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Measuring and Modeling the Hydraulic Environment for Assessing Instream Flows

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Abstract.—Detailed measurements of water depth and velocity in natural channels, though rare, show that the velocity fields are complex and irregular even in streams with moderate gradients and gravel substrates. This complexity poses a challenge for instream flow studies, most of which use the physical habitat simulation (PHABSIM) model, a set of computer models that combine the results of hydraulic modeling with estimates of channel substrate or cover and habitat suitability criteria to compute weighted usable area (WUA), an index of habitat. Some recent studies have replaced the transect-based one-dimensional hydraulic modeling in PHABSIM with two-dimensional models that allow better definition of the depth and velocity fields in the modeled stream reach. The accuracy of the estimates as a function of channel geometry and data collection effort remains unclear, however, as does the utility of the estimates for evaluating instream flow needs. Here we review the assumptions, accuracy, and precision of hydraulic modeling and the measurements that provide input data for the models; we also consider some implications of the limitations of hydraulic modeling for describing fish habitat and assessing instream flows. Highly accurate hydraulic modeling seems infeasible for streams with complex channel geometry, and in any event practical hydraulic modeling cannot resolve flow patterns at the short length scales at which fish often respond to the hydraulic environment. Information on depth, velocity, and substrate is important for assessing instream flows, but information from hydraulic models should be treated with great caution and is not a substitute for biological understanding.

Detailed measurements of depth and velocity in natural channels are rare, but those that exist show that the velocity fields are complex and irregular, often with substantial cross-stream components (Dietrich and Smith 1983; Petit 1987; Whiting and Dietrich 1991; Larsen 1995; Whiting 1997). This complexity in the flow patterns in natural channels poses a challenge for methods of assessing instream flows that depend on hydraulic modeling, such as the physical habitat simulation (PHABSIM).

PHABSIM consists of a set of computer models that combine hydraulic and biological models to evaluate the habitat value of a reach of stream for a given fish species and life stage. The weighted sum of calculated habitat values for the reach is expressed as the weighted usable area (WUA), which is taken to represent the ''living space'' available for the organism; water quality and temperature are evaluated separately. PHABSIM is widely used in North America to quantify the biological effects of alterations in flow regimes or the relative benefits of different release regimes from reservoirs (Reiser et al. 1989), and it is increasingly being applied elsewhere as well, either directly or in modified form (Jowett 1989; Pouilly et al. 1995). PHABSIM has even been used to evaluate the instream flow needs of blue ducks *Hymenolaimus malacorhynchos,* which forage for invertebrates in steep, boulder-bedded upland streams in New Zealand (Collier and Wakelin 1996). However, the hydraulic and biological aspects of PHABSIM have also been the subject of continuing criticism (Marthur et al. 1985; Shirvell 1986, 1994; Osborne et al. 1988; Gan and McMahon 1990; Elliott 1994; Castleberry et al. 1996; Ghanem et al. 1996; Heggenes 1996; Williams 1996; Lamouroux et al. 1998).

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FIGURE 1.—Solfatara Creek looking downstream over the reach studied by Whiting and Dietrich (1991) and Whiting (1997). Note moderate gradient and apparently tranquil flow.

In this paper, we consider the adequacy of hydraulic models in general, and PHABSIM in particular, for making predictions of the depth and velocity fields in natural streams that are useful for assessing instream flows. We begin with data from the literature that demonstrate the complexity of the depth and velocity fields in natural steams. We then consider the sampling and measurement problems associated with developing data for modeling the flow fields in natural channels and for describing those fields empirically. We next review modeling approaches that reflect the practical restrictions on data collection. Finally, we discuss some biological aspects of the problem and offer recommendations. We confine ourselves to the problem of estimating the habitat value of a stream for a single species and life stage of fish, even though we recognize the inadequacy of that perspective for real environmental protection. We do not consider recently reported hydrologically based methods for assessing instream flow regimes (Richter et al. 1996, 1997); although these methods appear promising, they do not explicitly link the physical characteristics of channels to flows or biological habitats.

Depth and Velocity Fields in Natural Streams

The data of Whiting and Dietrich (1991) illustrate the complexity of patterns in natural channels. Whiting and Dietrich took detailed measurements on Solfatara Creek, a 5-m-wide gravel bed stream that drains 62 km^2 in Yellowstone National Park, Wyoming. The 20-m-long study reach is located downstream of a bend where the creek flows over and around a midchannel bar; the substrate is coarse sand to medium gravel, and the average channel slope is 0.001 (Figure 1). Measurements were made at about one-third of the bankfull stage by means of an array of small current meters suspended from a portable wooden bridge that was placed so as to give 11 cross sections spaced 2 m apart.

