Wat. Sci. Tech. Vol.17, Amsterdam, pp.879-890.
Printed in Great Britain.

0273-1223/85 $0.00 + .50

AQUATIC HABITAT ANALYSIS AS AN ELEMENT OF WATER RESOURCES PLANNING AND MANAGEMENT

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ABSTRACT

With increased emphasis on environmental quality objectives in water resources planning and management, past practices of simply considering water quality as the only environmental quality objective are inappropriate. Expanded environmental quality objectives include maintenance of high quality aquatic habitat. Water resource systems must provide both physical and chemical conditions appropriate for the propagation and maintenance of healthy diverse aquatic communities. Managing water resources to provide high quality habitat involves planning to meet both water quality and water quantity objectives. Existing technology based water quality controls and stream based water quality criteria can now be supplemented by aquatic habitat management. An approach to aquatic habitat management is illustrated by use of the Incremental Methodology developed by the U. S. Fish and Wildlife Service. The Incremental Methodology uses measures of aquatic habitat to assess instream flows required for by aquatic life. Thus the range of environmental quality objectives in resources planning and management is expanded by application of these methods to include aquatic habitat as well as water quality management. Methods used to determine instream flow needs for rivers in Illinois are reviewed, and the use of this information in developing regulations limiting water extraction for off stream use are described. Aquatic habitat based management is shown to provide workable methods to meet expanded environmental quality objectives in water resources planning and management.

KEYWORDS

Water resources, instream flow needs, aquatic habitat, river management, water resources management, hydraulic simulation, habitat frequency analysis.

INTRODUCTION

The management of water resources systems has taken on new dimensions as environmental quality (EQ) issues have grown in importance. In the past, water resources planning and management was narrowly directed to providing suitable quantities of water with acceptable quality for domestic and industrial needs. If EQ issues were included in the planning and management process, the primary focus was maintenance of stream water quality. Water quality management was often limited to providing dilution flows from reservoir storage. Even though the United States and most other countries have abandoned simple dilution as a solution to water quality problems, the integration of water quality and water quantity planning still occurs through dilution calculations. Dilution factors, often determined from some statistically defined return flow such as the seven day ten year low flow (7-Q-10), are the basis concentration limits in effluent permits. Water quality management is based on a set of criteria which define the acceptable concentration of pollutants which allow the maintenance of a specified stream use. In most river basin management, the primary mechanism of water quality control is implementation of wastewater treatment technology. When insufficient dilution flows are available, effluent limitations are often based on some minimum assumed dilution flow, such as the 7-Q-10, which is a design flow for calculation of effluent concentration limits. Final permit limits are developed to assure that stream water quality criteria are not exceeded at or above the design dilution flow.

This emphasis on water quality in water resource systems often overshadows the need for more realistic EQ considerations in water resources management. An assumption is often made that maintenance of water quality will meet all EQ requirements, supporting healthy diverse aquatic communities. A closer examination of the relationship between flow quantity and water quality reveals a number of EQ issues which are aquatic habitat dependent. Aquatic habitats are time varying constructs of physical and chemical conditions which meet the requirements for the maintenance and propagation of aquatic organisms. Aquatic habitat can be narrowly defined in relation to single species "niche" requirements or generally described in terms of physical and chemical conditions which maintain healthy diverse aquatic communities. Karr and his co-workers (Gorman and Karr, 1978; Karr and Dudley, 1981, and Karr and Schlosser, 1981) have identified that physical habitat conditions may be the primary determinant of fisheries diversity, even under poor water quality conditions.

Quantifying aquatic habitat in stream and river bioassessments can often provide insight into conditions which produce field data which runs counter to common wisdom. For example, often biological assessments of rivers report good water quality but fisheries and aquatic insect communities have low diversity or population size is low. In other assessments, unusually high diversity is found when water quality would predict low diversity, degraded aquatic communities. The resolution to these unexpected findings is often found in the characteristics of the physical habitat. Where physical habitat conditions are good, the aquatic communities will often be diverse and healthy even when water quality is degraded. If suitable physical habitat is not provided, aquatic organisms will have low diversity even when water quality is good. Placed in the context of water resources management, simply maintaining good water quality may not support acceptable aquatic organism communities. Unless high quality physical habitat is maintained, EQ objectives may not be met.

