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INSTREAM FLOW METHODS: A COMPARISON OF APPROACHES

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ABSTRACT

Minimum flows in rivers and streams aim to provide a certain level of protection for the aquatic environment. The level of protection is described by a measure such as a prescribed proportion of historic flows, wetted perimeter or suitable habitat. Conflicting minimum flow assessments from different instream flow methods are arguably the result of different environmental goals and levels of protection. The goals, the way in which levels of protection are specified, and the relationship between levels of protection and the aquatic environment are examined for three major categories of flow assessment methods: historic flow, hydraulic geometry and habitat. Basic conceptual differences are identified. Flow assessments by historic flow and hydraulic methods are related to river size and tend to retain the 'character' of a river. Habitat-based methods make no *a priori* assumptions about the natural state of the river and flow assessments are based primarily on water depth and velocity requirements. Flow and hydraulic methods assume that lower than natural flows will degrade the stream ecosystem, whereas habitat methods accept the possibility that aspects of the natural ecosystem can be enhanced by other than naturally occurring flows. Application of hydraulic and habitat methods suggests that the environmental response to flow is not linear; the relative change in width and habitat with flow is greater for small rivers than for large. Small rivers are more 'at risk' than large rivers and require a higher proportion of the average flow to maintain similar levels of environmental protection. Habitat methods are focused on target species or specific instream uses, and are useful where there are clear management objectives and an understanding of ecosystem requirements. Flow and hydraulic methods are useful in cases where there is a poor understanding of the ecosystem or where a high level of protection for an existing ecosystem is required. ©1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Organizations responsible for water management are becoming increasingly aware of their responsibilities for environmental protection, creating an increasing interest in methods of assessing flow requirements for different instream uses (e. g. Petts, 1989). In Europe, there are attempts to rehabilitate large rivers that have been controlled and channelized for centuries. In the USA, attempts are being made to rehabilitate the lower Mississippi River (e.g. Gent *et al*., 1995) and, in Australia, the extensive flow regulation of the Murray–Darling River system is being questioned (McPhail and Young, 1992). On a smaller scale, the impact of water use on the stream environment is often assessed whenever development of the water resource is proposed or when the rights of use for that resource are reviewed. In 1976, the American Fisheries Society convened a landmark conference that discussed methods of assessing instream flow requirements. The debate over the merits of different methods has continued since then. The discussion of flow assessment methods has been extensive, without any real resolution (e.g. Stalnaker and Arnette, 1976; Wesche and Rechard, 1980; Schuytema, 1982; Karim *et al*., 1995; Trihey and Stalnaker, 1985; Estes and Orsborn 1986; Morhardt and Altouney, 1986; Richardson, 1986).

Quantitative instream flow methods are generally divided into three major categories: (1) historic flow regime, (2) hydraulic and (3) habitat (e.g. Orth and White, 1993; Karim *et al*., 1995). Methods within these categories tend to be based on similar principles and assumptions. Although all three categories aim to maintain the stream

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environment, they focus on different aspects of the stream, such as flow, wetted perimeter or physical habitat. An instream flow policy requires clear and measurable goals, ideally defining the goal (e. g. retention of a resource or instream use), the extent to which this is to be achieved (i.e. level of protection) and criteria for evaluating the achievement (Beecher, 1990). In practice, either the proportion of flow, wetted perimeter or physical habitat that is retained by a minimum flow is used as a measure of the level of protection. For example, Tennant (1976) considered that 10% of the average flow provided minimum protection and that 30% of average flow was satisfactory. Habitat methods use habitat/flow relationships to define the flow that provides maximum habitat, or a flow below which the area of suitable habitat begins to decrease rapidly. In all methods there is an implicit assumption that the proportion of flow, wetted perimeter or physical habitat specified as a level of protection will reflect the condition of the stream environment. Furthermore, it is often assumed that there is a linear relationship between the amount of flow and the state of the stream environment, and/or some cut-off level or 'minimum' flow below which aquatic life would not be sustained. However, environmental response to flow is probably a continuum along which a decision can be made in order to achieve different levels of protection.

It is generally accepted that current is the driving force of stream ecosystems. Current affects most of the six primary factors that influence stream ecosystems; food, physical habitat, temperature, water quality, flow regime and biotic interactions (Orth, 1987). No flow assessment method addresses all these factors specifically, although Orth (1987) suggests that the IFIM process (Bovee, 1982) allows the consideration of these ecological factors. Similar considerations could also be made in conjunction with other methods of flow assessment.

