Ecological and Geomorphological Concepts for Instream and Out-of-Channel Flow Requirements

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ABSTRACT: Healthy fish populations are dependent on streamflow regimes that protect the ecological integrity of their habitat. Fish habitats are the consequence of lin a e amon the stream ttood lai ran and upland zones, and watershe geograpny, luvial-geomorphic processes form an habitat. Because this, multiple in-channel and out-of-channel flows are needed to maintain these processes. We present a conceptual methodology for measuring four types of streamflow regimes: instream flows, channel maintenance flows, riparian maintenance flows, and valley maintenance flows. The combination of these four streamflow types is designed to protect fish and their habitat. Using a case study of the Salmon River near Whitebird, Idaho, we demonstrate how the methodology could be used to develop a multiple flow recommendation.

KEY WORDS: Ecology, floodplain, flow management, geomorpholo , instream flow, Instream *Flow* Incremental Methodology, riparian.

INTRODUCTION

Alteration of streamflow for power production, irrigation, flood control, and other purposes adversely affects aquatic resources. The question of how much streamflow is required to protect aquatic resources has been examined over the years from several perspectives including fisheries, channel maintenance, and riparian zone. Instream flow requirements for fisheries have been extensively studied and many technical approaches have been advanced (Stalnaker and Arnette 1976; Wesche and Rechard 1980). Instream flows to maintain channels and geomorphological processes have also been investigate (Beschta and Platts 1986; Rosgen et al. 1986; Reiser et al. 1989). Other investigati ns have focused on o -of-channel flows necessary for ripar n vegetation and floodplain processes (Franz and Bazzaz 1977; Harris et al. 1487; Junk et al. 1989; Stromberg and P;iten 1991). However, no models or approaches have been suggested that link the instream and out-of-stream flow requirements of all aquatic resources. Consequently, streamflow management typically focuses on one or two critical resource ues rather than the simultaneous protection of multiple resources.

Our purpose is to suggest a conceptual or theoretical method for evaluating both instream and out-of-stream flow requirements within a holistic streamflow management framework. We combine well-known streamflow approaches into a unified methodology that recognizes flow requirements for fish, riparian habitat, floodplains, and channel morphology. Establishing streamflows only on the basis of fish needs may result in the degradation of the stream channel, alteration of geomorphological processes, reduction or alteration of riparian vegetation, and may cause changes in floodplain function. We review physical processes that lead to the ecological linkage between instream and out-of-stream resources and the dependency of riverine resources on streamflows.

The U.S. Fish and Wildlife Services' Instream Flow Incremental Methodology (IFIM) (Bovee 1982) and the Physical Habitat Simulation system (PHABSIM) (Milhous et al. 1984) have many limitations as habitat-based models for the instream flow needs of fish (Annear and Conder 1984; Mathur et al. 1985; Orth 1987). Although it would be convenient for fish populations to be limited by three or four environmental factors, such situations are the exception rather than the rule. In the simplest example of limitations within IFIM, trout populations often fluctuate considerably and in a manner that is apparently independent of direct simultaneous environmental control (Platts and Nelson 1988). Seldom do we measure variables that truly affect fish populations. Models that fail to account for the natural fluctuations in animal populations are destined to be only coincidentally accurate (Platts and Nelson 1988). Broader thinking and more ecologically centered approaches are needed when managing streamflows. However, as we explain later in this paper, PHABSIM-derived fish flows play a key role in the overall flow evaluation.

Multiple flow regimes are needed to maintain biotic and abiotic resources within a river ecosystem. The four flow groups we examine are (1) flood flows that form floodplain and valley features; (2) overbank flows that maintain surrounding riparian habitats, adjacent upland habitats, water tables, and soil saturation zones; (3) in-channel flows that keep immediate streambanks and channels functioning; and (4) in-channel flows that meet critical fish requirements. When natural flow patterns are altered, we must look beyond immediate fish needs to determine how streamflows affect channels, transport sediments, and influence vegetation.

STREAM PROCESSES

Watersheds reflect the long-term influence of geology, climate, and topography as well as shorter-term influences of vegetation (Chorley et al. 1984). Flows resulting from climatic conditions create and maintain stream-forming processes. When natural flow patterns are changed, fluvial processes change, and condition of the valley, the stream, and all other ecological components must change as a consequence (Lotspeich 1980).