Although the stream appears relatively tranquil at this discharge, the velocity field is quite complex (Figure 2), displaying large vertical and horizontal variations within given sections as well as between closely spaced sections. The large variation in channel form and velocity distributions from one section to the next illustrates the spatial sampling problems inherent in any transect-based method

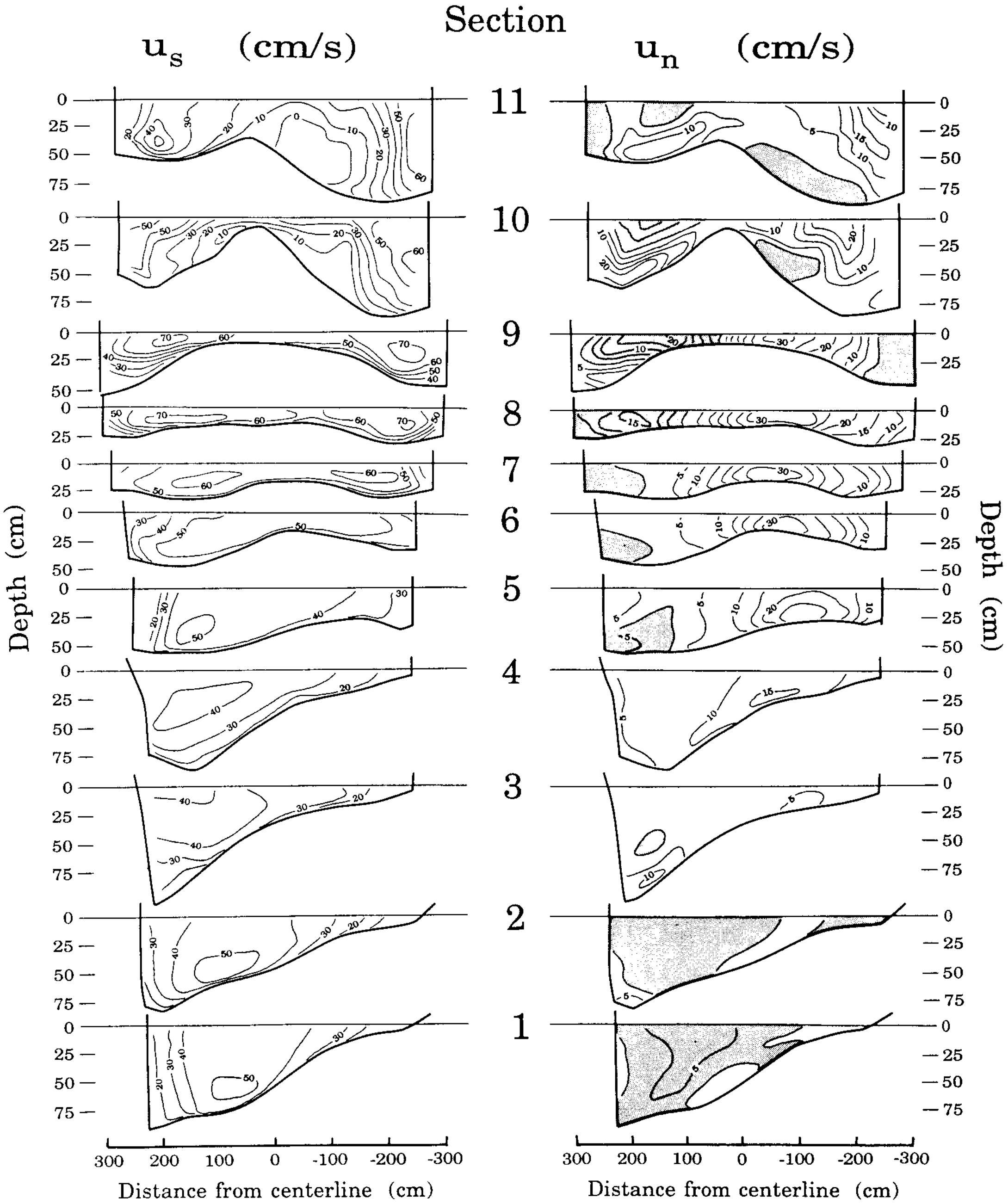

FIGURE 2.—Downstream (u_s) and cross-stream (u_n) velocity fields at sections spaced 2 m apart in Solfatara Creek, Wyoming, reprinted from Whiting and Dietrich (1991). Isovels (lines of equal velocity) are at 10-cm/s intervals; shaded areas indicate flow toward the left bank. Downstream isovels range from 0 to 70 cm/s, cross-stream isovels up to 20 cm/s to the left and up to 30 cm/s to the right. The high-velocity core near the bottom in sections 1 and 2 (>50 cm/s downstream) moves up and splits going over the bar in sections 7–10, with downstream velocity peaking at more than 70 cm/s in sections 8 and 9. Velocity is highest near the right bank in section 11 (>60 cm/s), with a secondary maximum (>50 cm/s) forming to the left of the bar. Water close to the right side of the bar in section 11 is eddying upstream (<0 cm/s). Section numbers increase in the downstream direction. See text for site description.

for evaluating instream flows: The results will vary substantially depending on the precise location of the transects. Spatial sampling problems would be even more serious in steeper streams with a coarser substrate.