Annear and Conder (1984) compared flow assessments by different methods, rather than the mechanics of the methods. They found that, relative to other methods, habitat methods usually gave higher minimum flow estimates for small streams and lower estimates for large streams. Other investigators using hydraulic and habitat methods have also found that flow requirements, as a proportion of average flow, are relatively higher for small streams than for large ones (Jowett, 1993; O'Shea, 1995). Differences between methods do not mean that one is right and the other wrong. Some methods may be better suited to some conditions than others. In order to select a method that is appropriate to management needs, it is essential to understand the morphological implications and ecological assumptions that underlie methods, and the effect of these assumptions on flow assessments.

In this study, three categories of flow assessment methods and their associated methods for selecting minimum flows are reviewed. For each category, potential outcomes are examined in terms of fluvial morphology and the ecological assumptions that form the basis of the methods. Finally, the practical application of these methods to water allocation planning and the need for clear definitions of the resource to be protected, management goals and appropriate levels of protection are discussed.

INSTREAM FLOW METHODS AND MINIMUM FLOW REQUIREMENTS

Historic flow methods

As the name implies, historic flow methods rely solely on the recorded or estimated flow regime of the river.

The Tennant (1976) method [also known as the 'Montana' method although it is not used in that state (Reiser *et al.*, 1989)] is perhaps the most widely known of these methods. It is the second most popular method in the USA and is used or recognized by 16 states (Reiser *et al.*, 1989). The Tennant method assumes that some percentage of the mean flow is needed to maintain a healthy stream environment. Tennant examined cross-section data from 11 streams in Montana, Nebraska and Wyoming. He found that stream width, water velocity and depth all increased rapidly from zero flow to 10% of the mean flow, and that the rate of increase declined at flows higher than 10%. At less than 10% of the mean flow, he considered that water velocity and depth were degraded and would provide for 'short-term' survival of aquatic life. He considered that 30% of the average flow would provide satisfactory stream width, depth and velocity for a 'baseflow regime'. Tennant's assessment of the environmental quality of different levels of flow was based on the quality of the physical habitat that they provided. At 10% of average flow, average depth was 0·3 m and velocity 0·25 m/s, and Tennant considered these to be lower limits for aquatic life. He showed that 30% of average flow or higher provided average depths of 0·45–0·6 m and velocities of 0·45–0·6 m/s and considered these to be in the good to optimum range for aquatic organisms. Fraser (1978) suggested that the Tennant method could be extended to incorporate seasonal variation by specifying monthly minimum flows as a percentage of monthly mean flows.

Other historic flow methods recommend flows based on the flow duration curve or an exceedance probability of a low flow, where the level of protection is implicit in the magnitude of the percentage.

For example, both a percentage (30–75%) of the 1 in 5 year low flow, and the flow equalled or exceeded 96% of the time have been used to assess 'minimum' flows in New Zealand (Forlong, 1994). In Denmark, a proportion of the median of the annual minima has been recommended as a minimum flow (Miljoestyrelsen, 1979). In Australia, Arthington *et al.* (1992) suggested an 'holistic' approach that 'rebuilds' a natural flow regime, where monthly minimum flow would be based on either a percentage exceedance for each month or a low flow that occurs 'often'. This is similar to Fraser's (1978) suggestion, but with added requirements for wet season flows and floods to preserve the pattern of natural variability.

Hydraulic methods

Hydraulic methods relate various parameters of the hydraulic geometry of stream channels to discharge. The hydraulic geometry is based on surveyed cross-sections, from which parameters such as width, depth, velocity and wetted perimeter are determined. Because of the field and analytical work involved in this, they are more difficult to apply than historic flow methods. Variation in hydraulic geometry with discharge can be established by measurements at different flows (Mosley, 1982), prediction from cross-section data and stage–discharge rating curves, Manning's or Chezy's equations (Bovee and Milhous, 1978), or calculation of water surface profiles (e.g. Cochnauer, 1976; Dooley, 1976; White, 1976; Bovee and Milhous, 1978).

The most common hydraulic method considers the variation in wetted perimeter with discharge. This method is the third most popular method in the USA, being used or recognised in six states (Reiser *et al*., 1989).

Two criteria have been suggested for specifying minimum flow requirements using hydraulic methods. Wetted perimeter usually increases with flow, sometimes showing a point of inflection (Figure 1). Tennant (1976) used the inflection point criterion when he found that depth and width began to decline sharply at flows less than 10% of the mean in his study rivers. The other criterion, percentage habitat retention, retains a percentage of the width or wetted perimeter of the river at mean flow. For example, Bartschi (1976) suggested that a 20% reduction in wetted perimeter at mean flow might be the maximum allowable degradation.