To understand stream processes, one must first consider a watershed in four dimensions (Ward and Stanford 1989). These are the longitudinal dimension from headwaters to mouth, the lateral dimension extending beyond the channel boundaries, and a vertical dimension resulting from out-of-channel flows moving downward into the soil and groundwater. Each of these dimensions must then be analyzed in a temporal dimension.

To determine which flow patterns are needed to maintain a stream system, one must match the respective valley bottom type, riparian type, and floodplain and channel type to the hydrologic processes that control form and function. Typically, steep high elevation streams flowing through V-shaped valleys lack floodplains or even riparian habitat. Other valley types create streams with riparian habitat but lack floodplains. The fluvial-geomorphic processes vary by valley type (Leopold et al. 1964).

An assemblage of geomorphic processes develop characteristic land forms as they construct the valley and its stream system (Strahler 1957). Flowing water erodes, transports, and deposits sediment and controls vegetation species and growth In generally predictable ways (Morisawa 1968). Thus, valley type can be determined through land classification, historical analysis, and hydrological approaches (Lotspeich and Platts 1982).

The temporal distribution of flow, interacting with geology, topography, and vegetation, influences the form and condition of a stream system and valley. We can broadly describe watershed changes that occur when fluvial processes are altered by reducing natural flood flows: (1) valley floors no longer flood; (2) local water tables are no longer recharged; (3) stream bar and channel areas no longer *become* inundated and scoured; (4) sediment accretes on bars and channel edges and forms lower, narrower streambanks; (5) side channels and backwater areas become disconnected from the main channel or abandoned by the mainstream as they fill in; (6) tributary channel confluences with main stems locally aggrade and push out into the main channel; and (7) the ratio of pools to riffles is significantly altered (Morisawa 1968; Platts 1979; Leopold and Emmett 1983). These factors need to be considered in any analysis of flow alteration because biotic conditions such as riparian habitat or long-term fish community structure and fish populations may depend on them.

Streams generally go through an aging process. They are seldom at equilibrium because they adjust to a wide range of factors and processes within the watershed (Kellerhals and Church 1989). Once a stream approaches an equilibrium condition, the controlling factors may change. Such adjustments may occur daily, seasonally, or over long periods. Nevertheless, over time a channel and associated streamside vegetation will develop characteristics and features that balance the effects of a varied flow and sediment regime (Platts et al. 1985).

Channel adjustments are a natural component of the channel-forming processes in all valley bottom types (Lotspeich and Platts 1982). Hence, local channel dimensions and characteristics will change as a result of natural or altered flow regimes. For example, the removal of all peak flows will cause near-term channel adjustments, but over the long term reduced peak flows will impair floodplain functions, which in turn alter streamside vegetation and channel conditions (Platts 1979) that provide habitat for fish.

The morphology of streams, especially alluvial ones, is controlled by the interaction of flow regime with streamside vegetation and sediment input (Hynes 1970). The magnitude and duration of the bankfull flows (and larger) are particularly important. Geology, climate, and resulting sediment supply (including quality and quantity) and size of channel bed materials, within the geomorphic setting, also provide form control (Beschta and Platts 1986).

In sand-bed streams, bedload transport generally occurs over a wide range of flows (Leopold et al. 1964). However, in gravel-bed streams the channel materials are usually stable except during relatively high flows (Beschta 1987). Therefore, if fine sediments that have become deposited between the gravels are to be removed by flowing water, sufficiently high flows must periodically occur to cause local scour and transport *of* bed materials (Beschta and Jackson 1979; Beschta 1987). Natural high flow events normally provide the necessary level of streambed mobilization to flush fine sediments from both the bed and the gravel and rubble (Rosgen et al. 1986).

Regulated flows that occur downstream from water diversion and storage facilities can have both a positive and a negative effect on channel substrates. For example, a positive effect is the reduction in availability of fine sediments from upstream sources that may deposit in spawning gravels. A negative effect is the reduction in gravel recruitment and loss of fines for bank-building processes.

Streambank form depends on a balance between erosive forces of flowing water and resisting forces of the bed, bank, and streamside vegetation (Platts 1979). Vegetation buffers the streambank from flowing water, and flowing water in turn keeps vegetation from occupying the channel (Rosgen et al. 1986). The duration of over-bankfull flow is also important to channel and floodplain characteristics. Flow duration determines the amount of time available for deposition of sediments, recharge of subsurface moisture, and other maintenance processes.

