.)

imately 0.03.[98,108] From investigations of 24 self-formed gravel-bed rivers in Colorado, Andrews[109] found that the mean critical dimensionless shear stress value relative to the median particle diameter was 0.033. Milhous and Bradley[94] suggest that surficial flushing of fines can be achieved with a Shields parameter of about 0.02 and that depth flushing sufficient to release trapped fine material occurs at a Shields parameter of about 0.035.

Manning's equation for a wide channel can be expressed as:

$$q = (S^{1/2}\,Y^{5/3})/n \tag{7}$$

where q = unit discharge (cms/m), S = the energy slope (m/m), Y = the flow depth (m), and n = Manning's coefficient.

Analysis of data from many rivers, canals, and flumes indicates that Manning's coefficient can be predicted by the equation

$$n = 0.049\, d_{50}^{1/6} \tag{8}$$

where d_{50} = median grain size (m).[110]

If Equations 6, 7, and 8 are combined (assuming R ≈ y), the discharge at incipient motion can be expressed as:

$$q = 47\, k^{5/3}(d_{50}^{3/2}/S^{7/6}) \tag{9}$$

The relationship in Equation 9 is shown in Figure 7 for k = 0.03 as a set of curves of unit discharge vs. grain size for various channel bed slopes.

There are several problems with applying the tractive-force approach to gravel-bed rivers and streams. The total boundary shear (τ_o) was equated with the forces resisting particle movement. Some of the boundary shear, however, is associated with irregularities that include bed-form roughness such as riffle and pool sequences, channel alignment variations such as meanders, and large bed elements such as boulders strewn along the channel bed. Each of these factors accounts for some portion of the tractive force acting on the channel boundary. Many well-known sediment transport relationships account for this effect, including the formulations of Einstein[111] and Meyer-Peter and Muller.[108]

Prestegaard[112] has developed data indicating that approximately half of the total bed shear is expended by bar resistance in gravel-bed streams at bank-full stage. In addition, her data suggest that significantly higher form-type losses are associated with gravel-bed streams that have numerous large boulders in the stream bed. This is a common occurence in many steep mountain streams, where spawning gravels are located in relatively isolated patches in the more protected areas of the channel.

In many gravel-bed rivers, mean channel properties are not representative of the actual conditions. Local velocities and tractive stress often vary greatly both across and along the channel. The presence of bed forms in the channel causes nonuniformity in the flow and results in local tractive stresses much higher than those predicted by mean channel parameters. This would imply that initial bed material movement should occur at lower values of critical shear stress, as those are determined by mean channel properties.

Thus, the presence of bed forms in natural gravel channels reduces the net tractive stress available for bed mobilization, but it also causes a nonuniformity which has the effect of increasing some local tractive stresses. These two counterbalancing effects may explain why both laboratory data, for which there were no bed forms present, and field data for natural streams both suggest a Shields parameter in the range of 0.03 for gravel-bed mobilization.

It would be reasonable to conclude from the above discussion that some adjustment to the incipient motion Shields parameter of 0.03 should be made for stream channels in which bed forms play a greater or lesser role than those for which the data were developed. It should be noted that the use of an empirical equation for the prediction of roughness effects (e.g., Equation 8) will tend to underestimate Manning's n when significant bed forms are present. However, this helps to compensate for the fact that some of the total bed shear is not available for bed mobilization.

2. *Sediment Transport Functions*

The transport of bed material is controlled by the transport capacity of the stream, while the transport of fine sediments is controlled by the supply delivered to the stream. Many equations have been developed to estimate bed load transport rates. These equations often predict widely varying sediment discharges for the same set of hydraulic conditions: a factor of 100 between predictions by different methods is not uncommon. In order to obtain useful information, the limitations of each method must be recognized. For gravel-bed streams, the bed material is transported mostly as bed load and not as suspended load. Three bed load transport functions that have been applied to gravel-bed streams are briefly discussed below. These are the Meyer-Peter/Muller transport function, Einstein's bed load function, and Parker's bed load function.

a. Meyer-Peter/Muller Formula

The formula of Meyer-Peter and Muller[108] was developed on the basis of flume experiments using mixed and uniform sand particles, natural gravels, coal particles with a specific gravity of about 1.25, and barite particles with a specific gravity above 4. Sediment sizes in the experiments ranged from 0.02 to 1.2 in. (0.4 to 30 mm). The flows used for the experiments contained little or no suspended load. The relationship was developed assuming that the energy slope is a characteristic of the interaction between the solid and liquid motion of a sediment-laden flow, as indicated by Simon and Senturk.[113] Some of the energy is expended in solid transport and the remaining is expended in liquid transport. The relationship was based on the assumption that the sediment transport process is governed by the same parameters that govern the incipient motion process. The equation was originally presented in the form

$$\frac{Q_b}{Q}\gamma\left(\frac{K_s}{K_r}\right)^{3/2} RS = 0.047(\gamma_s - \gamma)d_m + 0.25\left(\frac{\gamma}{g}\right)^{1/3} q_b^{2/3} \tag{10}$$

where Q = the water discharge (cfs); Q_b = the water discharge determining the bed load transport rate; γ = the specific weight of the fluid; γ_s = the specific weight of the sediment; $\frac{K_s}{K_r}$ = the ratio of the total bed shear which is utilized in mobilizing the particles; R = the hydraulic radius (units); S = the energy gradient; d_m = the effective diameter of the sediment = d_iP_i with d_i and P_i the size fraction and percentage of the fraction, respectively; q_b = the bed load transport rate in submerged weight per unit time per unit width, and K_r = Manning's n value determined from the velocity, hydraulic radius, and slope of the channel.

They also suggest that

$$K_s = 0.034\, d_{90}^{1/6} \tag{11}$$

where d_{90} = the bed particle size (in feet) of which 90% is finer by weight.

