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ESTIMATION OF INSTREAM FLOW REQUIREMENTS FOR FISH*

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ABSTRACT

Flows required for sustaining fish population in a stream are examined in this study. The instream flow incremental methodology (IFIM) which has been developed for estimating these flows requires data which are not commonly available and are expensive to acquire. Other methods to estimate instream flows, which are based only on flow rates, do not consider the characteristics of the fish population in the stream and hence are unrealistic. A modification of the IFIM is proposed in this study. Various factors which are involved in the modification are investigated. Based on these investigations, a method which is much less data intensive than the IFIM but which gives results of the same order of magnitude as the IFIM is proposed. The method is illustrated by using data from streams in Indiana.

INTRODUCTION

"The Water Resources Management Act" gives the Natural Resources Commission in Indiana the authority to "establish by rule, the criteria for the determination of minimum stream flows and minimum ground water levels" [1]. Recent developments such as the need to obtain a permit for water withdrawals from a navigable body of water, the formation of a two-year legislative study committee

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in 1989 which may establish withdrawal permit requirements for all streams in Indiana, and water use conflicts during the 1988 drought have necessitated the determination of flows that are needed for stream functions and that are therefore protected from out-of-stream withdrawals. The flows which are protected in the stream are commonly referred to as *instream flow requirements*.

Low flow statistics are commonly used throughout the United States to establish the instream flow requirements. The low flow statistic which is used to establish instream flow levels is chosen after instream flow requirements have been determined. Because each instream use requires a different flow, the statistic chosen is usually a compromise between the many uses. The flows commonly used are exceedances corresponding to different frequencies. These and similar statistics are computed by flow duration analysis.

Maintaining fish habitat is an important instream use. In several states, it is the one use with the highest flow requirements. For this reason, an understanding of the effects of low flow on fish habitat is essential to making any decisions regarding instream flow requirements.

The Instream Flow Incremental Methodology (IFIM) is a method used to determine effects of low flows on fish habitat. The IFIM can also show the effects of low flows on recreational uses. The IFIM requires hydraulic modeling of low flow profiles in streams and determination of fish habitat or recreation needs at various depths and velocities in a stream. Because acquisition of the necessary field information for development of hydraulic models is labor intensive, the IFIM is usually used for fish habitat or recreational studies on a particular reach of a stream.

When instream flow criteria for several streams are needed, the use of IFIM would be costly. A modification of the IFIM that is not data intensive is presented in this article. Simplification of the IFIM results in some loss of precision, but an understanding of the relationship between low flows in streams and fish habitat and recreational availability is gained at a much lower cost.

THE INSTREAM FLOW INCREMENTAL METHODOLOGY (IFIM)

The IFIM requires hydraulic modeling of low flow profiles in streams and the estimation of habitat response at various depths, velocities, and temperatures and for various substrate and cover conditions. The most significant flow parameters related to fish habitat are depth and velocity [2]. The method is used to determine the usable area for fish habitat and recreation. IFIM application in the eastern United States includes the initial planning of the proposed Louisville Reservoir on the Little Wabash River in Illinois [3] and recreational evaluation on the Chattahoochee River in Georgia [4].

The IFIM builds upon the concept of a weighted usable area (WUA). WUA is the surface area for a given discharge usable for fish or recreation in a 1000 ft.

length of channel. Some definitions related to WUA are shown in Figure 1. WUA's are computed for several levels of stream discharge along the same reach. The flow rates and corresponding WUA's are used to develop a habitat response curve; the flow-WUA curve is used to demonstrate the effects of different flows on WUA.

Before WUA and habitat response curves are computed, a hydraulic model of the river reach is developed. The reach is divided into cells and the average velocity and depth of each cell are determined. The division of a stream reach into cells is shown in Figure 2. A brief discussion of hydraulic modeling, computation of WUA, and development of the habitat response curve follows.