FLOODPLAIN PROCESSES

Except in under-fit or deeply entrenched to the discharge of the stream and slope of streams, floodplain size is generally related valley bottom (Hack 1957). Surface erosion and mass wasting of upstream sideslopes provide material for floodplain deposits. Low-gradient reaches of many streams, and especially large rivers, have geomorphic settings that often produce relatively large floodplains and valuable wetlands.

Floodplain habitats provide cover, nesting, spawning, and rearing for fish and wildlife. Floodplains also play an important part in the transfer of sediments and nutrients that maintain stream productivity (Sedell et al. 1989). If the stream and its associated floodplain are separated from water by improper flow management, both will change over time because the original dynamic balance between flows and floodplains has been altered.

For floodplain ecosystems, timing and duration of flooding is particularly important. Seasonal flooding affects seed dispersal, seedling survival, and growth of many plant species that occupy channel banks and floodplains (e.g., cottonwoods and willows) (Platts 1979). Flooding during the growing season apparently has a greater effect on floodplain productivity than does an equal amount of flooding during the nongrowing season (Junk et al. 1989).

Floodplains receive a wide range of nutrients, organic matter, and fine soil particles during overbank flows. Floodplain nutrients can, however, establish their own cycles because organisms and environmental conditions differ considerably from those of the main stream (Vannote et al. 1980; Minshall et al. 1983). Floodplains also import, store, produce, and recycle materials used in downstream food chains, thus providing energy flow to detrital food webs (Vannote et al. 1980).

Riparian vegetation is a major factor affecting floodplains, fisheries habitat, and channel characteristics (Platts 1979). The fundamental importance of vegetation to long-term channel stability and form is usually the weakest part of most flow analyses. Corridors of riparian vegetation along streams influence light, temperature, and organic input; provide cover; and control bank morphology (Larsen et al. 1986). Natural flooding that maintains the riparian system in a productive growth stage, if reduced, can enable nonriparian species to invade riparian zones and floodplains. Although extreme events may play an important role in shaping channels, Wolman and Miller (1960) indicate that the less extreme and more frequent flooding events (such as bankfull) are probably most influential. In high desert streams, Platts et al. (1985) found that large storm events dominated the channel-forming process.

A CONCEPTUAL APPROACH FOR FLOW DETERMINATIONS

Maintenance of stream ecosystems rests on streamflow management practices that protect physical processes which, in turn, influence biological systems. Consequently, multiple flow regimes are needed in most streams to protect multiple resources. We use U.S. Geological Survey (USGS) stream gage data from the Salmon River at Whitebird, Idaho (Table 1), to illustrate our flow regime concepts. Mean monthly flows are derived from 76 years of daily records (Figure 1). Instream flows for fish, such as the Tennant (1975) method used here, and out-of-channel flow requirements are all illustrated at this site.

The Whitebird reach of the Salmon River can be classified using Cupp's (1989) method for valley segments as an alluviated mountain valley that is deeply entrenched in mountainous side-walls with a relatively wide floodplain and alluvial/colluvial deposition. There are local inclusions of steep competent hillslopes with steep colluvial complexes.

Four potential flow requirements are illustrated in Figure 1; procedural methodologies for evaluating these flows are summarized in Table 2. Flow magnitude increases from flow regime 1 (fish maintenance), flow regime 2 (channel maintenance), flow regime 3 (riparian maintenance), to flow regime 4 (valley process maintenance).

Fishery Flows

The PHABSIM, part of IFIM (Bovee 1982), is the most commonly used model for quantifying instream flow habitat needs of selected fish species (Orth 1987). The model allows resource managers to predict what conditions are favorable for fish and to select appropriate year-round flows.

The primary purpose of PHABSIM is to describe the relation between streamflow and usable quantities of physical water column space (discharge versus habitat). Such relationships represent the space in a stream that can be used by a specific species during its life stage. PHABSIM is particularly useful during late summer, which corresponds to the period when most habitat suitability index (HSI) curves are developed. PHABSIM-derived fish maintenance flows carry fish mainly through low-flow conditions. Seldom would PHABSIM flows be a restriction during moderate to high flow regimes. PHABSIM is necessary to determine base flow needs, particularly in late summer and fall. Thus, PHABSIM will adequately handle some phases of an instream flow assessment. However, other analytical methods are needed to address channel maintenance flows, and especially riparian and valley maintenance flows.