The measured velocity fields show that vertical velocity profiles often deviate substantially from the logarithmic profile commonly assumed (Figure 2), as has been noted elsewhere (e.g., Dingman 1989; Beebe 1996); in particular, the highest velocities are sometimes near the bed (e.g., cross sections 1 and 2). This implies that measurements of velocity at 0.6 depth (i.e., 40% of the vertical distance from the bed to the water surface) may give only an approximation of the true column velocity. To illustrate this point, we used data for eight of the sections or transects shown in Figure 2 (not all data were available because of a storage media failure) to compare the vertically averaged velocity computed from measurements spaced up to 5 cm apart with the velocity at 0.6 depth (Figure 3). The velocity at 0.6 depth overestimates the vertically averaged velocity in most cases (the median difference is about 6%) but underestimates it by almost 60% at some verticals in section 10, where the flow deepens after passing over a mid-channel bar. In steep streams with large roughness elements, flow patterns would be even more complex. It may be possible to model the spatially averaged vertical velocity gradient in such streams (Weiberg and Smith 1987), but only if the stream is straight and the roughness elements are distributed approximately randomly, that is, not organized into bars. These conditions are fairly restrictive, and as is often noted in discussions of instream flows, fish do not live in averages.

Details of the flow can vary in important ways even where the general patterns are similar. This is illustrated in sections 1–4, which have approximately the same shape and general lateral distributions of velocity, with higher velocity in the deeper part of the channel. Yet the velocity gradients in sections 1 and 2 are quite different from those in sections 3 and 4. In sections 1 and 2, the vertical gradient is almost nonexistent near the outside of the bend but becomes very steep under the high-velocity core, which is near the bottom. Such steep gradients do not occur in sections 3 and 4. If velocity gradients matter to fish, as the literature indicates (e.g., Jenkins 1969; Bachman 1984; Heggenes 1994, 1996), such differences would be important; but they would remain undetected without detailed measurements of velocity and bed topography.

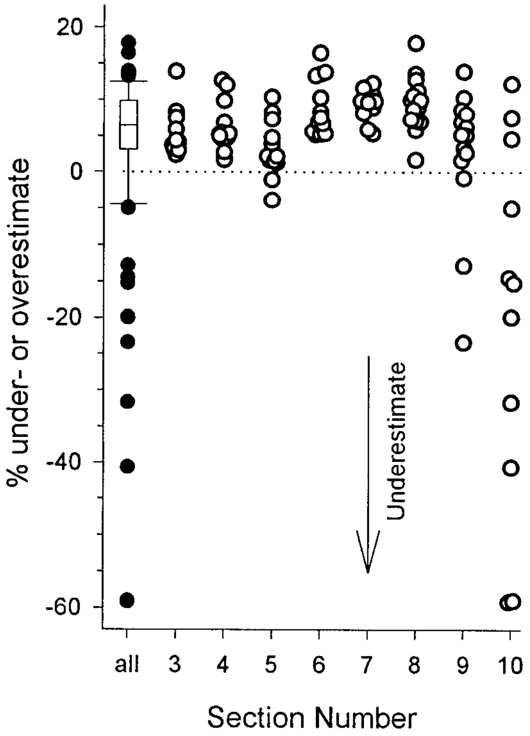

FIGURE 3.—Percentage differences between the estimates of water velocity that were obtained by measuring velocity at 0.6 depth and those that were obtained by averaging the detailed velocity measurements made by Whiting and Dietrich (1991) for eight of the sections shown in Figure 2. Positive differences indicate that the measured velocity at 0.6 depth is greater than the average of the detailedmeasurements. Each circle represents one vertical; the box plot summarizes the differences for all sections.

Note that the change in channel shape with distance downstream forces significant changes in the velocity field that are known as convective accelerations. This has implications for modeling because one-dimensional (1-D) models ignore convective accelerations.

Velocity Measurement in Streams

For each cross section or transect measured at Solfatara Creek, Whiting and Dietrich took an average of 160 point-velocity measurements, each a time-average over two minutes. The entire set of measurements required 8–10 h to complete. In most practical applications, it is not possible to spend that amount of time per transect to measure velocity. For this reason, PHABSIM procedures are typically modeled after the standard procedures of the U.S. Geological Survey (USGS) for measuring velocity in discharge measurements near stream gauges, as described in Rantz et al. (1982).

Velocity is measured at 20–30 stations across the channel with a Price AA current meter or the smaller mini current meter, both of which consist of cups that spin around a vertical axis in response to moving water. The researcher either suspends the meter from a cable or bridge or wades into the water with the instrument in his or her hand. For depths less than 0.8 m, velocity is measured at 0.6 depth, which is assumed to reflect the mean column velocity. In deeper water, the average of the measurements made at 0.8 depth and 0.2 depth is taken as the mean column velocity. The mean column velocities for each point are then multiplied by the measured water depth and the width of the vertical slice of the cross section represented by this measurement to obtain the discharge for that vertical slice. Finally, the discharges for the individual ‘‘verticals’’ are summed to obtain the total discharge past the cross section.

