A Literature Evaluation of Montana's Wetted Perimeter Inflection Point Method for Deriving Instream Flow Recommendations

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INTRODUCTION

Since the inception of the Montana Department of Fish, Wildlife and Parks' (MDFWP's) instream flow program in the mid-1970's, the wetted perimeter inflection point method has been the primary means for deriving instream flow recommendations for the preservation of aquatic resources during the low-water period in Montana's streams and rivers. Because the field of instream flow method (IFM) development has continually expanded over the past decade or so, the Department felt a need to review its method in light of recent advances in the "state-of-the-art." The purpose of this document is to (1) provide an up-to-date synopsis of the history of the wetted perimeter inflection point method, (2) examine its theoretical and experimental basis, and (3) identify its strengths and weaknesses as compared to other available procedures. We will also discuss the applicability of the wetted perimeter inflection point method to a variety of streams, both large and small, guidelines for its use, and provide a justification for the use of the method in Montana.

HISTORY

The development of methods to determine the amounts of water to remain instream for the protection of fish and wildlife resources and related recreational opportunities has been a relatively recent phenomenon (Loar and Sale 1981). The primary reason for this has been a reluctance of various state governments to recognize instream uses as "beneficial" uses of water. Because of limited water availability and resultant user conflicts, it was in the arid western states where instream flow methods (IFM's) were first devised. These developments followed the establishment of institutional frameworks (instream flow programs), which have proliferated in the western states since 1973 (Lamb and Meshorer 1983). However, the degree of protection afforded to fish and wildlife by instream flow programs differs markedly among states due to differing levels of statutory protection, water availability, and user conflicts. Consequently, a variety of IFM's have been devised by state fisheries agencies to meet the needs of their particular instream flow programs (Trihey and Stalnaker 1985). Another factor contributing to the diversification of IFM's was that the characteristics of aquatic resources (such as warmwater vs. coldwater habitat, anadromous vs. resident species) vary both within and between states.

Many of the first studies concerning instream flow needs were conducted during the 1950's and 1960's below federally funded hydroelectric and irrigation dams on large rivers in the West (Trihey and Stalnaker 1985). Because these projects had their most visible impacts on naturally occurring low summer streamflows, biologists were most concerned with setting minimum flow "standards" for the summer-fall periods. The first applications of IFM's to streams and rivers on a statewide basis began in Oregon during the late 1960's. The early development of IFM's in Oregon was not just coincidence because in 1955 Oregon became the first western state to provide for the administrative establishment of flow standards. Their program was quite successful and has been a prototype for other western states, including Montana (Lamb and Meshorer 1983).

A series of workshops were held in the Northwest during the early 1970's to review and discuss available IFM technology. Three of the more significant events in the development of IFM's did not occur until 1976. The first event was a publication by Stalnaker and Arnette (1976) that comprised the first compilation and critical evaluation of existing IFM's. Second, a conference sponsored by the Western Division of the American Fisheries Society was held in Boise, Idaho. This landmark event brought together IFM practitioners, developers and administrators to discuss the legal, social and biological aspects of the instream flow issue, and resulted in the publication of a two-volume document (Orsborn and Allman 1976). The third significant event was the formation of the Instream Flow Group (IFG) by the U.S. Fish and Wildlife Service at Fort Collins, Colorado. The purpose of this group was to advance the "state-of-the-art" and become the center of activity related to instream flow assessments. In the late 1970's the IFG developed the Instream Flow Incremental Method (IFIM), which has been in a continual state of refinement ever since.

The timetable for the development of Montana's IFM closely paralleled those for the other western states. In the early 1960's a series of unsuccessful legislative attempts were made to obtain "beneficial use" status for fish and wildlife and to develop a procedure to obtain instream flows for these resources (Peterman 1979). The first provisions for the instream flow needs for fish and wildlife were made in 1969 when the Montana legislature authorized the Fish and Game Commission to file for rights to the unappropriated waters in portions of 12 streams. Because the "state-of-the-art" of IFM development was in its infancy, most of these original filings were based on the professional judgment of local fisheries biologists. In 1980 and 1981 they were quantified using the wetted perimeter method.

The passage of the Montana Water Use Act in 1973 and the Yellowstone Moratorium in 1974 provided the main stimuli for the development of methods to quantify the instream flow needs of fish and wildlife in Montana. The Water Use Act was a revolutionary legislative act that specifically defined fish and wildlife as beneficial users of water and established a process for reserving unappropriated water for these purposes. The Yellowstone Moratorium was enacted in response to a "rush" of applications for Yellowstone River water by industrial and water-marketing concerns and placed a moratorium on all large diversion or storage applications in the Yellowstone Basin. The Yellowstone Moratorium provided a period of three years to quantify all future beneficial uses (including fish and wildlife) in the basin and allocate water to meet those needs (Peterman 1979).

In 1973 and 1974, in response to this mandate, the MDFWP began in earnest to develop an IFM that was appropriate for the rivers and streams of Montana and could be cost and time-effectively applied on a basinwide scale (Spence 1976). After a review of available IFM's, the MDFWP decided to enter into a cooperative program with the U.S. Bureau of Reclamation and in 1974 began using the Bureau's WSP (water surface profile) model to generate hydraulic and channel configuration information on which instream flow recommendations were based (Spence 1975; Dooley 1976). Data from the WSP model were used to define

(1) passage flows for migratory fish, (2) nest protection flows for Canada geese, and for the first time in Montana, (3) to define minimum flows for fish during the low flow periods based on the relationship between wetted perimeter and discharge in riffles (Elser 1976). Preliminary field testing of the WSP model was conducted during the mid-1970's by MDFWP personnel (Elser 1976; Workman 1976). These evaluations were geared towards the technical aspects of the WSP hydraulic model as well as the appropriateness of using wetted perimeter-discharge relationships to derive instream flow recommendations for the low flow period.

Following the completion of fieldwork associated with the Yellowstone water reservation in 1977, the MDFWP shifted emphasis to the Upper Clark Fork and Upper Missouri River Basins. An action plan was devised to guide Department efforts at securing instream flows (Nelson and Peterman 1979). The wetted perimeter method using the WSP hydraulic model continued to be the primary means of deriving minimum flow recommendations for the low flow period until the results of an evaluation study were published by MDFWP (Nelson 1980a, 1980b and 1980c). This study, funded by the U.S. Fish and Wildlife Service under the auspices of the IFG, evaluated four IFM's applied to five river reaches in southwest Montana. Besides providing a basis for using the wetted perimeter inflection point method, the study led to the development of an improved and simplified method to generate wetted perimeter- discharge relationships for streams and rivers (Nelson 1984a). The resultant WETP computer program replaced the WSP model and since 1980 has provided the wetted perimeter-discharge data upon which the Department's flow recommendations are based.

RELATIONSHIPS BETWEEN STREAMFLOWS AND FISH POPULATIONS

Many physical and biological factors interact to regulate fish abundance in streams. Hall and Knight (1981) list five major factors: streamflow, habitat quality, food abundance, predation, and movement and migration. In a natural stream environment, it is difficult to measure the effect of one factor independently of the others. The exact role each factor plays in regulating a given stream population is often masked by the interaction of the others. This complexity hampers the ability of fishery scientists to predict the response of a fish population in a given stream to environmental variations, such as man-caused changes in streamflow. Accurate predictions require the development of a model that quantitatively describes the relationship between fish abundance and all regulating variables. The "state-of-the-art" has not yet advanced to this level, nor is it evident that such models, if ever developed, would be applicable to a broad range of streams.

Because there are wide gaps in our knowledge of how fish respond to environmental changes, fishery scientists must rely on broad, general assumptions when discussing the means by which stream fish populations are regulated. These assumptions may not fully describe the means of regulation for a given stream of interest or apply to all streams in a particular region, and many have not been tested in definitive scientific studies. Despite these limitations, the assumptions, in general, are logical and defensible, but not immune to criticism. These assumptions are an essential part of all instream flow methods. This section will briefly discuss some of the assumptions regarding the regulation of fish abundance in Montana's streams, and provide a basis of support from the scientific literature.

The standing crops (number and total weight) of fish that a particular stream supports can vary over time. For Montana's streams, standing crops are typically lowest following the rigors of winter and highest in fall after the summer growing season. The magnitude of these annual lows and highs can vary substantially from year-to-year.

A factor often considered a major, if not the overriding, cause of this variability within a particular stream is the year-to-year variation in streamflows. Simply stated, more water translates into more space for fish and the population increases to fill this void. Conversely, lower flows provide less space and lead to a reduction in fish standing crops. It is the logic of this relationship that has led many to believe that the period of lowest streamflows is the single factor having the greatest impact on a stream's carrying capacity. Carrying capacity here is defined as the standing crops of fish that can be maintained indefinitely by the aquatic environment.

Substantial support for this belief is provided in the literature. Positive correlations between the magnitude of a stream's annual low flows and the variation in fish standing crops over time have been documented in numerous studies (Neave 1949 and 1958, McKernan et al. 1950, Wickett 1951, Henry 1953, Neave and Wickett 1953, Pearson et al. 1970, Burns 1971 and White et al. 1976). In Montana, such relationships have been suggested for the Gallatin, Big Hole, Madison, Bighorn and Yellowstone rivers (Nelson 1984b, Fredenberg 1985, Vincent 1987, and Clancy 1988).

Flows can increase to a level where they no longer benefit fish populations. High flows, especially those associated with floods, have been shown to adversely impact fish, with eggs and young generally affected more severely than adults (Allen 1951, Elwood and Waters 1969, Seegrist and Gard 1972 and Anderson and Nehring 1985). However, the magnitude of the impact on the population can vary by species, the time of year high flows occur and the physical stream characteristics.

Not all space in a stream is equally suited for fish. Fish tend to concentrate and spend much of their time in specific habitats, which consist, among other things, of a preferred range of bottom substrates, current velocities and water depths, and contain cover. Components of the preferred fish habitat - not all of which are readily identifiable - can vary with the species, life stage and size of fish and by stream and season.

Cover, or shelter, has long been recognized as one of the basic and essential components of fish habitat. Cover serves as a means for avoiding predators and provides areas of moderate current speed used as resting and holding areas by fish. Cover is provided by such things as undercut banks, overhanging and submerged bank vegetation, woody debris, aquatic vegetation, instream boulders and cobbles, and surface turbulence. Water depth by itself is a form of cover.

Fish habitat can be improved through artificial manipulation, thus increasing a stream's carrying capacity. One of the most cited examples occurred at Lawrence Creek, Wisconsin, where the brook trout biomass (total weight) increased almost threefold following extensive habitat improvements that increased bank cover by 416% and pool area by 289% (Hunt 1971 and 1976). Fish habitat can also be degraded by man's activities. The destruction of bank vegetation is a prime example that leads to habitat losses and, in turn, reduces the carrying capacity. For example, a study evaluating the effects of habitat manipulation on trout abundance in a small Montana stream reported that the removal of a portion of the overhanging brush cover reduced the trout biomass in a test section by 41% (Boussu 1954). It is thus well established that fish do respond, sometimes dramatically, to habitat alterations.

The amount of available fish habitat in a particular stream is strongly influenced by streamflow. This is an obvious relationship because many habitat components, such as water velocity, depth, and available bank cover, are directly affected by the magnitude of the flow (Randolph 1984 and Wesche 1973). It is through its influence on fish habitat that streamflow is believed to primarily regulate fish abundance. Greater flows expand the available habitat, allowing the fish population to increase. Conversely, following flow reductions, fish populations decrease in response to shrinking habitat. Numerous studies have documented positive relationships between fish standing crops and various indices of habitat quantity (Gunderson 1966, Lewis 1969, Stewart 1970, Wesche 1974 and 1980, Nickelson and Hafele 1978 and Loar et al. 1985b).