Hydraulic Modeling

Hydraulic models of study reaches commonly are derived either from surface profile models such as HEC-2 [5] or from log-linear stage-discharge curves (for

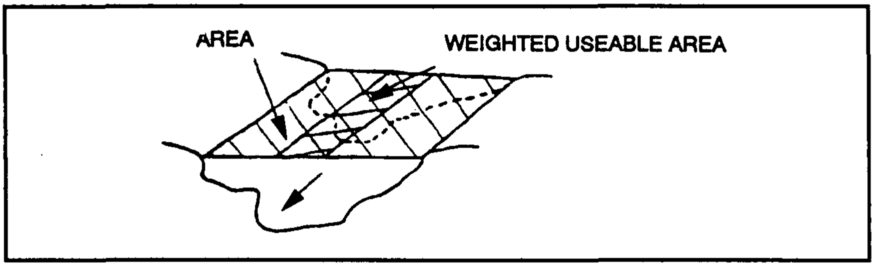

Figure 1. Definitions related to WUA.

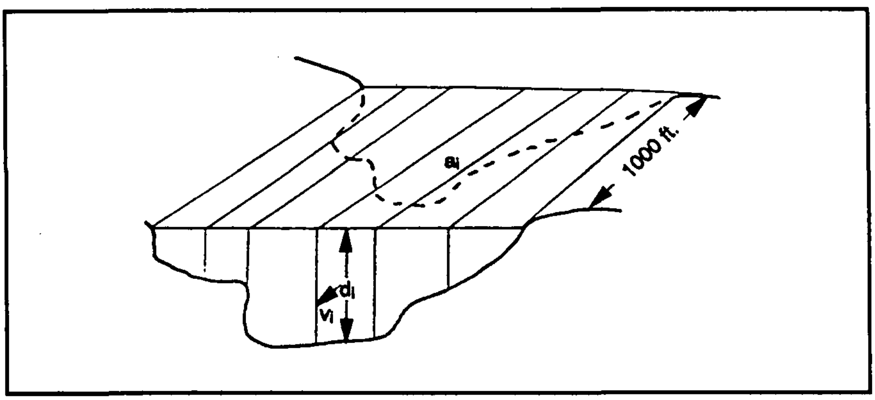

Figure 2. Division of a stream reach into cells.

the reach) and velocity-discharge curves (for each cell). Water surface profile models are difficult to apply at low flows because gradually varied flow is not achieved through the riffle-pool sequence [2]. (It is also difficult to establish Manning's n values for each section in the stream reach.)

The method of using stage-discharge and velocity-discharge relationships requires at least three separate field measurements of discharges. The stage-discharge curve is developed for a reach along with the velocity-discharge curve for each cell by plotting three or more points on logarithmic paper. Although the velocity-discharge curve is assumed to be log-linear, it is often nonlinear for low flows [2].

Because of the difficulty in using these two methods for modeling low flows and in transferring the results to other stream reaches, no procedure is given by the Instream Flow Group [6] for developing basinwide models for use in the IFIM analysis. In the "Interactive Basinwide Model for Instream Flow and Aquatic Habitat Assessment" [2] a method of applying hydraulic information at a basin-wide level using the IFIM analysis is developed. Methods to extrapolate observed velocities and depths in one reach to unmeasured reaches are given. Field data and United States Geological Survey (USGS) flow measurements are used in [2] to make a model that links width, depth, and velocity for different streams in the basin. The hydraulic geometry developed by the USGS flow measurements reflect riffle conditions more closely than average values in a reach. For this reason, the basin-wide model requires correlation factors to obtain reach average values. Only data collected at natural stream sections are used in calibration.

Computation of WUA

The weighted usable area (WUA) is computed for the river reach by using Equation (1).

$$\mathrm{WUA} = \frac{\sum_{i=1}^{n} (a_i f(v_i) g(d_i) h(c_i))}{L} \times 1000 \tag{1}$$

where, a_i is the surface area (ft^2) of the channel reach, $f(v_i)$ is the fish or recreation preference value as a function of velocity, $g(d_i)$ is the preference value for depth, $h(c_i)$ is the preference value for substrate, cover, or temperature, n is the number of cells used in the stream reach, and L is the length of the channel reach (ft.).