The Meyer-Peter/Muller equation is often transformed into the form

$$q_b = \frac{8}{\sqrt{\rho}}(\tau_o - \tau_c)^{3/2} \tag{12}$$

where τ_c = the critical bed shear for incipient motion, τ_o = the actual bed shear for flow conditions, ρ = the fluid density, and q_b = the bed load transport rate as submerged weight per unit time per unit width.

Equation 12 is in the form of many sediment transport functions which express the sediment transport rate as some function of the excess shear stress ($\tau_o - \tau_c$). Although the Meyer-Peter/Muller relationship is often used for gravel-bed rivers, poor agreement between predicted and observed transport rates has been reported for channel slopes above about 0.001.[103,113]

b. Einstein's Bed Load Function

Because the critical point at which bed motion begins is difficult to define, Einstein[111] took a different approach in the development of a sediment transport formula. He postulated that the bed load transport is related to turbulent flow fluctuations rather than the average stresses on the sediment particles. He therefore theorized a probabilistic approach to the forces acting on an individual particle. The method provides estimates of the transport rate of individual size fractions that compose the bed material. Consequently, changes in bed material composition can be predicted.

Einstein's bed load function is plotted in Figure 8, in which

$$\Psi_{*i} = \xi_i Y\left[\frac{\log 10.6}{\log\dfrac{10.6 \times X}{d_{65}}}\right]^2 \frac{(\gamma_s - \gamma)d_{si}}{\gamma r_b' S} \tag{13}$$

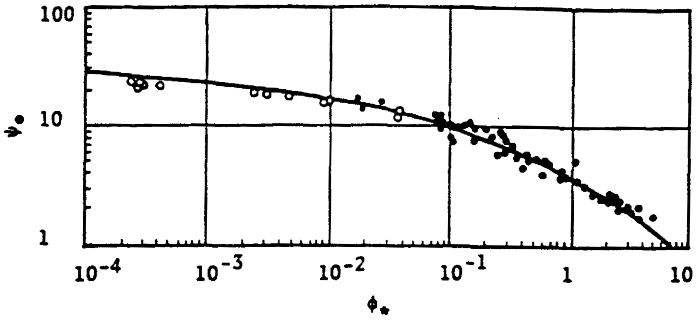


FIGURE 8. Einstein's bed load function. (Modified from Richardson, E. V., Simons, D. B., Karaki. S., Mahmood, K., and Stevens, M.A., Highways in the River Environment, Hydraulic and Environmental Design Considerations: Training and Design Manual. Federal Highway Administration, U.S. Department of Transportation, U.S. Government Printing Office, Washington, D.C., 1975.)

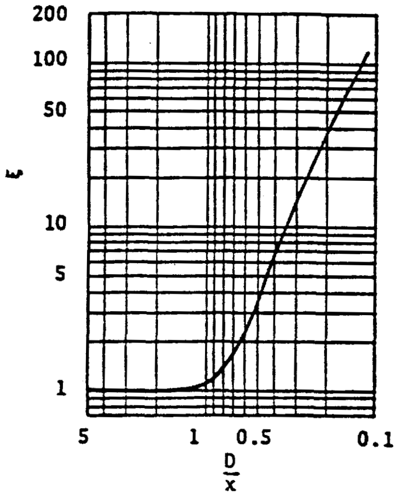


FIGURE 9. Einstein's hiding factor. (Modified from Richardson, E. V., Simons, D. B., Karaki, S., Mahmood, K., and Stevens, M. A., Highways in the River Environment, Hydraulic and Environmental Design Considerations: Training and Design Manual, Federal Highway Administration, U.S. Department of Transportation. U.S. Government Printing Office, Washington, D. C., 1975.)

$$\Phi_{*_i} = \frac{1}{P_i}\frac{g_{sbi}}{Y_s}\sqrt{\frac{\gamma}{\gamma_s - \gamma}\frac{1}{gd_{si}^3}} \tag{14}$$

In these equations ξ_i = a function of d_{si}/X given in Figure 9; Y = a function of d_{65}/δ given in Figure 10.

$$X = 1.398\ \delta \quad \text{when} \quad d_{65}/x\delta > 1.80 \tag{15}$$

$$X = 0.77\ d_{65}/x\delta \quad \text{when} \quad d_{65}/x\delta < 1.80 \tag{16}$$

$$\delta = 11.6\frac{v}{U_*'} \tag{17}$$

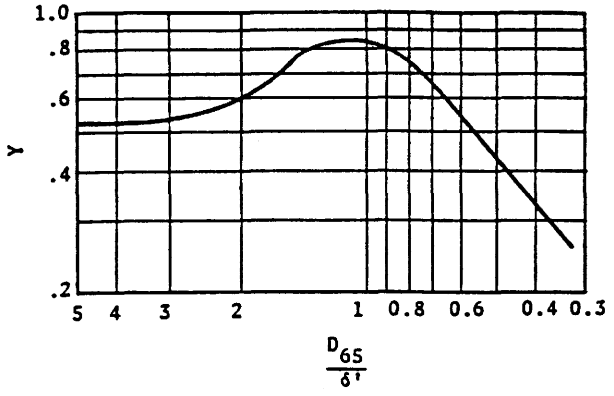


FIGURE 10. Einstein's pressure correction. (Modified from Richardson, E. V., Simons, D. B., Karaki, S., Mahmood, K., and Stevens, M. A., Highways in the River Environment, Hydraulic and Environmental Design Considerations: Training and Design Manual, Federal Highway Administration, U.S. Department of Transportation, U.S. Government Printing Office, Washington, D.C., 1975.)