To obtain a good measurement of flow, the hydrographer measures the stream by wading (when possible) and selecting the cross section with the most uniform flow conditions available on the channel, that is, one with flow lines that are parallel and that do not vary downstream. The hydrographer will often ‘‘improve the [measurement] cross section by removing rocks and debris within the section and in the reach of channel immediately upstream and downstream from the section’’ or by constructing ‘‘temporary dikes to eliminate slack water’’; both serve to transform the flow conditions in an irregular natural channel into more uniform ones (Rantz et al. 1982). Each measurement is rated as excellent, good, fair, or poor, with assumed error margins of 3%, 5%, 8%, or more than 8%, respectively; these ratings are assigned on the basis of the hydrographer's judgment (Rantz et al. 1982). Ratings of excellent are uncommon in natural streams, despite the hydrographer's freedom to select the most uniform reach available and to modify channel geometry. The reaches selected for discharge measurements are probably not the preferred habitats for fish, or at least they are not typically the sites where anglers would look for fish. In essence, the hydrographer seeks the reach of channel that most closely resembles a canal. Highly irregular channels with shallow marginal areas, back eddies, still water, or boulder beds, which may be important as fish habitats, are sites that a hydrographer would avoid for flow measurement (unless the stream offered nothing better) because the resulting measurement would be poor.

Sources of Error in Measurements

Errors in point measurement of depth are usually small. At some locations the depth of flowing water can fluctuate by several centimeters at constant discharge, but this can be detected by reasonably careful observation of the section. Errors in estimating the average depth of a vertical are most likely to be sampling errors, especially when the cross section is irregularly shaped or the substrate is coarse. These conditions should be obvious, especially when measurements are made by wading, and with reasonable care a good estimate should be possible.

Potential sources of error in velocity measurements include the inherent limits in the accuracy of the meter in registering downstream current velocity, temporal variations in velocity at the point of measurement, vertical and cross-sectional components of velocity, and sampling errors within each vertical. Instrument errors associated with measuring unidirectional flow are relatively minor with Price meters; in the controlled environment of a tow tank, Carter and Anderson (1963) found that Price meters register within 0.6% of the actual downstream velocity. However, the meters that they tested were in excellent condition; poorly maintained meters and ones clogged with sediment or organic debris would not perform as well.

Replicate discharge measurements that were made in rivers with both Price and Ott current meters (the latter a screw-type meter) were found to differ by up to 2.8% in total discharge (Carter and Anderson 1963). This degree of agreement between the two meters seems acceptable, though the actual differences in point velocity measurements were not reported. However, PHABSIM studies often employ Marsh−McBirney current meters, which use the distribution of pressure around a rounded sensor to estimate velocity. This is conceptually attractive, and Marsh−McBirney meters can also provide either instantaneous or time-averaged readings of velocity. The manufacturer's specifications state the meter's accuracy as ± 2% of the reading, with a ± 0.05 ft/s offset. Although one Marsh−McBirney meter performed well in initial tests by USGS (Fulford et al. 1994), in subsequent tests with a number of meters the measurements were inconsistent, with low velocities being both under- and overregistered (J. Fulford, USGS, personal communication). In our experience, these meters can be unstable and require frequent calibration; after informal field compar-

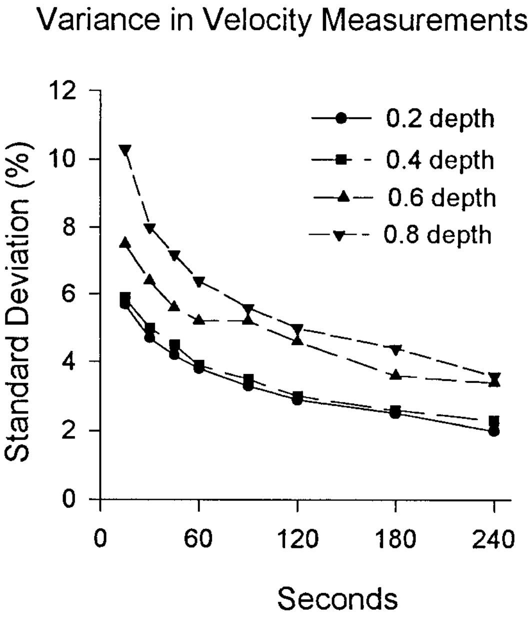

FIGURE 4.—Standard deviations of velocity measurements averaged over different time periods, as percentages of the overall (1-h) means. Data from Carter and Anderson (1963). The anomaly in the 0.6 depth curve probably results from a typographical error.

isons with a Price meter, we are skeptical of data collected with Marsh−McBirney meters.

