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USE OF WETTED PERIMETER IN DEFINING MINIMUM ENVIRONMENTAL FLOWS

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ABSTRACT

In regulated rivers, the relationship between wetted perimeter and discharge is sometimes used as an expedient technique for determining the minimum flow allowable for environmental purposes. The critical minimum discharge is supposed to correspond to the point where there is a break in the shape of the curve (usually a logarithmic or power function). Below this discharge, wetted perimeter declines rapidly. This critical point on the curve is almost universally, but incorrectly, termed an ‘inflection’ point, and is usually determined subjectively by eye from a graph. The appearance of a break in the shape of the curve is strongly dependent on the relative scaling of the axes of the graph. This subjectivity can be overcome by defining the break in shape using mathematical techniques. The important break in the shape of the curve can be systematically defined by the point where the slope equals 1, or where the curvature is maximized. The technique can be applied to other habitat–discharge relationships, provided the habitat variable increases with discharge. These techniques were applied to two regulated headwater streams located in the Melbourne catchment area. Channel survey data were used to model the relationship between discharge and wetted perimeter, flowing water perimeter and blackfish habitat area. A logarithmic function could be fitted to the wetted perimeter data for Starvation Creek, but the relationship for Armstrong Creek was linear. Both streams showed logarithmic relationships between discharge and flowing water perimeter. For these streams, the wetted perimeter relationships did not suggest an optimum environmental flow, nor did they suggest a flow level that would maintain the macroinvertebrate community in its unregulated state if it was applied for a long period of time. Fish habitat area does not necessarily increase with discharge, so the method of curve analysis suggested here for wetted perimeter may not be applicable to some fish habitat area data. Flowing water perimeter is preferable over wetted perimeter as a variable to define habitat suitable for macroinvertebrates. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: wetted perimeter; aquatic habitat; environmental flow; instream flow; inflection point; macroinvertebrate; fish habitat; water diversion; weir; velocity; transect

INTRODUCTION

The relationship between channel wetted perimeter and discharge is sometimes used to assist decision making when defining environmental (instream) flows in regulated rivers. This approach assumes that there is a relationship between wetted perimeter and habitat availability. While Annear and Conder (1984) considered this a logical assumption, the literature contains very few supporting field observations. As discharge decreases, riffles are the first locations to be exposed. It is known from ‘at-a-station’ hydraulic geometry relationships that as discharge decreases, stream velocity generally decreases at a faster rate (Leopold and Maddock, 1953). Riffles are usually more productive of invertebrate species than pools. Also, aquatic insect drift is a function of transport from riffles to pools, with a positive correlation between current velocity and the quantity of drifting insects (Stalnaker and Arnette, 1976). Pearson *et al.* (1970) found that the production of macroinvertebrates was a function of the velocity of water through riffle areas, and the total amount of riffle area, but the habitat diversity offered by pools and runs is also important (Humphries *et al.*, 1996). A flow that covers a reasonable proportion of the bed area of riffles with flowing water should be adequate as a minimum flow for riffle, pool and run macroinvertebrate habitat.

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Commonly used environmental flow evaluation techniques range in complexity from those that require stream flow records alone, such as the Tennant (1976) and Texas (Mathews and Bao, 1991) methods, to the instream flow incremental methodology (IFIM) (Bovee, 1982), which explicitly accounts for the habitat requirements of individual species life-stages and physical characteristics of the stream. The wetted perimeter method is the simplest of the field survey-based, site-specific techniques commonly used in environmental flow analysis, but it has no explicit representation of aquatic habitat. Environmental flow determination is concerned with specifying a regulated flow regime that will maintain the aquatic environment. The minimum flow is one component of this regime. This paper is concerned only with minimum flow determination, but it is emphasized that this is only one of the steps in a comprehensive environmental flow analysis.

The wetted perimeter–discharge relationship is a basic tool in the 'transect' approach to environmental flow evaluations (Gordon *et al.*, 1992, p. 428). One procedure is to derive the relationship from channel cross-section surveys at several discharge levels. The transects are often located only at riffle sites, or at sites where fish passage is likely to be limited. Alternatively, the relationship can be modelled using the channel morphology, and other data, using a flow equation such as the Manning equation (Gordon *et al.*, 1992, p. 171). Computer programs are available to perform these calculations (e.g. Grant *et al.*, 1992). A line is generally fitted through the surveyed or modelled points. The lowest breakpoint in the curve is taken to represent a critical discharge below which habitat conditions for aquatic organisms (usually fish or macroinvertebrates) rapidly become unfavourable. The breakpoint indicates where small decreases in flow result in increasingly greater decreases in wetted perimeter (Annear and Conder, 1984). IFIM relies heavily on transect data for physical habitat assessment. While sophisticated hydraulic habitat modelling techniques such as PHABSIM (Milhous *et al.*, 1989) are available, they require detailed hydraulic and morphological surveys, and knowledge of habitat preferences for the species of interest. For these reasons, the simpler approach based on examination of the wetted perimeter–discharge relationship is more appropriate in many locations.

The wetted perimeter–discharge breakpoint has been used to define optimum or minimum flows for fish rearing (food production) in the US (Collings, 1974; Cochnauer, 1976; Nelson, 1980), and Australia (Richardson, 1986). Stalnaker and Arnette (1976) reported that the breakpoints for some US streams occurred at discharges corresponding to approximately 80% of the maximum available wetted perimeter. The Oregon Department of Fish and Wildlife recommend (among other criteria) that at least 50% of the maximum wetted perimeter be provided at riffles (Stalnaker and Arnette, 1976). Filipek *et al.* (1987) found that for Arkansas streams the breakpoint in the wetted perimeter–discharge relationship occurred at 50% of the mean flow. Below this discharge, riffle areas became exposed and unproductive, stream bank cover for fish diminished, the water quality decreased and fish overcrowding was possible. For a river in Portugal, Alves (1994) also defined the breakpoint as corresponding to a threshold discharge below which habitat quality becomes significantly degraded. For Wyoming and Montana streams, Tennant (1976) found that the flow equivalent to 10% of the average flow provided about 50% of the maximum wetted perimeter, while flows greater than 30% of the average flow provided close to the maximum wetted perimeter.