The data plotted in Figure 8 were taken from flume experiments with two well-sorted sediments that had mean sizes of 1.1 in. (28.6 mm) and 0.03 in. (0.78 mm).

c. Parker's Bed Load Function

Parker[96,97] developed a bed load function which pertains specifically to gravel-bed streams. Using 278 experimental and field data sets, Parker fitted the data by eye to the relationship

$$q^{*} = 11.2\left[\frac{\tau^{*} - 0.03}{\tau^{*3}}\right]^{4.5} \tag{18}$$

where

$$q^{*} = q/(d_{50}\sqrt{R'_{g}\, d_{50}}) \tag{19}$$

and q = volumetric bed load discharge per unit width, τ^{*} = Shields stress = $\tau/(\rho R'_{g}\, d_{50})$, R' = submerged specific gravity of sediment, and d_{50} = grain size for which 50% is finer by weight.

Equation 19 is plotted in Figure 11, along with the data used to derive it. Although this equation has not had widespread use, its advantage is that it was derived specifically for gravel-bed streams.

IV. FLUSHING FLOW PRESCRIPTIONS

Although this chapter is not intended to be a handbook for selecting and implementing flushing flow methods, in this section some practical guidance is provided for addressing this complex issue. The section is divided into four major tasks corresponding to determinations of flushing flow need, timing, magnitude, and effectiveness.

A. Purpose and Need for Flushing Flows

What is the purpose of — is there a need for — a flushing flow? These are two fundamental questions which should be addressed before any flows are relegated for flushing. The purpose of a flow can be described in both broad, use-related terms and narrow, size-specific terms. The former would include categories such as channel maintenance, fish habitat improvement,

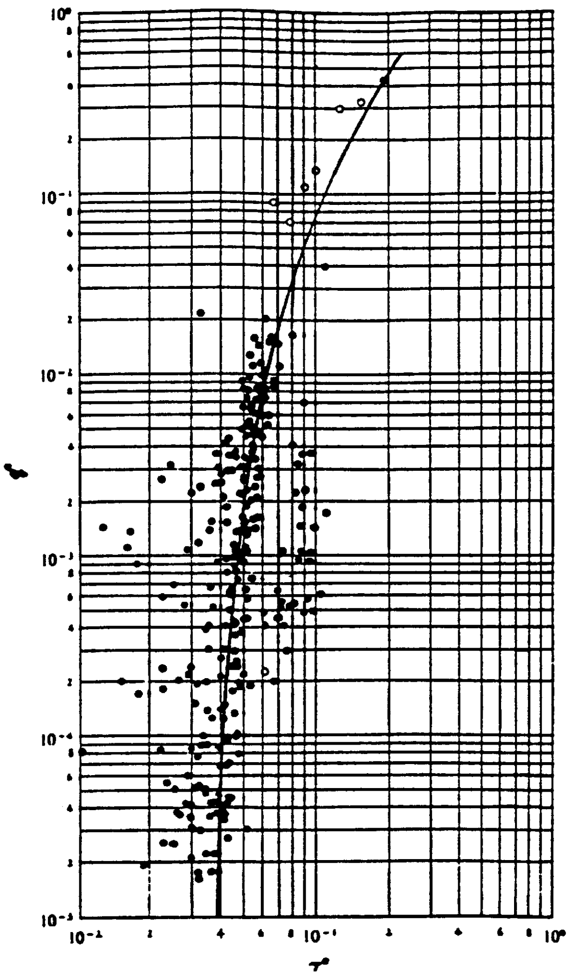


FIGURE 11. Parker bed load relation for gravel beds. (From Parker, G., *J. Fluid Mech.*, 89(1), 127, 1978. With permission.)

and recreation, while the latter may focus on the specific size of materials to be flushed (e.g., removal of sediments smaller than 2 mm).

Once the purpose has been identified, a determination of the actual need for the flow can be made. Such a determination should be made even before a real problem is recognized and should focus on the geomorphic and hydrologic characteristics of the drainage and how they might influence the biotic environment. Through this evaluation, it should become evident whether sedimentation problems are likely to occur in the drainage below the water development project. Specific points for consideration include (1) physical location of the water development project (i.e., above or below major sediment sources), (2) topography and geology of the project area, (3) susceptiility of the drainage to catastrophic events (e.g., landslides, storms, etc.), (4) sensitivity of important fish species and their life history stages to sediment depositional effects (salmonids vs. centrarchids vs. catostomids, etc.), (5) extent of man-induced activities within the drainage which may increase sediment recruitment (mining, logging, etc.), and (6) operational characteristics of the project (storage, hydroelectric, or multipurpose). This last point is important in determining whether the systems will be open or closed to upstream sediment recruitment. From a biological perspective, it can be generalized that flushing flows are needed when sediment concentrations exceed historic levels and begin to affect important aquatic habitats and life history functions. Flows for channel maintenance are needed when vegetative encroachment begins to affect flow transport capacity and channel shape, thus predisposing the reach to further encroachment and sedimentation.

To the extent possible, the determination of need should be based upon an objective, rather than subjective, evaluation. This can be accomplished through the establishment of test sections for monitoring sediment levels and channel morphology. The sections should be representative of other stream reaches and, from a biological perspective, should include habitats (e.g., spawning areas, riffles, and pools) used by important fish or aquatic invertebrate species. The intent is to define baseline sediment and channel conditions which reflect an unperturbed state. Continued monitoring of the same sections will permit temporal and spatial comparisons and will delineate changes in sediment concentration and channel morphology. A variety of techniques can be used for this purpose, ranging from cross-sectional profiling to photographic documentation. Table 2 is a summary of some potential techniques which could be used for this. Many of these are described in further detail in Section IV.D. Any changes in sediment level within the test section must be evaluated with respect to possible impacts on aquatic biota. Ideally, designated standards or limits of sediment deposition and encroachment should be established for each section, above which a flushing flow would be required. Such standards could be derived from the literature but would be best developed on an individual stream or drainage basis. This type of approach is important in that it triggers the release of a flushing flow only when there is clear evidence that one is needed. This prevents the common practice of automatically releasing flows from a dam regardless of need, a situation that, in addition to wasting water, can actually prove detrimental to the aquatic resources.