There can be considerable temporal variation in velocity at a particular point in a stream, especially one with a rough bed. The standard USGS approach to the problem is to take the velocity measurement over at least 40 s. This may not be sufficient, however. Carter and Anderson (1963) took measurements continuously for 1 h in 23 different rivers, at four different depths. They recorded data every 15 s, which allowed them to calculate the deviations in velocity measured over shorter intervals from the 1-h average (Figure 4). Although there are some problems with these data, they show that sampling errors are still significant at 40 s. Errors are also greatest near the bed, where ''focal point'' velocity measurements are often made. Thus, the 40-s rule reflects a compromise between the gain in accuracy from averaging over a longer period and the cost of the additional time required. However, this compromise was developed for discharge measurements, where random errors in individual measurements tend to average out over the transect. Because PHABSIM measurements are not averaged over the transect, it is not clear that the same compromise is appropriate. Moreover, the Carter and Anderson data are from reaches selected for discharge measurements, and greater temporal variation should be expected in reaches with more complex geometry.

The vertical and cross-channel components of velocity are not well captured in the standard USGS measurement of flow. The Price AA meter does not measure flow direction. Although any cross-channel flow can be accounted for by means of the hydrographer's estimate of the angle of approach, the existence of cross-channel flow at a vertical indicates a complex flow structure, so that one or two measurements may give a poor estimate of the spatially averaged velocity in the vertical. The Price meter is also affected by vertical velocity components in steep, turbulent channels but cannot measure them separately from the downstream components (Townsend and Blust 1960; Linsley et al. 1982). As a result, the velocities recorded in such channels may be greater than the true downstream velocities (Marchand et al. 1984). A modified Price meter that has solid cups composed of a polycarbonate polymer (the PAA meter) initially appeared to be less affected by vertical velocity components than the standard AA meter with stainless steel cups (Marchand et al. 1984), but subsequent experience has shown that the polymer cups are less accurate than the stainless steel ones (R. Jarrett, USGS, personal communication).

Spatial sampling errors within each vertical will depend on the complexity of the flow field. In canal-like sections, these errors will be small enough to allow good or excellent discharge measurements. In a complex field, however, even in a relatively tranquil stream such as that illustrated in Figures 1 and 2, the spatial sampling errors in estimating the average velocity of a vertical from only one or two velocity measurements can be substantial.

In PHABSIM studies, the discharge is often assumed to be known from a nearby gauge. If the total flow calculated by summing the individual PHABSIM measurements differs from this ''known'' discharge, the individual velocity measurements are adjusted by a ''velocity adjustment factor,'' which is a percentage change that is applied to all the measurements across the channel (Milhous et al. 1984). Although this adjustment may account for systematic errors, it does nothing to change the distribution of sampling and measurement errors across the channel.

In summary, instrument errors with well-maintained and properly used Price and Ott current meters are likely to be small relative to the temporal and spatial sampling errors. Figure 4

TABLE 1.—Rules of thumb from Herschy (1978) for 95% confidence intervals for hydraulic measurements, expressed as percent of measured values.

Type of uncertainty	Confidence interval
Current meter error	1% at 0.5 m/s, 2% at 0.25 m/s, 5% at 0.1 m/s
Width measurement	0.5%
Depth measurement	2.5%
Time variation in velocity measurement	5% at 0.3 m/s, 22% at 0.1 m/s; 3 min exposure
Vertical spatial variation in velocity	7% (0.2 and 0.8 depth), 15% (0.6 depth)

provides some guidance regarding temporal sampling errors. Although the figure probably underestimates the magnitude of the errors for transects with complex flow patterns, a similar decrease in the sampling error with increased measurement time can be expected. With standard methods, spatial sampling errors are probably as large as or larger than temporal sampling errors. Herschy (1978) provides a more detailed discussion of measurement errors at sites selected for discharge measurements and gives rules of thumb for estimating the 95% confidence intervals around measurements at such sites (Table 1). Unfortunately, there have been too few detailed studies of the flow fields in natural channels to allow quantitative generalizations about measurement errors in channel reaches like those in which PHABSIM is typically used (as opposed to those selected by hydrographers for discharge measurements). Under the conditions applicable to most instream flow studies, however, we believe that the errors in estimating the average velocity of verticals by the standard methods will be large enough to affect the ultimate results, so the ordinary scientific practice of estimating errors by appropriate repetitive measurements should be followed.

Modeling Flow in Natural Streams

One-Dimensional Models

One-dimensional (1-D) models typically treat a river as a series of cross sections, for each of which a stage and cross-sectionally averaged velocity are computed based on hydraulic principles, the channel form, and calculated values of stage and velocity at downstream cross sections. Probably the best-known 1-D model is HEC-2 or HEC-RAS, which is widely used for predicting flood levels. WSP, a similar, 1-D gradually varied flow model, is an option for modeling stage in PHABSIM (Milhous et al. 1984).

One-dimensional models typically assume that the channel is straight, with all flow perpendicular to the cross section, and that the flow is either uniform or ‘‘gradually varied.’’ Uniform flow does not change in the downstream direction and therefore has a vertical velocity profile that reflects a balance between the acceleration of gravity and the resistance of the channel bed. These conditions can occur in canals, but they are generally not found in natural streams. Gradually varied flow occurs where channel topography and roughness change only slowly along the channel, so that convective accelerations can be ignored.