The acquisition and utilization of aquatic habitat information in water quality management has been the subject of several recent meetings in the United States (Orsborn and Alleman, 1976 and Armantrout, 1981). Among the methods proposed, the U. S. Fish and Wildlife Service has devoted major resources to the development of the Incremental Methodology for the assessment of instream flow needs (IFN) (Stallnaker and Arnette, 1976; Bovee, 1981). IFN are directly related to minimum flow requirements, but in addition to dilution flows, IFN recognize that recreation, navigation, and aquatic life require maintenance of minimum instream flows. Instream flow, particularly flows which support healthy, productive aquatic communities can now be stated as a quantitative EQ objective in multi-objective planning and management of water resource systems (Fraser, 1972, Ward and Stanford, 1979; Sale, et al., 1982). The development of IFN for fish and aquatic life is dependent on the quantification of aquatic habitat as habitat conditions change with flow. The Incremental Methodology provides a quantitative method of habitat assessment and is a powerful tool, assisting water resource managers to meet broadly defined EQ objectives for river or stream systems.

This paper is presented to provide a review of the application of the Incremental Methodology in aquatic habitat assessment. Basin wide application of IFN analysis is demonstrated as a management tool which integrates EQ objectives in water resource regulation. IFN analysis provides essential information for the establishment of regulatory flows and provides technical support for permit systems which limit extraction of water for off stream uses.

HABITAT ANALYSIS PROCEDURES

The Incremental Methodology is described by Bovee (1981) and Milhous, et al. (1981), and is implemented in a computer based analysis system termed PHABSIM (PHysical HABitat SIMulation). PHABSIM consists of two major elements. The first is a hydraulic simulation routine which requires the collection of field data, depth and velocity information for two or more cross sections of a representative reach. The field data is used to calibrate a hydraulic simulation model which provides depth and velocity data at various flows for the representative reach. Habitat is assessed for individual species and for various life stages of each species through the use of suitability curves for specific habitat parameters. Example suitability curves are illustrated in Figure 1. Suitability curves are

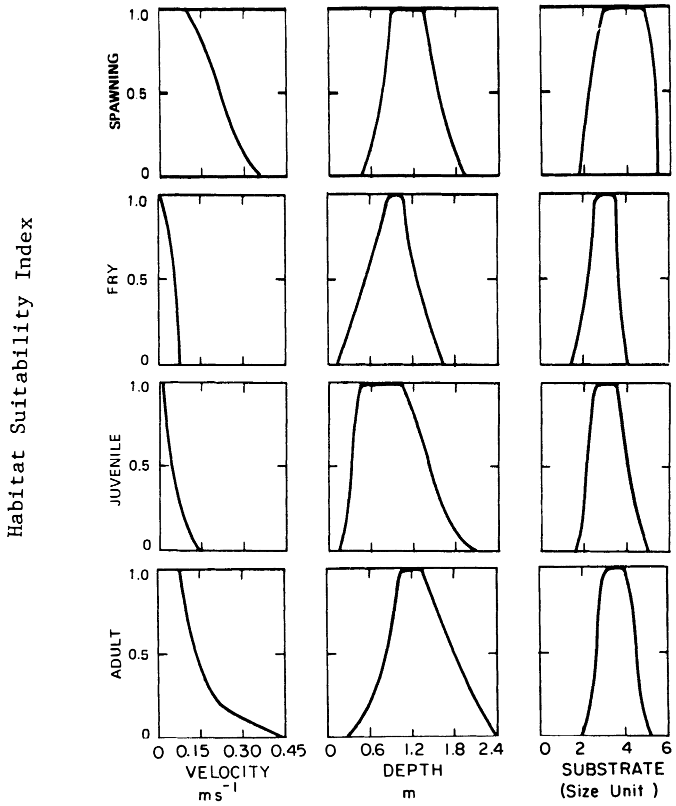

Fig. 1. Habitat suitability curves for four life stages of the bluegill Lepomis macrochirus for velocity, water depth, and substrate.