Channel Maintenance Flows

Channel maintenance flows consist of moderately high flows that are expected to prevent vegetation growth in the channel and remove sediments (Reiser et al. 1989). Most channel-maintenance flow methods suggest that bankfull discharge is a simple discriminator for differentiating between channel-forming and floodplain-forming processes (Wesche and Rechard 1980). Leopold and Emmett (1983) suggest 1.5-year recurrence intervals for bankfull flows. However, Chorley et al. (1984), in studying 36 active floodplains, showed that bankfull recurrence intervals vary between 1 and 32 years. Therefore, bankfull flow must be evaluated for a specific stream.

For certain snowmelt stream channels much of the fluvial process response occurs during the ascending limb of the peak flow hydrograph (Rosgen et al. 1986). Thus, the entire range of the hydrograph may be duplicated by short timed releases of flows at appropriate intervals. These observations were made in reference to channel processes but not to those associated with riparian habitats and floodplains.

To illustrate complex flow regimes, Rosgen et al. (1986) used simplified relationships. The relationships are based on the assumption that flows on the ascending hydrograph mimic the range of frequently occurring discharges that form and maintain channels over time. It was further assumed that sediment loads are not changed appreciably by those factors controlling flows. Given these assumptions, then three basic flow components are required in snowmelt streams: (1) a snowmelt peak flow that is defined as bankfull discharge, (2) a low flow that is defined as base flow discharge, and (3) snowmelt rising and recession discharges (flow regimes over time) (Rosgen et al. 1986).

Apparently, an intermediate range of discharge transports most of the sediment load over the long term and thus determines channel form and condition. Rosgen et al. (1986) further determined that a sediment rating curve and a frequency curve of daily discharges, based on the work of Andrews (1980), could be used to define effective flow. Andrews determined that effective discharge was nearly equivalent to the discharge at bankfull stage. This simplifies the estimation of channel maintenance flows because only those measurements that determine bankfull flows are needed. In contrast, Platts et al. (1985) found that bankfull flows were not always an adequate indicator of channel form and condition. This *was* the case for certain types of basin-range streams, especially those that tend to experience lateral shifts in channel location when stressed by management activities. Overall, the intermediate range of discharges (i.e., approximately bankfull stage) is, in our opinion, an important hydrological benchmark that is related to the shape of many alluvial channels.

Base flow discharge is determined from low-flow statistics. Rosgen et al. (1986) suggested that 7-day low flow at the 1.5-year return interval be used for calculating base flow. The difference between base flow and bankfull flow is large in most streams. Therefore, there is a need to prevent rapid changes in the rise or fall of streamflow so as not to accelerate bank erosion unduly. Duration of each increment on the rising curve is determined from hydrograph analysis to approximate the normal rate of rise of the ascending limb (Figure 2).

The duration of recession flows gener-

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Month
October
November
December
January
February
March
April
May
June
July
August
September
Annual

Period (consecutive days)
Low flow
1
3
7
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30
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120
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Period (consecutive days)
High flow
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TABLE 1
Hydrologic data base for the Whitebird gaging station, Salmon River, Idaho, U.S. Geological Survey

Monthly and annual mean discharges 1911–1917, 1920–1989

Month	Maximum (cfs)	Minimum (cfs)	Mean (cfs)	Standard deviation (cfs)	Coefficient of variation	Percent of annual runoff
October	8,590	2,950	4,860	1,200	0.25	3.6
November	8,250	3,010	4,960	1,150	0.23	3.7
December	9,490	2,750	4,540	1,250	0.27	3.4
January	8,390	2,740	4,190	987	0.24	3.1
February	8,100	2,880	4,440	1,040	0.24	3.3
March	11,700	3,520	5,460	1,520	0.28	4.0
April	27,100	5,400	11,600	4,400	0.38	8.6
May	56,000	10,500	32,100	10,100	0.32	23.8
June	82,600	9,530	39,000	16,500	0.42	28.9
July	35,500	3,520	13,800	7,300	0.53	10.2
August	8,890	2,300	5,430	1,710	0.31	4.0
September	7,080	2,490	4,480	1,080	0.24	3.3
Annual	17,500	5,810	11,300	2,890	0.26	100

Magnitude and probability of annual flow
based on period of record 1912-1917, 1921-1989