Milhous makes three points about the relationship between WUA and actual fish population [7]. 1) There is a relationship between WUA and fish population within a river, 2) Other needs of the target fish, such as food, may limit the population as well as the physical habitat, 3) A knowledge of the history of the physical habitat is needed before analyzing the relationship at any given time.

The preference curves $f(v_i)$, $g(d_i)$, and $h(c_i)$ are obtained from laboratory and field data. Different preference curves are developed for each fish species.

Separate curves are also developed for the various stages of development of each fish species. These development stages include spawning, fry, juvenile, and adult. The preference curves used in the present study were obtained from the National Ecology Research Center in Fort Collins, Colorado.

Examples of preference curves for *adult smallmouth bass* are shown in Figures 3 and 4. As shown in Figure 3, if the velocity of a stream reach cell is greater than 2 ft/sec, there is no WUA available for adult smallmouth bass in that cell. On the other hand, if there is a zero velocity and a depth of 2 ft. in the cell, the entire cell is usable for adult smallmouth bass.

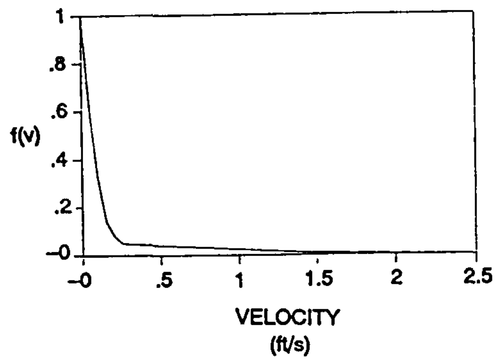

Figure 3. Velocity preference curve for adult smallmouth bass (Herricks et al., 1982).

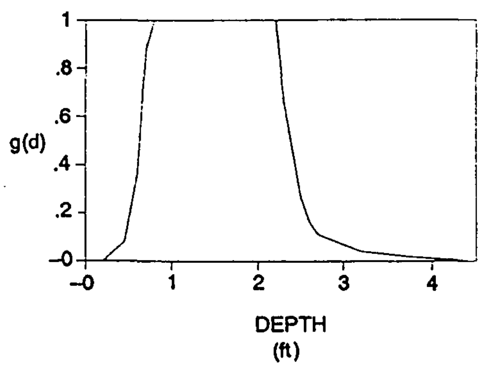

Figure 4. Velocity preference curve for adult smallmouth bass (Herricks et al., 1982).

The substrate, cover, and temperature values ($h(c_i)$ in Equation (1)) are not always used [2]. If modifications that include cover devices, deflectors, weirs, and headgates are considered for enhancing fish populations, then some of these preference values should be included in estimating WUA. Nestler also emphasizes that the channel characteristics such as substrate and cover must be included in the equation before a comparison of WUA can be made between streams [8].

Habitat Response Curves

To develop habitat curves, Equation (1) is used to compute WUA, for each fish species and developmental stage, at several levels of discharge in the stream. These discharge levels and corresponding WUA's are plotted to obtain the habitat response curve. An example of a habitat response curve computed for bluegill in the Little Wabash River [3] is shown in Figure 5.

When a 500 cfs discharge occurs in this reach of the Little Wabash River, the WUA for adult bluegill is 5000 ft^2, and the WUA for juvenile bluegill is 100 ft^2. Thus the surface area of the stream used by adult bluegill is 50 times greater than that used by juveniles. At 500 cfs, the adults will find this reach of river much more desirable than juveniles. In fact, for any discharge, the available habitat for adult bluegill is higher than for juvenile bluegill.

As shown in Figure 5, the WUA is nearly constant when flow rates are greater than 700 cfs for adult both and juvenile bluegill. The WUA for juveniles shows greater variation at different discharge levels than for adults.