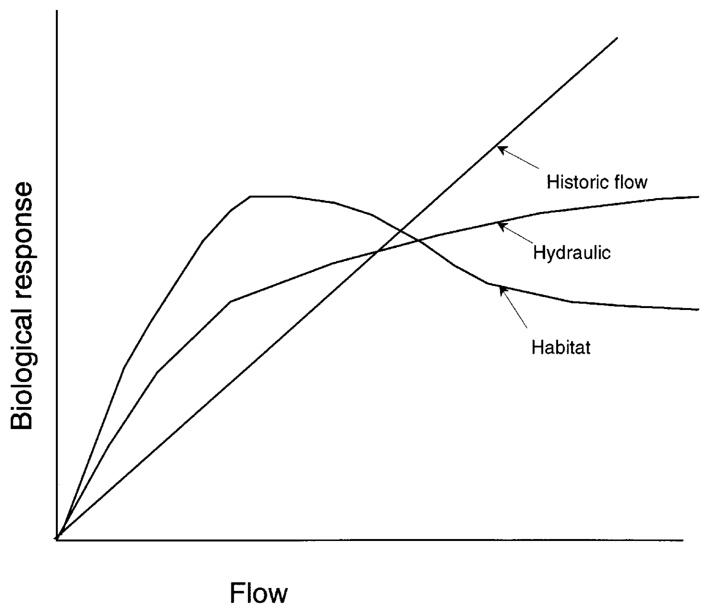

Figure 1. Relationships between flow and biological response for a hypothetical river, where biological response is expressed in terms of the measures used in the flow assessment methods; flow for historic flow methods, wetted perimeter for hydraulic methods and weighted usable area for habitat methods

If flow requirements are based on retaining a percentage of the wetted perimeter at mean flow and there is a linear or near linear relationship between wetted perimeter and flow, the criterion is, in effect, the same as a percentage of the mean flow.

Hydraulic methods are not usually used to assess seasonal flow requirements.

Habitat methods

Habitat is an encompassing term used to describe the physical surroundings of plants and animals. Some habitat features, such as depth and velocity, are directly related to flow, whereas others describe the river and surroundings.

Habitat methods are a natural extension of hydraulic methods. The difference is that the assessment of flow requirements is based on hydraulic conditions that meet specific biological requirements rather than the hydraulic parameters themselves. Hydraulic models predict water depth and velocity throughout a reach. These are then compared with habitat suitability criteria to determine the area of suitable habitat for the target aquatic species. When this is done for a range of flows, it is possible to see how the area of suitable habitat changes with flow.

Because habitat methods are quantitative and based on biological principles, habitat methods are considered in the USA to be more reliable and defensible than assessments made by other methods (White, 1976; Annear and Conder, 1984). Habitat methods were first used for the assessment of flow suitability for spawning salmon (McKinley, 1957), but have been applied to most instream uses, biological and recreational, since then (e.g. Collings, 1972; Waters, 1976; White, 1976). The most widely known method is the physical habitat simulation component (PHABSIM: Milhous *et al*., 1984) of the instream flow incremental methodology. It is the most common method in the USA, being used or recognized in 38 states and the preferred method in 24 of them (Reiser *et al*., 1989).

Habitat suitability curves are the biological basis of habitat methods. Habitat suitability can be specified as seasonal requirements for different life stages, but this is not limited to aquatic organisms. Depth, velocity and width criteria for bathing, wading, kayaking, canoeing and other recreational pursuits have also been described (Mosley, 1983). When considering multiple species, there can be conflicting habitat requirements with a decline in habitat for one species corresponding to an increase in habitat for another. The concept of habitat guilds or an ‘indicator’ species can be applied in these situations (Leopold and Orth, 1988; Gore *et al*., 1991; Aadland, 1993; Jowett and Richardson, 1995).

When using habitat methods, there are more ways of determining flow requirements than for either historic flow or hydraulic methods. The relationship between flow and the amount of suitable habitat is usually non-linear (Figure 1). Flows can be set so that they maintain optimum levels of fish habitat, as required by Oregon State law (Beecher, 1990), retain a percentage of habitat at average or median flow (Jowett, 1993), or set so that they provide a minimum amount of habitat defined either as a minimum percentage of water surface area (e.g. Jowett, 1992) or as a percentage exceedance value on the habitat duration curve (e.g. Beecher, 1990; Johnson *et al*., 1993). Flows can also be set at the point of inflection in the habitat/flow relationship. This is possibly the most common method of assessing minimum flow requirements using habitat methods. While there is no percentage or absolute value associated with this level of protection, it is a point of ‘diminishing return’ where proportionally more habitat is lost with decreasing flow than is gained with increasing flow. In some rivers, the relationship between flow and habitat for flow-sensitive species is linear, especially in the low flow range. In these cases, flow recommendations using percentage retention or exceedance for instream habitat are, in effect, the same as recommendations of hydraulic and historic flow methods that specify a percentage or exceedance value for flow or wetted perimeter.