provided as a part of PHABSIM but can be generated by the user if required (Bovee and Cochnauer, 1977). The primary output of PHABSIM is species and life stage specific habitat data, a weighted usable area (WUA) for a specified discharge value. The WUA is an index of habitat quality calculated from the suitability curves for depth, velocity, and substrate:

$$WUA = \sum_{i=1}^{n} S_d(d_i) \cdot S_v(v_i) \cdot S_s(s_i) \cdot A_i$$

where:

S_d, S_v, and S_s are suitability functions
d_i, v_i, and s_i are the predicted physical conditions in the ith incremental area of the stream reach which has been modeled
A_i is the area of the ith cell

It is possible to generate a habitat response curve by determining WUAs for a range of discharge values, Figure 2. The habitat response curves for each species and life stage will have different characteristics.

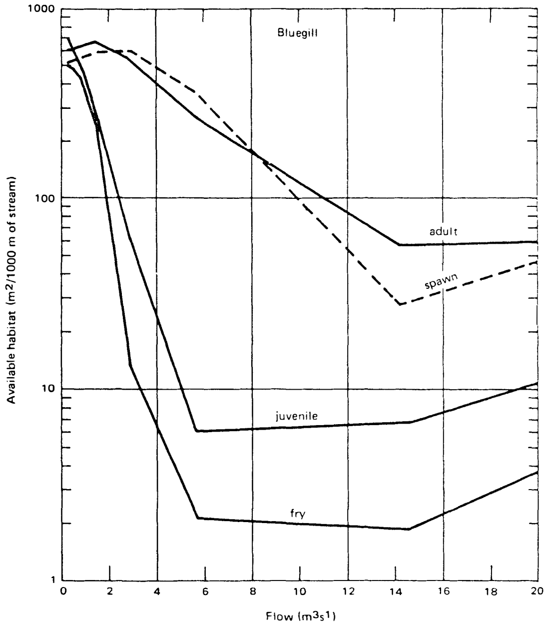

Fig. 2. Habitat response curve of the bluegill from the Clay City Reach of the Little Wabash River, Illinois.

Flow is highly variable in natural streams. Figure 3 illustrates the expected monthly variation in flow volumes which produce seasonal trends in habitat availability, Figure 4. Flow will also vary from year to year. From the historical flow records at a gaging station, it is possible to develop a probabilistic estimate of how often a given discharge occurs in a stream. This estimate is illustrated in Figure 3 as an expected exceedence frequency, the expected percentage of flows which will equal or esceed a specified discharge. In developing management strategies based on aquatic habitat, the natural variability in habitat conditions must be recognized. A review of the example habitat response curves reveals that more than one flow may produce the same WUA value.

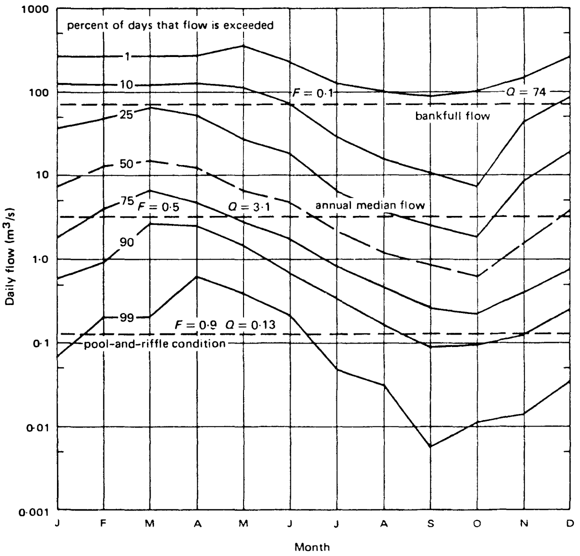

Fig. 3. Seasonal flow variability for the Little Wabash River near Clay City.