Nelson (1980) found that wetted perimeter curves for streams in Montana had single, well-defined breakpoints. The discharges at the breakpoints corresponded to the minimum flow levels required to maintain trout populations. Use of multiple transects resulted in less distinct breakpoints. Prewitt and Carlson (1977) reported that the wetted perimeter approach did not suit the unique fauna of the Upper Colorado River Basin.

The transect approach to defining environmental flows is widely used in Victoria, Australia (Hall, 1989, 1990). Tunbridge and Glenane (1988) defined an optimum flow as one that maintains $>90\%$ of the maximum available fish habitat, fish passage and wetted perimeter; a minimum environmental flow maintains $>70\%$ of the maximum available fish habitat, 10% of the maximum fish passage and 80% of the maximum wetted perimeter; a survival environmental flow maintains $>50\%$ of the maximum available fish habitat, 10% of the maximum fish passage and 60% of the maximum wetted perimeter.

Although the wetted perimeter approach has been widely used in environmental flow evaluations, there is no conventional, objective method for selecting the critical breakpoint on the curve. The point is usually chosen solely on a subjective basis, and recommendations can vary between investigators (Annear and Conder, 1984). Also, complications can arise when no clearly defined breakpoint is found, or where multiple breakpoints occur. The only attempt to develop a systematic method of selecting the breakpoint was that of Annear and Conder (1984), who suggested a statistical technique to identify significant reductions in wetted perimeter from predefined reference flows.

This paper has two main parts. The first presents a numerical method of characterizing the wetted perimeter–discharge relationship. A systematic approach to defining the important break in the shape of the curve is given. Using hypothetical data, the nature of the relationship is examined for several different stream channel shapes. The second part of the paper describes the application of the suggested method of analysis to two regulated headwater streams in Victoria, Australia. For comparison, the method of breakpoint determination was also applied to the relationships between discharge and two other habitat indices: flowing water perimeter and blackfish preferred hydraulic habitat area. The minimum flows recommended by the numerical method were compared with the unregulated and regulated flow regimes of the streams. The regulated flow regimes were assessed in terms of their ability to maintain populations of target macroinvertebrates and blackfish.

CHARACTERIZING THE WETTED PERIMETER–DISCHARGE RELATIONSHIP

The breakpoint in the wetted perimeter versus discharge relationship is referred to in the literature almost universally as a point of 'inflection' (Cochnauer, 1976; Stalnaker and Arnette, 1976; Prewitt and Carlson, 1977; Wesche and Rechard, 1980; Annear and Conder, 1984; Richardson, 1986; Filipek *et al.*, 1987; O'Keefe *et al.*, 1989; Alves, 1994). The term 'inflection point' is also sometimes mentioned in literature on IFIM, in reference to the weighted usable area versus discharge relationship (Orth and Maughan, 1982; Gan and McMahon, 1990; King and Tharme, 1993, p. 47). This is an incorrect use of the term inflection point. Analytical geometry texts define an inflection point as occurring where: a tangent at the point cuts through the curve; where the first derivative (slope) increases on one side of the point and decreases on the other; and where the second derivative at the point equals zero (Goodman, 1980, pp. 200–201). None of these conditions occur at the point on wetted perimeter curves that is often referred to as an inflection point. What then is the nature of this breakpoint, and how can it be systematically defined?

Effect of graph scaling

The breakpoint on wetted perimeter–discharge curves that is being sought is not an inflection point, but rather is a point where the curvature is maximized, or where there is a marked change in the slope of the curve. Most people probably try to select the point corresponding to where the tangent to the curve is 45° (i.e. the apparent slope is unity). It is not possible to select this point reliably by eye, since the appearance of the slope of the curve is strongly dependent on the relative scaling of the axes (Figure 1). Variability in the presentation of the graphs will cause inconsistency in the selection of breakpoints.

Shape of the wetted perimeter–discharge curve

The shape of the relationship between wetted perimeter and discharge is a function of the geometry of the channel, and the manner in which discharge increases with depth. Channels have geometries that range from roughly triangular to roughly rectangular, although the latter shape is more prevalent. For rectangular and trapezoidal channels that have relatively flat beds, as the depth of water in the channel increases from zero, there is an initial rapid increase in wetted perimeter. After the bed is inundated, continued depth increases produce only relatively small increases in wetted perimeter (Bovee and Milhous, 1978). The form of this relationship is accentuated by the way discharge increases with water depth. At low flows the velocity is low; as depth increases, flow velocity increases, so that discharge increases at a faster rate than depth. The nature of this relationship is described by the Manning equation:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad (1)$$

where Q = discharge (m^3 s^{-1}), n = Mannings roughness coefficient, A = cross-sectional area of the flow (m^2), R = hydraulic radius (m) and S = water surface slope.

For triangular channel geometries where the wetted perimeter increases proportionately with depth, from Equation (1) it can be seen that the wetted perimeter–discharge relationship is a power function. Such curves do not display a sharp break in slope. The power function relationship does not apply to channel geometries that produce more rapid changes in wetted perimeter at lower discharges.

Wetted perimeter–discharge relationships were calculated for four hypothetical channel cross-sections. The channels had different shapes, ranging from roughly rectangular to roughly triangular, but for all, the ratio between maximum width and maximum depth was 8 (Figure 2). For each channel, discharge was estimated for 25 values of depth using the Manning equation [Equation (1)], assuming a Manning roughness coefficient of 0.04 and a water surface slope of 0.002. The channel geometry and discharge data were plotted as dimensionless variables, with each value being expressed as a proportion of the maximum value. This enabled direct comparison of the shapes and slopes of the wetted perimeter–discharge curves for the different channel geometries (Figure 2). Roughly triangular geometries give a power relationship between wetted perimeter (P_w) and discharge (Q) [Equation (2)], while roughly rectangular geometries give a logarithmic relationship [Equation (3)].

$$P_w = Q^b \qquad (2)$$

$$P_w = a \ln(Q) + 1 \qquad (3)$$

It is relevant to note that Leopold and Maddock's analysis of the at-a-station hydraulic geometry of US streams found that the general relationship between channel width (closely related to wetted perimeter) and discharge was a power function of the form of Equation (2) (Leopold and Maddock, 1953).