Habitat methods are more flexible than either historic flow or hydraulic methods. It is possible to examine the variation of the habitat utilized by many species and life stages throughout the year and to select flows that provide this habitat. However, this means that it is necessary to have a good knowledge of the stream ecosystem and some clear management objectives in order to resolve potential conflicting habitat requirements of different species or life stages.

Habitat methods are particularly suitable for ‘trade-off’ situations, where incremental change in habitat can be compared with the benefits of resource use. Habitat/flow relationships can be used to evaluate alternative flow management strategies and are part of the information base used in the process of choosing appropriate flow rules for river management (Cavendish and Duncan, 1986).

Flow assessment methods rarely consider the duration of low flows or flow variability. The ecological effect of a low flow for one day is likely to be very different from the effect on the ecosystem if that flow persisted for six months. Diversion of water from a river usually has little effect on the frequency and duration of floods and freshes. However, damming or diversion of a large proportion of natural river flow can significantly alter the flow and sediment regime of a river. In such situations, there can also be morphological change (Petts, 1979) and simple application of habitat methods may be inappropriate.

Habitat methods can be extended to consider flow regime requirements, both seasonal variation and flood frequency. Seasonal requirements can be estimated using habitat requirements for different life stages and activities. Maintenance flood flows can be 'constructed' based either on the natural flow regime or a knowledge of biological requirements. Arthington *et al*. (1992) approached this problem by maintaining the characteristics of the natural flow regime.

FLUVIAL MORPHOLOGY

Channel shape is determined primarily by geology and the flow regime of a river. For alluvial rivers, there are general relationships between channel form and flow (e.g. Leopold and Maddock, 1953; Kellerhals and Church, 1989). River width increases with the square root of discharge (exponents range from 0·45–0·54; Park, 1977; Kellerhals and Church, 1989), both at a site and between sites. Water depth and velocity also increase with discharge, although the relationships are not as well defined. Mosley (1992) gives the following average relationships as:

$$W \propto Q^{0.5} \qquad D \propto Q^{0.4} \qquad V \propto Q^{0.1}$$

where Q is the discharge, W the average width, D the average water depth and V the average velocity. These relationships are averages derived over normal to high flow ranges. For any particular river, the slope (or exponent) of the relationship can change if there is an abrupt change in geometry, such as at the point where a river overflows its banks on to its floodplain, or at the point where a river is no longer confined between its banks. These abrupt changes in geometry will correspond to inflection points of width/flow or depth/flow curves (e.g. Mosley, 1992).

Points of inflection for width, depth or habitat are usually well defined in rivers of moderate gradient in well-defined channels. Braided rivers are more problematical. As flows increase, additional braids form increasing width and usable habitat, until the wide gravel flood plain is inundated (Mosley, 1982). In this situation there are no clear points of inflection, at least not in the low to median flow range.

Historic flow methods

The effect of setting a percentage or exceedance value of historic flows as a minimum flow requirement on river width, depth and velocity can be deduced from average morphological relationships. For example, at 30% of average flow the water velocity is $0{\cdot}3^{0.1}$ or 88% of the velocity at average flow. Similar changes would also occur to river width and depth. Thus, the hydraulic conditions that result from applying the same percentage minimum flow recommendation to different rivers will vary from river to river. Moreover, the conditions will tend to reflect conditions under natural flows in that a swift river will still be relatively swift compared to a slow flowing river, and a large river will still be large compared to a small river. This helps to maintain the 'character' of the river, where the width, depth, velocity and volume of water determine the visual appearance or 'character'. Similarly, methods using a percentage exceedance flow will also tend to give flow assessments that maintain hydraulic characteristics in proportion to river size. Beecher (1990) remarks that a flow reduction in large or high gradient streams often reduces velocity into a usable range, whereas in small streams a flow reduction often reduces depth below a usable range, implying that there is a river size bias in flow methods when compared in terms of habitat.

Hydraulic methods

Most channel forms are approximately rectangular, or at least parabolic. As the flow increases above zero, width and wetted perimeter rapidly increase as the channel fills with water. A point of inflection occurs where the flow just fills the channel base and begins to be confined by the banks. Hydraulic methods, if based on a point of inflection, identify the minimum flow that will just keep the main channel full.

General relationships between flow and river width, depth, and velocity (Leopold and Maddock, 1953; Richards, 1982) would suggest that inflection points in rivers that are hydrologically similar might be a consistent proportion of the average flow, as found by Tennant (1976). However, O'Shea (1995) applied the wetted perimeter method to 27 Minnesota rivers and found that the points of inflection, as a percentage of average flow, decreased with increasing stream size. Even for rivers of the same size, points of inflection were between 40 and 100% of average flow. Inflection points are sometimes difficult to determine. Rivers with well-defined banks have at least two points of inflection. One is at the flow that just fills the channel to the top of the banks and is known as the 'bank-full discharge', and the other occurs at the flow that just fills the channel to the base of the banks. Many larger New Zealand rivers have poorly defined banks and hydraulic parameters increase smoothly with discharge without any clear points of inflection. One or both banks are usually formed of alluvium (Jowett and Richardson, 1995) and a characteristic shape would be triangular or parabolic rather than rectangular, making it difficult to identify any threshold in channel shape.

