HISTORY, THEORY, USE, AND LIMITATIONS OF THE PHYSICAL HABITAT SIMULATION SYSTEM

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1.0 ABSTRACT

The Physical Habitat Simulation System (PHABSIM) was developed as a water management tool to assist in the establishment of instream flow requirements (environmental flows) to support water control and water allocation activities. The theory of PHABSIM is that the quality and quantity of physical habitat is related to the environmental needs of aquatic animals. The use of the physical habitat calculated by PHABSIM requires consideration of other factors because physical habitat is a necessary, but not a sufficient, condition for the existence of a species, or a collection of species; and interactions between species and between life stages will influence the state of the ecosystem. Contributions to the development of PHABSIM came from water managers and fisheries managers with real management problems. Two examples of the application of PHABSIM are presented. The first was part of water development planning studies of the late 1970's and the second is the development of an instream flow need for a hydroelectric project. Analysis of the relation between physical habitat and the populations of aquatic animals shows the physical habitat is a necessary but not sufficient condition for a viable population of aquatic animals. Future developments in physical habitat analysis require improvements in the analysis of the substrate and in the approach to how the substrate is included in the physical habitat. Also needed are improvements in understanding the time dimension of physical habitat. A significant limitation is that there are many interactions between species, life stages, and other variables that influence the state of the ecosystem that are not modeled by PHABSIM.

Key Words: Habitat Modeling, PHABSIM, Physical habitat, Instream flows, aquatic populations, sedimentation

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2.0 INTRODUCTION

The Physical Habitat Simulation System (PHABSIM) shows the relation between the flow of water and the physical habitat for aquatic animals in rivers and was designed for application to water management issues. Later, a collection of semi-analytical procedures called the Instream Flow Incremental Methodology (IFIM) was woven about PHABSIM. The design of PHABSIM assumes knowledge of the pattern of streamflows must be integrated with the results obtained from PHABSIM in order to do an effective instream flow analysis; this is often called time series analysis. In this paper, reference to PHABSIM will include the development and use of the discharge versus physical habitat function *and* the analysis of the time pattern of streamflows to interpret the physical habitat information. The topics covered are the history, theory, use, and limitations of PHABSIM but other factors such as needed new developments and the use of physical habitat in wedge modeling of ecosystems are also considered. An important goal of the paper is to demonstrate that there is not a simple relation between physical habitat and aquatic biomass but one that must include other aspects of the ecosystem and the history of streamflows.

Two basic principles for the application of PHABSIM distinguish PHABSIM from nearly all other approaches to instream flow or instream habitat analysis. The first is the need to define the habitat as a function of stream discharge (physical habitat simulation), and the second is the need to define the variation of the habitat as a function of time (habitat time series analysis). An example of the results of a physical habitat analysis are given in Figure 1 (cms is cubic meters per second). This diagram is the keystone to the use of PHABSIM.

Understanding the variation of the physical habitat is just as important as knowing the relation between streamflow and the physical habitat. To understand the variation of habitat requires development of a time series of habitat. The critical assumption is that many important characteristics of an ecosystem are related to the variation in the physical habitat. In other words, the aquatic ecosystem of a stream with considerable variation in streamflow is not the same as one with a nearly steady streamflow, all other factors being equal. The determination of the instream flow needs of an aquatic ecosystem is related to the natural variation in the habitat. An example of a time series of physical habitat is shown in Figure 2. The annual index used in Figure 2 is the average of the monthly values. Other annual indices are possible, for example the minimum weekly habitat in a year.

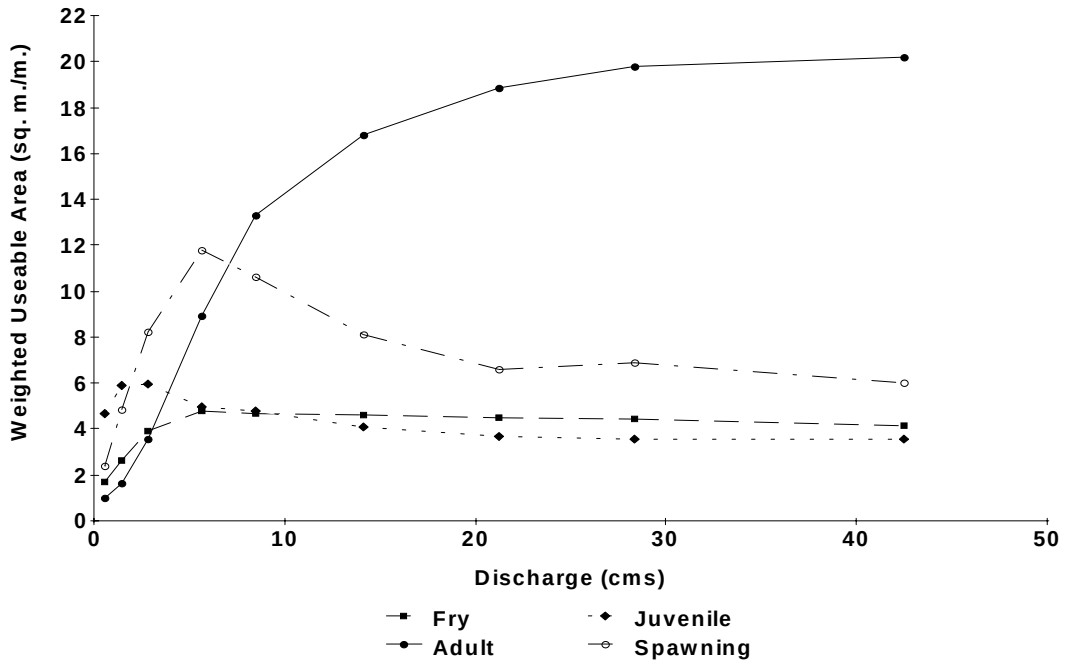

Figure 1. Habitat versus discharge functions for Smallmouth Bass in the Little Wabash River, central Illinois. (Data from the University of Illinois, 1978.)