The habitat response curve is useful for depicting the changes that occur in available habitat for fish at various stream flow rates. Because changes in habitat

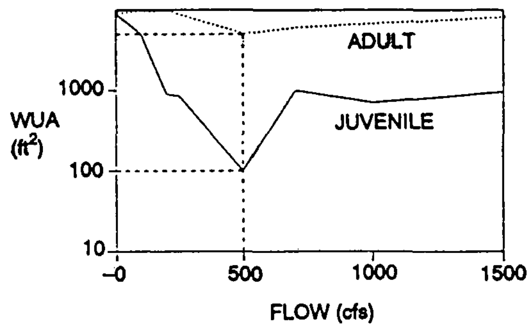

Figure 5. Habitat response curve for adult bluegill on the Little Wabash River (Herricks et al., 1980).

are not the same for various fish species and stages of development, quantification of instream flow rights using the IFIM is difficult. However, there have been attempts to use the IFIM to establish instream flow requirements.

An example of determining instream flow requirements is given by Herricks et al. [3], using the following steps: 1) Develop habitat response curves for each fish species and development stage (juvenile, adult, etc.), 2) Use the habitat response curve to transform the flow time series of the river reach into WUA time series for each fish species and development stage, 3) Compute the median WUA of the time series for each species and development stage, 4) Use the habitat response curve to determine the minimum flow required to achieve median WUA. The minimum flow and corresponding median WUA are determined for each fish species and development stage, 5) For each month determine the prevalent development stage of each fish species, 6) For each month, using the prevalent fish species and development stages, determine the highest of the minimum flows required to achieve median WUA. The highest of the minimum flows is the instream flow requirement needed for the month.

The method assumes that all types of fish used in the analysis are of equal importance. The instream flow is the highest flow needed to achieve median WUA without consideration of the fish species or stage of development corresponding to this highest flow. The median WUA is used so that the instream flow will protect the habitat that occurs at least 50 percent of the time. Because the habitat response curves for different fish species are not the same, this median WUA is protected only for the fish species and stage of development that is used for establishment of the instream flow requirement. It does not protect the median WUA for the other fish species.

Milhous gives six different methods for using habitat response curves to quantify instream flow requirements [9]. Only one of these methods can be applied at any time, and only one fish species can be used in the analysis. The Milhous methods can be used for only one fish species or one form of recreation. In most streams there are more than one fish species or form of recreation that is of interest. As a result, only a range of flows can be specified for a stream reach as being desirable.

MODIFIED IFIM

As discussed earlier, the present study was limited to using commonly available data for the IFIM. United States Geological Survey cross-sections are used for analysis. The cross-sections were developed using USGS field surveys for rating curve development at their stream gaging sites. For this study, only one USGS cross-section was available to represent each reach.

In Indiana, the cross-section surveys are usually conducted a few feet upstream of riffle areas. These are the locations where the most accurate velocity measurements can be taken in a river reach. Therefore, velocities measured at these cross-sections are usually higher than the typical velocities found in the stream reaches. Consequently, when USGS cross-sections are used, the IFIM will better model riffle conditions than pool conditions.

First Modification of the IFIM

The first attempt at modification of the IFIM consisted of using a constant value for the velocity and depth in the IFIM equation. The equation used is given below:

$$WUA = 1000\, w\, f(\bar{v})\, g(\bar{d}) \qquad (2)$$

where w is the width of the cross-section (ft.), $f(\bar{v})$ is the preference for average velocity, $g(\bar{d})$ is the preference value for average depth. As explained earlier, because WUA comparisons across different river systems are not treated in this study, the substrate, cover, and temperature index are not included in Equation (2).

The results obtained by using this first modification of the IFIM were checked against results obtained by using the full IFIM. The data chosen for comparison was taken from the report by Singh et al. [2]. Comparisons were made by using preference curves for adult catfish and bluegill. The preference curves for adult bluegill are shown in Figures 6 and 7. Both the modified IFIM and full IFIM were applied to a cross-section used by Singh et al. [2]. Results of the comparisons are shown in Figures 8 and 9.