While streamflow primarily regulates fish standing crops through its effect on physical habitat, other factors that can contribute to the variation in fish abundance over time are also influenced by flow. One such factor is food supply. The abundance, production and composition of food items can be altered by variations in flow (Cushman 1985).

Aquatic insects, such as caddisflies, stoneflies and mayflies, and other aquatic invertebrates are the primary food of Montana's stream-dwelling game fish (Brown 1971). It is widely accepted that the production of these aquatic food organisms is greatest in riffles of streams (Hynes 1970). Needham (1934) and Briggs (1948) reported that 80 percent of the invertebrate production in their study streams occurred in riffles. A riffle is a section of stream in which the water flow is rapid and shallower than the sections above and below. Streams usually consist of a succession of pools and riffles.

Aquatic invertebrates normally become available as a food source when drifting in the current, although salmonids and other fish also rely heavily at times on bottom foraging. The majority of the studies reported in the literature support the general conclusion that a strong positive correlation exists between the abundance of aquatic drift and water velocities (or stream discharge) (Chapman 1966, Waters 1969, and Everest and Chapman 1972). Increasing velocities, which are necessary to free invertebrates from the bottom substrate, should increase the quantity of drift up to the point where flows near flood levels (Waters 1969).

While increased water velocity is the generally accepted mechanism for creating drift, sufficient riffle habitat must be available to produce this food source. To sustain maximum invertebrate production, the riffle habitat should be wetted year-round because the majority of aquatic insects live from one to three years on the stream bottom before emerging as air breathing, winged forms and completing their life cycles. These organisms cannot be expected to readily recolonize those areas that are alternately wetted, dried and rewetted each year. Up to 47 days may be required to fully recolonize a dewatered substrate (Gerisch and Brusven 1981). Thus, both the total amount of wetted riffle area and the velocities through these riffles appear to be important factors determining the quantity of drift.

The assumption that food supply can be an important factor controlling fish abundance is supported by a number of studies. Mason and Chapman (1965), Peterson (1966), Elliott (1973) and Gibson and Galbraith (1975) reported that stream sections having the higher incoming drift supported greater fish standing crops. Murphy et al. (1981) found that trout biomass at six stream sites in Oregon's Cascade Mountains was highly correlated with the biomass (in riffle samples) of the collector-gatherer group of invertebrates (r=0.99, P<0.01) and moderately correlated with the total invertebrate biomass (r=0.83, P<0.05).

Fish abundance can reflect the quantity of the food supply and, in those streams where food is limiting, populations will benefit if food production was optimized. One means for accomplishing this goal is to maintain a flow level that wets the maximum amount of a stream's riffle area. The underlying assumption is that fish standing crops will respond to increases in wetted riffle area via the impact on food production. Support for this logic is provided by Pearson et al. (1970), who found that pools having larger upstream riffles averaged higher production of coho salmon per unit of pool area than did pools with smaller riffles. On the negative side, Cada et al. (1983) were unable to show a consistent relationship between invertebrate densities and riffle wetted perimeter (an index of wetted riffle area) at various flows for four southern Appalachian trout streams. However, they concluded that their analysis was only preliminary and, in a subsequent correspondence with the MDFWP, Cada stated that he hoped to restudy the relationship in greater detail and suspected that there was some value in examining wetted perimeter when considering flow effects on aquatic invertebrates.

Streamflow will control the amount of riffle area that is covered by water and, as a result, may influence food production. This potential relationship between streamflows and food production is of particular significance during the warmer months when higher water temperatures initiate fish growth and young fish are hatched and enter the population. Due to this growth and recruitment, the population increases over summer in both numbers and biomass, typically reaching its highest level in fall. The fact that fish populations in Montana's streams tend to increase over summer suggests that the amount of preferred habitat needed for population expansion is in excess at this time. Vacant habitat would have to be available in order for this expansion to occur. This is consistent with the fact that streamflow in Montana's unregulated streams is normally highest in summer and lowest in winter (Figure 1). (Prairie streams, regulated streams and those heavily depleted for irrigation often violate this "rule of thumb"). Consequently, habitat availability is expected to be greatest during summer and lowest in winter. On these streams, food supply may be more influential in limiting the summer population expansion than is a lack of unfilled habitat. Experiments of Wilzbach (1985) suggested that, in summer, food abundance was the over-riding factor determining the abundance and distribution of adult cutthroat trout in streams. (In 1987, the Cooperative Fisheries Research Unit at Montana State University began a study to assess the role of summer food supply in regulating trout abundance in Montana's streams. No study results are available at this time.)

In winter, Montana's streams normally exhibit high fish losses, which are attributed to the seasonally low flows coupled with the detrimental effects of sub-surface ice formation, ice scouring and other harsh physical conditions that typically characterize a Montana stream in winter. The severity of the winter environment on trout survival has been discussed by a number of authors (Maciolek and Needham 1952, Needham and Jones 1959, Butler 1979 and Kurtz 1980) and borne out by the high over-winter mortality rates that have been documented for a number of Montana streams (MDFWP 1984 and Schrader 1985). By winter's end, populations are typically reduced to the lowest level of the year in response to the adverse habitat conditions. The winter period and its associated low flows are believed to ultimately regulate the capacity of most Montana streams to sustain fish.

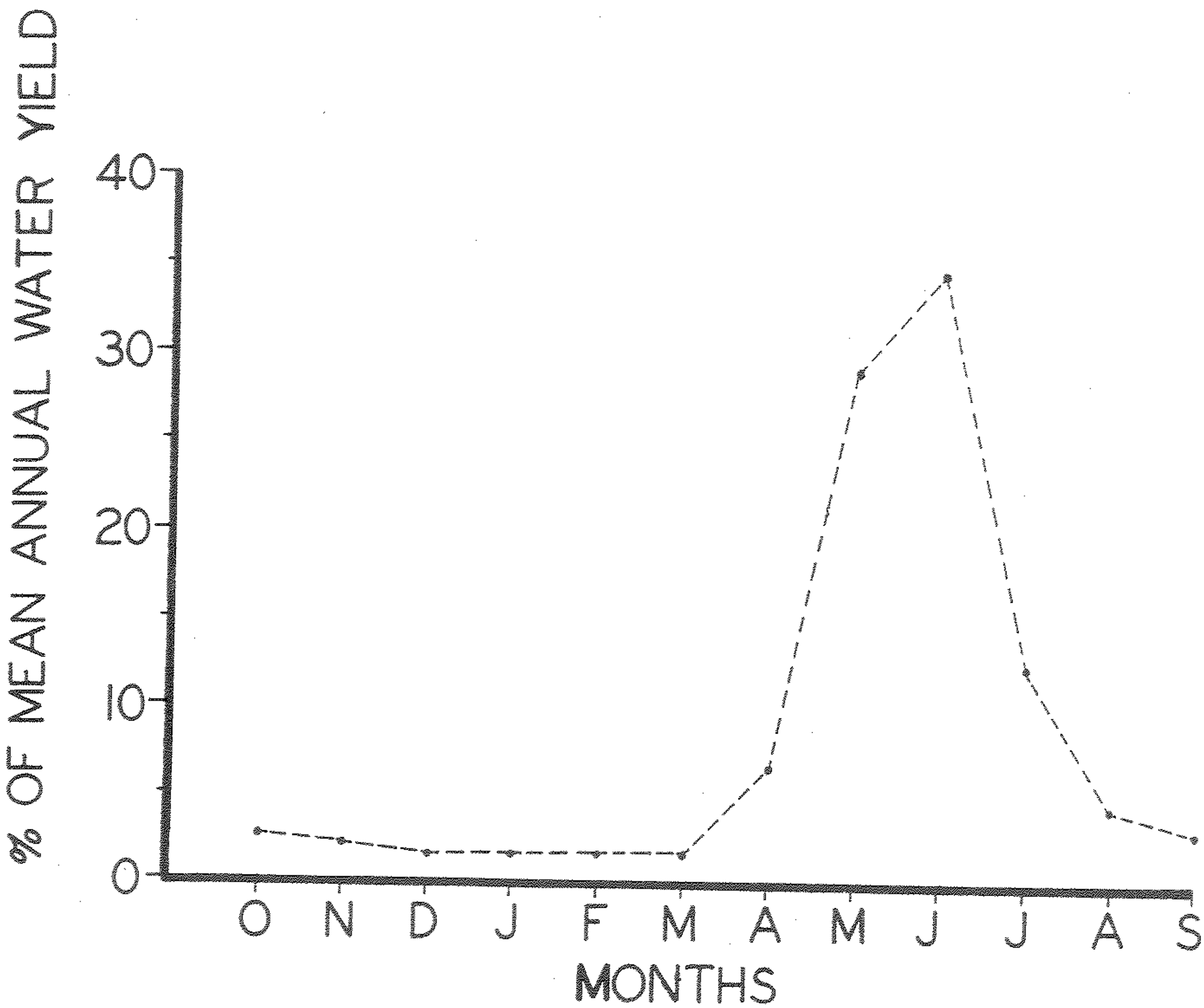

Figure 1. Monthly water availability for mountain trout streams in Montana. The monthly values are the averages for five unregulated streams east of the Continental Divide.

A better understanding of the connection between food supply and winter habitat in regulating fish abundance is provided by Mason (1976). He was able, through supplemental feeding, to increase the summer biomass of juvenile salmon in a small British Columbia stream by 6-7 fold when compared to natural levels. However, the over-winter loss of these fish was extremely high, resulting in a spring population that was numerically similar to the population under natural conditions (no supplemental feeding). This study demonstrated that food supply was the most important factor controlling population size in summer, but physical habitat in winter ultimately limited the population, preventing a high carry-over of fish from the previous summer's supplemental feeding.

The role of habitat in regulating fish abundance in Montana's streams is probably dominant in winter and of lesser importance in summer when food supply likely plays a key role. During the transition period between summer and winter when flow levels start to approach the winter lows (Figure 1), habitat should begin to play a more prominent role in controlling population size. As natural flows progressively decline, a theoretical point is reached when habitat reductions overtake food supply as the primary limiting factor. Justification for habitat becoming a key limiting factor prior to the winter low flow period being reached is based on the fact that the habitat needs of individual fish are generally considered greatest during the warmer months when fish grow, reproduce, and actively defend territories. In winter, escaping from the rigors of the harsh physical environment appears to be the primary life function. For protection, wintering fish tend to seek out the deeper pools, enter the bottom substrate or congregate amid heavy accumulations of brush and debris (Chapman and Bjornn 1968). Because wintering fish typically confine their activities to limited areas and are less active, their individual habitat requirements appear to be less than their non-winter requirements. Thus, a greater flow is needed in the warmer months than is required during winter to support the same fish abundance. Stated another way, a given flow should provide less fish habitat during the warmer months than in winter. (This generality applies only to those time periods when sub-surface ice is not the dominant determinant of channel structure. When icing is severe, physical habitat is grossly altered and is no longer comparable to the habitat in summer.)

The amount and availability of physical habitat may limit fish populations during the non-winter months in streams that are depleted for irrigation. The habitat reductions that result when irrigation water is removed, especially in late summer and fall when natural flow levels have dropped considerably, become more limiting to the population than the food supply and, if flow depletions are severe, replace winter habitat as the ultimate population control. Data collected for the Gallatin, Big Hole and Shields Rivers - Montana streams that are severely depleted for irrigation - suggest that the summer low flow has become the ultimate population regulator on portions of these streams (Nelson 1984b and Clancy 1985).