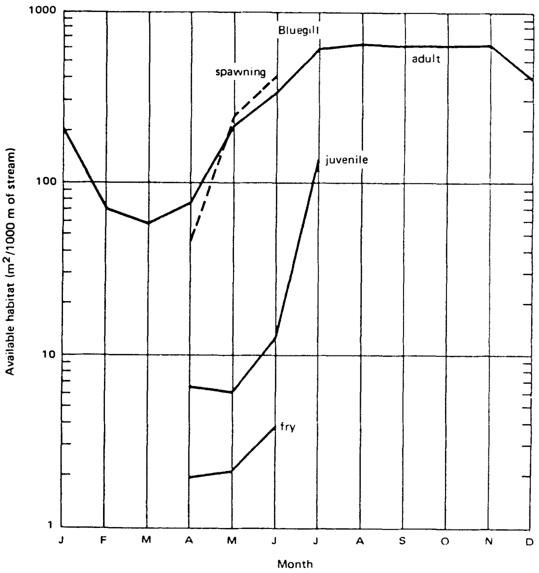

Fig. 4. Seasonal variability in habitat for the bluegill in the Clay City Reach of the Little Wabash River. Habitat values indicated only for months of expected presence in the reach.

Both high and low flows are important in aquatic habitat management. To account for expected flow variability, habitat response curve characteristics, and the effect of both high and low flow conditions, my co-workers and I have developed a method of habitat frequency analysis (Sale, et al., 1981). The calculation procedures is similar to flow duration analysis. Historical flows, in this case daily flow values which are averaged weekly, and the habitat response curve are used to calculate a historical habitat record. The WUA values from this record are used to develop a probabilistic estimate of how often a particular WUA occurs and an exceedence table is constructed. The habitat exceedence frequency is similar to flow duration and provides similar information to a manager. For example, a habitat (WUA) which is equaled or exceeded with a frequency of 50% (f = 0.5) could be determined for each time period in the analysis (we have found monthly summaries the most convenient), Table 1. The habitat frequency information can be used in several ways. First, comparing the f = 0.1 with the f = 0.9 WUA provides an estimate of the range of habitat which might be expected to occur naturally. Comparison of these values between species provides an indication of the general suitability of the reach for species which might be subject to intensive management. The range of WUA values also provides insight into the general requirements of a species/life stage on a monthly basis, as well as how well the historical stream flow met these requirements.

Table 1.

Example habitat frequency data and minimum discharges required for species/life stage protection.

Species: Bluegill; Life Stage: Adult; Period of Record: 1916-1976

Discharge (Q) in m^3/sec

f=	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.1	61.24	46.24	7.61	7.61	31.72	57.87	71.74	81.14	76.10	76.10	73.64	70.72
0.3	8.18	8.18	8.18	8.18	8.18	8.18	36.31	50.03	45.36	53.71	35.80	22.39
0.5	8.18	8.18	8.18	8.18	7.02	7.36	8.18	22.39	24.39	31.33	8.18	8.18
0.7	2.21	4.25	2.41	2.24	2.07	2.01	2.38	4.36	7.64	8.94	3.28	2.41
0.9	1.10	1.10	1.13	1.10	1.16	1.08	1.16	1.30	1.19	1.87	1.10	1.16

Minimum discharge for the protection of a habitat frequency f = 0.5

Discharge (Q) in m^3/sec

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
adult	0.31	0.31	0.31	0.31	0.34	0.31	0.57	0.57	0.45	0.37	0.31	0.31
spawn	0.45	0.42	0.42	0.42	0.51	0.51	0.82	0.65	0.51	0.45	0.45	0.48
fry	0.02	0.06	0.06	0.06	0.06	0.06	0.06	0.14	0.20	0.06	0.06	0.06