Although adult catfish habitat response curves (Figure 8) compare well, bluegill habitat response curves (Figure 9) do not. This poor comparison is caused by the sensitivity of bluegill to velocities greater than 1.5 ft/sec. as shown in the velocity preference curve for bluegill in Figure 6. Most Indiana fish are warm water fish,

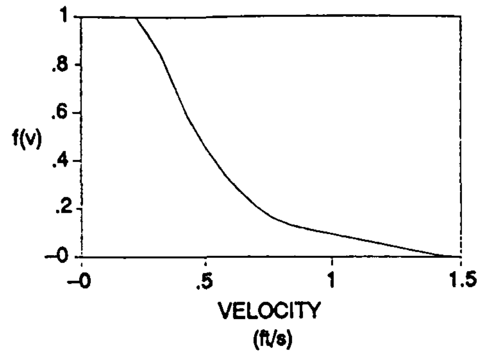

Figure 6. Velocity preference curve for adult bluegill (Herricks et al., 1982).

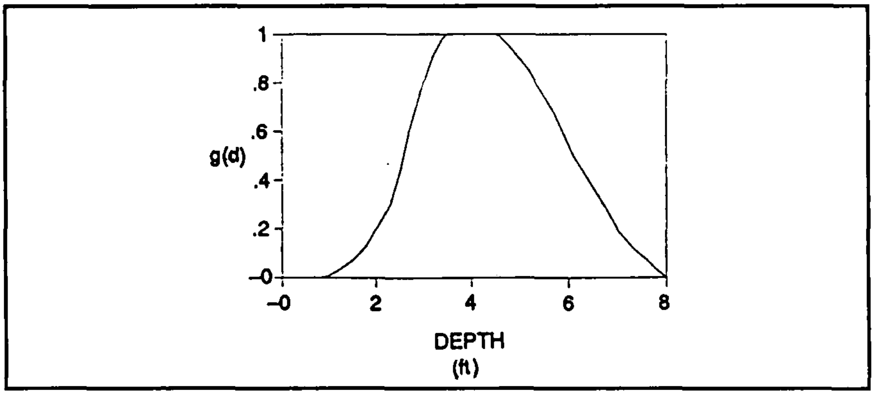

Figure 7. Depth preference curve for adult bluegill (Herricks et al., 1980).

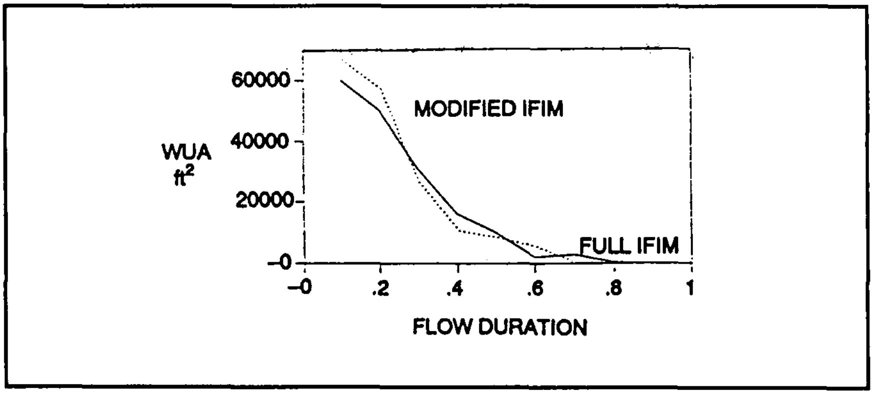

Figure 8. Comparison of habitat response curves for adult catfish using the full IFIM and the first modification of the IFIM. (Full IFIM results from Singh et al., 1986.)

with a similar sensitivity to high velocities. As shown in Figure 3, adult smallmouth bass cannot use stream areas with velocities higher than 2.5 ft/sec.