These are large assumptions, and although reasonable approximations of river stage are routinely obtained if the models are used with adequate skill and professional judgment, by definition the models can provide only cross-sectionally averaged velocity. Moreover, gradually varied flow models are commonly used for predicting flood stage during high flows when variations in the bed topography may be less important; for example, hydrologists speak of riffles being ‘‘drowned out’’ at the bankfull stage and above. Whiting (1997) has shown that convective accelerations are less important at higher flows in Solfatara Creek. Instream flow assessments, however, are typically concerned with the lower-magnitude flows in which fish spend most of their time. These flows are too low to modify the bed, so they occupy a channel geometry inherited from past high flows. Downstream changes in channel geometry that are small relative to high flows may be large relative to low flows (such as when a low flow spills over a longitudinal bar), so that the assumption of gradually varied flow is violated, as noted by Osborne et al. (1988). As a result, a model that gives reasonable estimates of stage in a channel at high flows may fail to do so at low flows.

Because PHABSIM is concerned with the distribution of velocity and depth across the channel, the hydraulic models it employs divide the cross section into vertical slices (cells) that are either centered on or lie between point measurements of velocity (much as is done in USGS discharge measurements). The vertical cells are analyzed separately, either by conducting a regression analysis of the measurements of velocity in the cell at different stages or by doing a back-calculation of Manning’s n from a single velocity measurement (Milhous et al. 1989). The latter approach has been properly criticized by Shirvell (1986), and more recently by Ghanem et al. (1996), who point out that the cells are no longer tied to one another through hydrodynamic principles. For this reason, Ghanem et al. (1996) describe the velocity modeling in PHABSIM as ‘‘zero-dimensional.’’ In the single-measurement approach, Manning’s roughness factor is used to calculate velocity and discharge for each cell at other discharges, but the individual cell discharges are adjusted to equal the modeled flow so that the roughness factor is really a weighting factor rather than a true roughness coefficient. With the multiple-measurement approach, there is also a problem with obtaining the required three velocities for verticals near the bank, which may be dry at the lower measured discharges (Ghanem et al. 1996).

Errors associated with the PHABSIM approach to distributing velocity across channels were investigated by Bartz (1990) as part of a broader assessment of PHABSIM. Bartz used data from the U.S. Fish and Wildlife Service for three streams spanning a flow range of two orders of magnitude. For each stream, he calibrated different PHABSIM hydraulic models to the data at three flows and then compared the measured and modeled velocities for each vertical. The averages and standard deviations of the differences were substantial, as illustrated by the data for the medium-sized stream (Figure 5). Mean errors ranged from 4.6% to 12.8% and standard deviations from 29.6% to 42.7%. The results for the small and large streams were similar.

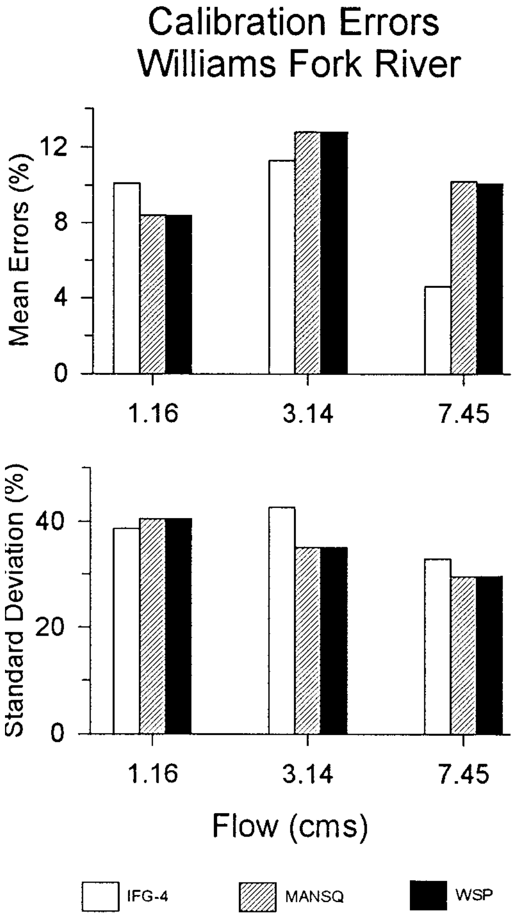

FIGURE 5.—Means and standard deviations of the differences between measured and modeled mean column velocities at verticals on the Williams Fork River, Colorado, for three PHABSIM hydraulic models (IFG-4, MANSQ, and WSP) calibrated at three discharges. Data from Bartz (1990), Table 4.5.

Two-Dimensional Models

Two-dimensional (2-D) models are increasingly being used for instream flow studies (e.g., Leclerc et al.1995; Ghanem et al. 1996). Two-dimensional models require the simultaneous solution of a system of governing equations, which typically include relationships (expressed as differential equations) for the conservation of fluid mass, the conservation of downstream fluid momentum, and the conservation of cross-stream fluid momentum. To simplify these relationships, certain approximations are assumed, which yield the so-called ‘‘shallow water equations.’’ These 2-D velocity models give only vertically integrated velocities, but they show the variation in cross-stream direction as well as in downstream direction.