A second set of tables is also produced in the habitat frequency analysis. These tables identify for each species the minimum discharge required for the protection of a specified habitat frequency. The nomograph, Figure 5, constructed by plotting the habitat response and habitat frequency curves is used to illustrate the method of minimum flow selection. First the habitat exceedence is selected (ex. 0.8 or 80%). A line is drawn intersecting the habitat frequency. A horizontal line is then drawn to intersect the habitat response curve and a discharge determined which is the minimum discharge necessary to maintain a WUA value which is equaled or exceeded 80% of the time (Q_{min}). The utility of habitat frequency analysis in river basin management is found in the incorporation of historical flow conditions in the IFN analysis. Baseline conditions may be better defined, and historical habitat analysis may identify natural limitations to species considered for intensive management.

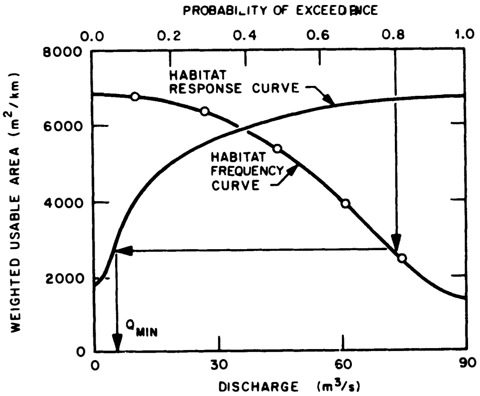

Fig. 5. Nomograph for calculating minimum flow using habitat response and habitat frequency data. (from Sale, et al., 1982)

BASIN HABITAT ANALYSIS

Using the habitat analysis methods reviewed in the previous section, supplemented by additional analysis of basin hydraulic geometry, it is possible to perform a basin habitat analysis. The Incremental Methodology is designed for use on a limited reach of stream. By careful selection of the reaches analyzed the data produced may be considered representative of a much larger reach of stream. This representative reach analysis can be applied to other streams of similar stream order or with similar watershed areas to support basin wide habitat analysis. A critical feature of basin habitat analysis, then, is selection of representative reaches and validation of the extrapolation of representative reach analysis results to the entire basin.

A fundamental assumption made in the representative reach selection is that even though streams or rivers change significantly from headwaters to higher order rivers, these changes occur gradually and long reaches of the stream will be quite similar. Thus if a representative reach is carefully selected, it will represent, or be similar to, all streams in the basin with that character. This approach recognizes the fundamental difficulty of designing a sampling program which characterizes each change in habitat throughout the stream continuum. It is assumed that if analysis is made on a reach where all major habitats are analyzed that this analysis can be used to generally assess other reaches where similar habitats occur. The limitations to a representative reach analysis should be apparent. In general, the analysis of a representative reach can only be applied to additional reaches along the same stream or to other reaches on similar streams in the same basin which have demonstrated similarities.

The demonstration of reach similarities begins with reach selection. The selection of the representative reach requires a detailed analysis of basin geology, land use, discharge, and hydraulic geometry. It is essential for habitat frequency analysis to have actual or synthetic historical flow records near the representative reach. We have found that reach selection is facilitated by aerial reconnaissance and development of a detailed photographic record of stream habitat characteristics. The validation of reach extrapolation is dependent on hydraulic geometry analysis (Stall and Herricks, 1982). Basin hydraulic geometry relationships are developed from a Horton-Strahler drainage network analysis

(Stall and Fok, 1968). Data on the number of streams, length, and slope of a given order are plotted, Figure 6. When consistent relationships between stream order for these parameters are demonstrated, it is possible to evaluate the "representativeness" of the representative reach in terms of hydraulic geometry and provide a justification for extrapolation of representative reach results.