If average velocities are used in the first modification of IFIM, it is impossible to model low velocities at the channel banks which are used by warm water fish for habitat. The average velocities for various discharges in Indiana streams are usually greater than 1 ft/sec. Using average velocities in the IFIM produces poor results such as those shown in Figure 9 for the modified IFIM. Nestler [8] cautions that "results using average velocity and depth are preliminary and should

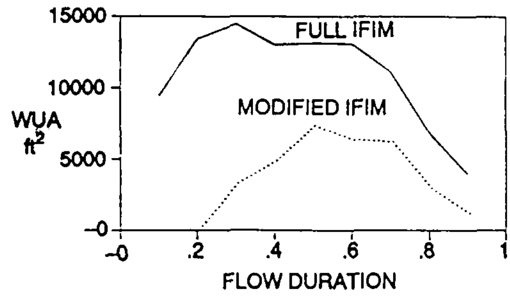

Figure 9. Comparison of habitat response curves for adult bluegill using the full IFIM and the first modification of the IFIM. (Full IFIM results from Singh et al., 1986.)

be used cautiously for reconnaissance only and not at all for projects that are controversial."

Second Modification of the IFIM

It was decided to use a parabolic velocity distribution to characterize the velocity variation across the stream. The definitions used in this procedure are displayed in Figure 10. Sixteen velocities along the width of the cross-section are computed by using a parabolic velocity distribution. The dashed line in Figure 10 is the constant velocity used for the first modification of the IFIM discussed earlier. The parabolic velocity distribution allows for low velocities along the sides of the channel. By approximating these low velocities along the sides of the channel, the modeled area usable for warm water fish (WUA) would be larger for streams that have high average velocities. WUA is computed using Equation (3),

$$\text{WAU} = 1000\, g(\bar{d}) \left(\sum_{i=1}^{16} w_i\, f(v_i) \right) \tag{3}$$

where w_i is the width of the cross-section (ft.), $f(v_i)$ is the preference value for cell velocity and $g(\bar{d})$ the preference value for average depth.

The habitat response curves computed using Equation (3) for the cross-section used on the Sangamon Basin were again compared to those computed by Singh et al. [2]. The velocities, depths, and widths used to determine WUA for each flow exceedance value using Equation (3) are given in Figures 11 and 12. The trends of the habitat response curves compare well, and an increase in resolution over using average velocity is gained by the use of this velocity distribution.

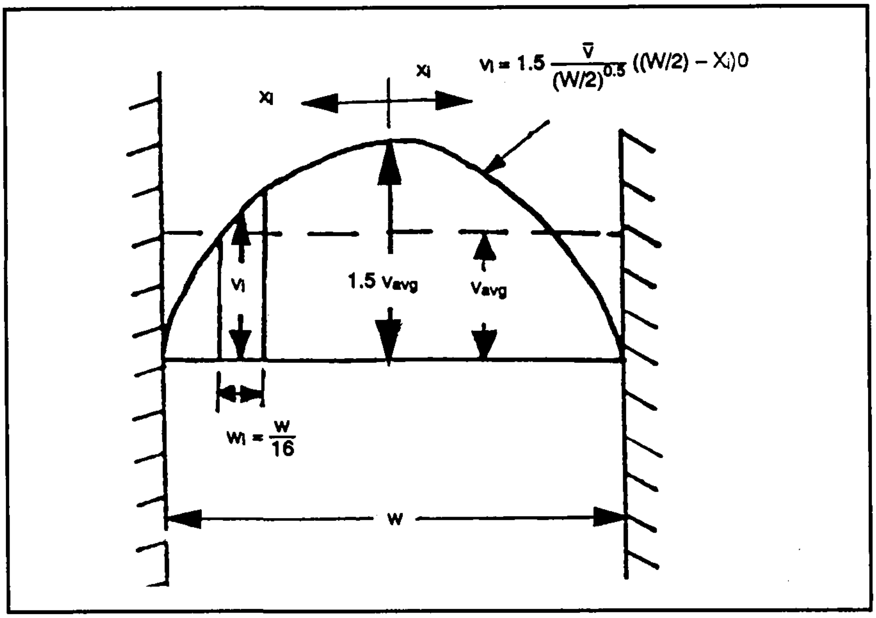

Figure 10. Definitions for the synthetic velocity distribution used in the second modification of the IFIM.