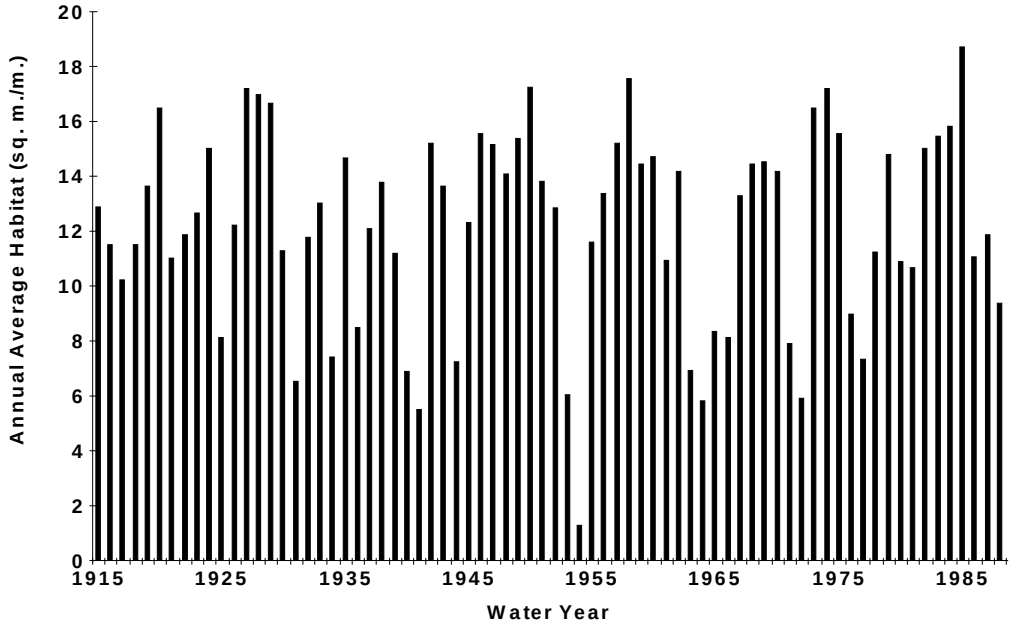

Figure 2. Annual habitat time series for adult smallmouth bass in the Little Wabash River, central Illinois. Annual index is the average of the monthly adult habitats during a water year.

From the birth of PHABSIM in 1978 to the present, the use of habitat time series

analysis has been essential to the use of the physical habitat versus streamflow function produced by PHABSIM. Although not everyone used a formal time series analysis, most at least considered the streamflows that actually exist in their application of the habitat versus streamflow function. Few investigators have totally ignored streamflow variability.

3.0 THE PHYSICAL HABITAT SIMULATION SYSTEM

The Physical Habitat Simulation System has two major sub-systems: 1) a group of programs used to simulate physical habitat , and 2) a group used to simulate river hydraulics.

3.1 Habitat Simulation

The physical habitat is related to the physical characteristics of the stream. The equation relating the river characteristics to the river habitat (weighted usable area) is:

$$HA(Q) = \Sigma \{f(v,d,CI)\ \Delta A\} \qquad (1)$$

where HA is the physical habitat area (weighted usable area) at discharge Q, ΔA is an area of the stream, and f(v,d,CI) relates physical conditions in the stream to a life stage of a particular species of aquatic animal (species criteria). The usual function used for f(v,d,CI), is:

$$f(v,d,CI) = g(v) * h(d) * k(CI) \qquad (2)$$

In words, this equation says the weight to assign to a sub-area of a stream (cell) is a weight assigned to the velocity times a weight assigned to the depth times a weight assigned to some property of the channel; weights are between 0.0 and 1.0. Equation 1 says the sum over the area of the stream of the weight assigned to a sub-area times the area of the sub-area is the weighted usable area of the stream for the life stage of a species of aquatic animal.

3.11 Species Criteria

An example of the velocity and depth functions of the species criteria for adult smallmouth bass (Edwards et al, 1983) are given in Figure 3. The velocity in Figure 3 is the mean column velocity; other velocities that may be used in PHABSIM are the nose velocity (the velocity where a fish is located), and the shear velocity (a representation of the shear stress on the stream bed).