How streamflow regulates populations during the non-winter months - via food supply, habitat or a combination of both - is less relevant than the fact that regulation does occur. As a result, there are distinct benefits to maintaining non-winter flow levels that exceed the winter lows. One important benefit is that the higher flows of the non-winter period allow the population to achieve maximum growth and expansion over summer, providing anglers with a harvestable surplus of fish before the upcoming population adjustment in winter. Anglers have the opportunity to take a portion of the fish biomass that will normally be lost over winter, without materially impacting future fish abundance. Maintaining flows year-round at the low level of winter would not allow for this summer expansion and would, therefore, diminish or eliminate fishing opportunities. Another real possibility is that a year-round low (winter) flow would reduce the fall population to a level below the carrying capacity of the winter habitat, and thus lead to a major reduction in future fish abundance. This stems from the likelihood that habitat requirements of individual fish may be greater in the warmer months than in winter. Clearly, neither fish nor fishermen would benefit if flows were maintained year-round at their low winter levels.

While streamflow is often considered the most important variable regulating fish densities, its influence can be masked or overridden by other controls, such as man-caused pollution and the over-harvesting of fish by anglers. In these situations, fish standing crops are suppressed by factors unrelated to flow and held at a level far below the stream's carrying capacity. The influence of flow levels, therefore, becomes secondary except possibly under extremely low flows. If these other controls were reduced or eliminated, streamflow would again become the dominant population regulator.

When deriving flow recommendations for Montana's streams, fishery managers strive to provide a level of protection that will maximize fish populations. Given this goal, a prudent and defensible approach is to fully protect winter flows. Flow reductions during the winter low flow period would only serve to aggravate an already stressful situation for fish (MDFWP 1984), potentially leading to even greater over-winter losses. For the remainder of the year, a reasonable strategy is to provide a flow that maintains food production and fish habitat at a level that maximizes the growth of individual fish and the expansion of the population over the summer growing season.

SURVEY AND ANALYSIS OF INSTREAM FLOW METHODS

Survey of Available Techniques

Probably the best and most defensible method for determining streamflows necessary to maintain existing aquatic resources is to observe responses of fish populations to changing flow regimes in a specific water over a period of years. While this approach is desirable, it is impractical for use on a broad scale because of time and manpower requirements. The need to collect data over a wide range of annual flow conditions is an additional constraint since researchers seldom have control over this variable. Although such information exists for a few of Montana's "blue ribbon" trout streams (Nelson 1980a and 1980b), it is not a viable alternative to the commonly used IFM's.

Recent reviews by Wesche and Rechard (1980), Loar and Sale (1981), and Trihey and Stalnaker (1985) have shown that the commonly used and accepted instream flow methods can be classified into three categories. They will be referred to as:

1. Non-field
2. Habitat retention
3. Incremental

Non-Field Methods

The first category includes a variety of "non-field" methods that set minimum flows based on existing historical streamflow records. One of the most common of these is the Tennant Method, also known as the Montana Method. The name "Montana Method" is a misnomer because it is not the preferred method in the MDFWP's program to set instream flows. This method derives flow recommendations based on percentages of the mean annual flow for the stream in question. Other related methods are based on manipulations of water yield or flow duration information. All such methods are similar in that they are usually performed in the office using existing hydrologic information with few, if any, on-site visits required. These methods are also generally weak in establishing a biological basis for the recommended flows.

Habitat Retention Methods

The second group of IFM's includes a wide array of techniques that examine relationships between discharge and generalized fish habitat indices to derive flow recommendations intended to maintain the stream resource at a desired level. They are called "habitat retention" methods because they specify flow levels where certain desirable aquatic habitat characteristics (such as riffle wetted perimeter) are retained. These methods require one or more visits to the stream or river where habitat measurements are made along established cross-sectional transects. Some methods employ hydraulic simulation models (such as Manning's equation or stage-discharge relationships) while others rely on repetitive measurements made at several different flows.

Habitat retention methods commonly apply criteria to define flows necessary to provide suitable conditions for one or more of the following life functions:

1. unimpeded passage to spawning areas
2. adequate spawning habitat
3. adequate rearing habitat
4. adequate food producing habitat.

For example, the Oregon Method addresses fish passage requirements by examining water depths and current velocities over a range of flows at several transects. These transects are established across critical riffles where fish passage problems would first appear as discharge decreases. Criteria developed for various fish species from field observations and laboratory studies are then compared to cross-sectional information to identify flows where channel width, water depth, and current velocity conditions no longer allow adequate passage. Depth and velocity passage criteria for a variety of fish species were presented by Thompson (1972). Similarly, several habitat retention techniques use either species-specific or generic depth and velocity criteria and carefully placed cross-sectional transects to derive flow recommendations for known spawning areas (Wesche and Rechard 1980).

While not all of the habitat retention methods described by Wesche and Rechard (1980) consider passage and spawning requirements, they do share a common emphasis on defining flows required to provide adequate fish rearing habitat. However, as pointed out by Thompson (1972), the identification of appropriate rearing flows is far more difficult than determining passage and spawning flows. Fish habitat requirements for rearing purposes are complex because preferences for water depth, velocity, cover, and substrate usually vary not only between species but also between life stages (i.e., fry, juveniles, adults) of a single species. Further, the habitat requirements (primarily current velocity, substrate and depth) of the numerous species of aquatic macroinvertebrates that comprise the main food base for trout in most streams also vary significantly between species.

Because rearing habitat requirements of lotic fish species and food organisms are so complex and interrelated, the habitat retention IFM's typically evaluate the relationship between streamflow and some general index of physical habitat conditions in deriving flow recommendations. Many of these methods focus on riffles because of their importance as food producing areas and the belief that the maintenance of riffles will provide adequate amounts of habitat in other areas of the stream (Stalnaker and Arnette 1976). As shown in Table 1, four of the seven common "habitat retention" methods specifically consider riffle habitats and five methods give at least some consideration to the amounts of wetted perimeter retained in the stream.

Incremental Methods

The third group of IFM's can be referred to as "incremental." These techniques produce habitat-discharge relationships for specific life stages of various fish species. They are termed "incremental" methods because they attempt to predict the actual amount of suitable fish habitat present as flow changes incrementally. The "California Method" for rainbow trout and the "WRRI Method" for brown trout (both described by Wesche and Rechard 1980) are included in this group. However, the best known technique is the Instream Flow Incremental Method (IFIM). IFIM is the most sophisticated instream flow method and it continues to be refined by the IFG at Fort Collins, Colorado.

The IFIM has been described in detail elsewhere (Trihey and Wegner 1981, Bovee 1982, Milhous et al. 1984). Loar and Sale (1981) describe the method as follows:

> "A package of computer programs, collectively called PHABSIM (Physical HABitat SIMulation system), is used to implement this analysis of instream flow needs. The overall approach combines (1) multiple-transect field data from a representative and/or critical river reach, (2) hydraulic simulation models to predict physical habitat parameters such as mean velocity (v), depth (d), and substrate (s), and (3) species-specific suitability functions (S_v, S_d, S_s). Suitability functions are used to calculate weighting

Table 1. Summary of the common "habitat retention" methods used to determine rearing flow requirements (derived from Wesche and Rechard 1980).

Method	Species	Habitat Unit Considered	Rearing Criteria
Oregon	salmonids	riffles	- adequate depth - 60% wetted - velocity 1.0 to 1.5 ft/sec
		pools	- velocity 0.3-0.8 ft/sec - pool-riffle ratio near 50:50
Colorado (USFS Region 2)	salmonids	riffles	- 50% wetted - average velocity 1.0-1.5 ft/sec - depth 0.2-0.4' if width less 20' 0.5-0.6' if width more 20'
USFS Region 4	salmonids	all units (pools, riffles, runs, etc.)	- numerical rating system for pool quality, pool structure, streambed and bank environment
USFS Region 6	salmonids	"typical rearing habitat"	- depth 0.5-3.0 ft - velocity 0.2-1.6 ft/sec
		"food producing habitat"	- depth 0.1-3.0 ft - velocity 1.0-4.0 ft/sec
Washington	salmonids	riffle/pool sequence	- inflection point on wetted perimeter: discharge curves
Idaho	warmwater	riffles	- inflection point on wetted perimeter: discharge curves
Montana's WETP	salmonids	riffles	- inflection point on wetted perimeter: discharge curves

coefficients representing the habitat preferences of various life stages of target fish species. Finally, measures of habitat suitability and availability (as wetted surface area, a_i) are used in computation of Weighted Usable Area (WUA), an index of habitat condition. This index is computed for each life stage [e.g., spawning (S), fry (F), juvenile (J), and adult (A)] and can be plotted against discharge" (Figure 2).

A major difference between IFIM and the "habitat retention" methods is that it builds a two-dimensional surface area model of a stream section while the other methods usually examine habitat characteristics in terms of usable width at discrete cross-sectional transects. IFIM divides the study section into a matrix of rectangular cells (Figure 3) and uses either a single-flow (WSP-type model incorporating Manning's equation) or a multiple-flow stage-discharge hydraulic modeling approach to describe flow-related changes in depth and velocity within each cell. Once the hydraulic model for each cell is constructed, habitat suitability curves are consulted to determine habitat suitability for a given life stage of a given species for each flow of interest.

Example habitat suitability curves for velocity, depth, and substrate are shown in the upper right on Figure 2. Suitability factors range between 0.0 (most unsuitable) and 1.0 (most suitable). A composite habitat suitability factor is determined for each cell in the study section at each flow of interest by multiplication of factors for depth, velocity, substrate and/or cover. This composite suitability factor also ranges between 0.0 and 1.0 and it is multiplied by the surface area of the cell to determine the "usable" area in the cell at a particular flow. These values are tabulated for all

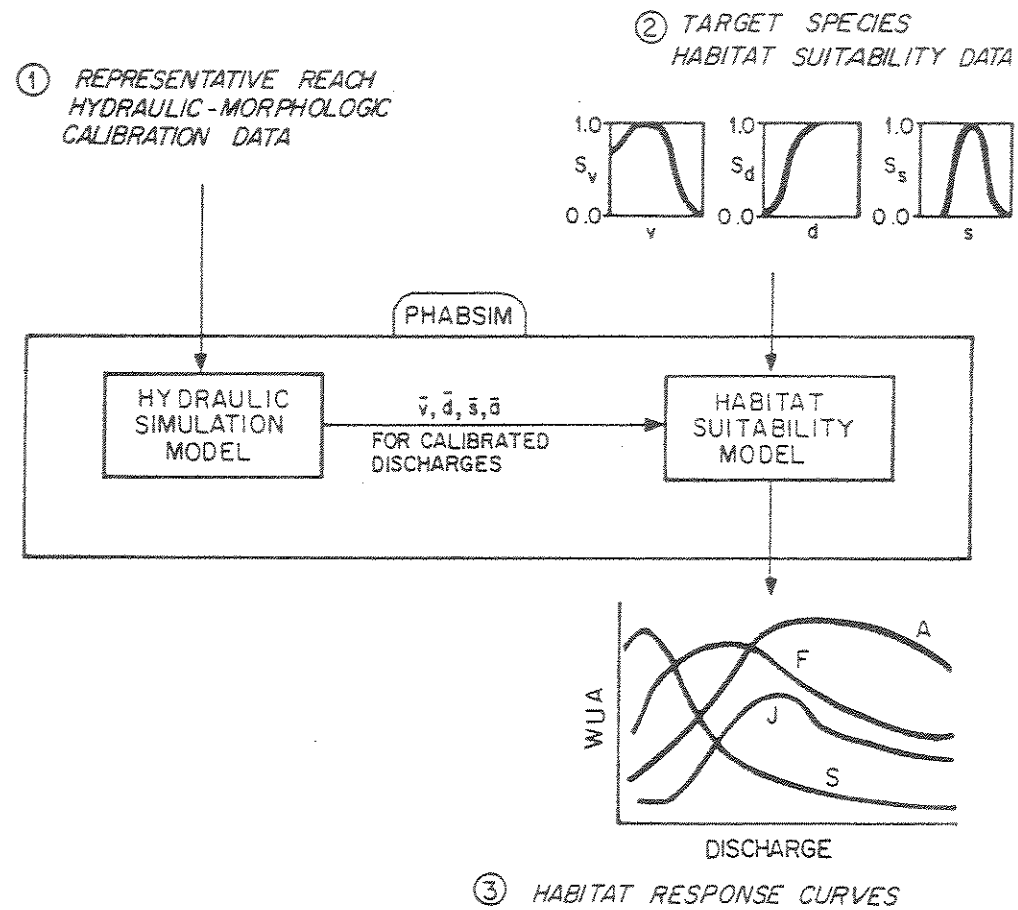

Figure 2. Organization and information processing in the Instream Flow Incremental Method (IFIM) for instream flow assessment (from Loar and Sale 1981).