As with historic flow methods, hydraulic methods will retain some of the 'character' of the river, at least in terms of width. Water will be retained across the full or near-full channel width, so that the distinction between large and small rivers is maintained.

Habitat methods

General morphological relationships can be used to predict flows that maintain suitable habitat, at least within the flow ranges for which the equations apply. For example, Tennant's requirements for a satisfactory base flow were a depth greater than 0·46 m and a velocity greater than 0·46 m/s. Applying the morphological relationships shown above to a river with an average flow of 50 m^3/s, velocity of 0·6 m/s, and depth of 0·8 m; a flow of 3·5 m^3/s would result in a velocity of 0·46 m/s, whereas a flow of 12·5 m^3/s would result in a depth of 0·46 m. Both depth and velocity requirements would be met by a flow of 12·5 m^3/s or 25% of the average flow. However, in a smaller stream with an average flow of 1 m^3/s and velocity of 0·22 m/s, a flow increase is required before the same habitat requirements can be met.

This illustrates a fundamental difference between flow and habitat methods. The hydraulic conditions that are maintained by a percentage of historic flows are related to the natural conditions in the river, whereas habitat-based methods result in prescribed hydraulic conditions, regardless of the hydraulic condition under natural flows. With habitat methods, minimum flow requirements can be lower than naturally occurring low flows, or can even be higher than the average flow.

In some river types, it may not be hydraulically possible to provide an ideal depth and velocity combination for a particular species. For example, a species with a limited range of suitable habitat, such as lowland river habitat of deep, low velocity water, will not be suited to conditions in a high gradient river because velocity will be too high when depth is suitable and depth too low when velocity is suitable. Clearly, it is important that habitat requirements are appropriate for a particular river.

ECOLOGICAL RATIONALE

Historic flow methods

The ecological goal of most historic flow methods is to sustain existing life forms by recommending a minimum flow that is within the historic flow range. Factors like food, habitat, water quality and temperature are not considered explicitly, but are assumed to be satisfactory because the aquatic species have survived such conditions in the past. The Tennant method (1976) differs from other flow methods in that it is based on the assumption that a proportion of the average flow will maintain suitable depths and water velocities for trout and this assumption obviously applies only to rivers similar in size and gradient to Tennant's study rivers. Whether the goal of sustaining existing aquatic life is achieved or not will depend upon the percentage of flow retained, or exceedance levels selected. However, even within this group of methods there can be conflicting ecological goals. Tennant (1976) claimed that one virtue of his method was that it never produced a zero flow recommendation, and likened methods that produced zero flow recommendations, to ‘prescribing a person’s alltime-worst health condition, as a recommended level for a portion of his future well-being’. In contrast, Arthington *et al*. (1992) state that zero flows are appropriate in Australia, ‘where rivers naturally dry out in some months of some years’. Some Australian ecologists believe that ‘an aquatic ecosystem is tightly coupled with its catchment’ (Cullen, 1992) and therefore suggest that the natural flow regime of a river is a guide to instream flow requirements, including practically all aspects of the flow regime, such as seasonal patterns of flow, low flows, periods of no flow and flood flows (Karim *et al*., 1995). Arthington *et al*. (1992) suggested the ‘holistic’ approach to overcome a lack of detailed ecological data on the water requirements of riverine ecosystems. This is a ‘low risk’ approach to an instream flow policy aimed at maintaining an ecosystem in its existing state and precludes the possibility that a riverine ecosystem can be enhanced by other than a natural flow regime.

Hydraulic methods

Hydraulic methods consider river width or wetted perimeter because the stream bed supports primary and secondary stream production (periphyton and benthic invertebrates) and is considered to be the food-producing area of a stream (White, 1976). The aim is to keep the main river channel ‘full’ to maximize food production. Water velocity is not usually considered in hydraulic methods, possibly because it shows less clearly defined inflection points (e.g. Mosley, 1992). Like the Tennant method, hydraulic methods never result in a zero flow recommendation. If the inflection point method is used as the flow requirement, the resulting water depth, velocity and ecological response will depend on channel geometry. For example, in uniform channels only a small and shallow flow is required to maintain a water across the full stream width. Under such conditions, the water depth and velocity may be unsuitable for many species. However, in less extreme situations, the water depth and velocity will be characteristic of those at natural flow, thus retaining both the ‘character’ and ecology of the natural system.