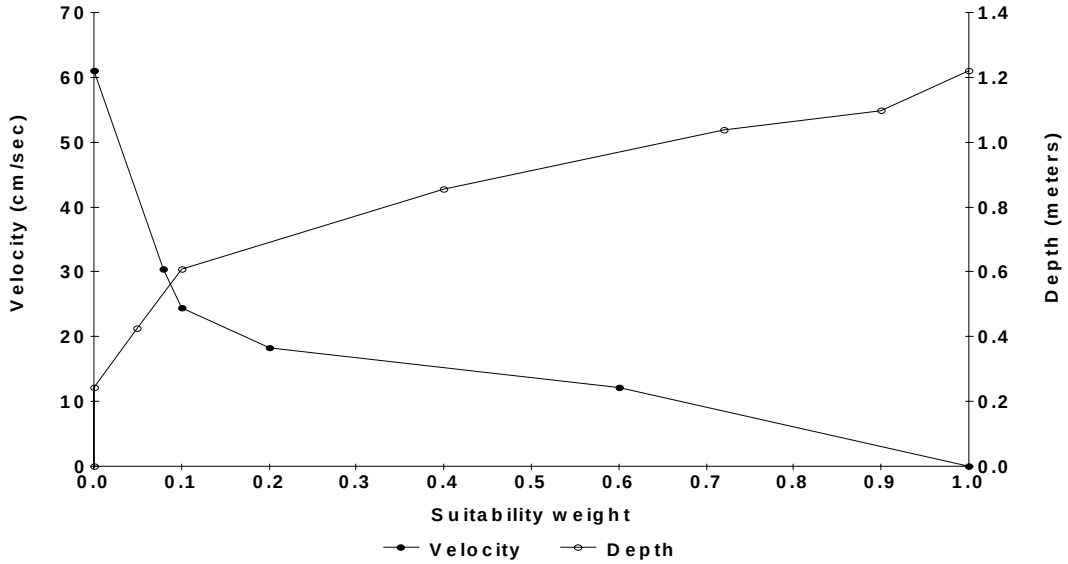

Figure 3. The velocity and depth weighting functions for adult smallmouth bass. (Edwards et al, 1983)

The channel index must be defined by the user. Many possible channel indices can be formulated. The objective is to link the physical properties of the channel with the habitat. Examples include particle size of the bed material, cover , and the vegetation in the channel. The data for the channel index weighting functions for the various life stages of smallmouth bass given by Edwards et al (1983) are presented in Figure 4.

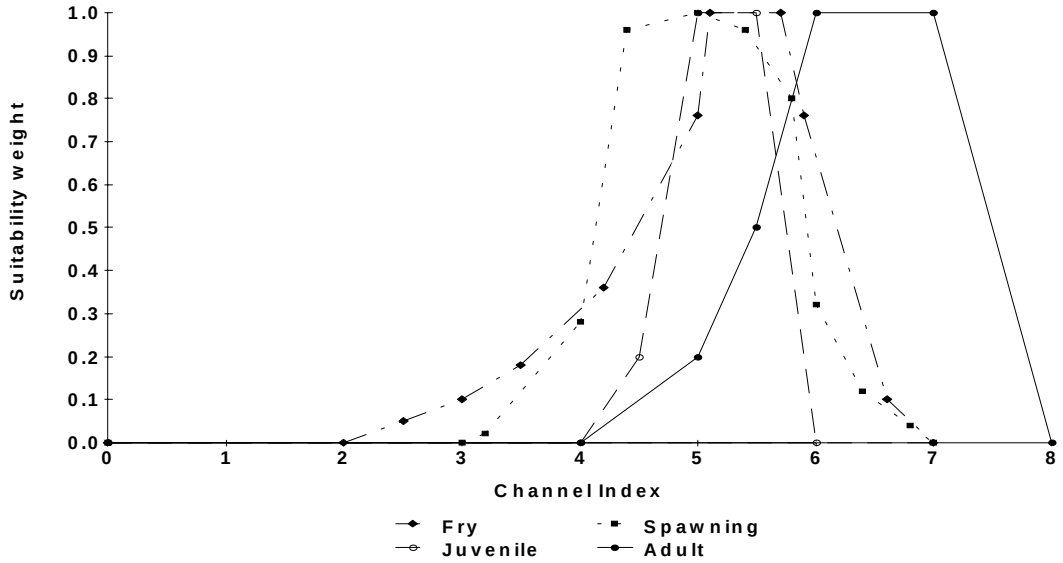

Figure 4. The channel index (substrate) functions for smallmouth bass. See Table 1 for definition of the indices. (Edwards et al, 1983)

Users must design their own channel index; this is no small task. The logic used for the channel index in Figure 4 was developed by Bovee and Cochnaur (1977) and is the simplest possible, the most often used, and possibly the least effective. The meaning of each index value is presented in Table 1.

Table 1. The Channel Index used in the initial development of species criteria for use in the Physical Habitat Simulation System. (from Bovee and Cochnaur, 1977)

Channel Index	Channel Properties
1	Plant detritus/organic material
2	Mud/soft Clay
3	Silt
4	Sand
5	Gravel
6	Cobble/rubble
7	Boulder
8	Bedrock

3.2 Hydraulic Simulation

Hydraulic simulations in PHABSIM are needed to develop the physical habitat versus streamflow function. There are two needs: one is to simulate the water surface elevations, and the second is to simulate the velocities.

The weighted usable area is typically much more sensitive to velocities than to depths (calculated from the water surface elevations). This has suggested to some the simulation of a good estimate of the water surface elevation is not of much importance. The problem is that the simulated velocities are sensitive to water surface elevation and, therefor, to depths.