Defining the breakpoint

One method of determining the breakpoint is to select the point on the curve where the slope, $\Delta P_w/\Delta Q$ (first derivative dy/dx) equals a nominated value. It is necessary to normalize the two axes to cover the

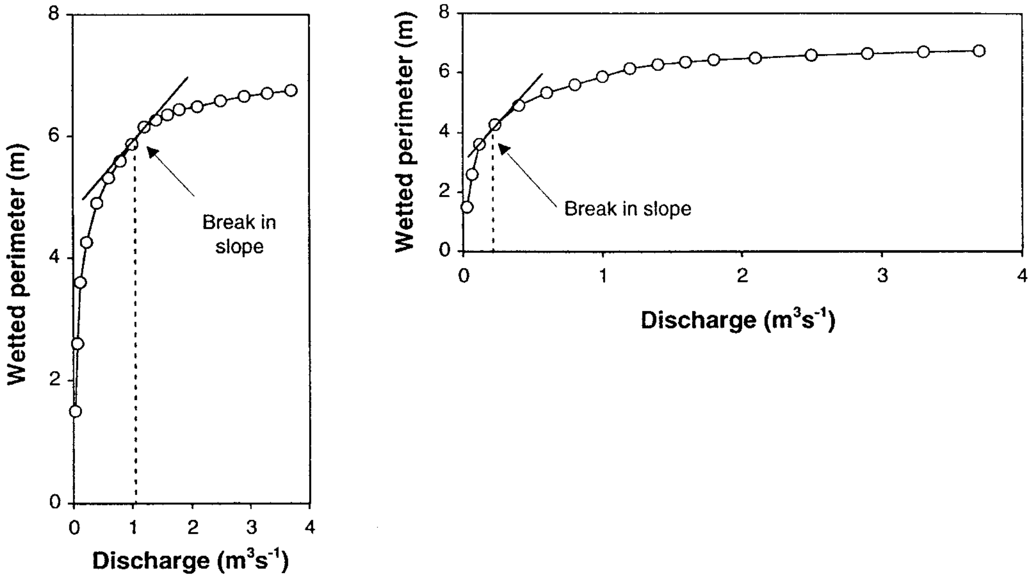

Figure 1. Hypothetical wetted perimeter–discharge relationship plotted on two differently scaled sets of axes. Different breakpoints are apparent, even though the same data are plotted on both graphs