Undoubtedly there will be circumstances when a flushing flow is warranted even though a formal monitoring program has not been instituted. As previously noted, this could occur with a catastrophic input of sediment such as with a landslide or debris flow. In such cases, "spot" measurements using some of the techniques listed in Table 2 should be taken. These measurements, coupled with a review and discussion of the problem by a team of hydrologists, geologists, and aquatic biologists, should result in a mutually agreeable plan for dealing with the added sediment. Depending upon the severity of the problem and its potential impact on the aquatic system, the solution could range from a programed release of flow to transport sediments, to the physical removal of material through mechanical means.

B. Timing of Flushing Flows

When the need for a flushing flow has been established, it is equally important to determine the best time for its implementation. Important considerations in this regard include the species of fish present in the system, the life-history requirements of the important species, the historical run-off period, and perhaps most important, flow availability.

Assuming that our primary concern is for the maintenance of aquatic biota, flow timing should be based upon the life-history requirements of important fish in a system. Depending upon their magnitude and duration, flushing flows may simulate a short-term peaking or ramping regime, with a rapid increase and decrease in discharge. In addition to the intended objective of sediment removal, such flows could have deleterious effects on the aquatic resource, including the dislodgment and transport of eggs and aquatic invertebrates,[150,151] dewatering of egg nests (redds) constructed during high flow periods,[152-154] and stranding of fish.[155-159] From a fisheries standpoint, the best timing for the flow is that which provides the greatest benefits or imparts the least harm to the biotic communities. This would not be the case if flows were released during or immediately after fish spawning. Released then, such flows could dislodge eggs and fry and result in reduced recruitment. In contrast, flushing flows released prior to the spawning of salmonid species would remove and clean fine

Table 2
METHODS FOR ASSESSING THE NEED FOR AND EFFECTIVENESS OF FLUSHING FLOWS

Method	Description	Before and after approach[a]	Ref.
Substrate core sampling (grab sample)	6- to 12-in. diam tube (generally stainless steel) (see Figure 6)	Sampler inserted into substrate within sediments removed from encased area; particle size analysis (sieving) performed on sample; quantification of fine sediments in sample	115—117
Substrate core sample (freeze core)	Single or multiple (tri-core) standpipes; dimensions ca. 4 ft long × 1.5 in. O.D. (see Figure 7)	Sampler driven into substrate within test area; injection of liquid nitrogen or carbon dioxide (preferable) into tubes; remove frozen core; thaw and perform particle size analysis; quantification of fine sediments in sample (approach allows for evaluation of sediments deposition in different strata)	118—124
Sediment traps	Small plastic devices (open on top) containing artificial medium (e.g., marbles or glass beads)	Sediment traps installed in gravels at set intervals from target areas (at bed surface); upstream gravels are "disturbed" for a standard time interval; sediment is deposited in traps which is then quantified on-site; sediment accumulated in traps is related back to sediments in target riffles (device selects for fine sediments)	125
Intergravel sediment sampling	Modified Whitlock-Vibert boxes, 5.5 in. long × 3.5 in. deep × 2.4 in. wide, containing artificial or natural medium (see Figure 9)	Sediment samplers installed intergravelly in target riffles for set time interval; samplers removed and fine sediments quantified on site (device selects for fine sediments); could be used as monitoring device	126,127

Table 2 (continued)
METHODS FOR ASSESSING THE NEED FOR AND EFFECTIVENESS OF FLUSHING FLOWS

Method	Description	Before and after approach[a]	Ref.
Sediment deposition cans	Open-ended (top) no. 10 cans containing clean gravel medium	Cans containing gravels are weighed, then buried flush with substrate surface; cans removed after set time period, oven dried, and weighed to determine sediment addition; could be used as monitoring device	25
Mesh cylinders	Stainless steel mesh cylinder (18 in. deep × 12 in. diam) filled with gravel medium	Cylinders with gravel installed flush with substrate surface; cylinders removed after set time period; gravel and sediment fraction quantified by particle size analysis (sieving); could be used as monitoring device	25
Bed material tracers	Brightly colored (painted) substrate or artificial medium	Position known numbers of different-sized colored substrate in pool or riffle areas and compare locations pre- and postflows; initial locations should be surveyed or marked to allow an accurate estimate of replacement	88,125
Embeddedness	Ocular rating of degree that larger particles are surrounded or covered by fine sediments (see Figure 6)	Embeddedness ratings taken at specific intervals along permanent transect line	125,128,129
Substrate score	Ocular rating of substrate characteristics	Substrate scores evaluated at specified intervals along permanent transect lines	130
Photo transects	Photographic documentation of substrate characteristics and sediment deposits	Photographs taken at specified intervals along permanent transect lines; general photos also taken from permanent photo marks	131,132