Period (consecutive days)	Discharge, in cfs, for indicated recurrence interval, in years, and nonexceedence probability, in percent					
	2 50%	5 20%	10 10%	20 5%	50 2%	100 1%
Low flow						
1	2,670	2,240	2,030	1,870	1,700	1,590
3	2,810	2,380	2,180	2,010	1,840	1,730
7	3,120	2,660	2,430	2,240	2,050	1,920
14	3,370	2,870	2,630	2,430	2,220	2,080
30	3,610	3,060	2,790	2,580	2,350	2,200
60	3,810	3,240	2,960	2,750	2,520	2,380
90	3,960	3,380	3,100	2,890	2,660	2,510
120	4,120	3,510	3,230	3,010	2,780	2,640
183	4,400	3,710	3,390	3,140	2,870	2,710

Magnitude and probability of annual high flow
based on period of record 1911-1917, 1920-1989

Period (consecutive days)	Discharge, in cfs, for indicated recurrence interval, in years, and nonexceedence probability, in percent					
	[redacted] 50%	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
High flow						
1	62,000	81,900	93,100	105,000	113,000	120,000
3	60,200	79,800	90,800	103,000	111,000	118,000
7	56,600	75,500	86,300	98,300	106,000	113,000
15	51,600	68,900	78,800	89.700	96,900	103,000
30	45,700	60,000	67,900	76,300	81,700	86,500
60	36,700	47,400	53,000	58,700	62,300	65,400
90	29,500	37,800	42,100	46,700	49,500	51,900

TABLE I
Continued

Instantaneous peak flow based on 76 years of record[a]					
63,000	83,500	95,200	108,000	117,000	125,000

Duration of daily mean flow for period of record 1911-1917, 1920-1989: discharge (cfs) equaled or exceeded for indicated percent of time

1	5	10	15	20	30	40	50	60
69,900	44,500	29,800	20,700	14,500	8,110	6,180	5,330	4,750
70	80	90	95	98	99	99.5	99.9	
4,320	3,900	3,410	3,050	2,690	2,520	2,330	2,010	

a Weighted skew, 0.500.

ally has not been considered as important to channel processes as rising limb flows. Consequently, Rosgen et al. 1986 suggest decreasing flows by 10 of peak flow each day. This would allow a regulated stream to go from peak flow to base flow over a 10-day period. However, natural high flows seldom operate in this short a time frame. Reducing the duration of peak flows may impair some channel-forming processes and certain types of vegetation seeding and growth Franz and Bazzaz 1977 .

In the absence of supporting research, we recommend that flows be reduced by no more than 10 of the previous day's flow, and in most cases a reduction of less than 10 of the previous day's flow would be highly preferred. A less than 10 reduction would assist in protecting fish from stranding and provide a longer period of high flows for vegetation seeding. At higher flows, we recognize that the incremental changes in flow reduction rates are not greatly different; however, as flows decrease there is increasing separation between drawdown rates. We illustrate these differences in Figure 2, using three drawdown rates for the Whitebird site. In practice, streamflows would not be reduced below some minimum instream flow for fish.

One of the commonly used hydraulic simulation models for evaluating flood flows is the HEC-2 model U.S. Army Corps of Engineers 1982 . This model utilizes a step-backwater approach to determine the velocity and water surface elevation for