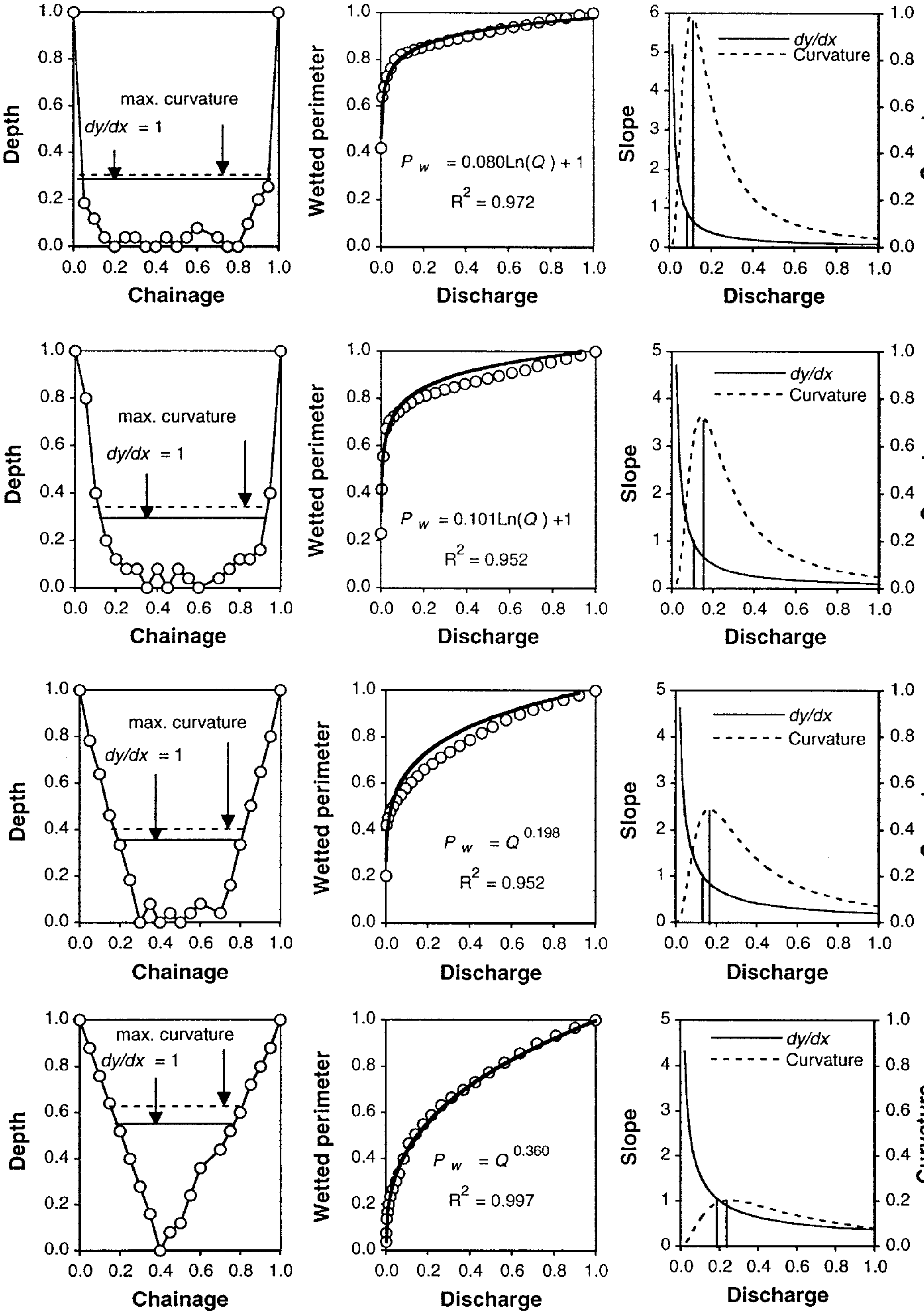

Figure 2. Cross-section (vertical exaggeration = 8), wetted perimeter–discharge relationships, and curvature of wetted perimeter relationship for four channel geometries using hypothetical data

same range. This can be done by expressing each discharge and wetted perimeter value as a proportion of their respective measured or modelled maximum values (Figure 2). Alternatively, discharge may be expressed as a percentage of a flow index, such as mean annual flow. At the point where the slope of the curve is unity, a small change in discharge (as a percentage of the maximum value considered) will produce the same change in wetted perimeter (as a percentage of the maximum value considered). At higher discharges where the slope is greater than 1, a large increase in discharge will produce a small increase in wetted perimeter. At lower discharges, where the slope is less than 1, a small decrease in discharge will produce a large decrease in wetted perimeter. In this study, we decided to use a slope value of 1 ($\mathrm{d}y/\mathrm{d}x = 1$), but a different slope could be used to determine the breakpoint, depending upon the relative values attached to discharge and habitat area. The slope selected should reflect the management objectives for the stream and represents a trade-off between habitat protection and water resource development. For example, if habitat was particularly precious, and water not in desperately short supply, then a slope of < 1 would be more appropriate. The equations for slope for the power function [Equation (4)] and logarithmic function [Equation (5)] are:

$$\frac{\mathrm{d}y}{\mathrm{d}x} = bQ^{b-1} \tag{4}$$

$$\frac{\mathrm{d}y}{\mathrm{d}x} = \frac{a}{Q} \tag{5}$$

For the logarithmic function [Equation (5)], the slope of unity occurs simply at $Q = a$ (Figure 2). In cases where it is not possible to fit a simple curve to the data, the slope of the relationship can be calculated for each plotted (surveyed or modelled) point. Compound cross-sections with multiple benches will produce an irregular relationship between wetted perimeter and discharge, and there may be more than one breakpoint where the slope is unity. The lowest breakpoint is probably the most relevant to minimum flow determination.

A second systematic method of selecting the breakpoint in the curve is to define the point of maximum curvature. The curvature (κ) is the rate at which a curve turns [Equation (6)]; it is a function of the angle that the tangent to the curve makes with the x-axis, and the arc length (Goodman, 1980, p. 610):

$$\kappa \frac{\dfrac{\mathrm{d}^2y}{\mathrm{d}x^2}}{\left[1 + \left(\dfrac{\mathrm{d}y}{\mathrm{d}x}\right)^2\right]^{3/2}} \tag{6}$$

The equations for absolute curvature for the power function [Equation (7)] and logarithmic function [Equation (8)] are:

$$|\kappa| = \frac{|bQ^{b-2}|}{[1 + (bQ^{b-1})^2]^{3/2}} \tag{7}$$

$$|\kappa| = \frac{\left|\dfrac{-a}{Q^2}\right|}{\left[1 + \left(\dfrac{a}{Q}\right)^2\right]^{3/2}} \tag{8}$$

The point where curvature is maximized ($\kappa_{\max}$) is best determined by plotting the functions given in Equations (7) and (8) as appropriate (Figure 2).

The $\mathrm{d}y/\mathrm{d}x = 1$ and $\kappa_{\max}$ methods give similar breakpoints (Figure 2). The slope method of selecting the breakpoint is intuitively the most appropriate, and the simplest to apply. The selected breakpoints for the rectangular channel geometries are close to the bases of the banks (Figure 2). This is appropriate as a minimum discharge for maintaining flowing water over most of the bed. For the trapezoidal and triangular channel geometries (Figure 2), the breakpoint is determined more by the way discharge increases with depth (non-linear), than the way the wetted perimeter changes with depth (linear).

CASE STUDY APPLICATION OF THE WETTED PERIMETER APPROACH TO DEFINING MINIMUM REGULATED FLOWS

Introduction

The water harvesting system that supplies water to metropolitan Melbourne (Figure 3) consists of several large storage reservoirs, supplemented by a number of small diversion weirs, 1–5 m in height, located on headwater streams. The weirs divert water, via aqueducts or pipelines, to the larger water supply reservoirs. Typically, about half of the annual runoff is harvested from these small regulated streams (long-term mean daily flows range from 0.02 to 0.90 $m^3 s^{-1}$). Regulation significantly reduces the magnitude of baseflows and minor storm events, but flows greater than the mean daily flow generally overtop the weirs. Although not legally obliged to do so, the managing authority (Melbourne Water) maintain minimum downstream releases from most of the weirs. The release discharges are arbitrary, and are not based on known environmental requirements.

Apart from flow regulation, the streams used for water supply are in an undisturbed condition, and they drain catchments that are closed to any form of land use or public access. The streams support populations of river blackfish (*Gadopsis marmoratus*), a native freshwater fish species that has high conservation value in Victoria. With the aim of improving the management of the environmental releases from these weirs, a research programme was undertaken to investigate the effect of regulation on the downstream environment (Gippel *et al.*, 1996). This paper focuses on the issue of minimum flows, which was investigated at two weir sites, located on Armstrong Creek and Starvation Creek. The objective of the investigation was to determine the extent to which the current arbitrary minimum environmental flows provide what is thought to be minimum adequate habitat requirements for macroinvertebrates and fish, as identified by analysis of the relationships between habitat availability and discharge. The adequacy of these minimum flows was then reviewed in light of biological survey data collected from these sites.