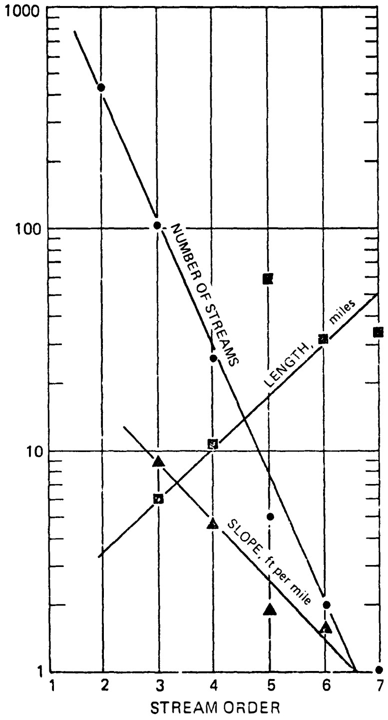

Fig. 6. Horton-Strahler relationships used in evaluation of extrapolation validity.

Following representative reach selection, hydraulic data is collected for each representative reach (Herricks, et al. 1980). A series of cross-sections are designated and surveyed in the reach. Cross-sections are placed to identify hydraulic controls, important habitat components, and general stream channel characteristics. Depth and velocity data is collected across each cross-section and substrate characteristics of the cross-section determined. The depth and velocity data is used to calibrate the hydraulic model component of PHABSIM and species suitability curves are selected from those available in the PHABSIM library or those developed as part of the basin study. PHABSIM output is in the form of habitat response curves which are further analyzed in habitat frequency analysis. The example habitat frequency analysis results, provided in Table 1, illustrate the form of data which can now be used in river basin planning and management.

The argument made in the introduction to this paper emphasized that planning and management of water resource systems could not rely entirely on water quality management to meet environmental quality objectives. Aquatic habitat was recommended as a useful measure of environmental quality. The use of the Incremental Methodology, in particular PHABSIM, provides a connection between physical and biological components of water resource systems. As instream uses are quantified, the management opportunities for water resources are expanded. An example of the utility of aquatic habitat quantification in water resources planning is provided in Sale, et al. (1982). An approach to optimizing reservoir operation was reviewed which combined linear decision rule modeling with an objective function representing the value of reservoir releases to downstream fisheries. In this optimization, ecological or environmental quality objectives can be considered together with flood control, water supply, and other considerations usually analyzed in an engineering analysis of reservoir operation.

Habitat analysis, in particular, habitat frequency analysis was also used to assist in the development of flow regulation policy in Illinois. Although the midwestern United States receives ample rainfall and is provided with major groundwater resources, the prospects of conflicting uses of surface water resources exist. For example, Eheart and Libby (1980) have identified a scenario where demand for irrigation water from surface sources may adversely affect meeting instream flow needs. In addition, extraction for both domestic and industrial water use may make additional demands on surface water resources. Construction of reservoir projects also modify flow regimes and may adversely affect instream uses. To deal with conflicting use of surface water resources, the State of Illinois has developed a basis for flow regulation in the form of an interim low flow standard. This low flow standard was evaluated using habitat analysis procedures.

The proposed standard was developed from a detailed analysis of historical flow records which identified an inflection in the range of the 75% duration flow (a flow equaled or exceeded 75% of the time). The interim standard was structured to account for the design dilution flow used in effluent permit preparation, while supporting a concept of shared resource utilization (e.g. between instream and off stream water use). The proposed interim standard is stated as: The flow available in a stream for offstream use (either storage or withdrawal) is the maximum value of either the streamflow minus the 75% duration flow or the difference of the streamflow minus the 7 day-ten year low flow divided by two. The effect of application of the interim standard would be to allow reduction of streamflow throughout the year to the average annual Q75. If flow dropped below the average annual Q75 only 50% of the difference between a 7-Q-10 flow and the Q75 could be withdrawn.