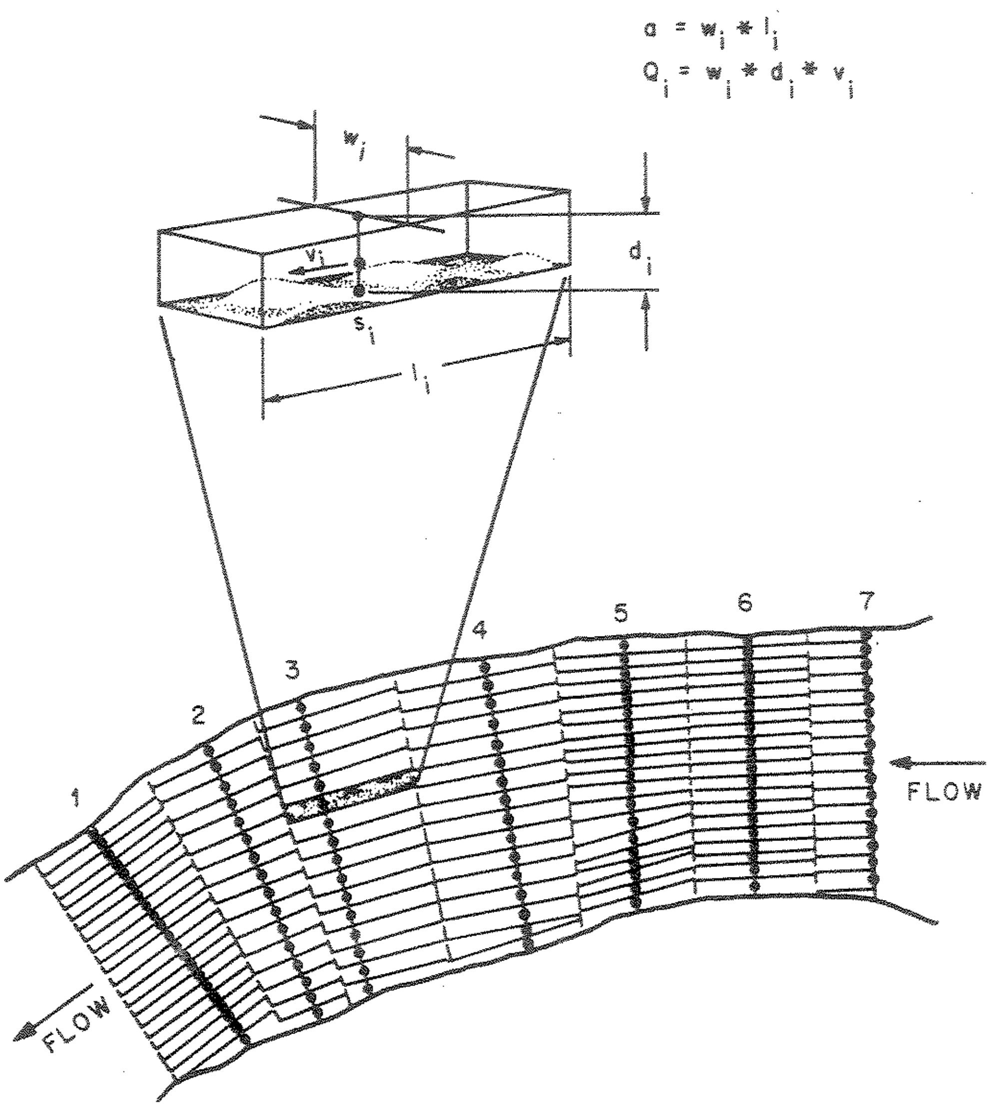

Figure 3. Subdivision of a stream reach into transects and mapping cells for computational purposes with the Instream Flow Incremental Method (IFIM) (from Loar and Sale 1981).

cells in the study section to determine total weighted usable area (WUA) at a given flow for a life stage of a species (i.e., WUA for rainbow trout fry in stream section "x" at 13 cfs). Using habitat suitability curves and depth and velocity predictions from the hydraulic model, graphs of WUA versus discharge for various life stages of a fish species can be generated (i.e., lower right in Figure 2).

Advantages and Limitations of IFM's

There are a number of IFM's that can be employed to determine the instream flow needs for fishery resources. Wesche and Rechard (1980) listed 11 common techniques, many of which are still in use. There is no consensus on which method is the most appropriate for all situations. Such a consensus may not be possible because of regional differences in instream flow program structures and goals, hydrology, channel morphology, fish community structure and habitat use, available funding, and continuing advances in the "state-of-the-art" of instream flow analysis.

Because there is no "best" method to determine instream flows to meet fishery needs under all conditions, the following discussion will examine the assumptions, strengths, and limitations of the main IFM's. The interested reader is encouraged to consult the excellent review by Loar and Sale (1981) since much of the following is derived from that source. Since the main objective of this report is to evaluate Montana's wetted perimeter inflection point method, particular attention will be paid to this technique.

We will discuss the advantages and limitations of the various IFM's with regard to the following main subject areas: hydraulics and channel morphology, decision-making capabilities, and data and manpower requirements. Many of the IFM evaluation studies conducted to date will be discussed with particular attention paid to assumptions and experimental design. Finally, the results of studies that evaluate the effectiveness of Montana's wetted perimeter method are summarized, and criteria for selecting a particular IFM are discussed.

Hydraulics and Channel Morphology

The ability of various IFM's to account for differences in channel morphology between watersheds or even individual stream reaches is an important consideration. The "non-field" IFM's have the least ability to compensate for such differences because they do not rely on site-specific relationships between habitat and discharge. For example, the Tennant Method (probably the most widely used non-field IFM) assumes that a certain percentage of mean annual flow will provide adequate channel width and depth to maintain aquatic resources at some desired level. However, watershed geomorphology investigations have identified a number of variables besides flow frequency (such as watershed area, geology, slope, age, and stream order) that play important roles in determining stream channel and flow characteristics. These variables have been shown to vary significantly between watersheds but none of the common "non-field" IFM's address this problem (Loar and Sale 1981). Hence these methods are best suited for regional application where assumptions regarding the relationship between channel geometry, stream flow and habitat are met.

The "incremental" and "habitat retention" IFM's utilize site-specific habitat measurements that account for differences in channel morphology between watersheds or stream reaches by developing habitat-discharge relationships for each stream reach. To develop these relationships, some form of hydraulic model (either empirical or mathematical) is used. Each type of hydraulic model is based on certain assumptions and has certain advantages and limitations.

Empirical relationships between habitat and discharge are derived by direct measurement over a range of stream flows. This is a simple and straightforward approach but it involves extensive time and manpower investments and offers limited ability to predict habitat characteristics outside the range of observed flows. Trihey and Baldridge (1985) recommend an empirical approach for high gradient streams with complex hydraulic features, but their method requires three or more field visits to develop acceptable habitat-discharge relationships. The need for a large number of site visits is common with empirical approaches because habitat-discharge relationships are seldom linear, thus necessitating numerous "points" (data sets) on graphs to adequately describe these relationships. Extrapolation between and beyond observed test flows can be a questionable practice if empirical field data are inadequate to properly describe the shape of habitat-discharge curves.

Mathematical models are used by many of the field-oriented IFM's to (1) reduce the amount of field effort required and (2) provide more ability to extrapolate beyond observed flows. Three general types of hydraulic models are typically used. The simplest and most direct hydraulic models are those based on stage-discharge relationships generated by regression techniques. These relationships are commonly derived from field measurements made at three different flows, although accuracy can be improved by additional measurements. In certain instances, measurements can be made at two flow levels but significant "two-point" errors can result (Bovee and Milhous 1978).

Several "habitat retention" IFM's such as the R2-Cross, or Colorado Method utilize a second type of hydraulic model based on Manning's equation. This model develops a simulated stage-discharge relationship for a given cross- section based on field measurements of cross-sectional area, hydraulic radius, energy slope, and channel roughness at a single discharge. This method is advantageous because it entails only one set of field measurements. However, it is not well suited to natural stream channels where flow conditions are not always uniform. Manning's equation was developed to describe flow conditions in manmade channels where energy slope and channel roughness (Manning's "n") remain relatively constant as flow changes. These coefficients often vary significantly in natural channels as discharge changes, thus reducing the accuracy of the predicted stage-discharge relationship (Bovee and Milhous 1978). Consequently, for most natural stream channels, stage-discharge relationships are best obtained using an empirical approach using three (or more) sets of field observations. The regression approach also allows extrapolation over a greater range of flows (Bovee and Milhous 1978).

"Step-backwater" models comprise the third main group of hydraulic models used in IFM's. The most well known of these models is the WSP (Water Surface Profile) model. This method produces three dimensional depth and velocity maps of a stream section using Manning's equation and the Bernoulli Energy Equation. It can be applied using only one set of field measurements, but its accuracy and range of extrapolation can be enhanced by one or more additional sets of field data (Bietz et al. 1985). Step-backwater models require more precise and detailed field survey data and also require accurate and mandatory placement of transects across all hydraulic control points in the study section. IFIM is the most flexible IFM in terms of hydraulic modeling because it allows the use of empirical, regression, or step-backwater procedures as well as combinations of the latter two.

Decision-Making Capabilities

All the various IFM's have advantages and disadvantages in terms of ease of interpretation for decision making, ability to "customize" flow recommendations, and defensibility of decision criteria and processes. Trihey and Stalnaker (1985) identified two types of IFM's that relate to decision-making capabilities. They are the "standard setting" methods and the "incremental" methods. What we've called "non-field" and "habitat retention" methods are standard setting methods. These methods identify minimum flow standards that may constrain development, whereas incremental methods (of which IFIM is the best known) quantify tradeoffs by examining fish habitat responses to flow alterations.

The standard setting methods are by far the easiest to interpret for making decisions since they are concerned with setting minimum flows, whether it be for spawning, passage, incubation, rearing, or food production. However, because these methods recommend minimum flows they can actually compromise some portion of the aquatic resource if these minimum flows are all that is maintained during the period of recommendation. Trihey and Stalnaker's (1985) analogy was that fish communities may be able to withstand near-drought conditions for one year in ten (or one month per year), however, standard setting methods may impose such conditions for 10 out of 10 years (or all months of the year). This could have serious biological consequences because fish and other aquatic organisms are often dependent on seasonal variations in streamflow.

Incremental methods, in particular IFIM, can compensate for this problem to some degree because they can develop seasonal flow recommendations for several life stages of many species if adequate hydrologic and habitat suitability data are available. In this regard it is a superior method to the "habitat retention" methods that consider flow-related changes in only one (such as riffle wetted perimeter) or a very few habitat components to indicate overall ecosystem response. The ability of IFIM to generate complex seasonal/species/life stage-specific flow recommendations can also be a limitation. At times, an almost overwhelming amount of information can be generated, creating problems with data synthesis and determination of recommended flows. Problems that must be addressed include determining which life stage is most limiting to a species, and which life stage of which species is most important during a given season. These difficult decisions often require "professional judgment" and are necessary because a flow that is beneficial to one life stage of a given species may be detrimental to other species or to other life stages of the same species.