Water surface elevations are calculated using water surface profile (WSP) calculations, an empirical stage discharge relation, or the Manning equation. Often, all three are required in order to obtain acceptable results. The simulation of velocities is done using a mixture of theoretical techniques and empirical techniques. (For specifics see Milhous et al, 1989).

4.0 ORIGINS OF PHABSIM

The origins and concepts behind PHABSIM are in the western states of the United States and Canada. The aquatic species of interest have historically been fish and more specifically salmon and trout. The different ideas incorporated into PHABSIM were derived from the following activities:

> Instream flow analysis in Montana was being done using a water surface profile program to simulate the average wetted perimeter versus discharge function for a reach of stream. The instream flow need was at the inflection point in the wetted perimeter versus streamflow relation. (Elser, 1976.)
>
> In California the velocities and depths were being measured and the actual measurements of velocity and depth were used with species criteria to simulate the habitat as a function of discharge. (Waters, 1976.)
>
> The Washington Department of Fisheries and the Washington District of the U.S. Geological Survey developed a habitat versus discharge function for spawning of salmon and trout. The wetted perimeter versus discharge function was used for all other aspects of the aquatic ecosystem (Collings et al, 1972). The concept of using time series analysis of the variation in habitat came from the work of the Washington Department of Ecology (Clarke, 1976) and the U.S. Geological Survey (Collings et al, 1972).
>
> The Colorado Division of Wildlife used a width with a minimum depth function for critical riffles, the depth was related to the size of trout in the stream. The objective was to have an instream flow that had the depth of the thickness of the target size of fish. The width with a minimum depth relation was used to select an instream flow need.

Contributing significantly to the concepts that led to PHABSIM were workers dealing with real problems - not academics. Most of the people developing the predecessors of PHABSIM were employees of various water and fisheries agencies; specifically, state fisheries biologists, federal fisheries biologists in both the United States and Canada, state water managers, federal water managers, and the U.S. Geological Survey. One of the unique features in the Canadian federal government was a team of both engineers and biologists working on the habitat needs of salmon in rivers.

The original target activity was water management with a secondary objective of fishery management; not an academic ecological investigation of the lotic ecosystem. Water managers and fisheries managers had real problems - the objective of their work was to contributed to the solution of these problems.

The initial problems associated with PHABSIM were, and still are: limited testing

(both biological and water management), the existence of true believers willing to apply PHABSIM (or IFIM) without really understanding the ecosystem, and the existence of one way thinkers demanding PHABSIM be easy to use and be a 'cookbook'. PHABSIM fails the 'cookbook' test because natural systems are just too complex (and interesting).

5.0 APPLICATION OF PHABSIM RESULTS

Two examples of the application of PHABSIM are presented in this section. The first is similar to early (1977-1978) applications of PHABSIM to instream flow need analysis. The work was part of water development planning studies of the late 1970s that were made to determine water available for use in energy production. The second is the development of an instream flow need for a hydroelectric project.

5.1 Instream flow needs for energy development projects.

One of the initial applications of the time series of streamflows and the physical habitat function used the median streamflow for each month and the monthly streamflow not exceeded one in ten years for each month in the determination of an instream flow need (IFN). These were first used to determine the physical habitat at the median and the 1-in-10 year monthly streamflows. The monthly habitats in the Little Wabash River are given in Figure 5.

The monthly streamflow requirement (IFN) is the minimum streamflow yielding the minimum of monthly habitats at the median monthly flows (the habitat in October on Figure 5), or streamflow yielding the habitat at the one in ten year monthly flow, which ever is larger (minimum streamflow giving the 1-in-10 habitat for February - June in Figure 5). The overall instream flow need was the maximum of the instream flow requirements for the various life stages. The results of the analysis considering all life stages are given in Table 2.

The end result of this analysis is shown in Figure 6 along with the median and 1-in-10 year monthly flows.