Habitat methods

The ecological goal of habitat methods is to provide or retain a suitable physical environment for the aquatic organisms that live in a river. The basic concepts of habitat and habitat preference are well established. The consequences of loss of habitat are well known: the environmental ‘bottom line’ is that if there is no suitable habitat for a species it will cease to exist. With the focus of habitat methods on ‘target’ species, there is a risk of failing to consider other essential components of a stream ecosystem. On the other hand, habitat methods ‘tailor’ the flow assessment to the resource needs and can, potentially, result in improved allocation of resources. The selection of appropriate habitat suitability curves and consideration of other factors, such as food, temperature and water quality is crucial (Orth, 1987; Jowett, 1992). The key to successful flow recommendations is to provide sufficient habitat for the maintenance of all life stages of the target species and to consider the requirements of the stream ecosystem as a whole.

Potentially, habitat methods can be used to predict optimum flows for particular river uses. In cases where trout fisheries have improved or shown no noticeable change as a result of flow changes, instream conditions for trout and food production under modified flows have been shown to be near the optimum predicted by habitat methods (Jowett and Wing, 1980; Jowett *et al*., 1995).

Habitat methods aim to preserve, or even improve, habitat in terms of depth and velocity, rather than river ‘character’. For example, a swift flowing river may contain large areas of deep, high velocity water that are not utilized by most aquatic species. A flow assessment based on habitat would suggest that the area of suitable habitat could be increased by reducing flows so that water velocities and depths were in the range of those preferred by a ‘target’ species. This would result in a loss of the high velocity areas that lend ‘character’ to a river. Flow assessments based on habitat tend to reduce rivers to a common denominator—the habitat used by the ‘target’ species.

LEVELS OF ENVIRONMENTAL PROTECTION PROVIDED BY INSTREAM FLOWS

Instream flow management implies that there is a resource to be protected and that there is some way to measure or specify levels of protection for that resource. Legislation often sets guidelines for levels of environmental protection. In the USA, 15 states have laws that refer to the protection of the instream environment, albeit with vaguely defined levels of protection in most of them (Beecher, 1990). In Denmark, the proportion of the median of the annual minima that is used as a minimum flow is varied according to the perceived value of the stream. Higher flows are maintained in streams that support sea-run brown trout than in streams that do not (Miljoestyrelsen, 1979). In New Zealand, the Resource Management Act requires that the 'life-supporting capacity' of a river be safeguarded when considering water use. Unfortunately, the act is not clear about what life is to be supported nor the level of support that should be provided. However, legislation can provide the framework within which to consider the goals of instream flow management.

Goals

Beecher (1990) stated that instream flow management should have clear, measurable goals, and that failure to do this would lead to controversy and achieve vague results. He discussed a number of possible biological goals in order of the levels of protection they provide. The highest level of protection was provided by enhancement above natural condition. Decreasing levels of protection were provided by goals of non-degradation, set percentage loss and population survival.

Levels of protection allow the goal to vary with the relative value of the resource. Highly valued trout or salmon fisheries may merit better protection than average or poor fisheries. Headwater streams that contain rare species may merit more protection than streams that contain more common species. Once an initial resource assessment has been made, it is possible to decide on management goals for that particular river and to consider the appropriate method of flow assessment to achieve this goal.

Goals of an environmental protection policy can vary from enhancement at the upper end of the scale to species survival at the lower end (Beecher, 1990). These goals must be translated into practical operating guidelines or measures within the existing flow assessment methods.

Resource

Environmental protection is a term that encompasses all instream resources and uses. Beecher (1990) points out that different instream uses require quite different flows, citing the conflict in velocity requirements of white-water boating and swimming. Jowett and Richardson (1995) point out the conflict in habitat requirements of fast-water fish and fish using other habitats. Obviously, it is not possible to protect all instream resources equally if flows are to change. The goal of non-degradation of all instream resources is attainable only if there is no change in the natural flow regime. In practice, water management agencies tend to focus on the most valued or sensitive resource, with trout and salmon ranking highly as the most valued resource in many North American and New Zealand rivers.

Measurement of environmental goals

Ideally, environmental management goals should be measured in terms of the resource, e.g. to maintain certain levels of abundance or to maintain a particular assemblage of species. However, this is usually impractical for most biological goals because aquatic populations are both variable in time and difficult to monitor in practice. Research has not yet reached the stage where a flow or flow regime can be associated with community composition and abundance. Instead, either flow, wetted perimeter or habitat is used in flow assessments as a surrogate for biological response.