These models contain the convective acceleration terms neglected by 1-D models, but they require more detailed descriptions of channel geometry and the accuracy of the results depends on the accuracy and spatial resolution of the measurements (Leclerc et al. 1995; Ghanem et al. 1996). For example, Leclerc et al. (1995) constructed a computer representation of the bed of a large stream by measuring the bed elevation with one measurement for every 50–400 m^2, so their results are generalized accordingly.

However, with detailed specification of the channel bed topography and planform, more sophisticated modeling may not be necessary. One-dimensional models are not all the same, and in some settings they can be as accurate in simulating vertically integrated velocity fields as 2-D models. Dietrich (1987) modeled flow in Muddy Creek, Wyoming, for geomorphic purposes using a 1-D approach that explicitly accounted for the effect of channel curvature and that predicted the distribution of velocity across the transects. Larsen (1995) applied the same approach, comparing observed velocity patterns on two gravel-and-cobble-bedded meandering rivers. He showed that, with good bed topography as input, the 1-D model performed as well as more sophisticated models. However, understanding the appropriateness and limitations of a model seems critical. For example, it is unlikely that the excellent results obtained by Dietrich and Larsen could be achieved in a straight channel with irregular bed topography, such as the reach of Solfatara Creek studied by Whiting and Dietrich (1991), for which a 2-D model that accounts for convective accelerations would be more appropriate.

Statistical Hydraulic Models

Following a suggestion by Dingman (1989), Lamouroux et al. (1995) developed an empirical model that predicts the statistical distribution of hydraulic variables (such as velocity and water depth) for reaches with intermediate and large roughness elements, for which they believe the conventional deterministic models are ineffective. The model predicts the distributions of the hydraulic variables over an entire reach based on inputs of discharge, mean width and depth, and roughness. Lamouroux et al. (1998) coupled this hydraulic model with multivariate habitat use models to estimate the habitat value of a reach as a function of discharge. The need for validation is perhaps more obvious with such straightforwardly empirical models, which is a virtue.

Model Validation

Models by nature involve simplifications of reality, and model predictions always entail some error. For hydraulic modeling of fish habitat, the errors can arise from measurement errors, model errors, or sampling errors. With the standard 1-D versions of PHABSIM, one should ask how accurately depth and velocity were measured at the selected points on the transects, how well the model predicts depth and velocity at the selected points at other discharges, how well the selected points represent the verticals or cells, and how well the selected transects represent the stream.

In practical applications, it is important to estimate the probable errors in model predications. This is typically done by ‘‘model validation,’’ in which model predictions are compared with measured data different from those used to develop or calibrate the model. Although Oreskes et al. (1994) have pointed out that this is not really validation, we will use this common term for the process. Lamouroux et al. (1995) present graphical comparisons of measured and predicted velocity distributions, though they acknowledge that their procedure is not strictly correct. Aceituno and Hampton (1988) compared the distributions of point measurements of depth and velocity separately with comparable distributions from PHABSIM verticals, but they did not consider their joint distributions or estimates of WUA. Unfortunately, even these imperfect examples are exceptions. Typically, validation is not even discussed, even though it seems particularly important in the case of PHABSIM predictions. Because PHABSIM offers users a wide variety of options that can produce a wide range of results, there is a danger that the options may be selected (consciously or unconsciously) to produce a desired result (Bartz 1990; Gan and McMahon 1990).

The proper form of the validation will depend on the underlying conceptual model. As originally developed, the conceptual model for PHABSIM assumed that the data from the transects applied half-way upstream or downstream to the next transect (Bovee 1982; Thomas and Bovee 1993). In other words, the stream is divided into horizontal cells, each of which is represented by measurements at one point on the transect. With this conceptual model, validation could simply involve measuring the depth, velocity, and substrate at random points in the study reach at various discharges and comparing these measurements with the values PHABSIM assigned to those points. It is important that the validation include the habitat variables and not just the WUA, so that ‘‘correct’’ estimates of WUA that result from offsetting errors are revealed.

Recently, some PHABSIM users have employed a different conceptual model in which transect data are treated as samples stratified by habitat types rather than as representing specific areas of the channel (e.g., CDFG 1991). With such a model, the particular approach to validation will depend on the details of the sampling scheme, but the basic process will remain the same: Model predictions of the joint distributions of depth, velocity, and substrate would have to be compared with independent data. If transect sites are selected randomly, they will provide an unbiased estimate of conditions in the study reach, so that models can be validated at the transects and the streamwise spatial sampling errors estimated separately using statistical methods such as bootstrapping (Williams 1996). Because the PHABSIM hydraulic models cannot be calibrated for the more turbulent areas of many streams, however, the condition of randomly located transects is difficult to meet in PHABSIM studies. Where this is the case, validating the model with data from randomly located points seems more appropriate. As with any statistic developed by sampling, estimates of WUA should be reported with standard errors or confidence intervals so that decision makers are informed of the uncertainty associated with the estimates (Castleberry et al. 1996).