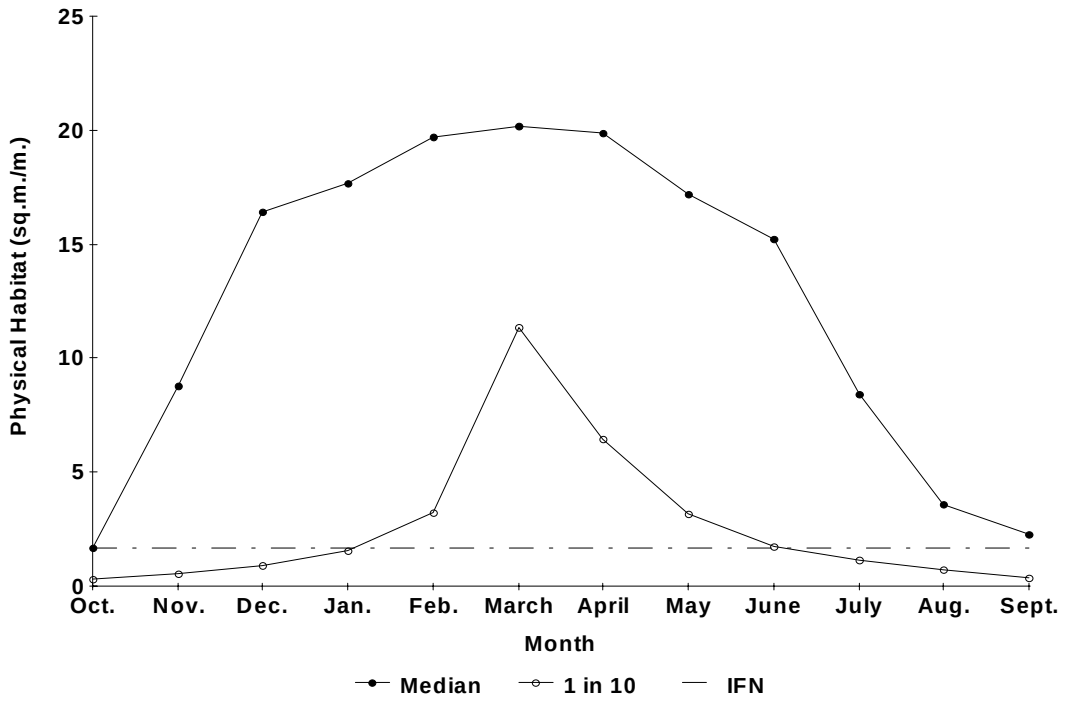

Figure 5. Adult habitat for smallmouth bass at the median, and the one in ten year, monthly streamflows, Little Wabash River, central Illinois.

Table 2. The smallmouth bass instream flows needs (IFN) for the Little Wabash River, central Illinois.

	Life Stage				
Month	Adult (cms)	Fry (cms)	Juvenile (cms)	Spawning (cms)	IFN (cms)
October	1.42	1.42	0.43		1.42
November	1.42		0.43		1.42
December	1.42		0.51		1.42
January 1.42		1.32		1.42	
February	2.56		2.56		2.56
March	7.25		0.70		7.25
April	4.36		1.08		4.36
May	2.54		2.54	4.73	4.73
June	1.48	1.48	1.48	4.73	4.73
July	1.42	1.42	0.76	4.73	4.73
August	1.42	1.42	0.43		1.42
September	1.42	1.42	0.43		1.42

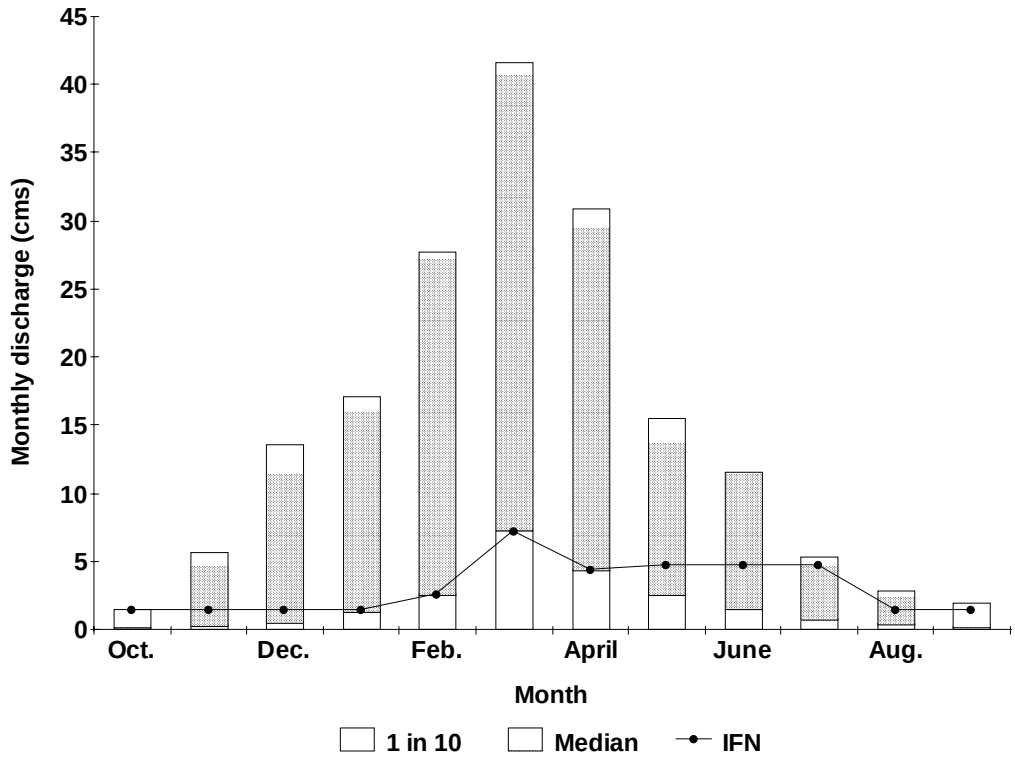

Figure 6. The median monthly, one in ten year, and the instream flow needs for the Little Wabash River near Clay City, Illinois. Smallmouth Bass was the target species.

5.2 Terror River, Alaska

Another application of PHABSIM was the selection of the instream flow needs of a river on Kodiak Island in Alaska. The proposed project was a hydroelectric project that enlarged a natural lake and diverted water to an adjacent watershed. The species of fish used as a target for the instream flow analysis was pink salmon. The rivers on Kodiak Island have good discharges during the spawning period in the fall when the precipitation is rain and there is still runoff because the ground is not frozen. This period is followed by a long incubation period during which cold clear weather could, and often does, cause a significant reduction of the runoff because of frozen ground and storage of the precipitation as snow. The result is low flows during the incubation season. The usual spawning habitat versus discharge function considers only the conditions during the spawning season. Suppose the function also considers the conditions during the incubation season following the spawning period (Figure 7). Each curve in Figure 7 is the effective spawning area considering the incubation flow shown for the curve. In other words, the spawning areas for a given discharge also had to have suitable conditions during the incubation period with the discharge shown for the curve.