Sediment mapping	Physical mapping of sediment deposits (see Figure 6)	Physical mapping of sediment deposits using surveying techniques and planimetric analysis; preparation of map overlays which depict sediments	29,133,134
Instream flow incremental methodology — weighted usable area (WUA)	Determination of WUA based on substrate characteristics	Quantification of WUA within test reach before and after release flows (as a function of substrate change)	5, 89, 135
Cross-channel transects	Permanent headpins (1/2 in rebar stakes) positioned across important pool or riffle areas	Bed elevations and visual substrates measured across channel transects at specified intervals	89,125,136
Scour cords	Chain links buried in substrate	Chains driven vertically into test areas noting length of chain (or number of links) exposed; comparisons made after flow releases (chain locations should be surveyed to ensure relocation)	8, 125,137
Tethered floats	Tethered floats (e.g., ping pong balls or plastic balls) buried in substrate	Same as for scour cords except floats are buried manually (not driven); comparisons of the number of floats exposed are made before and after flow releases	138,139
Deposition pins	30 in sections of 1/2 in rebar buried in substrate	Deposition pins driven vertically into the gravel at specified intervals along permanent cross-channel transects; bed elevations from top of pin to substrate surface noted as well as ocular substrate analysis adjacent to pin	140
Radioactive spikes	Injection of low-level radiation spikes into gravel sediments	Injection of spikes into gravel sediments and subsequent monitoring downstream during and after flow augmentation	
Gravel permeability	Steel, aluminum, or PVC 1.25-in. diam standpipe with perforations at bottom	Fixed standpipes installed along cross-channel transects at specified intervals; permeabilities measured pre- and postflushing flows (permeabilities related to sediment deposition)	116, 117, 132, 141—143

Table 2 (continued)
METHODS FOR ASSESSING THE NEED FOR AND EFFECTIVENESS OF FLUSHING FLOWS

Method	Description	Before and after approach[a]	Ref.
Intragravel (apparent) velocity measurements	Dye dilution, salt bridge (conductivity), thermistor	In conjuction with standpipes, measure intragravel velocity (apparent velocity related to sediment deposition)	141, 142, 144, 145
Intragravel dissolved oxygen (DO)	DO meter, Winkler technique	In conjunction with standpipes, measure intragravel DO (DO indirectly related to permeability and apparent velocity)	116, 117, 132, 142—144, 146, 147
Bedload samplers	Measurement of bedload sediments using standard sampling equipment	Bedload quantification made at specified intervals along a permanent cross-channel transect at specified flows; comparisons made pre- and postflows	138, 148, 149
Sediment-biological response model	Method for predicting effects of sediment yield on stream habitat and fisheries	Useful in determining the initial biological need of the flushing flows	129
Ocular analysis of fines	Documentation of surface fines based on ocular assessment of size classifications	Composition of substrate evaluated at specified intervals along permanent line; individual classifications are totaled to obtain amounts representative of different size categories; this could be used with the PHABSIM model to reflect sediment change as a function of WUA	8, 15, 124

[a] Unless specified, all techniques would require a pre- and postflow assessment.

sediments from the substrates and serve to enhance egg and alevin survival. Development of detailed life-history periodicity charts for species in a given system will help determine the best timing for the flows. Such charts provide a way of reviewing the timing of all life-history functions and help to identify those most sensitive to flow augmentation (e.g., spawning, egg incubation, juvenile rearing, and migration).

A review of historical flow records will also be beneficial in determining the timing of releases. It can be presumed that for most systems, the fish present in the stream have evolved around and adapted to the normal hydrograph of the system, including run-off and base flow conditions. In these cases, flow releases scheduled during normal peak-flow periods may provide the most benefits. This pattern would not necessarily apply to systems managed for introduced fish species, which might have adapted to the regulated flow regimes.

In general, determination of the timing of flushing flows should be geared to maximize the benefits of the water released. Scheduled correctly, it may be possible for a given flushing flow to be multifunctional. Thus, a single flow could serve to remove fine sediments from important fishery habitats, maintain channel shape, and provide recreational opportunities such as for white-water rafting, canoeing, etc. In the U.S. Pacific Northwest, flows from some dams are specifically released to assist the outmigration of salmon and steelhead smolts from the rivers to the ocean. Such flows are undoubtedly beneficial in removing sediments from important mainstream spawning areas. To the extent possible, the economics of the flow release should also be factored into the timing determination. This is directly linked to flow availability and competing water use. For example, water released from a hydroelectric project for flushing during periods of high flows and abundant supply (often excluding generating capacity) would be much less costly (in terms of lost power revenues) than if released during low flow periods.Although economics should never become the governing factor in the scheduling process, it should always be given due consideration. For projects which have little or no storage capacity, the timing of the releases may be solely dependent upon water availability.

C. Magnitude of Flushing Flows

Determination of the magnitude of the required flows is the most important yet most difficult and least understood aspect of formulating a flushing flow recommendation. No standard method or approach has been developed for this purpose and it is unlikely one will ever be developed. There are simply too many variables and interactive parameters to allow the formulation of a single method applicable for all stream systems for all purposes.

The methods presented and reviewed in this chapter and summarized in Table 1 should provide some guidance in formulating recommendations. A careful review of the techniques may result in development or adaptation of a specific approach for addressing a given problem. However, given the many uncertainities associated with the methods, selection of one over another does not guarantee any better resolution in the final recommendation. In general, for studies in the planning stage in which flushing flows are to be integrated into the operation of a water development project, the best approach may be to use the office technique providing the highest flow estimate. This should be easy to determine because most of the techniques have the same general data requirements. With this approach, water budgets and operating rules for proposed hydroelectric or water development projects can be formulated around these needs.

For implementation studies, which would include the development of final recommendations for new or existing facilities and the precise determination of flows for remedial purposes (following a catastrophic input of sediment), both office and field techniques should be used. Office methods can provide an initial estimate of needed flows which can then be refined through field evaluations. Depending upon the project and its physical setting, field techniques can range from collection of data for use in one of the sediment transport models to empirical assessments of bed transport under different flow releases. In addition to collecting data for making a flow prescription, the field component is important for verifying and refining the initial recommendation.

It is of interest to note the disparity in flow recommendations that can result from the use of different methods. Wesche et al.[140] noted an average difference of 60% in the flushing flows recommended in two independent studies for the same stream system in Wyoming. The approach of Estes[3] and Orsborn[85] may result in as much as a 600 to 900% difference in flows when compared with recommendations derived using the Tennant methodology.[81,82] Kondolf et al.[158] compared estimates derived from several methods for streams in the Sierra Nevada of California and likewise found a wide disparity in results, in some cases exceeding 800%.