Biological response and the surrogate measures used in flow assessment methods do not necessarily vary linearly with flow (Figure 1). Historic flow methods assume that the biological response, and hence level of protection, is directly related to flow, with the level of protection increasing with flow. Hydraulic and habitat methods assume that biological response is related to either wetted perimeter or habitat with a non-linear relationship with flow (Figure 1).

Use of a percentage or exceedance flow as a measure of environmental protection does not necessarily ensure a consistent environmental outcome. Morphological and hydraulic considerations suggest that flow effects on aquatic organisms will vary with stream type and size. Small streams are more at risk than large ones because velocity and depth is already relatively low. Logically, habitat should provide a more consistent measure of environmental outcome than flow, given the widely recognized relationships between habitat and stream biota (e.g. Hynes, 1970; Binns and Eisermann, 1979; Minshall, 1984; Bowlby and Roff, 1986).

Practical application: comparison of historic flow and habitat methods

Minimum flow assessments were made for reaches in 22 rivers in the North Island, New Zealand, and were compared to 10 and 30% of average flow (Tennant, 1976). In order to assess minimum flow requirements based on habitat, measures of habitat retention and minimum habitat were arbitrarily selected. The level of habitat retention was to retain two-thirds of the food-producing habitat at median flow and the level of minimum habitat was 20% food-producing weighted usable area (WUA). The second criterion was selected because it was the lower quartile of a group of 65 New Zealand rivers (Jowett, 1993a, b). It was assumed that the same food-producing habitat criteria (depth, velocity, and substrate) were applicable to all rivers. Points of inflection were not used to assess flow requirements because they were not discernible in most cases. Minimum flow assessments based on the two habitat guidelines and Tennant's two criteria were compared with median flows in each river and trend lines were fitted (Figure 2). As found in other studies (Annear and Condor, 1984; Beecher, 1990; O'Shea, 1995), habitat-based assessments suggest that minimum flow requirements, as a proportion of the flow, decrease with increasing stream size. Habitat-based assessments varied with the median flow to the power of 0·3–0·4, whereas flow assessments using Tennant's method varied linearly with median flow. Minimum flows that retained two-thirds of the food-producing habitat at median flow were within 10–30% of the average flow; roughly 10–20% of average flow for larger streams (median flow 5–15 m^3/s), and 20–30% of average flow for

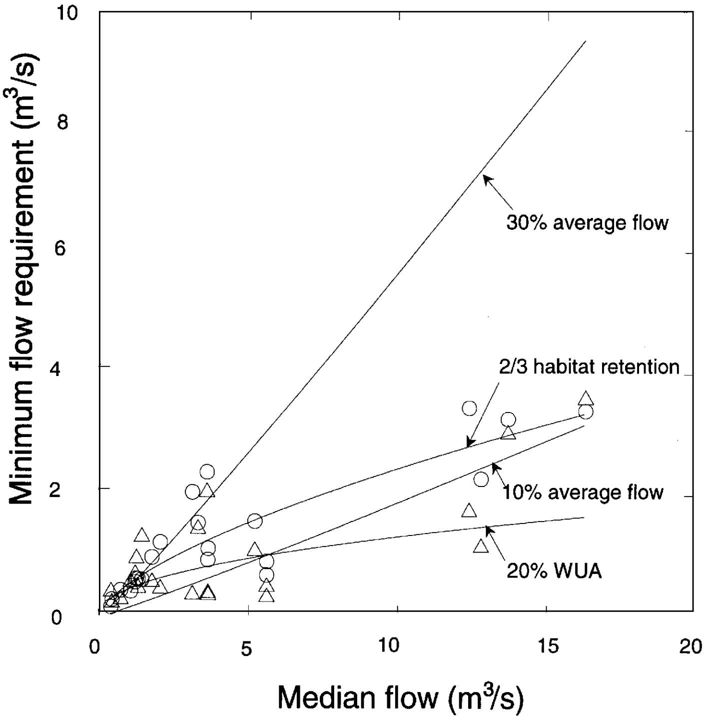

Figure 2. Trend lines of relationships between median flow and minimum flow requirements assessed using 10 % average flow, 30% average flow, minimum of 20% food-producing WUA, and retention of two-thirds of the food-producing habitat at median flow. Minimum flow requirements based on minimum habitat are shown as triangles, those based on habitat retention are shown as circles. Minimum flow requirements based on 10 and 30% average flow were close to the fitted lines and are not shown for clarity

smaller streams. In most of the smaller rivers, habitat/flow relationships were linear, so that the flow that retained two-thirds habitat at median flow was two-thirds of the median flow, or approximately 30% of average flow.