The technique of wetted perimeter curve analysis described in the first part of this paper is conceptually very simple and works well for hypothetical data. Real environmental flow problems are usually more complex. In attempting to transfer the suggested technique of wetted perimeter curve analysis to the case study of Armstrong and Starvation creeks, some difficulties and opportunities were encounted. (i) When multiple transect data for the reach were lumped, the relationship between discharge and wetted perimeter

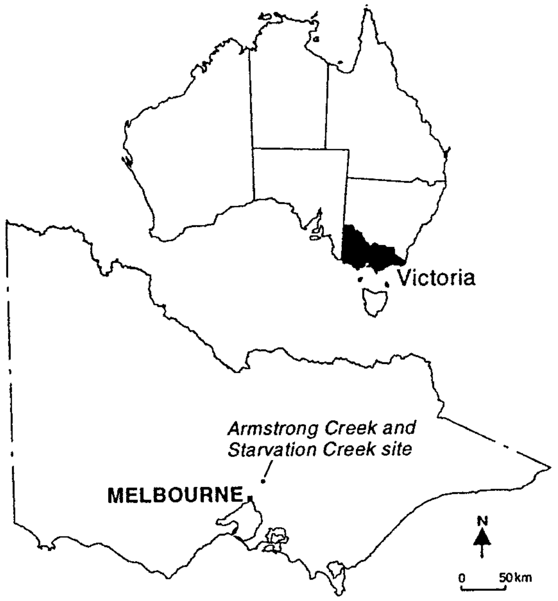

Figure 3. Site map showing location of Starvation and Armstrong creeks

Table I. Summary of analysis of flow records at Armstrong Creek and Starvation Creek, with percentage of maximum surveyed wetted perimeter provided by each discharge

	Starvation Creek	Armstrong Creek
Historical mean daily unregulated flow (m^3 s^{-1})		
	0.47	0.85
Historical 50% exceedance unregulated flow (m^3 s^{-1}) (*% of maximum wetted perimeter*)		
December	0.44 (*100*)	0.56 (*100*)
January	0.34 (*98*)	0.36 (*91*)
February	0.28 (*97*)	0.27 (*85*)
March	0.25 (*96*)	0.23 (*82*)
Historical 95% exceedance unregulated flow (m^3 s^{-1}) (*% of maximum wetted perimeter*)		
December	0.20 (*94*)	0.21 (*81*)
January	0.17 (*92*)	0.15 (*77*)
February	0.16 (*92*)	0.13 (*76*)
March	0.16 (*92*)	0.16 (*78*)
Historical minimum unregulated flow (m^3 s^{-1}) [maximum duration in days] (*% of maximum wetted perimeter*)		
December	0.12 [1] (*89*)	0.10 [1] (*74*)
January	0.14 [3] (*90*)	0.10 [1] (*74*)
February	0.07 [3] (*84*)	0.05 [1; 24 $<$ 0.09 m^3 s^{-1}] (*71*)
March	0.08 [4] (*85*)	0.05 [1; 21 d $<$ 0.08 m^3 s^{-1}] (*71*)
Estimated historical minimum regulated flow (m^3 s^{-1}) (*% of max. wetted perimeter*)		
	0.10 (*87*)	0.14 (*77*)
Arbitrary minimum regulated flow (m^3 s^{-1}) (*% of maximum wetted perimeter*)		
	0.023 (*74*)	0.059 (*71*)

was quite different from the relationships for the individual transects, and this prompted creation of a new habitat descriptor which we termed the flowing water perimeter. (ii) Availability of fish habitat was of particular concern at these sites, hence the technique of curve analysis was tested on fish habitat area data. (iii) Hydraulic habitat modelling was attempted in an effort to increase the number of data points from which to fit curves. These issues are expanded on in the following sections.

Site characteristics

Armstrong Creek at the weir site has a catchment area of 54.5 km^2, a mean channel width of 4.6 m (range 2.5–6.2 m), a mean bed slope of 0.017 and a median bed particle diameter of 0.13 m. Starvation Creek at the weir site is smaller, with a catchment area of 31.6 km^2, a mean channel width of 2.9 m (range 1.2–3.7 m), a mean bed slope of 0.017, and a median bed particle diameter of 0.07 m. Annual precipitation in the catchment area is estimated to be 1500–2000 mm, with most precipitation falling as rain during winter.

Daily unregulated flow (i.e. upstream of the weirs) records were available for Starvation Creek from 1 January 1969 to 31 December 1995, and for Armstrong Creek from 1 March 1970 to 31 December 1995. Mean daily flow was higher in Armstrong Creek, but in terms of summer median flows and flows exceeded 95% of the time, the two streams were similar (Table I). Armstrong Creek actually had lower minimum recorded flows than Starvation Creek (Table I).

In recent times, the minimum flows actually released from these weirs have been higher than the arbitrary minimum environmental flows allocated to these streams (Table I). The flows from the weirs are not measured regularly, but the minimum flows released were estimated on the basis of gauging the streams on several occasions, and information provided by the weir keepers.

Methods

Downstream of both weirs, ten transects spaced 20 m apart were pegged. At each transect, approximately ten measurements were made of width across the stream, depth from a datum, water depth, mean column velocity and velocity at 0.1 m from the bed (blackfish nose velocity). The surveys were repeated at three different discharge levels at Starvation Creek, and at four different discharge levels at Armstrong Creek. Downstream flow levels were easily controlled by adjusting the weir gates, allowing the surveys to be completed by four people in three days. The streams were surveyed over a range of discharge from just below the arbitrary minimum regulated flow to 70–85% of the mean daily flow. At the maximum surveyed discharges the beds of both channels were fully inundated, such that the wetted perimeters would have increased only marginally at higher discharges.