Under natural conditions incubation flows of 0.5 cms to 1.5 cms were typical; thus the optimum spawning flows would be about 3.5 cms instead of the 10 cms optimum for a spawning curve unconstrained by incubation flow considerations. The sponsors of the hydroelectric project had agreed to a minimum discharge of 1.7 cms; the optimum spawning flow for this incubation flow is in the range of 4 to 5 cms.

The PHABSIM analysis confirmed the previously agreed upon 1.7 cms as an acceptable incubation flow and showed that the spawning flow should be in the range of 2.8 to 5 cms. A spawning flow of about 4.25 cms was selected. What PHABSIM did not do was help in the determination of streamflows needed for out-migration of the fry to the ocean because criteria were not available for that life stage.

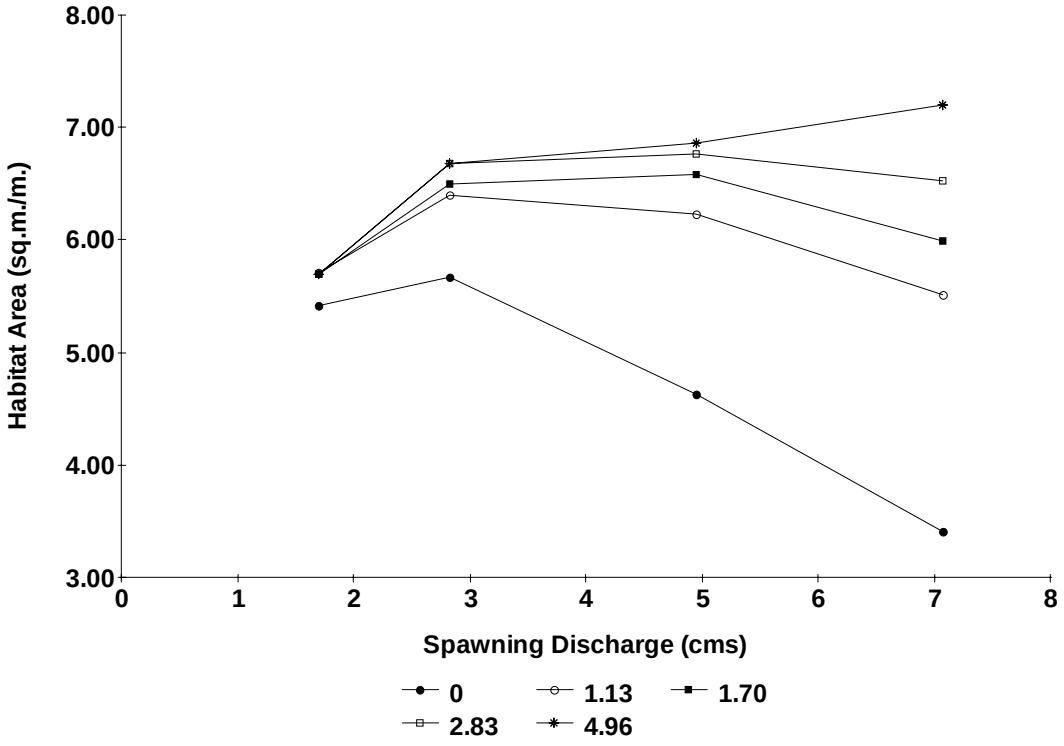

Figure 7. Terror River habitat function for Pink Salmon considering effective habitat based on spawning areas meeting both a spawning criteria and incubation criteria. The legend is the incubation flow.(adapted from Milhous, 1982).

6.0 THE PHYSICAL HABITAT - AQUATIC POPULATION RELATION

The objective of this section is to illustrate the importance of factors not considered in the usual application of the weighted usable area as simulated by PHABSIM by examining the relation between physical habitat and the population of fish in a stream. The presentation is in the form of a series of case studies based on information in the literature. Interpretations of the information are made and, in each case, other interpretations are possible. The relationship between physical habitat and populations of aquatic animals is not simple, and it is difficult to understand because physical habitat is a necessary condition and not a sufficient condition.

6.1 Brown Trout in Southwestern Wyoming

The habitat (weighted usable area) versus population of Brown Trout in southwestern Wyoming is given in Figure 8. These data are confusing because there appears to be a threshold and an upper limit. The threshold may illustrate a problem in the usual application of habitat simulation with weighting factors give a large quantity of poor quality habitat the same value as a much smaller quantity of high quality habitat. There are ways of dealing with this problem in PHABSIM. One way is to establish a minimum quality (the f(v,d,CI) term in equation 1) below which the habitat value is zero; the second is to change the formulation of the composite suitability function. Both techniques are explained in the users manual (Milhous et al, 1989). The upper bound may occur because the relatively low nutrient waters of southwestern Wyoming may produce only enough food for a limited number of fish, or it may be a result of fishing pressures. The two points with known high fishing pressures are displaced about the same to the right as the two points suggesting an upper limit. In other words, a modeling problem causes a lower threshold, and the upper limit results because the physical habitat is not the limiting factor when the habitat is very good or harvesting fish in streams with good habitat reduces the population. The data suggest habitat is the limiting factor between some upper limit and the lower threshold.