Milhous and Bradley[94] compared flushing flow prescriptions for the Willians Fork River in Colorado resulting from five different methods. The recommendations ranged from 142 cfs, based on the Hoppe[86,87] method, to 800 cfs, based on the method of O'Brien.[15] Interestingly, Milhous and Bradley[94] did not consider any of the methods satisfactory because they were not based on physical process logic. As a result, they developed an alternative method based on physical process which suggested that suitable flushing flows would occur at 250 cfs (surficial flushing) or 640 cfs (flushing at depth). Such variability of results amplifies the importance of follow-up evaluation studies. Indeed, such studies currently remain as the only way to verify the sufficiency of a recommendation and furthermore provide a means to test the predictability of the methods themselves.

D. Effectiveness of Flushing Flows

The effectiveness of a given discharge should be evaluated as part of every flushing flow study so that actual vs. desired results are compared and refinements made (Figure 12). Unfortunately, most recommendations made today are not followed up with this type of assessment so that the actual value of the flow in terms of meeting its objective is questionable.

Various methods and procedures which can be used to evaluate the effectiveness of flushing flows are presented in Table 2. The utility of the techniques is contingent upon their application both before and after a prescribed flushing flow. In most instances, however, the preflow assessment should already be part of the process for determining flow need.

The implementation of a given technique should be preceded by a review of the data collection and analysis needs and its applicability to a given stream system. Special emphasis should be made to design statistically sound sampling programs to promote collection of meaningful data which can be factored into the evaluation process.

1. Substrate-Sediment Analysis (Core Sampling)

Perhaps the oldest, yet most often used, approach for assessing sediment deposition in gravels is the complete removal of a small portion of stream bed for size distribution analysis. The approach has been used extensively to document the impacts of fine sediment accumulation in gravels resulting from a variety of land-use activities (e.g., channelization, logging, road construction, mining, and water development projects). The collection of such substrate samples is generally accomplished using one of two techniques: grab (or manual) sampling techniques[115-117,129,160] and freeze core sampling techniques.[118-125] Grab sampling techniques often employ a metal tube (open at both ends) which is manually forced into the gravel to a specified depth. The material encased in the tube is removed by hand and analyzed for particle size distribution. Tube diameters which have been used range from 6 to 12 in. (15 to 30.5 cm). Freeze core sampling techniques entail the driving of a hollow probe(s) into the substrate, injecting the probe with a cryogenic medium, and, after a set time, removing the probe and frozen core of sediment adhering to it. The core sample is then thawed for particle size analysis. The core sample collected in this manner can be analyzed

FIGURE 12. The results of a flushing flow can be dramatic as evidenced by these before and after photographs of a regulated river. However, the effectiveness of such releases can only be determined through follow-up field studies. One technique (illustrated in the lower photograph) uses cross-channel transects to document bed profile change.

by strata and sediment deposition over time can thus be assessed. To date, the most effective and economical freezing medium is liquid CO_2.[119,122]

Substrate samples collected using either method are generally analyzed using a series (12 to 16) of sieves, with recommended diameter sizes ranging from 4 to 0.002 in. (100 to 0.06 mm). Two sieving techniques can be used: wet sieving, which is based on volumetric displacement, and dry sieving based on gravimetric analysis. Regardless of the technique

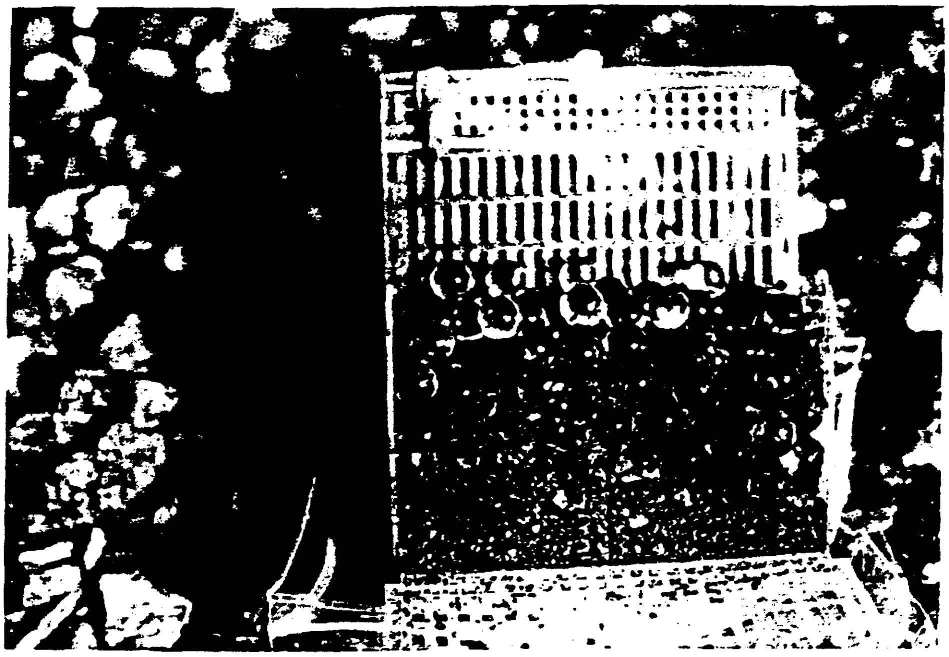


FIGURE 13. Sediment trapping devices such as this modified Whitlock-Vibert box can be used to determine the need for and effectiveness of flushing flows. In this photo, glass marbles have been added to the box to serve as a standard substrate medium.

employed, the general approach for evaluating the effectiveness of flushing flow is to collect and analyze a series of samples before and after the flow release. Effectiveness can be measured in terms of the change in sediment content within the test reach expressed as the percentage difference between actual vs. estimated (or targeted) sediment levels.