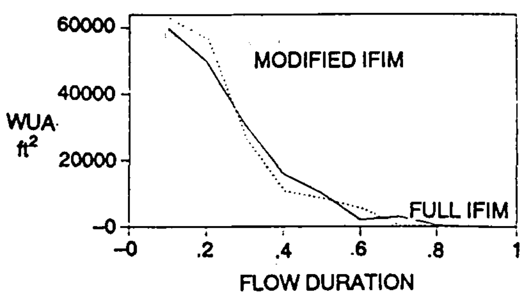

Figure 11. Comparison of habitat response curves for adult catfish using the full IFIM and the second modification of the IFIM. (Full IFIM results from Singh et al., 1986.)

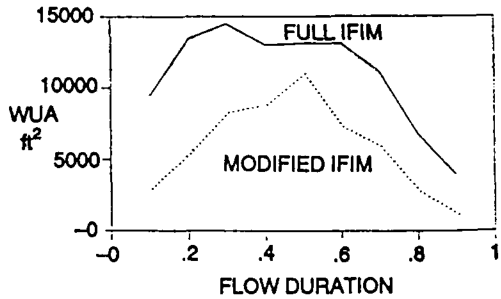

Figure 12. Comparison of habitat response curves for adult bluegill using the full IFIM and the first modification of the IFIM. (Full IFIM results from Singh et al., 1986.)

Although the trends compare well in Figure 12, the WUA computed by using the modified IFIM is still constantly lower than the WUA computed by Singh et al. [2]. These results can be attributed to either the use of the velocity distribution shown in Figure 10 or the use of only one average depth for computing the WUA.

To examine the effects of using only one average depth and velocity distribution shown in Figure 10, the full IFIM using Equation (1) is applied by using the velocity distribution shown in Figure 10 and various depths computed by using the procedures of Singh et al. [2]. Singh et al. [2] computed WUA by first determining the depths and corresponding velocities which have equal probability of being found in a river reach located in the Sangamon basin. The depths and velocities reflect both the flows which are strongly as well as weakly affected by wetted perimeter. If the flow is significantly affected by wetted perimeter, then the velocity will usually increase as depths increase. If the flow is not significantly affected by the wetted perimeter, then the velocity will usually decrease as depths increase.

Although the depths with equal probability of occurrence can be determined for this cross-section shown in Figure 12, there is a difficulty in assigning depths to the velocities derived by using the velocity distribution shown in Figure 10. Singh et al. do not show the locations of depths in the cross-section [2]. Hence, two approaches were taken to using Equation (1). In the first case the low velocities were assigned to low depths and in the second case low velocities were assigned to high depths. The velocity and depth data were taken from Singh et al. [2].

As shown in Figure 13, assigning low depths to low velocities produces excellent results for flows less than the 70 percent exceedance flow in the Sangamon river basin. The low depths correspond to low velocities for flows less than the 70 percent exceedance flow because the wetted perimeter has a significant effect on all the flows including flows in the center of the channel.

For flows with exceedances between 50 percent and 70 percent, the effects of wetted perimeter are not as easily defined. As discharges increase, pool reaches become more prevalent as high depths begin to be characterized by low velocities. As shown in Figures 13 and 14, the WUA computed by Singh et al. [2] is between the WUA computed using low depth-low velocity (Figure 13) and low depth-high velocity (Figure 14).

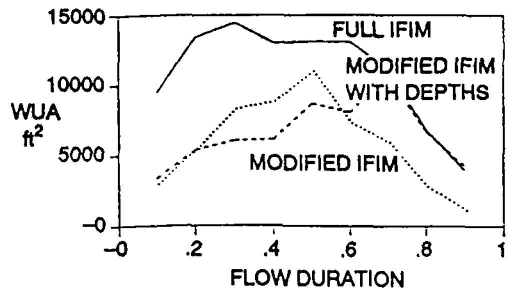

Figure 13. Comparison of habitat response curves for adult bluegill using results from Singh et al. (1986), the second modification of the IFIM, and Eq. 3.1 with low depth-low velocity.