Based on previous comments concerning the appropriateness of developing flow regulation on an annual flow value when seasonal and annual variability is recognized, the Illinois interim standard was evaluated using historical habitat frequency data. The Rock River basin was selected for analysis because representative reach characteristics were varied and corresponded to reaches analyzed in several other river basins in Illinois. Since the flow/habitat relationships are complicated by habitat response curve shape, two analyses were performed using both habitat frequency data and habitat response curves. For each species and life stage, the median habitat (WUA) for any month was determined and the corresponding WUA value was determined for the Q75. A percent change in habitat was calculated. A second analysis used the Q75 WUA to determine a frequency for the interpolated habitat value. The results of these analyses for an example representative reach are contained in Tables 2 and 3.

Table 2. Results of interim standard effects on aquatic habitat in the Kishwaukee River, a river characterized by shallow pool and riffle conditions.

Species	month(s) of maximum habitat reduction	percent reduction	range of % reduction in other months
Black crappie	Mar-Jun	25	2-5
Bluegill			
fry	Mar-Jun	60	9-16
juvenile	increase		
adult	Mar-Apr	4	increase
spawn	May	10	2-3
Carp	Mar-Jun	60	14-20
Channel catfish			
fry	Mar-Jun	15	5-10
juvenile	Mar-Jun	80-90	38-50
adult	Mar-Jun	63	18-25
spawn	Mar-Apr	37	7-10
Gizzard shad	Mar-Apr	61	24-30
Smallmouth bass			
fry	May-Jun	9	2-8
juvenile	increase		
adult	Apr-May	57	25-38
spawn	Aug	13	increase
Largemouth bass	Mar-Apr	24	8-10
White sucker	Jun-Jul	6	4 to increase

Table 3. Results of interim standard effects on aquatic habitat in the Pecatonica River, a river characterized by deep riffles and large pools.

Species	month(s) of maximum habitat reduction	percent reduction	range of % reduction in other months
Black crappie		increase to 80%	
Bluegill			
fry	Feb-Mar	9	1-5
juvenile	Jan	3	increase
adult		increase to 260%	
spawn		increase to 200%	
Carp	Jan	3	increase
Channel catfish			
fry		general increase	
juvenile	Mar-Apr	48	18-30
adult	Apr	16	6-10
spawn		increase to 100%	
Smallmouth bass			
fry		increase to 87%	
juvenile		increase to 200%	
adult		increase to 180%	
White sucker		variable 1-2%	

Based on habitat analysis, the most significant impact of the recommended interim standard would occur in March through June. For the species evaluated, a reduction of up to 90% of the species/life stage WUA would occur. In other than March through June, habitat reduction was in the 10 to 20% range. Of particular importance is the increase in available habitat for several species. The impact of the proposed interim standard was different on different rivers. Those rivers characterized by shallow riffle and pool conditions indicated a consistent reduction in habitat caused by adoption of the interim standard. Larger rivers, and rivers which had few riffles and large pools showed a consistent increase in habitat with fewer months with reduced habitat conditions.

In developing an interim flow standard for Illinois, habitat analysis contributed significantly to environmental quality evaluations. It was possible using habitat analysis to generalize the impacts which might be caused by the adoption of a standard and develop an understanding of differential impacts in some river basins. Of particular importance was the finding that habitat might actually be increased by somewhat reduced flows.

CONCLUSION

This paper has been intended as a demonstration of the contribution aquatic habitat analysis can make to water resources planning and management. Techniques such as the Incremental Methodology and computer based analysis systems such as PHABSIM and habitat frequency analysis can significantly improve environmental quality considerations in water resource systems planning.

ACKNOWLEDGEMENTS

The research supporting development of this paper was supported by the Illinois Department of Transportation, Division of Water Resources. Field data collection and analysis for the Little Wabash River basin was supported by the Ohio River Basin Commission through a grant to the Illinois Department of Transportation.

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