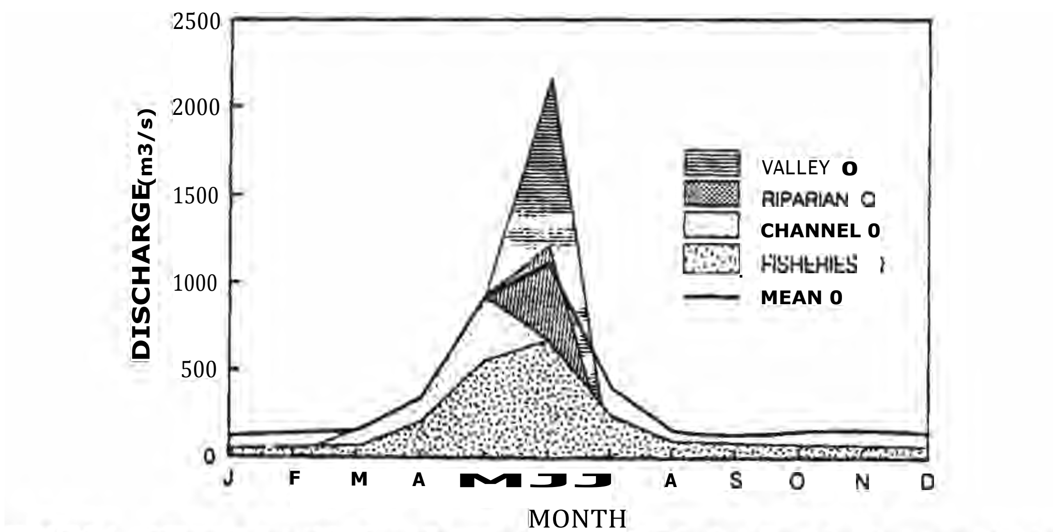

FIGURE 1. Minimum monthly stream flow requirements for fisheries, channel maintenance, riparian *habitat, and valley maintenance in Salmon River at Whitebird, Idaho.*

TABLE 2
Summary of steps and concepts for developing multiple stream flow recommendations

1. Average annual hydrograph	Indicates timing of high and low flows Indicates slopes for rising and falling limbs Can be used to index daily drawdown rate
2. PHABSIM flow analysis	Establishes minimum instream flow to maintain fish Late summer/fall flows are usually set lower than base flows
3. HEC-2 analysis	Used to estimate extent and elevation of riparian habitat in sampled reach Estimates elevation of bankfull conditions and floodplains in sampled reach Estimates discharge needed to provide bankfull flows and to maintain riparian zones and floodplains
4. Frequency of occurrence curve	Indicates return period for peak flows (determined from historical records or from HEC-2 analyses) Establishes the extent to which riparian and valley flow requirements exceed the average annual hydrograph
5. Flow duration curve	Demonstrates flow duration associated with specific exceedence values Demonstrates that recommended flows do occur in time

specific stream discharges. For a specified discharge and channel configuration, the program calculates an initial water surface elevation. The interaction between hydraulic variables and channel dimensions can assist in evaluating the dynamic relationships between discharge and habitat characteristics over time and space.

Riparian Flows

Riparian and floodplain flows are used synonymously in this discussion even though some floodplains could require higher flows than riparian vegetation. Floodplain landforms, which are generally considered to be represented by topographically flat areas, often include side channels, oxbow lakes, wetlands, swamps, and ponds. To date, there are no universally accepted or recognized methods for determining flow quantity or duration needed to maintain riparian habitats and their surrounding floodplains. Franz and Bazzaz 1977, Harris et al. 1987, and Stromberg and Patten 1990 have initiated modeling approaches to measure riparian response to altered flow regimes but these

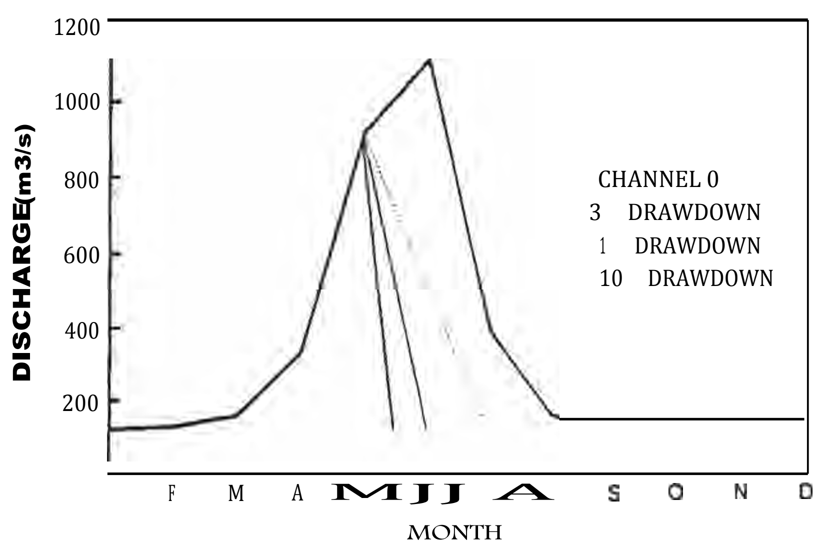

FIGURE 2. Curves comparing channel maintenance flows (m³/second) using the Rosgen et al. 1986 method to the mean monthly hydrograph for Salmon River at Whitebird, Idaho.