The various procedures used by IFM's to derive the final flow recommendation(s) offer certain advantages and limitations. The simplest and most direct procedures are employed by the "non-field" methods that simply select percentages of annual flow or some other measure of flow frequency. While this approach lacks biological sensitivity and, at times, is unrealistic, the mechanics of deriving the flow recommendations are relatively unassailable.

The approaches used by various "habitat retention" IFM's to derive final flow recommendations are the source of some controversy. Two approaches are typically used. The first uses habitat criteria for such things as depth, velocity, width, and wetted perimeter as shown previously in Table 1. For example, the Oregon method specifies that minimum flows for salmonid rearing must provide adequate depth in riffles, cover approximately 60% of riffle area by flow, provide 1.0 to 1.5 feet/sec riffle water velocity, provide 0.3 to 0.8 feet/sec pool water velocity, and must produce a pool:riffle ratio of 50:50

(Thompson 1972). The second approach relies on the identification of inflection (or breaking) points on habitat-discharge curves to identify critical flows below which habitat losses increase rapidly.

Loar and Sale (1981) and Annear and Conder (1984) criticized the inflection point approach as being too subjective and having the potential to "create rather than alleviate controversy over water allocation needs." Loar and Sale (1981) recommend using habitat criteria because they "are much less ambiguous than inflection-point calculations and are preferable because the value judgments are clear and relatively more defensible." However, Bietz et al. (1985) presented an entirely opposite argument and rejected the use of habitat criteria because none of the parameters have been directly related to habitat quality. They further state: "The relationship between <u>percent</u> (emphasis added) wetted perimeter retained and aquatic habitat quality is even more tenuous. Unlike the wetted perimeter inflection point, there is no currently available rationale for claiming that a fixed percentage of wetted perimeter represents an acceptable or non-acceptable level of aquatic habitat retention."

As emphasized by Loar and Sale (1981), all IFM's involve some level of subjectivity, and professional judgment is essential to formulate final flow recommendations. Inflection point methods require judgment in selecting inflection point flows, while methods employing habitat criteria require judgment in defining the criteria to use. The selection of inflection points is often very simple and requires little professional judgment. However, in some cases the biologist must use judgment to select inflection point flows that will provide adequate habitat for the existing aquatic resource. To employ habitat criteria, the judgment has to be made by the biologist at the outset, but it should not be construed as being any less subjective than that employed in selecting inflection points.

Data and Manpower Requirements

Each IFM has specific requirements for streamflow gaging information, field transect data, and site-specific habitat suitability data for target species. In Montana, the requirements for flow gaging information are critical because most of the stream reaches involved in water allocation proceedings have no gaging records. The habitat retention IFM's are best suited for ungaged streams since they require little or no long-term flow information and also involve one to three or more visits to the site. Flow measurements and channel morphology observations made during these visits give the biologist some idea of the annual hydrologic regime and a "feel" for the flow-related changes in fish habitat quality and quantity.

Many of the non-field IFM's require long-term streamflow records. However, mean annual flow of many streams can be adequately estimated using watershed analysis techniques requiring little or no fieldwork. The Tennant method (a non-field method based on percentage of mean annual flow) can, therefore, be used in the absence of good streamflow records, provided mean annual flow can be accurately predicted from basin characteristics. Long-term hydrologic information is considered essential by the IFG to negotiate flow recommendations.

The non-field IFM's typically require little or no transect information gathered on-site. On the other hand, the habitat-retention and incremental methods often require extensive amounts of transect data at several flows. Field data requirements for habitat retention methods can be substantial if passage, spawning, and rearing flow requirements all need to be determined. This could require two or more sets of transects in different habitats that would each need to be visited three or more times and possibly at different seasons. Montana's wetted perimeter inflection point method is one of the simplest field methods because it requires only three sets of water surface elevation data and one set of channel profile measurements at each transect. In contrast, many other habitat retention methods, as well as IFIM, require depth, velocity, substrate and/or cover measurements at numerous points across each transect for each visit to the site.

Habitat suitability curves for species of interest are essential to the application of IFIM as discussed previously and illustrated in Figure 2. Originally, preferences for depth, velocity, substrate, and cover for a single life stage of a species were thought to be similar in all streams. Hence, suitability data gathered in one stream would be transferrable to others, thus saving additional time and effort. However, problems in applying IFIM in some areas have been traced to the fact that fish may not use habitat equivalently in different stream environments (Nelson 1980c, Annear and Conder 1983). Moyle and Baltz (1985) recommend developing habitat suitability curves on-site for each species of interest because variations in fish population densities and species composition within and between streams can lead to differences in habitat use via intra- and inter-specific competition. Also, well known diurnal and seasonal habitat preference shifts can seriously complicate the use of IFIM (Campbell and Neuner 1985). Perhaps the best solution to this problem is to identify which limiting factors operate during each season to regulate fish populations and then focus instream flow analysis and habitat criteria on these conditions (Campbell and Neuner 1985). If site-specific habitat preference data are indeed mandatory, the costs and time involved in IFIM applications become very high.

Manpower requirements vary significantly among various IFM's and have been discussed in detail by Wesche and Rechard (1980) and Loar and Sale (1981). The "non-field" methods typically require little or no fieldwork and can usually be completed with less than one man-day of office effort. Manpower requirements are highly variable between "habitat retention" methods and depend upon which method is used and what life functions (spawning, incubation, passage, rearing) are considered. According to Wesche and Rechard (1980), the Oregon Method requires 3-6 man-days of field effort and 1-3 man-days of office work to derive recommendations for <u>each</u> of three functions: spawning, passage, and rearing. The Washington Method requires much more effort (man-days): 10-20 field days and 15-30 office days for spawning; the same for rearing; and 5-10 field days and 1-3 office days for wetted perimeter. The Montana wetted perimeter inflection point method requires relatively little manpower - about 4-6 man-days in the field and ½-1 man-days in the office. None of the above manpower estimates include travel time.

As might be expected, IFIM has very high manpower and training time requirements. Loar and Sale (1981) estimated that IFIM would typically require up to ten times the manpower as the simpler habitat retention methods such as the Colorado (R2-Cross) Method and Montana's wetted perimeter inflection point method. In addition to manpower, the training costs for IFIM are very high compared to other methods. The USFWS conducts a mandatory series of 4-5 short courses to train IFIM users. These courses involve 150-170 hours of training and cost $1,500-$2,000 to complete, excluding salary, travel, and lodging expenses. In addition, access to IFIM computer software is extremely limited for non-federal personnel.

IFM Evaluation Studies

The question of how effective various IFM's are for determining instream flow needs for maintenance of fisheries and other aquatic resources is one of the most important issues facing fisheries biologists today, yet remains the most difficult to resolve. Although many studies have been published that "evaluate" one or more IFM's (e.g. Nehring 1979, Prewitt and Carlson 1979, Stalnaker 1979, Hilgert 1981, Orth and Maughan 1982, Annear and Conder 1983 and 1984, Bietz et al. 1985), most of them are deficient because they tended to focus on the mechanics of the models used, or the uniformity of the results, rather than on the biological adequacy of the instream flow recommendations.

The problem of relating the results of various IFM applications directly to fish populations was recognized by Wesche and Rechard (1980), who stated, "the fallacy of the 'state of the art' has been that no methodology, no matter how detailed, addresses the question of potential biological consequences." The following statement by Trihey and Stalnaker (1985) indicates that we continue to face this dilemma:

> "Despite the successes, fisheries biologists have not yet achieved the capability of forecasting the number of fishes produced in response to any particular water management scheme. This question is being brought up more and more in present-day water development and constitutes a third phase. Within the next decade or so a scramble is expected for research and method development aimed at predicting changes in numbers of fish resulting from flow and channel alterations. This will be similar to the 1970's when methods to quantify the response of fish habitat to streamflow were developed. Only after reaching this third phase can we begin to quantify the <u>economic</u> value of altering the instream resource. This will provide an equivalent basis for comparison of fishery resources with other instream/out-of-stream values."

Our inability to thoroughly evaluate the adequacy of instream flow recommendations is related to two major difficulties. These are: (1)

lack of a thorough understanding of the carrying capacity of lotic systems and how various factors operate to limit carrying capacity, and (2) problems with experimental design. Both of these problems are complicated by the fact that aquatic ecosystems are comprised of complex assemblages of organisms that interact with one another as well as with their physical environment (Giger 1973). Further, these interactions may vary seasonally, between life stages of a species, and between stream environments.

Carrying Capacity and Limiting Factors

A persistent problem that hampers efforts to successfully evaluate and apply IFM's is the knowledge of what the carrying capacity of the stream is, whether or not fish populations are at carrying capacity, and what factor(s) act to regulate carrying capacity. Although the concept of carrying capacity may be simply defined (the standing crops of fish that can be maintained indefinitely by the aquatic environment) the controlling mechanisms are not easily quantified. Carrying capacity is determined by the action of one or more limiting factors.

Giger (1973) reviewed a number of publications and agreed with McFadden (1969) who concluded that it was impossible to identify any one factor that exclusively regulated populations of early trout and salmon life stages (fry and juveniles). Rather, a number of factors interact to regulate fish populations and "each factor can be understood properly only within the context of the network of relationships" (Giger 1973). It is likely that limiting factors vary between streams, or at least regionally, due to differences in species composition, hydrology, climate, and habitat.

There is general agreement among researchers that in most cases physical habitat during the late summer, fall, and winter months when streamflows are at annual lows is the primary factor limiting fish populations in western coldwater streams and rivers (Wesche and Rechard 1980, Giger 1973). Loar and Sale (1981) suggest that fish habitat may be a limiting factor only during very high or very low flow conditions. They further state that at intermediate flows when habitat availability is high, other factors such as food production may become more important as limiting factors. It is obvious that continued research is needed to develop consistent methods to identify limiting factors so that instream flow recommendations can be better tailored to suit differing seasons and stream environments (Campbell and Neuner 1985).

Experimental Design

Based on a review of available literature, three main approaches have been used to evaluate the adequacy of various IFM's for making appropriate instream flow recommendations. These are:

(1) Approaches that examine short-term relationships between streamflow or some habitat index (such as weighted usable area (WUA) derived using IFIM) and fish population size or standing crop.

(2) Approaches involving experimental manipulations of flow and fish populations or standing crops.

(3) Long-term studies of relationships between flow regimes and fish populations or standing crops.

Each of the above approaches has certain advantages and limitations. The first is probably the least suitable for evaluating IFM's. At least two studies (Stalnaker 1979, Annear and Conder 1983) have examined the relationships between WUA (a measure of habitat quantity) and trout populations in several streams at one point in time, typically during the low flow period when habitat is assumed to be limiting. While this approach does offer some insight into the ability of IFIM to quantify amounts and quality of fish habitat, it does little to address the question of the adequacy of IFIM's flow recommendations. The relevance of this approach in addressing the first question (relationship between WUA and fish population size) is questionable since one must assume that the fish populations were at carrying capacity during the one point in time when populations were estimated. This assumption is seldom tested, primarily due to a lack of rapid and accepted assessment techniques.

A similar approach was utilized by Orth and Maughan (1982) who examined relationships between WUA and biomass of several fish species in riffle areas of a warmwater stream during two consecutive summer low flow periods. Although significant positive correlations were observed, their work was strongly criticized by Mathur et al. (1985), primarily on the grounds of small sample size and assumptions concerning carrying capacity. Irrespective of these criticisms, the short-term nature of such studies and the lack of any *a priori* knowledge of what the minimum flow should be renders them ineffective in truly evaluating the adequacy of IFM recommendations.