2. *Intergravel Sediment Sampling*

Another useful approach is through the quantification of fine sediments within the intergravel environment using sediment "trapping" devices. Depending upon technique used, both instantaneous and continuous measurements can be made, the latter especially useful in monitoring studies. Mahoney and Erman.[125] Carling.[161] Meehan and Swanston,[25] and Wesche et al.[126] have all described methods potentially useful for measuring intergravel sediment accumulation. For use in flushing flow studies. the samplers would be positioned in a test reach for a sufficient time for sediments to equilibrate with ambient concentrations. Sediments in samplers removed at that time would represent "before" conditions (Figure 13). Flushing flows would then be released. additional samplers recovered, and changes in sediment concentrations noted.

3. *Ocular Assessment and Photographic Techniques*

Several ocular (visual) assessment techniques or indices exist which could also be used to evaluate the effectiveness of flushing flows. Four of these lend themselves to before and after type studies: visual analysis of substrate composition. embeddedness ratings, substrate score, and photographic documentation. For the first three methods, permanently marked transects would be positioned across test areas (riffles. pools, etc.). Individual ratings (before and after flow releases) would then be recorded at specified intervals across the transect and comparisons made. For photographic documentation. photographs would be taken (from permanent photo points) before and after each flushing flow and compared for changes in quantity and location of sediments (Figure 12). A more refined approach would be to photograph and compare specific cells along a given transect.

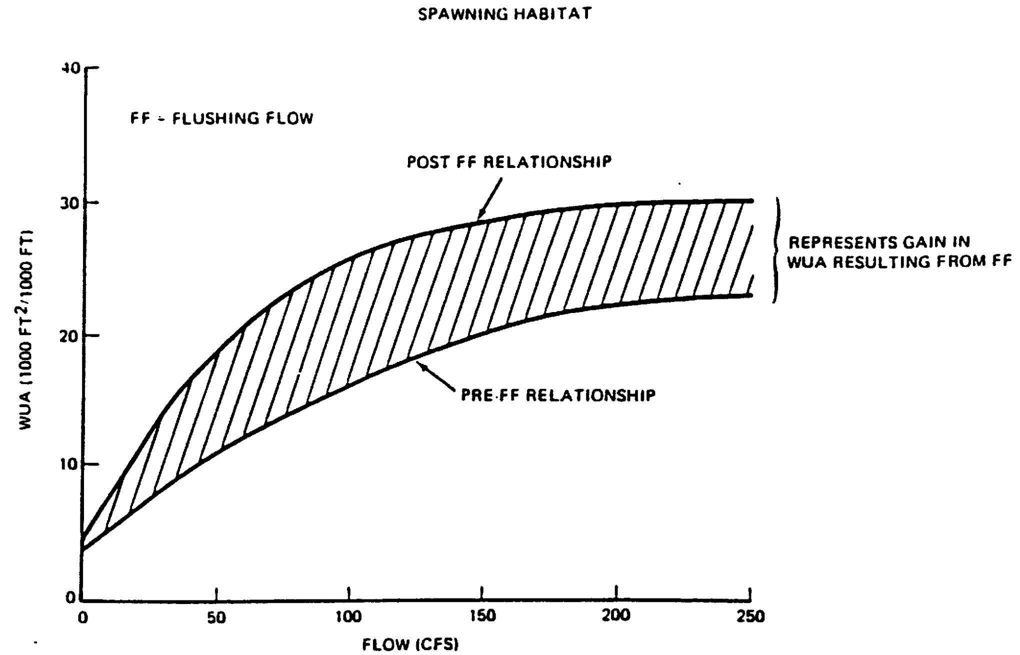


FIGURE 14. Hypothetical relationship between weighted usable area (WUA) and streamflow before and after implementation of a flushing flow. Area between the curves represents gain in habitat. (Modified from Reiser, D. W., Ramey, M. P., and Lambert, T. R., Review of Flushing Flow Requirements in Regulated Streams, Department of Engineering Research, Pacific Gas and Electric Company, San Ramon, CA, 1985.)

4. Survey Techniques

Methods which utilize standard survey techniques would also be useful in assessing the effectiveness of flushing flows. Such methods include cross-sectional profiling, sediment mapping, and the use of the U.S. Fish and Wildlife Service's instream flow incremental methodology (IFIM). According to Platts et al.,[124] the best method for quantifying channel aggradation and/or degradation is cross-sectional profiling. In this technique, bed elevations are measured at specified intervals across a permanent transect. Bed elevations taken at the same locations along each transect, as well as elevational differences among the transects, can be compared between pre- and post-flushing flows to illustrate the amount and location of bed elevation change (Figure 12).

Sediment mapping is an extension of cross-sectional profiling and is based upon two parameters: depth (bed elevation) and visual substrate characterization. The general approach used for this includes (1) establishment of a surveyed baseline along the periphery of the test reach, (2) depth (or bed elevation) profiling along each of the transects at specified intervals (measurements made before and after each flushing flow), (3) development of schematic overlay maps which depict depth isopleths or substrate types within the reach, and (4) comparison of data and map overlays to determine a real extent of change.

A modification of the use of the IFIM (a commonly applied method for determining instream flow requirements) may also prove useful for assessing flushing flows. The approach would involve the recharacterization of substrate types along each transect following a given flushing flow and the subsequent rerunning of the habitat computer model (HABTAT) to generate revised habitat vs. flow relationships. Any difference in the curves would be expressed as gains or losses in habitat attributable to the specific flushing flow (Figure 14). Milhous[161] used this type of approach for assessing effects of sediment transport on fisheries habitat.