SUMMARY

Each of the three categories of flow assessment method differs in its data requirements, methods of selecting flow requirement, ecological assumptions and effect on river hydraulics (Table I). The physical outcome of historic flow methods is to scale down the river width, depth and velocity from that at natural average flow. Because rivers of all types are scaled down to a similar degree, the relative change in 'character' between rivers will be similar. Historic flow methods are easy to apply and produce a single flow assessment. Levels of protection are specified as percentages or exceedance values of flow, but the relationships between flow and state of the ecosystem are poorly established in most cases. Tennant (1976) established relationships between the proportion of the flow and level of ecological protection for the rivers he studied, and Arthington *et al*. (1992) considered limiting flow events and constructed a flow regime that would preserve existing ecosystems. However, in most cases the basic ecological justification for most flow methods is that a proportion of the flow will retain a proportion of the natural ecosystem. Percentage or exceedance levels are not usually varied with stream size or type. If the risk of environmental degradation is higher in small streams than in large, as habitat considerations suggest, an adjustment of percentage or exceedance for stream size would result in more consistent levels of environmental protection.

Table I. Summary of major differences between historic flow, hydraulic and habitat flow assessment methods

Method	Historic flow	Hydraulic	Habitat
Data requirement	Flow record	Cross-section survey	Cross-section survey Habitat suitability criteria
Method of assessing flow requirement	% of average annual or monthly flow	% habitat retention	% habitat retention
	% exceedance	Inflection point	Inflection point Optimum Minimum habitat (exceedance or percentage)
Stream hydraulics	Effect on width, depth and velocity dependent on morphology	Effect on depth and velocity dependent on morphology	Prescribed depth and velocity
	Maintains 'character'	Maintains 'character' only in terms of variable considered (e.g. wetted perimeter)	Potential loss of 'character'
Ecological assumption	Close relationship between natural flows and existing ecology	Biological productivity related to wetted area	Close relationship between habitat and ecology
			Models consider ecological requirements, where known
Advantages and disadvantages	'Cook-book' flow assessment	Not necessarily a 'cook-book' flow assessment, some interpretation required	Not a 'cook-book' approach, application and interpretation critical
	Trade-off considerations not possible	Trade-off considerations not possible	Allows trade-offs
	Flow always less than, but related to natural	Flow dependent on channel shape	Flow assessment independent of natural flow
	Precludes enhancement	Levels of protection difficult to relate to ecological goals	Enhancement potential recognized

Hydraulic methods focus on maintaining water in the river channel and, in this way, maintain the appearance of a river. Field data requirements are similar to those of habitat methods. Levels of protection are determined by either a point of inflection or percentage retention. The ecological aim is to retain the wetted perimeter and thus productive area of a stream. However, velocity and depth are also important ecological requirements and a flow assessed only on the basis of wetted perimeter may result in adverse depths and velocities depending on river type and channel shape. For this reason, levels of protection in hydraulic methods are unlikely to be closely related to the state of the ecosystem.

Habitat methods provide the most flexible approach to flow assessments, but can be difficult to apply and interpret. Habitat methods provide information on how habitat changes with flow for instream uses, either biological or recreational. Because of this, the outcome depends critically on how the method is applied, what species or uses are considered and what suitability curves are used. Levels of protection can be specified as inflection points, optima or as minimum amounts of habitat. Because levels of protection are in terms of habitat, they are closely related to intended instream uses. On a conceptual level, habitat-based methods differ from both flow and hydraulic methods in that they make no *a priori* assumptions about the state of the natural ecosystem. Flow and hydraulic methods assume that lower than natural flows will degrade the stream ecosystem, whereas habitat methods accept the possibility that a natural ecosystem, or at least some particularly valued aspects, can be enhanced by other than naturally occurring flows.

Habitat methods are most suited to situations where there are clear management goals and defined levels of protection. In fact, application of such methods often causes water managers to realize that there is no simple answer to the problem of flow assessment and that flow requirements can vary depending on goals and levels of protection. Historic flow methods are easier to use because they incorporate their own levels of protection. Hydraulic methods are similar to flow methods in that they produce a single answer and incorporate their own levels of protection.

The understanding of biological systems is not complete. Many factors influence stream ecosystems (Orth, 1987) and, practically, flow assessments can only consider the most important and influential. Methods are often criticized for failing to consider some aspect of the stream environment. None of the methods consider temperature, water quality or biotic interactions explicitly and any change to the stream environment could potentially cause unexpected results. Flow assessments can only make use of the best available knowledge, and if necessary be conservative.

One answer is inevitable—there would be no aquatic ecosystem or instream uses without water in a river. However, because of the degree of diversity in a river and flexibility of most aquatic organisms, there is probably no sharp cut-off or single 'minimum flow'. Environmental response to flow is a gradient along which a decision must be made. It is unlikely that the state of knowledge of biological systems will ever reach a degree where the effect of flow changes on stream populations can be predicted with certainty. Experience, case studies, environmental risk and out-of-stream benefits all play a part in the decision-making process.

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