The study by Kraft (1972) illustrates the pitfalls that can be encountered by short-term studies where carrying capacity is not taken into account. In this study (conducted in southwest Montana), responses of a wild brook trout population were related to manipulated flows in a natural stream channel. The results indicated that significant dewatering (up to 90%) during a three-month, summer, low flow period had little effect on trout populations or biomass.

Kraft's results are somewhat surprising in view of the abundant evidence (both experimental and intuitive) supporting the contention that the flow regime plays a major role in regulating fish populations. Shortcomings in

Kraft's study that may explain these anomalous findings are that no attempt was made to determine (1) whether the stream was at carrying capacity, (2) what factor(s) limited the population, and (3) what the long-term effects of such a flow regime might be. (Another possible, although unproven, explanation that would support his findings is that brook trout are more tolerant of low flows than are other trout species.) Kraft's study apparently contained the only evidence that Mathur et al. (1985) could provide to support their suggestion that "short term" reductions in flow may not affect fish population size.

The second IFM evaluation approach involves the manipulation of fish populations and flow regimes in experimental channels. Examples of such designs are studies by Easterbrooks (1981), White et al. (1981), and Randolph (1984). A unique and key ingredient of these studies is the attempt to insure that initial fish population levels are at carrying capacity. This is accomplished by oversaturating the habitat with introduced wild fish, then allowing the population to reach equilibrium (via emigration) prior to dewatering.

This is a conceptually appealing method to examine responses of fish populations (at carrying capacity) and habitat to streamflow reductions, but it also has shortcomings. Randolph (1984) suggested that equilibrium fish population size before and after such experiments may be affected by initial stocking density. While this phenomenon obviously creates some "accounting" problems, it may not significantly affect the overall study objective, which is to identify critical flows and habitat conditions below which the stream's ability to support a healthy aquatic resource rapidly diminishes. Other limitations to this study design are that (1) only one (or a [illegible] at most) stream channel is examined, (2) investigations are usually confined to one flow regime during one period of the year (i.e., late summer low flow), and

(3) it is not applicable to larger streams and rivers because of logistical difficulties.

The third approach to IFM evaluation involves the examination of fish-flow information collected over a period of years on one or more streams. This empirical approach overcomes many of the shortcomings inherent in short-term and/or experimental studies, but it too has limitations. First, this method involves a long-term commitment of time and manpower, probably for at least five to ten or more years. This is essential to insure a diversity of observations at a variety of flows. Long study periods are also required to enable the researcher to follow individual year classes of fishes through their life cycle (from fry to adult) which commonly requires three to five years. Because of the long-term nature of such studies, the researcher must remain aware of, and try to account for, changes in the watershed (logging, grazing, other development) and management policies (fish stocking changes, fishing regulations) that may also affect fish populations. Further, long-term studies can generate enormous amounts of complex hydrologic and fisheries information (if multiple species and life stages are considered), which can prove difficult to compile in a consistent, meaningful, and defensible manner. Consequently, this approach has been applied to only a few waters.

Due to their intensive data requirements, long-term, empirical IFM evaluation studies are relatively rare. They are advantageous because they provide flow recommendations based on direct observations of fish population response to a flow regime under "natural" conditions. The adequacy of IFM flow recommendations can then be critically evaluated, as Nelson (1980a, 1980b and 1980c) and Anderson and Nehring (1985) have done. Annear and Conder (1984) stressed the continued need for such studies:

"The question of adequacy of any instream flow method for fisheries will only be resolved by long-term biological documentation - a component of all comparisons of instream flow methods that is noticeably missing. Until this issue is resolved, studies such as this one will continue to only hint at acceptable procedures for identifying realistic fishery needs for instream flow."

Evaluations of Montana's Wetted Perimeter Method

The adequacy of Montana's wetted perimeter inflection point method has been tested using all three of the above study approaches with generally good results. Orth and Maughan (1982) compared the wetted perimeter, Tennant, and IFIM methods on a warmwater stream in Oklahoma. They found that all three methods produced similar, acceptable minimum flow recommendations for the low flow period.

Randolph (1984) evaluated the wetted perimeter method in a small stream in southwestern Montana during a two-month period in late summer/early fall. Wild rainbow trout densities in three stream sections were enhanced to simulate "carrying capacity" by the relocation of wild fish from upstream areas. He concluded that the wetted perimeter inflection point method produced an accurate minimum flow recommendation for a section characterized by riffle-pool habitat, but it underestimated fish flow needs in riffle-run sections. Fish population response to reduced flows (emigration) appeared to be more closely related to riffle depth (total or longest, continuous top width having depth of 15 cm or more) than to changes in wetted perimeter. Hence, depth criteria may be violated before the wetted perimeter inflection point is reached in the relatively shallow riffle-run habitats of small streams.

Nelson (1980a and 1980b) compared minimum flow recommendations derived using the wetted perimeter, Tennant, and IFIM methods to long-term information on trout standing crop and flow in five reaches of four "blue ribbon" rivers in southwest Montana. With one exception, the empirical trout/flow data sets included information for 4-13 years. He concluded that inflection points on wetted perimeter-discharge curves for one riffle in each river provided acceptable flow recommendations. Recommendations based on composites of several transects through various habitat units (pools, runs, and riffles combined) were not as reliable because inflection points were less easily recognized. The Tennant method was found to be of some use in making minimum flow recommendations, but percentage of flow required appeared to vary between rivers. Finally, IFIM flow recommendations were inordinately low due to the application of a small stream habitat model to a large river and the program's use of mid-depth velocity measurements, rather than the velocities near the stream bottom, to describe the water velocities used by fish. The IFG has since corrected these problems.

Loar et al. (1985a) observed population fluctuations of three age classes of rainbow trout in two Appalachian streams over a two-year period in relation to late summer low flows. They found that young-of-the-year rainbow trout preferred shallow riffle habitats, and flow-related population declines of these fish were related to reductions in riffle wetted perimeter.

Studies by Annear and Conder (1984) and Bietz et al. (1985) examined the consistency of the wetted perimeter recommendations for a number of streams by comparing them to recommendations derived from other methods or by converting them to percentages of the mean annual flow and comparing these to each other. These studies, while contributing to the advancement of the state-of-the-art, are not considered in this discussion because they do not address the adequacy of the wetted perimeter recommendations in maintaining the stream fisheries at acceptable levels.

Criteria for Selecting an IFM

A number of factors must be considered before selecting an appropriate IFM for a given situation. These include biological goals, geographic scope, administrative goals, time and manpower availability, biological and historical streamflow data availability, ability to monitor and enforce flow recommendations, and the type of decision-making process followed.

The geographic scope and the type of water allocation process involved are the primary considerations in selecting an appropriate IFM. Trihey and Stalnaker (1985) concluded that standard setting methods (such as the Tennant method and Montana's wetted perimeter inflection point method) are most appropriate for:

1. Protecting the instream flow resource.
2. State water plans.
3. State water allocation permits or reservations.
4. Identifying target flow for use during project feasibility studies.

They concluded that incremental methods (primarily IFIM) are most appropriate for:

1. Time series analysis to identify limiting flow conditions.
2. Fine tuning a resource maintenance objective (maximum utilization of available water).
3. Avoiding or minimizing flow-related impacts.
4. Comparing mitigation alternatives.

These recommendations carry substantial weight and are based on considerable experience; one of the authors (Dr. Stalnaker) has been the leader of the

IFG since its formation one decade ago.

The "standard setting" methods are most appropriate for basinwide water allocation because they can provide cost effective, simple, single, minimum flow values for a large number of streams with a minimal amount of time consuming negotiations. Simple, minimum flow recommendations facilitate water allocation processes and can be monitored and enforced with relative ease. Other advantages are that these methods require little or no long-term streamflow data and (at least in Montana) appear to provide reasonable minimum flow recommendations for streams and rivers alike.

The high time and manpower requirements and the nature of the decision-making process make IFIM an impractical tool for use in State water allocation programs. As pointed out by the developers of the method (Bovee 1982, Trihey and Stalnaker 1985), IFIM is not designed to set minimum flows. Rather, it is designed for negotiating flow regimes for specific project areas by quantifying flow-related habitat tradeoffs.

We contacted water resource administrators in fish and wildlife agencies in several western states and the provinces of Alberta and British Columbia in early 1986 to solicit their views regarding the use of the wetted perimeter inflection point method and to ascertain which IFM(s) they utilized. The results indicated that most states or provinces follow a hierarchical approach similar to that described by Loar and Sale (1981) or Trihey and Stalnaker (1985). That is, they employ a variety of IFM's (non-field, habitat retention, and incremental) in their programs depending upon the needs of a particular situation. The use of IFIM is usually restricted to significant water development projects or highly controversial allocation disputes.

Six of the eight agencies (Colorado, Washington, Minnesota, Wyoming, Idaho, and British Columbia) that responded indicated that they used some variation of the wetted perimeter method in some part of their instream flow program. California and Alberta do not use the wetted perimeter method. California currently has no basinwide allocation process analogous to Montana's water reservation system, so they are primarily concerned with new water development projects on which they place "conditions" (personal communication with Gary Smith, Fisheries Biologist, California Fish and Game). California requires project developers to fund and conduct IFIM studies, which the State then reviews. Alberta is currently developing a modification of the Tennant method to be used on a basinwide planning scale and uses IFIM on large water development projects.

MONTANA'S INSTREAM FLOW METHOD

An IFM that was compatible with the State's water reservation process was a major consideration when the MDFWP selected its primary method for making instream flow recommendations. Under the reservation process, the unappropriated waters in a basin are allocated among all competing uses, including municipal, agricultural and industrial as well as instream for the protection of fish and wildlife and water quality. When granted, the instream reservation becomes a part of the priority date system, with some future uses subject to, or junior to, the instream reservation. During some time periods, especially in water short years, junior consumptive users will have to comply with the terms of the reservation and cease withdrawing water when streamflows fall below the granted instream flows. Given this requirement, complex flow recommendations that vary by time period and by year are generally unsuitable because they confuse junior water users and exacerbate problems with compliance and policing. A single, year-round recommendation tends to minimize these problems, but such a recommendation may fail to fully satisfy the instream flow needs of all fish species and all of their life stages and functions. However, keeping the recommendations simple appears, in the long run, to be in the best interest of the resource because compliance and policing problems are minimized.

Under the reservation process, the Department has the responsibility for requesting instream flow protection for literally hundreds of streams. Due to the large number of streams, funding, manpower and time limitations also became an important consideration in the selection of an appropriate method. Of the three broad categories of methods previously described, two were quickly relegated to a secondary role in deriving recommendations under the reservation process.

Office or non-field methods (Category 1) were judged less desirable because of the Department's contention that the recommendations would be more credible if they reflected stream-specific habitat and discharge relationships rather than a flow quantity derived solely from the historic flow record. Furthermore, the lack of sufficient historic flow data for the vast majority of Montana's streams precluded the use of virtually all office methods. In addition, the consensus in the literature is that this category should be confined to deriving preliminary or reconnaissance grade recommendations (Stalnaker and Arnette 1976), thus limiting their suitability for Montana's reservation program.

Methods that apply species- and life stage-specific habitat criteria in evaluating the condition of the stream environment at various flows (Category 3) proved to be incompatible with the basic goal of the Department's instream flow program, which is to set flow recommendations at a level that will sustain existing fishery resources. Category 3 methods, of which the IFIM is the best known and most commonly applied example, were designed to be used in negotiating flows rather than setting minimum standards. This is a costly, complex and time consuming analysis that has limited application in Montana's water reservation process.