Data from field hydraulic and morphological surveys were used to model the availability of blackfish rearing and macroinvertebrate hydraulic habitat as a function of discharge. For rearing, blackfish prefer depths >0.2 m and velocities <0.2 m s^{-1} (Koehn *et al.*, 1994). Macroinvertebrate habitat was defined in two ways: as the wetted area of the channel and, as the area of channel with flow velocity >0.01 ms^{-1}. An attempt was made to use PHABSIM (Bovee and Milhous, 1978) to model blackfish habitat availability and flowing water perimeter over a wider range of discharge, but the model habitat area predictions were in error by up to 100% when compared with the measured values. Errors resulted from the failure of the hydraulic models to represent adequately the effects of woody debris, dead water along channel margins at low flows and irregular vertical velocity profiles. These are common features of steep, coarse-bed channels and similar results could be expected in other upland streams.

A value of mean wetted perimeter (lumping all transects) was calculated from the transect data for each surveyed discharge level. Mean flowing water perimeter was calculated in the same way, except that those parts of the transects with effectively dead water (<0.01 m s^{-1}) were excluded. Mean blackfish habitat area was calculated for the reaches using the known hydraulic preferences. Blackfish habitat availability was expressed as area per longitudinal channel distance (m^2 m^{-1} = m).

Results

The relationship between discharge and wetted perimeter, flowing water perimeter and blackfish habitat for Starvation Creek were of a logarithmic form (Figure 4); the breakpoints in the relationship were calculated using the slope and curvature methods (Table II). In contrast, the relationship between wetted

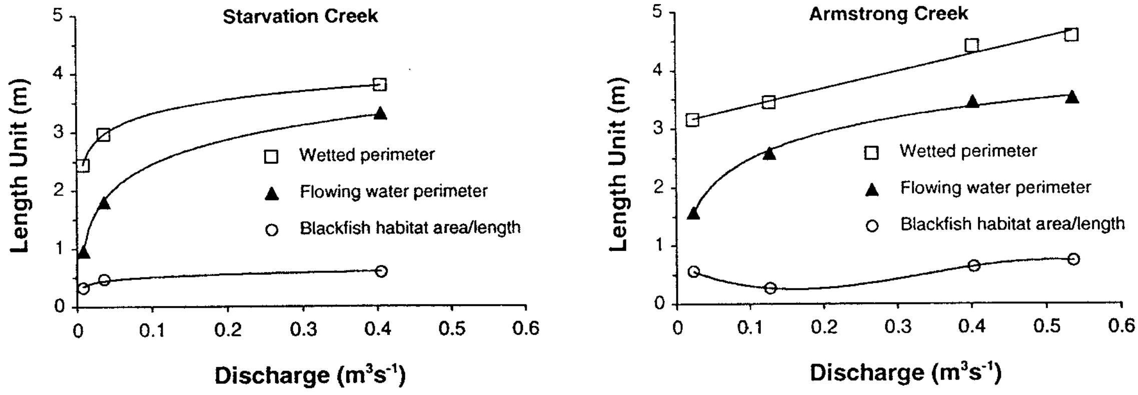

Figure 4. Habitat–discharge relationships for regulated reaches of Starvation and Armstrong creeks with habitat availability expressed as raw values. Blackfish rearing habitat area is expressed in m^2 of hydraulically suitable habitat area per longitudinal m of channel

Table II. Minimum flows suggested by breakpoints ($Q_{\text{crit.}}$) of the wetted perimeter, flowing water perimeter and blackfish rearing habitat area versus discharge relationship for Starvation and Armstrong Creeks. Results are given for the slope and curvature methods of defining breakpoints. Also given are the percentage of maximum surveyed habitat provided by the critical flows

	Slope method ($dy/dx = 1$)		Maximum curvature method		
	$Q_{\text{crit.}}$ ($m^3 s^{-1}$)	% Maximum habitat (%)	Maximum curvature	$Q_{\text{crit.}}$ ($m^3 s^{-1}$)	% Maximum habitat (%)
Starvation Creek					
Wetted perimeter	0.034	78	0.82	0.053	82
Flowing water perimeter	0.072	68	0.42	0.105	75
Blackfish habitat area	0.041	76	0.71	0.061	80
Armstrong Creek					
Flowing water perimeter	0.092	69	0.42	0.134	75

perimeter and discharge for Armstrong Creek was linear (Figure 4). This resulted from averaging data from the wide range of cross-sectional shapes surveyed at this site. Most individual transects had breakpoints, but they occurred over a wide range of discharges, so a distinctive breakpoint was not apparent when the data were lumped. Even at very low discharge levels, pooled water provided a substantial amount of wetted channel. This water was not flowing, so the flowing water perimeter relationship was logarithmic (Figure 4, Figure 5).

The curvature method gave higher values of critical discharge than the slope method. The minimum discharges corresponding to the breakpoints calculated from the flowing water perimeter data were higher than the breakpoints calculated from the wetted perimeter data (Table II).

In Armstrong Creek, blackfish rearing habitat was high at the lowest surveyed discharge (Figures 4 and 6), being limited only by depth. As discharge increased to 0.13 $m^3 s^{-1}$, increases in velocity in the limited deeper water available along the channel thalweg resulted in a reduction of habitat area (Figures 4 and 6). Above 0.13 $m^3 s^{-1}$, habitat area increased as a result of an increase in the area of channel with suitable