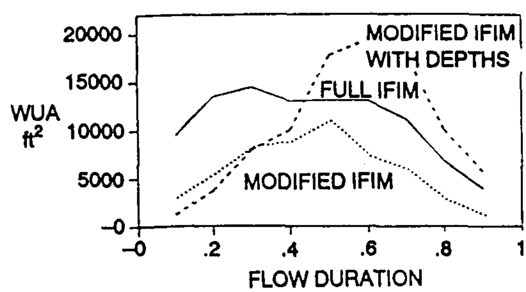

Figure 14. Comparison of habitat response curves for adult bluegill using results from Singh et al. (1986), the second modification of the IFIM, and Eq. 3.1 with low depth-high velocity.

For flows greater than the median flow, the WUA computed by using both low depth-low velocity and low depth-high velocity with the velocity distribution shown in Figure 10 are always less than the WUA computed by Singh et al. [2]. Therefore, the error of the computed WUA for flows higher than median flow is attributed to the velocity distribution used in the second modification of the IFIM.

RESULTS AND CONCLUSION

In Figure 15, the habitat response curves for adult smallmouth bass using the velocity distribution shown in Figure 10 and the velocity distribution measured by the USGS is shown for the Wildcat Creek at Kokomo, Indiana. In Figure 16 the habitat response curves are given for adult northern hog suckers using the parabolic velocity distribution and measured distribution for the Whitewater River at Alpine, Indiana. The velocity distribution measured by the USGS for one stream flow rate at each cross-section is used for all stream flows in developing the results for the actual velocity distribution shown in Figures 15 and 16. The habitat response curves have significantly shifted in the vertical direction but the trends remain approximately the same. If the changes in velocity distribution with different flow rates could be modeled, as done by Singh et al. [2], then the shift would not be entirely in the vertical direction. To model the changes in the velocity distribution requires that velocity measurements be taken for various stream flow rates.

Using an artificial parabolic velocity distribution across the cross section and average depth appears to be a good compromise between the low resolution obtained by using average velocity and average depth and the higher resolution gained by using the actual velocity distribution and actual depths. Using actual

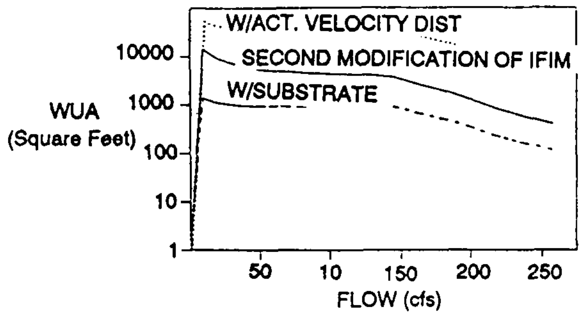

Figure 15. Comparison of habitat response curves for adult smallmouth bass on the Wildcat Creek at Kokomo.

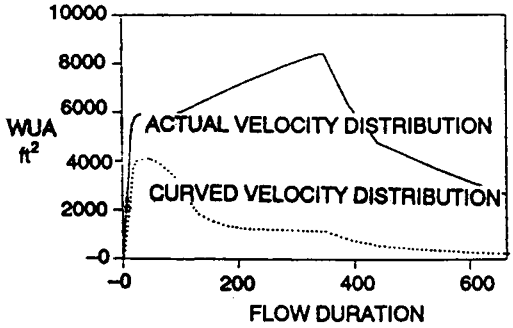

Figure 16. Comparison of habitat response curves for adult northern hog suckers on the Whitewater River at Alpine.

velocities and depths in Equation (1) will require more time to be expended on collecting field data, computing WUA, and developing habitat response curves.

Also shown in Figure 15 is the effect of using substrate for computing WUA. The use of substrate consistently shifts the habitat response curve downward. However, it does not affect the trends of the habitat response curve unless changes in the substrate can be modeled for various flows.

If WUA are to be compared between streams, then the actual velocity distribution, substrate, cover, and temperature should be included, and the full IFIM should be used for computing WUA. The modified IFIM is a good first approximation for demonstrating qualitatively the effects of various flow rates on habitat availability in a stream.

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