Those methods that examine various components of a stream's hydraulic characteristics at various flows for the purpose of developing generalized habitat-discharge relationships are included in Category 2. The flow recommendations would not, in most cases, be based on detailed evaluations of the habitat requirements of specific fish species or life stages. The simplified prediction techniques that this group uses in evaluating the condition of the stream environment reduce the field data requirements to the point where dollar costs, manpower needs and time expended are reasonable. The outcome of the analysis is a minimum flow standard that is intended to fully protect some aspect of the stream resource. These methods are most appropriate when instream protection is requested for a large number of streams, as occurs in state water allocation programs (Trihey and Stalnaker 1985).

The MDFWP was, therefore, limited to selecting a method from Category 2. The method chosen was the wetted perimeter inflection point method. A brief description of the method, its assumptions and data needs follow.

Wetted Perimeter Inflection Point Method

This method focuses on the previously discussed assumption that the food supply can be a major factor influencing a stream's carrying capacity during the non-winter months. The principal food of many of the juvenile and adult game fish inhabiting the streams of Montana is aquatic invertebrates, which are produced primarily in stream riffle areas. The method assumes that the game fish carrying capacity is related to food production, which in turn is related to the amount of wetted perimeter in riffles.

Wetted perimeter is the distance along the bottom and sides of a channel cross-section in contact with water (Figure 4). As the flow in a stream channel increases, the wetted perimeter also increases, but the rate of gain of wetted perimeter is not constant throughout the entire range of flows.

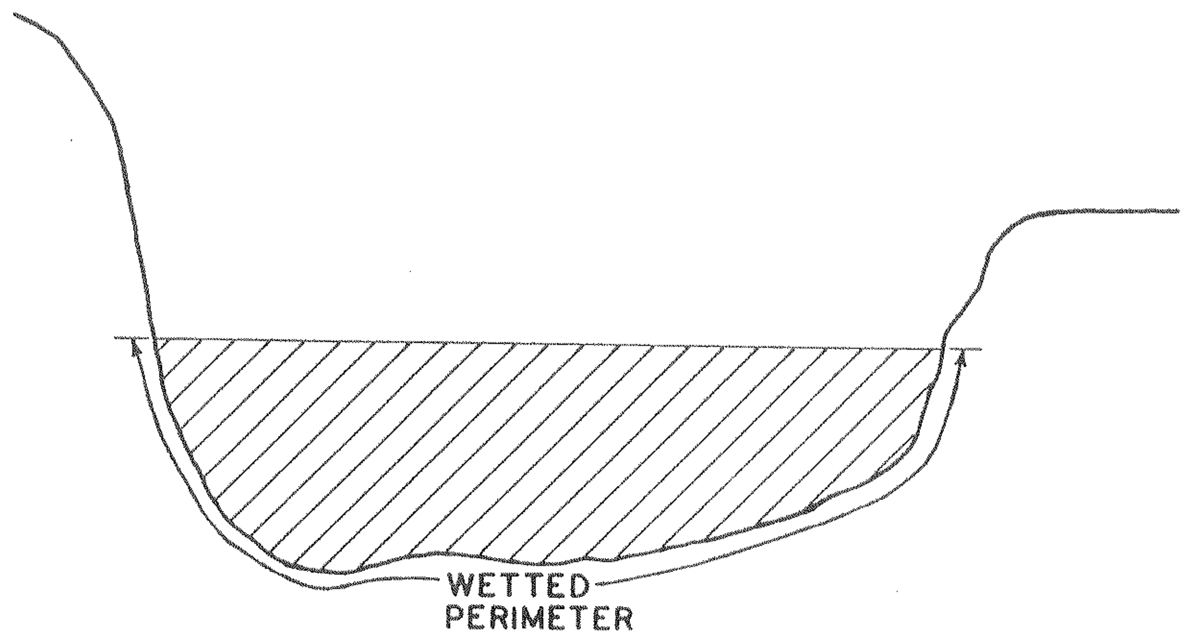

Figure 4. The wetted perimeter in a channel cross-section.

The plot of wetted perimeter versus flow for stream riffle cross-sections generally, but not always, shows two points, referred to as break or inflection points, where the rate of increase of wetted perimeter changes. In the example (Figure 5), these inflection points occur at approximate flows of 8 and 12 cfs. Below the lower inflection point, the flow is spreading out horizontally across the stream bottom, causing the wetted perimeter to increase rapidly for very small increases in flow. A point is eventually reached (at the lower inflection point) where the water starts to move up the sides of the active channel and the rate of increase of wetted perimeter begins to decline. At the upper inflection point, the stream is approaching its maximum width and begins to move up the banks as flow increases. Large increases in flow beyond the upper inflection point cause only small increases in wetted perimeter. Flow levels at these inflection points are depicted in Figure 6.

The area available for food production is considered near optimal at the upper inflection point because almost all of the available riffle area is wetted. At flows below the upper inflection point, the stream begins to pull away from the riffle bottom until, at the lower inflection point, the rate of loss of wetted bottom begins to rapidly accelerate. Once flows are reduced below the lower inflection point, the riffle bottom is being exposed at an even greater rate and the area available for food production greatly diminishes. The method is intended to establish a threshold below which a stream's food producing capacity begins to decline (upper inflection point) and a threshold at which the loss is judged unacceptable (lower inflection point).

While this inflection point concept focuses on food production, there are indications that wetted perimeter relates to other factors that influence a

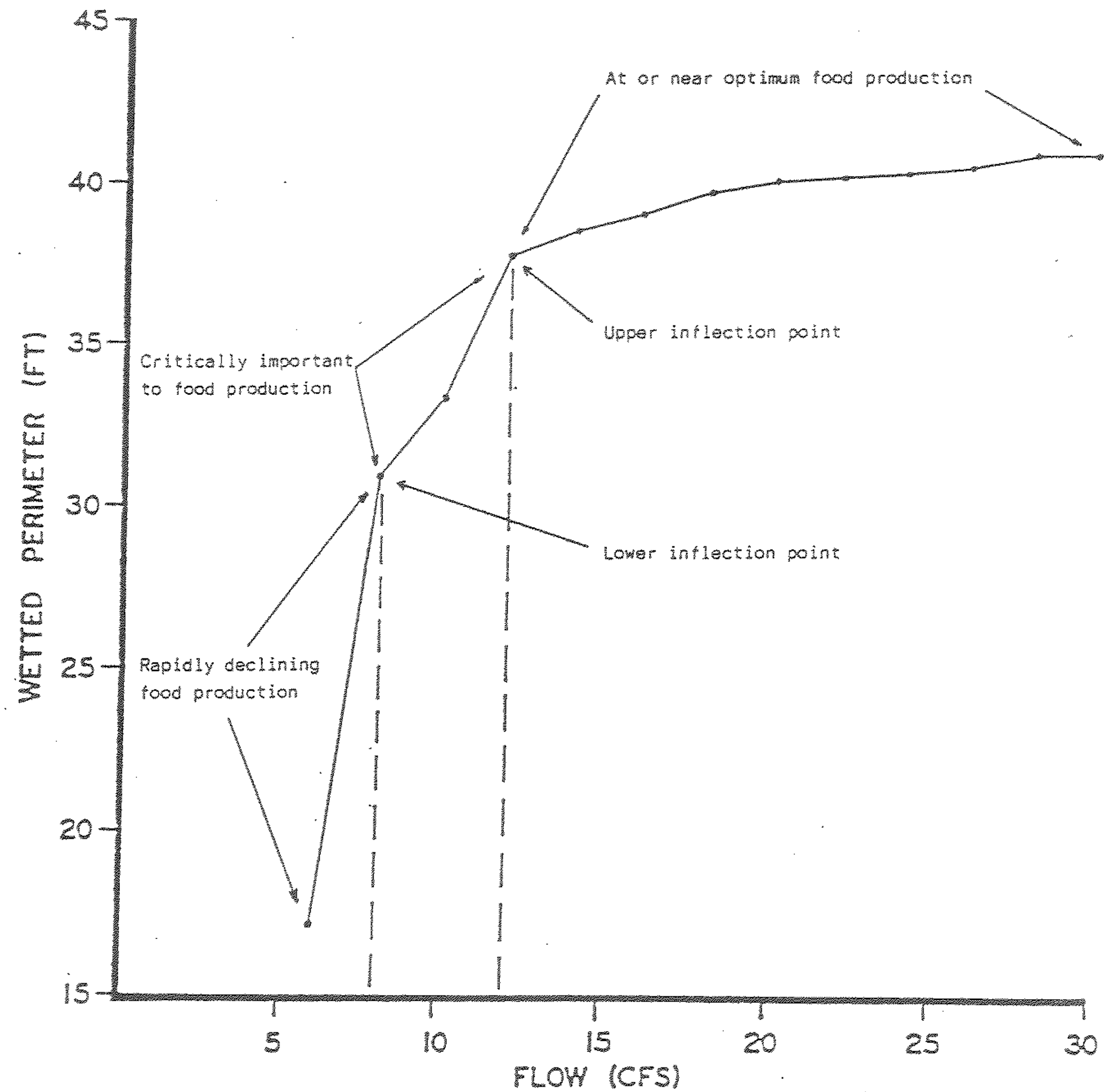

Figure 5. An example of a relationship between wetted perimeter and flow for a stream riffle cross-section showing upper and lower inflection points.

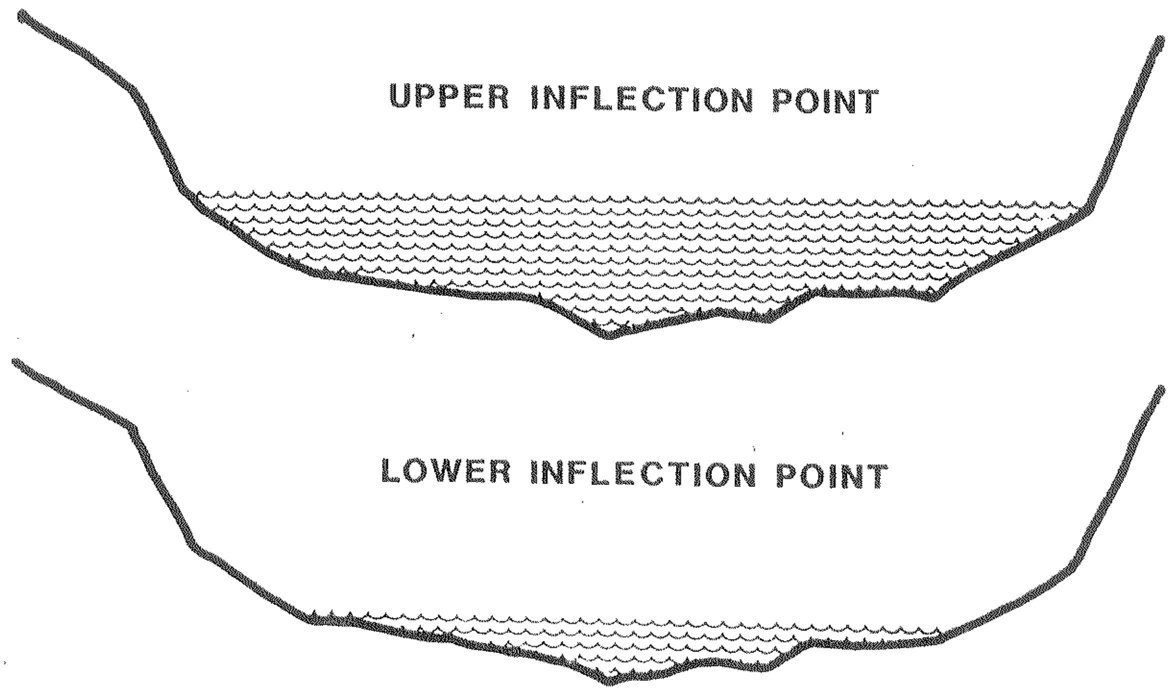

Figure 6. A diagrammatic representation of the flow at the upper and lower inflection points in a stream cross-section.

stream's carrying capacity. One such factor is cover (or shelter), a well recognized component of fish habitat.