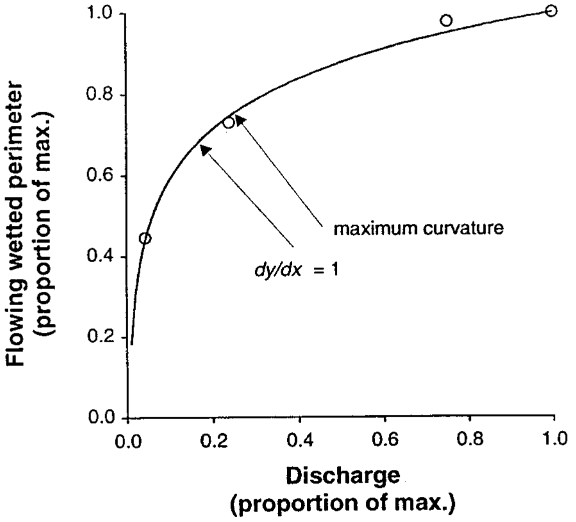

Figure 5. Flowing water perimeter curve for Armstrong Creek with axes normalized. The points on the curve where the slope is unity and where the curvature is maximized are indicated

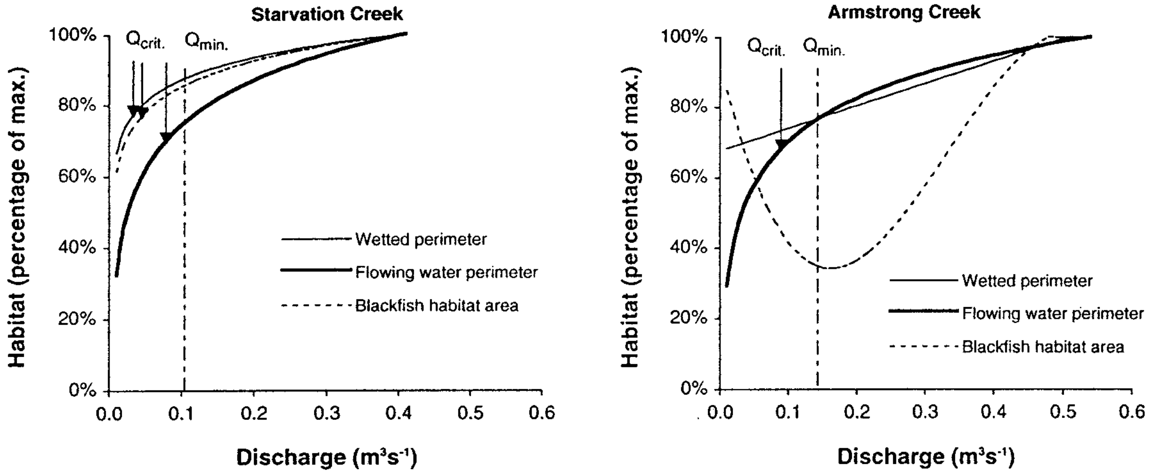

Figure 6. Habitat–discharge relationships for regulated reaches of Starvation and Armstrong creeks, with habitat availability expressed as a percentage of the maximum surveyed value. $Q_{\text{crit.}}$ corresponds to the point on each curve (logarithmic curves only) where the slope is unity. $Q_{\text{min.}}$ is the minimum environmental flow that has historically been applied to these sites

water depth (Figures 4 and 6). This trend was not apparent in the Starvation Creek data (Figures 4 and 6). Starvation Creek is considerably narrower than Armstrong Creek and has a smaller bed particle size, so at low discharges the amount of habitat available was not as strongly depth limited.

Analysis of flow records revealed that the minimum unregulated discharges recorded in these streams occurred during a severe drought in the summer of 1982–1983. The drought had a more severe effect on flows in Armstrong Creek (Table I). Here, the unregulated drought flows would have exposed up to 29% of the channel bed, while at Starvation Creek, a maximum of 16% of the channel bed would have been exposed (Table I). Droughts of this severity occur rarely; the flow exceeded 95% of the time is a better index of low flow. In Starvation Creek, at least 92% of the maximum surveyed area of wetted channel was provided by the flow exceeded 95% of the time. In Armstrong Creek, at least 76% of the maximum surveyed area of wetted channel was provided by the flow exceeded 95% of the time (Table I).

The arbitrarily selected minimum flows released from the weirs during recent times were, coincidentally, similar to the minimum flows determined from analysis of the flowing water perimeter relationships (Tables I and II). However, when applied to the relationship for wetted perimeter and blackfish rearing habitat area (Starvation Creek only), the slope and curvature methods of the minimum discharge definition gave values that were about half the current minimum flows. The arbitrary minimum regulated flows (not actually enforced) for these sites are much lower than the summer low flows normally experienced in these streams. At Starvation Creek, the arbitrary minimum flow is approximately one-third of the lowest unregulated flow recorded in the stream.

Available biological information

A previous survey of the physical habitat in the vicinity of ten water supply diversion weirs (including Starvation and Armstrong creek weirs) found that the most obvious change in the downstream physical environment was a reduction in the area of channel having a mean velocity greater than 0.4 m s^{-1} during times when water was being harvested (Rhodes, 1994). It was speculated that the flow reduction downstream of weirs would most likely adversely effect those aquatic species that prefer this type of habitat. Surveying three of the weirs examined by Rhodes (1994), located on Armstrong, Badger and Starvation creeks, Gaynor *et al.* (1995) found that the abundance and diversity of 11 target taxa (those known to prefer fast-water velocities) were significantly ($p < 0.05$) reduced below the weirs. The magnitudes of the reductions were not a simple function of the percentage of water harvested. There were no significant differences in the diversity and abundance of the target macroinvertebrates at two control weir sites (weir present, but no water harvested). These studies concluded that the altered macroinvertebrate community structure was most likely a response to the artificially low regulated minimum flows, because regulation had little or no effect on macroinvertebrate drift, water quality, substrate sedimentation, high flows or physical channel characteristics (Gippel *et al*., 1996).

Fish surveys conducted by the Department of Natural Resources and Environment (Steve Saddlier, personal communication) suggest that the abundance of blackfish in Starvation Creek below the weir is lower than would be expected for an unregulated stream of this size in this area. In contrast, in Armstrong Creek below the weir, blackfish abundance is within the range expected for an unregulated stream in this area.