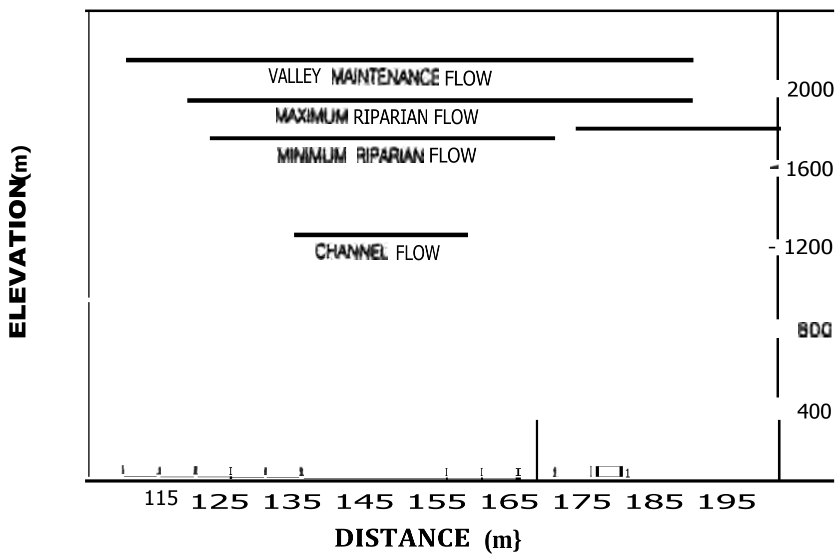

FIGURE 3. *Estimated HEC-2 model measurements on a cross section of Salmon River at Whitebird, Idaho.*

investigations have focused on local conditions and have not been tested on a regional basis.

The HEC-2 method can be used to estimate effects of flow changes on channels by predicting those velocities that disrupt bed armor and fines from gravel beds. We use HEC-2, however, to identify those out-of-channel flows that influence and maintain riparian and valley-forming processes. As shown in Figure 3 for the Whitebird site, HEC-2 predicts water surface at any given elevation. The upper and lower elevations of riparian habitat and the valley is measured and HEC-2 used to determine the discharge needed to reach those elevations. HEC-2 transects can be simple extensions of IFIM transects and, therefore, the required field effort for this model is very minimal.

Floodplain maintenance is dependent upon flooding at selected intervals if floodplain functions and vegetation are to be maintained (Junk et al. 1989). As shown in Figure 4, these flows occur at the peak of the hydrograph for the Whitebird site and

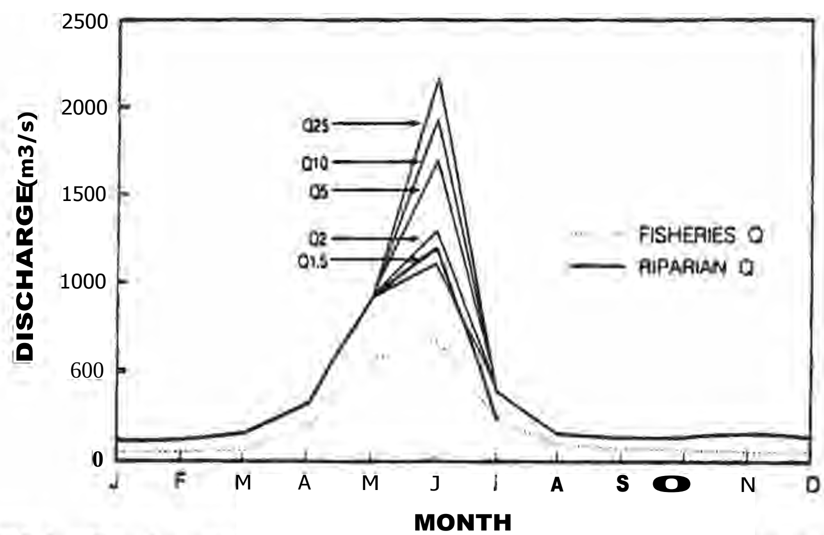

FIGURE 4. *Fisheries and riparian-flood flow curves for Salmon River at Whitebird, Idaho.*

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represent discharges within the $Q_{1.5}$ to 10 range where $Q_{1.5}$ and Q_{10} indicate flows that are equalled or exceeded, on average, once every 1.5 and 10 years, respectively . HEC-2 modeling predicts the discharge needed to flood riparian habitat and the floodplain. High flow frequency of occurrence or return period identifies when, in time, those discharges occur.