In the headwater streams of Montana, overhanging and submerged bank vegetation and undercut banks are often important components of cover. In Wyoming, overhead bank vegetation was the cover parameter that explained the greatest amount of variation in trout population size in small, brown trout streams (Wesche et al. 1987). The wetted perimeter-flow relationship for a stream channel is, in some cases, similar to the relationship between bank cover and flow. Flows exceeding the upper inflection point are considered to provide near optimal bank cover. Below the upper inflection point, the water pulls away from the banks, decreasing the amount of bank cover associated with water. At flows below the lower inflection point, the water is sufficiently removed from the bank cover to severely reduce its value as fish shelter. Support for this relationship is provided by Randolph (1984), who found a high correlation between riffle wetted perimeter at various flows and the total area of overhanging bank vegetation (r = 0.88-1.00) and undercut banks (r = 0.84-0.97) for three study sections in a small Montana stream.

In addition to producing food, riffles also are used by many game fish species for spawning and the rearing of their young (Sando 1981 and Loar et al. 1985a). Thus, the protection of riffles insures that the habitat required for these critical life functions is also protected.

Another important consideration that supports the keying of recommendations to riffles is the fact that riffles are the area of a stream most affected by flow reductions (Bovee 1974, Nelson 1977 and Loar et al. 1985a). By providing a recommendation that wets a large portion of the available riffle area, we are, at the same time, helping to protect both runs and pools - areas where adult fish normally reside.

The wetted perimeter inflection point method provides a range of flows (between the lower and upper inflection points) from which a single instream flow recommendation is selected. Flows below the lower inflection point are judged undesirable based on their probable impacts on food production, bank cover, and spawning and rearing habitats. Flows exceeding the upper inflection point are considered to provide near optimal conditions for fish. The upper and lower inflection points are believed to bracket those flows needed to maintain the high and low levels of aquatic habitat potential. These flow levels are defined as follows:

1. High Level of Aquatic Habitat Potential - That flow regime which will consistently produce abundant, healthy and thriving aquatic populations. In the case of game fish species, these flows would produce abundant game fish populations capable of sustaining a good to excellent sport fishery for the size of stream involved. For rare, threatened or endangered species, flows to accomplish the high level of aquatic habitat maintenance would: 1) provide the high population levels needed to ensure the continued existence of that species, or 2) provide the flow levels above those which would adversely affect the species.

2. Low Level of Aquatic Habitat Potential - Flows to accomplish a low level of aquatic habitat maintenance would provide for only a low population of the species present. In the case of game fish species, a poor sport fishery could still be provided. For rare, threatened or endangered species, their populations would exist at low or marginal levels. In some cases, this flow level would not be sufficient to maintain certain species.

The final flow recommendation is generally selected from this range of flows by a consensus of the biologists who collected and analyzed all relevant field data for the stream of interest. The biologists' rating of the stream resource forms the basis for the flow selection process. Factors considered in the evaluation include: (1) the level of recreational use, (2) the existing level of environmental degradation, (3) water availability and (4) the magnitude and composition of existing fish populations. Fish population information, which is essential for all streams, is a major consideration. A marginal or poor fishery would likely justify a flow recommendation at or near the lower inflection point unless other considerations, such as the presence of species of "special concern" (arctic grayling and cutthroat trout, for example) warrant a higher flow. In general, streams with significant resident fish populations, those providing crucial spawning and/or rearing habitats for migratory populations, and those supporting significant populations of species of "special concern" should be considered for recommendations at or near the upper inflection point.

Other candidates for upper inflection point recommendations are streams that have the capacity to provide outstanding fisheries, but are prevented from reaching their potential due to stream dewatering. The flow at the upper inflection point would provide a goal to strive for should the means become available to improve streamflows through such mechanisms as water storage projects or the purchase of irrigation rights. Streams that are subjected to other forms of environmental degradation, such as mining pollution, and which have the potential to support significant fisheries if reclaimed, are additional candidates for upper inflection point recommendations.

The process of deriving the flow recommendation for the low flow period thus combines a field method (wetted perimeter inflection point method) with a thorough evaluation by field biologists of the existing stream resource.

Brief Description of the Wetted Perimeter (WETP) Computer Program and Data Needs

The wetted perimeter-flow relationship for a stream of interest is derived using a wetted perimeter predictive (WETP) computer program developed in 1980 for the MDFWP.

Two pieces of information - the cross-sectional profile and stage-discharge rating curve - are required for each riffle cross-section as input to the WETP program. These data are obtained in the field using standard surveying procedures.

The stage-discharge rating curve describes the relationship between the height of the water surface (the stage) in the riffle cross-section and the magnitude of the flow (discharge) through the cross-section. This rating curve, when coupled with the cross-sectional profile, is all that is needed to compute the riffle wetted perimeter at most flows of interest.

The WETP program requires at least two sets of stage measurements taken at different known flows to develop the stage-discharge rating curve. However, the use of three sets of stage-discharge data collected at a high, intermediate and low flow is recommended. The three measurements are made when runoff is receding (high flow), near the end of runoff (intermediate flow) and during late summer-early fall (low flow). The high flow should be considerably less than the bankfull flow, while the low flow should approximate the lowest flow that normally occurs during the summer-fall season. Although the WETP program will run using only two sets of stage-discharge data, this practice is not recommended because substantial "two-point" error can result. However, when only two data sets are obtainable, the higher discharge should be at least twice as high as the lower discharge.

The channel profile also has to be measured for each cross-section. Unlike the measurements of water surface elevation, this has to be done only once. It is best to measure profiles at the lowest calibration flow when wading is easiest.

The wetted perimeter method is applied solely to riffles. Cross-sections can be established in a single riffle or in a number of different riffles. Cross-sections should describe the typical riffle habitat within the stream segment being studied. For each riffle, the upper limit is three cross-sections placed at the riffle's head, middle and bottom. Fewer can be used if the riffle is fairly uniform. To be safe, you may want to model two or three separate riffles in each study area. At least three and preferably five riffle cross-sections should be used in the WETP analysis. The WETP program accepts up to 10 cross-sections. The computed wetted perimeters for all riffle cross-sections at each flow of interest are averaged and the recommendation derived from the wetted perimeter-flow relationship for the composite of all riffle cross-sections.

An in-depth description of the WETP computer program and data collection procedures is provided in a publication titled "Guidelines for Using the Wetted Perimeter (WETP) Computer Program of the Montana Department of Fish, Wildlife and Parks" (Nelson 1984a).

MONTANA'S WETTED PERIMETER METHOD - FINAL CONSIDERATIONS

The wetted perimeter method is intended to quantify the flow needs of fish during the non-winter period from approximately April through October, excluding the high flow, or snow runoff, months of May, June and July when about 75% of a stream's annual water yield passes through the system (Figure 1). Flow recommendations for the high flow period should be based on those flows deemed necessary for flushing the annual accumulation of bottom sediments and maintaining the existing channel morphology.

A stream's annual high flow characteristics are generally accepted as being the major force in the establishment and maintenance of channel form. It is the high spring flows that determine the shape of the channel rather than the average or low flows.

The major functions of the high flows in the maintenance of channel form are bedload movement and sediment transport. It is the movement of the bed and bank material and subsequent deposition which forms the mid-channel bars and, subsequently, the islands. High flows are capable of covering already established bars with finer material, which leads successively to vegetated islands. Increased discharge associated with spring runoff also results in a flushing action, which removes deposited sediments and maintains suitable gravel conditions for aquatic insect production, fish spawning and egg incubation.

Reducing the high spring flows beyond the point where the major amount of bedload and sediment is transported would interrupt the [illegible] channel processes and change the existing channel form and bottom surfaces. A significantly altered channel configuration would affect both the abundance and species composition of the present aquatic populations by altering the existing habitat types.

Montana's high flow method, termed the dominant discharge/channel morphology concept (Montana Dept. of Fish and Game 1979), requires at least 10 years of continuous USGS gage records to derive recommendations and, consequently, cannot be applied to most streams. Recommendations from the wetted perimeter inflection point method do not satisfy flushing or channel maintenance requirements. Because most water users, particularly irrigators, are unable to divert a significant portion of the runoff flows and, therefore, are incapable of materially impacting the high flow functions of bedload movement and sediment transport, high flow recommendations may be unnecessary in most cases. Therefore, extending the wetted perimeter recommendations through the high flow period - a common practice of the MDFWP - should not jeopardize the maintenance of adequate high flows for most streams. Furthermore, Montana law limits the granted instream flows for gaged streams to no more than 50% of the average annual flow, thus eliminating flushing and channel maintenance flows from consideration in a reservation application.

As discussed in an earlier section, the protection of natural flow levels during the critical winter months is justified if the goal is to maintain fish populations at their existing levels. As a guideline, the winter recommendation should not be less than the base flow, which is defined as the lowest mean monthly flow during the winter months. Because the vast majority of Montana's waters are ungaged, winter base flows are unquantified for most streams. Past work by the MDFWP has shown that the upper inflection point recommendations of the wetted perimeter method typically exceed base flows (Leathe et al. 1985). Winter flows would, therefore, be protected if upper inflection point recommendations were extended through the winter period. This is a common practice of the MDFWP when recommending flows. Lower inflection point recommendations are normally inadequate for protecting winter base flows.

Regardless of the method used to quantify instream flows, there will be some time periods, especially during drought years, when the recommendations exceed the available flows. Only when the recommendations equal the historic low flows would they never exceed the available water supply. However, such recommendations would devastate a stream fishery if maintained for any length of time and are analogous to asking a farmer to produce his crops using only the amount of water available during the worst drought year on record.

Leathe and Enk (1985) evaluated the amount of time the wetted perimeter recommendations for five gaged, mountain streams in Montana's Swan River drainage exceeded the available streamflows. Year-round, upper inflection point recommendations were found to exceed daily streamflows from 24 to 64% of the time, depending on which of the five streams was evaluated. On the average, recommendations exceeded the available daily flows 41% of the time and, conversely, were less than the daily flows 59% of the time. In other words, excess water would be available for other uses 59% of the time, on the average. Unpublished data for a number of the larger rivers in southwest Montana showed that the wetted perimeter recommendations generally fell within the 60th to 90th percentile range of flows, meaning that the available daily streamflows, even with existing depletions, will still exceed the recommendations from 60 to 90% of the time.

The wetted perimeter inflection point method has primarily been applied in Montana to coldwater trout streams east and west of the Continental Divide. Results of validation studies in Montana support the use of this method in deriving minimum flow recommendations for these waters (Nelson 1980a, 1980b and 1980c and Randolph 1984). The logic behind the method should apply to warmwater streams as well. However, no biological studies have been conducted in Montana to confirm the reliability of warmwater recommendations, although a warmwater evaluation in Oklahoma supported the use of wetted perimeter (Orth and Maughan 1982).

The wetted perimeter method is unsuitable in certain situations. The method is designed for use on stream reaches in which the flow is confined to a single channel, although the application to side channels off of main river channels is a commonly used approach for deriving recommendations for those rivers in which side channels are crucial to the well-being of certain species. When the flow is distributed among many channels, cross-sections through these braided reaches are very difficult to model hydraulically, making most computer models, including WETP, unworkable in this situation. Waters having little or no riffle development, such as cascading mountain streams that plunge from pool to pool and some low gradient, prairie streams, are another exception, as are spring creeks. The stable, year-round flows that characterize spring creeks prevent the collection of field data at a high, medium and low flow - information needed to calibrate the WETP computer program.

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