6.2 Little Prickly Pear Creek, Montana.

The physical habitat (weighted usable area) versus population of trout for a stream in central Montana are shown in Figure 9. Cover was measured as the area of overhanging brush, undercut banks, stumps, rocks, and log jams.

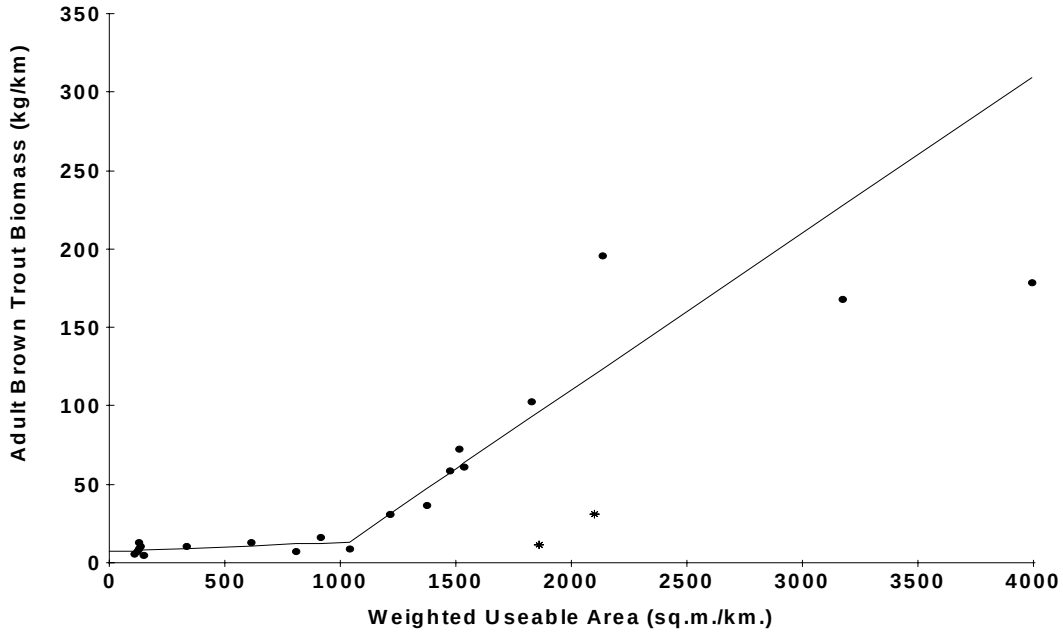

Figure 8. Habitat (weighted usable area) versus population of Brown Trout in Southwestern Wyoming. The two points marked with an asterisk have above average fishing pressures. (Original data from Wesche, 1976; the calculation of weighted usable area was done by Ken D. Bovee.)

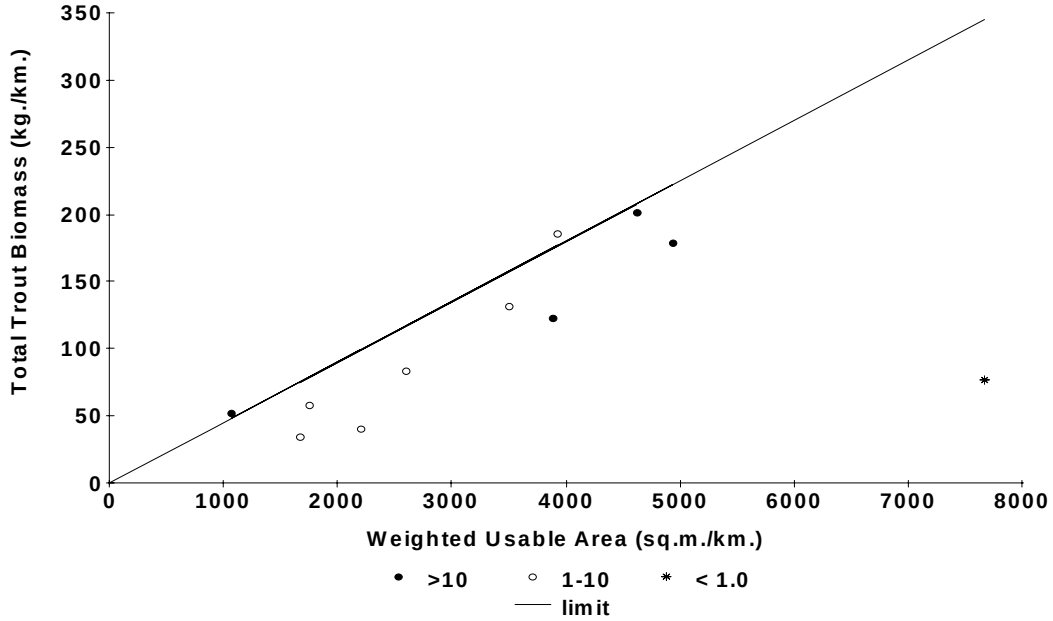

Figure 9. The physical habitat versus total trout population relation for Little Prickly Pear Creek in Montana. The data label is the percent cover for the sampled reach. (Data from Elser, 1968).