Valley floor gradient and width, elevation, fluvial processes, and soil parent material govern riparian type and the extent of the riparian zone Platts et al. 1985 . Kondolf et al. 1987 reported that in a large U-shaped glacial valley, the width of the riparian strip is highly variable, whereas on alluvial fan deposits the riparian strip is relatively uniform. It follows that not all valley types support riparian vegetation. Steep-sided, V-shaped valleys lack floodplains or even terraces that can support riparian habitat. Consequently, out-of-channel flows are not needed for riparian or valley maintenance in these types of valleys.

Valley Maintenance Flows

Climatic variability, expressed through the magnitude and frequency of high-flow events and modified by vegetation, determines valley form and condition in both natural and artificial systems (Platts et al. 1985 . Large hydrologic events affect valley sides, whereas smaller flow events affect channels and floodplains Platts et al. 1985 ; both, over the long term, affect valley form.

The steeper the valley slope, the greater the stream power of valley water flow Lanka et al. 1987). Also, the narrower the valley width, the less horizontal distance the flows cover. Changes in valley form and slope generally represent long-term adjustments because immense quantities of materials are redistributed and vegetation patterns changed Lotspeich and Platts 1982 . In many valleys, form and condition are still under the influence of Pleistocene events Platts 1979 . Other processes must continue for decades and centuries to override these prehistoric settings.

We identify valley-forming flows as those peak discharges that usually exceed Figure 4 . This flow regime is more difficult to establish because most valleys have been formed by forces other than fluvial processes, such as glaciers, faults, and lava flows Lotspeich and Platts 1982 . Establishing this flow must be done with caution. Valleys created over long periods thousands of years by historic flood flows may now be occupied by roads, homes, businesses, and other property. Furthermore, because of the infrequent occurrence of $>Q_{25}$ flows, relatively short-term gaging station records, and measurement errors associated with large flows, our ability to accurately determine Q_{25} is limited in many areas.

Not all valley types are dependent upon the energy from flood flows to maintain their geomorphology. In wide alluvial fan-type valleys, the energy associated with flood flows has no affect on valley geomorphology but it is the channel flow that induces meandering, scouring, and filling.

SUMMARY

Knowledge of fluvial-geomorphic processes that create and maintain streams and how aquatic and terrestrial ecosystems function synergistically is fundamental to identifying flows that maintain fish habitats and, ultimately, fish biomass and diversity. Protecting these parameters with multiple flow recommendations is necessary because of these ecological linkages. Single purpose instream flows alone, whether derived from the PHABSIM or other methodologies, provide only short-term protection for fish populations. Diversion or storage of bankfull and flood flows in different valley bottom types will result in habitat alterations and a reduction in fish populations and diversity.

The concepts we present in this paper examine broad interactions of fluvial-geomorphic processes, riverine-riparian habitat, and their geographic setting. We recognize the limitations inherent in using our conceptual method. For example, most tributaries lack historical flow records that define average annual discharge and there are frequently no data available on the duration and frequency of flow events. Channel maintenance flows vary by channel type and elevation, and the duration of out-of-channel flooding required for plant germination is unknown. Future research focusing on the hydrostatic and hydrodynamic requirements of floodplains may improve our understanding of geomorphic processes and provide the details necessary to refine in-channel and out-of-channel flow requirements.

Establishing multiple flows for protection of aquatic resources recognizes that natural systems were built and are maintained by different magnitudes of discharge occurring over time and space. This calls into question the conventional wisdom that excess water is available in all streams for diversion or storage purposes. It is likely that any substantial alteration of natural streamflows from snowmelt-controlled broad alluvial valley types will have significant impact on fish habitat and abundance.

Although the technical methods used in our analysis are not new, it is clear that streamflow management practiced only as a fisheries art is inadequate to protect river ecosystems. Multiple flow requirements are required for maintenance of ecological systems encompassing streams, riparian zones, and valleys. Such analysis is seldom conducted because of expense and complexity. However, we have demonstrated for the Whitebird site that multiple flow analysis is possible with methods currently in common use.

Fundamental research that quantifies the ecological links between instream and out-of-stream resources is needed to develop more refined methods. This research will come from hydrologists, aquatic and terrestrial biologists, botanists, and geomorphologists working together to establish multiple flow criteria. Meanwhile, techniques are available to perform more comprehensive analyses than are now the custom.

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Received: 25 January 1991
Accepted: 29 May 1991
Discussion open until 30 June 1992