Application of Models to Aquatic Habitat

Because our discussion of habitat models is in the context of their application to evaluating habitat for a particular species and life stage of fish, the most relevant question is whether such models can capture the aspects of the hydraulic environment that are most important to the organism in question. In some cases, the answer is clearly no. For example, chinook salmon *Oncorhynchus tshawytscha* select spawning sites on the basis of subsurface flow as well as depth, velocity, and substrate (Healey 1991; Vyverberg et al. 1997), so a model that does not address subsurface flow will be seriously incomplete in its evaluation of habitat for spawning chinook salmon.

More generally, we argue that fish often respond to features in their hydraulic environments, such as velocity gradients, over small length scales. For example, salmonids may hold in the flow separation zone downstream of a boulder, as described for a Pennsylvania stream by Bachman (1984):

> Typically, foraging sites were in front of submerged rocks or on top of but on the downward-sloping rear surface of a rock. From there the fish had an unobstructed view of oncoming drift. While a wild brown trout *Salmo trutta* was in such a site, its tail beat frequency was minimal, indicating that little effort was required to maintain a stationary position even though the current only millimeters overhead was as high as 60–70 cm/s. Most brown trout could be found in one of several such sites day after day, and it was not uncommon to find a fish using many of the same sites for three consecutive years.

Contrast the precise positioning of this fish in the hydraulic environment (i.e., within millimeters of a steep vertical velocity gradient) with the detail that can be provided by hydraulic models. Even with 2-D flow models, the resolution is scaled by flow depths (Ghanem et al. 1996) and cannot account for vertical velocity gradients. The best that can be done is to patch on some estimated average velocity gradient, and as should be evident from Figure 2, this would give only a crude approximation. Accordingly, there is a discontinuity in the spatial scale at which it seems feasible to model the hydraulic environment and the spatial scales at which fish often respond to it. This seems particularly true for fish that hold near steep velocity gradients, such as near the bed of the stream, boulders, or logs.

At best, practical modeling of the hydraulic environment to determine instream flows involves estimating the distributions, individual or joint, of depth and velocity over sizable areas. Where the channel conditions are sufficiently uniform that this can be done with reasonable accuracy, this exercise would obviously provide useful information about the effects of discharge on fish habitat. If such information can be developed by mapping (Collings 1972) or by an empirical approach (Lamouroux et al. 1995), it will be similarly useful. However, values of hydraulic variables averaged over sizable areas should not be confused with the local values to which fish and other organisms often respond (Bult et al. 1999; Railsback 1999). To combine hydraulic model results, which are accurate only on a coarse scale, with habitat preference or suitability data collected on a much finer scale raises troubling questions about meaning. The PHABSIM estimates of weighted usable area result, in effect, from multiplying biological apples by hydraulic oranges.

Railsback (1999) proposes dealing with this problem of scale mismatch by developing suitability data from observations in cells with a spatial scale comparable to the resolution of the hydraulic modeling. This raises another set of problems, however. If the cells are small, then occupancy of each cell may be affected by occupancy of adjacent cells as well as by hydraulic factors, and collection of enough hydraulic data for modeling any sizable length of stream will be difficult and expensive. If the cells are large, then describing a cell by single values for depth, velocity, and substrate/cover index is dubious, and the biological meaning of the weighted usable area is compromised.

Conclusions

Flow fields in natural channels are complex, and it is not feasible to model this complexity for any length of channel at the fine length scales to which fish often respond. We believe that a more modest approach to using hydraulic models for instream flow assessments is appropriate. In many streams, 2-D modeling can produce reasonable estimates of the amount of habitat with given combinations of depth and average velocity, and in other streams this can probably be estimated empirically. This is important information that any of us would want to have if we were charged with making decisions about instream flows, provided that it could be obtained without consuming too much of the available funding.

We suggest, however, that it is prudent to treat the hydraulic and biological inquiries as separate and distinct tasks, in part because this helps to avoid the appearance that models are providing answers rather than giving us aids to thought. We suspect that the best way to evaluate the importance of hydraulic conditions for a particular fish is to have a good understanding of the way that the fish uses the hydraulic environment. This kind of understanding is developed by careful observational studies such as those of Jenkins (1969), Bachman (1984), and Nielsen (1992), and especially from long-term studies, like those at Carnation Creek in British Columbia (Hartman et al. 1995) and Brows Beck in England (Elliott 1994).

Because such evaluations involve the use of professional judgment about data from hydraulic modeling or mapping, they can be criticized as subjective. However, modeling gives only the illusion of objectivity because it always involves simplifying assumptions. Therefore, judgment goes into deciding just what to model and how to do it, and good judgment requires knowledge of both the model and the thing being modeled. Models are not a substitute for knowledge and experience. Whether a model is good or bad depends on the purpose to which it is put. For simulating depth and velocity, different models are appropriate for different kinds of channels and different scales of resolution. However, all models have limitations. For simulating a particular reach of stream, proper use of any model requires consideration of the statistical problems arising from sampling and measurement errors, along with appropriate validation.

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