Discussion of case study

The channel surveys conducted at Starvation and Armstrong creeks were not restricted to riffle sites. Starvation Creek had a fairly consistent morphology along the surveyed 200 m reach. Armstrong Creek had a more variable channel morphology along the surveyed reach. This produced a linear relationship between mean wetted perimeter and discharge. The implication of this relationship (Figure 4) is that 68% of the maximum available channel bed perimeter is available when discharge is zero. This is realistic, since pools would inundate large sections of the channel at zero discharge. Many unregulated streams in south-eastern Australia occasionally cease to flow, yet they support healthy populations of native fish. River blackfish have a limited home range and spend much of their life cycle in pools, so their abundance is unlikely to be greatly affected by naturally occurring periods of low or cease to flow conditions (Davies, 1989).

The blackfish rearing hydraulic habitat curves (Figure 6) have limited application to the problem of setting minimum environmental flows. In Armstrong Creek, the habitat provided by pools, even at very low flow conditions, appears to be sufficient to sustain blackfish populations. The reason for low blackfish abundance at Starvation Creek is unclear. It could be related to the lack of deep pools in this reach of the stream. Regulated low flows are probably not directly responsible for low blackfish abundance, but it is possible that they have an indirect effect; for example, through reducing food supply.

Macroinvertebrate production is probably reduced by very low flows, when large areas of riffle habitat are exposed, and flow velocities are very low. Unlike the wetted perimeter model, the model of habitat availability based on the perimeter of flowing water was non-linear (Figures 4–6). It is proposed as a more appropriate model for macroinvertebrate habitat.

The maximum curvature technique of selecting the breakpoints on the habitat–discharge curves gave slightly higher values than the values based on a slope of 1. For both streams, the recommended minimum flows were lower than the historical unregulated 95% exceedance flow, and lower than the environmental flow that has been released in recent years. The recommended minimum flows, and the minimum flows actually released from the weirs, provide 68–87% of the maximum available habitat. Although this is within the range suggested in the literature as being adequate for environmental protection, the abundance and diversity of macroinvertebrates that prefer fast-flow environments have been severely reduced at these sites (Gaynor *et al*., 1995). Application of the arbitrary minimum flows at these sites would cause a reduction in habitat availability to levels substantially lower than would be experienced under unregulated conditions, even during severe drought conditions. This is particularly the case for the flowing water perimeter.

One limitation of applying the wetted perimeter approach to the problem of environmental flow determination is that it recommends only a minimum flow. In reality, a flow regime should be specified. For example, in the case of the weirs at Starvation and Armstrong creeks, the minimum flows suggested by the flowing water perimeter method could be applied in the drier months, and only during naturally dry periods. During these times the main water supply storage reservoirs are low, and the non-stream demand for water is at its highest. During wet periods, provided the main storage reservoirs were reasonably full, more generous releases could be allocated for environmental purposes. It should be possible to develop a simple relationship between the percentage of maximum storage capacity available and the amount of water available for release from the weirs for environmental purposes. The allocated flow could be reviewed and adjusted on a weekly or monthly basis.

CONCLUSIONS

Using the relationship between wetted perimeter and discharge to determine minimum environmental flows in regulated streams is problematic, and it should only be used in conjunction with other techniques, which together produce a recommended environmental flow regime. This paper provides a method of overcoming the major problem of subjective interpretation of the breakpoint in the wetted perimeter discharge curve. Provided a curve can be fitted to the data, the breakpoint of the curve can then be determined mathematically by calculating the point of maximum curvature or the point where the slope is equal to 1 (or some other selected value). Of these two approaches, the slope method is simpler to apply, but requires selection of a suitable slope. The suggested method of breakpoint determination can also be applied to curves of flowing water perimeter and fish habitat area as a function of discharge, provided the habitat variable increases with discharge over the range of interest.

The existence of a sharp breakpoint on the wetted perimeter discharge curve is largely a function of the channel geometry; rectangular cross-sections produce a more defined breakpoint than do triangular cross-sections. For rectangular cross-sections the breakpoint defined by the suggested curvature or slope technique corresponds to a discharge level that inundates the channel bed.

The suggested habitat curve analysis technique was applied to two regulated headwater streams in south-eastern Australia. Starvation Creek had a fairly consistent cross-sectional morphology throughout the surveyed reach, and the relationship between wetted perimeter and discharge was of the expected logarithmic form. In contrast, Armstrong Creek had a more variable channel morphology. While each of the ten transects showed a breakpoint in the relationship between discharge and wetted perimeter, the breakpoints corresponded to a range of discharges. When the transect data were averaged over the reach, the relationship between discharge and wetted perimeter was linear (i.e. without a breakpoint). Thus, the suggested technique of curve analysis could not be applied to wetted perimeter data at this site.

When considering wetted perimeter (Starvation Creek only) and fish habitat area, the suggested technique of defining a breakpoint on the habitat discharge curve produced minimum flow recommendations that were lower than the historical minimum unregulated flows or unregulated flows exceeded 95% of the time. Application of the technique to a new habitat descriptor, flowing water perimeter, produced minimum flow recommendations that were similar to the historical unregulated minimum flows. The minimum flows that have actually been applied to the regulated reaches downstream of the weirs were similar to the unregulated minimum flows. Biological data indicate that the regulated flows have not maintained the macroinvertebrate community in its unregulated state.

For the headwater streams investigated here, wetted perimeter curves did not suggest optimum environmental flows (as suggested in the literature), nor did they suggest a flow level that would maintain the macroinvertebrate community in its unregulated state if it was applied for a long period of time. Analysis of flowing water perimeter curves gave higher, but still inadequate, minimum flow values. Fish habitat area curves were found to be inappropriate for the problem of minimum flow determination. Flowing water perimeter is preferable over wetted perimeter as a variable to define habitat suitable for macroinvertebrates. Even so, the discharge corresponding to the breakpoint on the curve relating flowing water perimeter and discharge should be viewed as a minimum flow to be applied only during dry periods when the flow in the stream would have been low under unregulated conditions.

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