5. *Scour and Deposition Indicators*

Two other techniques which have proven useful in evaluating scour and deposition in streams may be useful in flushing flow studies. Scour cords consist of chain links which are driven vertically into the test area.[8,124,137] A pre- and postflow measurement of the length of chain exposed (or number of links exposed) is made for comparative purposes. Tethered floats using ping pong balls could be similarly used.[138,139] Deposition pins consist of sections of rebar driver vertically into the stream bed.[140] Bed elevation measurements are made at the top of the pin and at its intercept point with the substrate, and comparisons are made before and after each flushing flow.

6. *Tracers*

Tracer materials can also be used in conjunction with flushing flow assessments. This technique entails the marking of various-sized substrate particles, placing known numbers within pools or riffles areas, and monitoring their displacement after a given flow.[88,124] The marking of the materials can be done with fluorescent paint or other waterproof medium. Failure to recover the materials, or recovery of materials downstream from the original location, would be indicative of the size of material transported by a given flow.

V. GUIDELINES

In summary, it is hoped that the information and suggestions presented in this chapter will be useful to both the biological and water resource managers in developing and testing sound flushing flow recommendations. Clearly, much remains to be learned about the application of and effects from this important alternative in regulated flow management and the effects to be expected from it. Many answers will develop through a trial and error process following application of prescribed flows. However, the water resource manager would likely advocate more laboratory and theoretical research to refine the flow recommendation process since this approach implies a certain amount of flow wastage. Both empirical and theoretical approaches will undoubtedly prove useful. It can be concluded that there is no present "state-of-the-art" method or approach for prescribing flushing flow needs. Moreover, the few methods in use today are largely untested and may be providing unrealistic and unwarranted flow recommendations. Many of these methods are predicated on what is generally called regime methods. These methods assume that some flow rate, such as the bank-full flow, is the dominant channel-forming flow. However, a river "in regime" generally scours in some places and deposits in others. Flushing flow magnitudes based on these methods will therefore be of uncertain accuracy at best. The most certain method for establishing required flushing flow rates would be to observe various test flow releases. Field observations, such as the sampling and tagging of bed material, made before and after each release would be used to determine flow effectiveness. Under many circumstances, it may not be feasible to release and monitor test flow streams. In such cases, the use of methods based upon sediment transport mechanics would provide the most reliable approach for determining required flushing flow rates. However, the proper application of these methods requires collection of field data such as sediment gradation, channel geometry, and channel slope.

Until standard methods are developed, flushing flow evaluations should use an approach tailored to the specific needs and characteristics of each stream and project. This may dictate the use of several different office techniques to derive an initial flow estimate, followed by detailed field studies to refine the recommendations. For projects in the planning stage, an office approach may be all that is needed; implementation studies should include detailed field investigations. The following general guidelines are recommended for conducting flushing flow studies. A summary of the guidelines, including considerations and techniques to be used in assessing the need, timing, magnitude, and duration of flushing flows, is presented in Table 3.

- Use an interdisciplinary team approach. Study-team members should include (at a minimum) a hydraulic engineer, a hydrologist, and a fisheries biologist.
- Determine the actual need for the flushing flow before commencing detailed assessments.
- Tailor the approach to the specific needs and characteristics of each stream and project; office and field techiques may both be required.
- For comparative purposes, use more than one method for deriving flow recommendations.
- Include a determination of the timing and required duration of the flow as part of the assessment process.
- State flushing flow recommendations in terms of magnitude, timing, and duration.
- Conduct follow-up studies to evaluate the effectiveness of the flows and allow for necessary adjustments.

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Table 3
GUIDELINES FOR ASSESSING THE NEED FOR AND TIMING, MAGNITUDE, AND EFFECTIVENESS OF FLUSHING FLOWS

	Flushing flows			
	Need for	**Timing of**	**Magnitude of**	**Effectiveness of**
Considerations when assessing	Physical location of project — above or below major sediment sources	Species of fish present in the systems (native or introduced)	Level of investigation required: planning-level studies and implementation-level studies	Availability and reliability of background data for defining preflushing flow conditions
	Topography of project area — susceptibility to erosion	Timing of life history functions of important species		Time interval between end flushing flow and field assessment
	Extent of man-induced perturbations in the drainage	Historical runoff period	Availability of flow records	Potential influence of extraneous activities on the effectiveness of a flushing flow (e.g., sediment input from tributaries, road construction)
	Susceptibility of drainage to catastrophic events	Availability of project flows	Availability of test flows	
	Operational characteristics of the project			
	Sensitivity of target fish species to effects of sediment deposition			
Techniques for assessing	Establish and monitor test reaches by substrate analysis, cross-sectional profiling, photographic documentation, scour and deposition indicators, bedload samplers, etc.	Prepare and review species life-history periodicity charts and note preferred timing release periods	For planning-level studies, use appropriate office techniques for initial estimate	Pre- and postflow comparisons of substrate-sediment deposition and composition, substrate analysis, cross-sectional profiling, photographic documentation, etc. should be factored into necessary adjustments in recommendations
	Comparison of data with standards: literature-based or site-specific-based (preferred)	Review historical flow records and note timing	Implementation studies — refine estimates through field/laboratory sediment transport models, empirical assessments of bed transport, and physical modeling of stream reach	

Table 3 (continued)
GUIDELINES FOR ASSESSING THE NEED FOR AND TIMING, MAGNITUDE, AND EFFECTIVENESS OF FLUSHING FLOWS

Flushing flows			
Need for	**Timing of**	**Magnitude of**	**Effectiveness of**
Spot assessments made (as needed)	Review water budgets of project and note availability of flows		
	Adjust timing recommendations accordingly, (timing of flows should be based on maximizing benefits for the given water released)	No standard approach of method presently available	
		Recommendations should be based on site-specific in mates of flow duration	

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