If the point with less then 1 percent cover was weighed by a cover function based on the assumption that with zero cover there are no fish regardless of the amount of the weighted usable area, and is related directly to the weighted usable area when the percent cover is 1 percent; than the revised weighted usable area is 2500. The expected weighted usable area based on the equation for the 'best fit' line based on Figure 9 (not shown) and the measured population is 2200. The lesson here is that all of the physical habitat factors must be considered in the model or known not to change as a result of the changes being considered. In this case, if the cover was good and will not be changed, cover may not have to be considered in the model. For Little Prickly Creek cover must be considered.

6.3 Upper Gunnison River, Colorado

The fry habitat versus population of juvenile brown and rainbow trout one year later in the Upper Gunnison River in Colorado are presented in Figure 10. The figure strongly suggest the limiting habitat for the production of juvenile rainbow trout is the fry habitat the previous year. For brown trout this may not be the case.

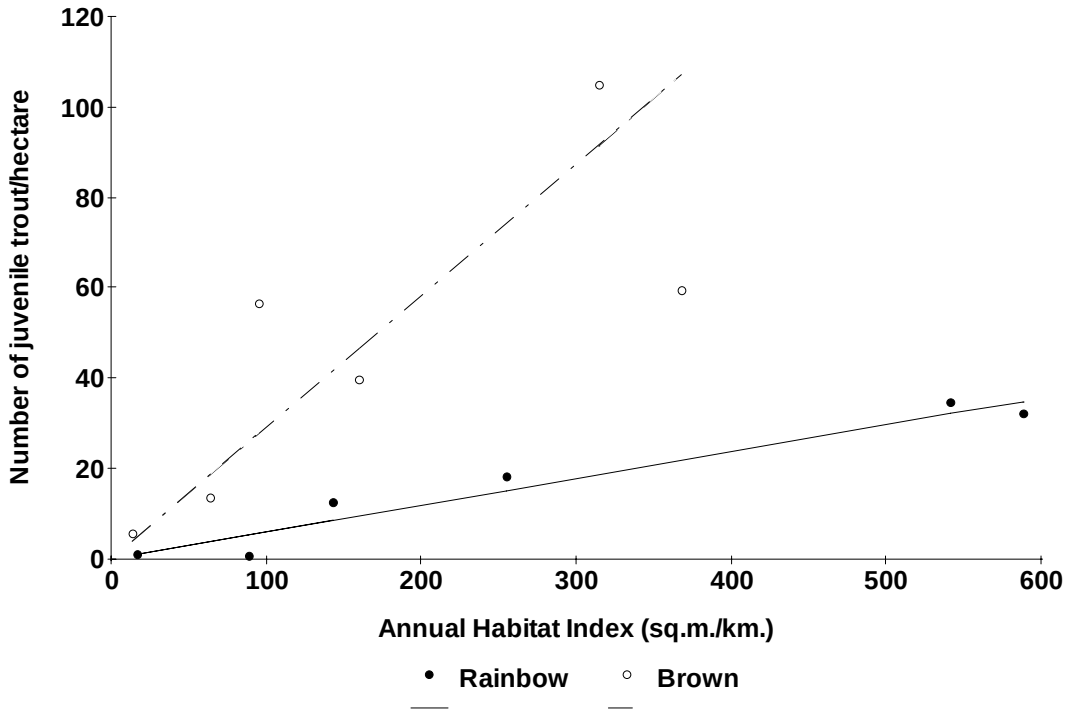

Figure 10. The effective habitat versus population for juvenile brown and rainbow trout in the Upper Gunnison River Colorado. Data from Nehring and Miller (1987).

There are two data points for brown trout in Figure 10 that are outliers. Likely

cause of the outliers is the conditions during the year before emergence of the fry. The concepts presented above for the Terror River are applicable to brown trout in the Gunnison River. The brown trout spawning period used in the following analysis is from 1 October to 15 November and the incubation period from 1 November to 15 April. Winters in Colorado can be from cold and dry (low winter runoff); to warm and wet (high winter runoff). If the concepts applied to the Terror River analysis are applied to the Gunnison than good spawning flows followed by poor incubation flows should give a point to the right of the line on Figure 10 because these conditions should cause low production of fry. The point to the left of the line should result from good spawning and good incubation which would be expected to give above average fry production. The spawning and incubation flows are given in Table 3.

Table 3. Spawning and incubation flows in the Gunnison River as measured below the diversion tunnel, and the Juvenile population and fry habitat at the Duncan/Ute Trail site just downstream. The juvenile population was measured the following year. The habitat and population data are from Nehring and Miller (1987).

Water Year	Spawning Discharge (cms)	Incubation Discharge (cms)	Juveniles (number/ hectare)	Fry Habitat
1980	22.4	14.0	105	314
1981	34.6	4.9	59	366
1982	11.6	4.1	40	160
1983	38.1	20.4	13	63
1984	33.7	15.4	6	14
1985	47.3	38.7	57	95

The outlier to the right occurred in 1981 and the one to the left in 1985. The spawning flows were good in 1981 but the incubation flows were much reduced. This was followed by good fry habitat but by that time the poor incubation conditions had reduced the fry that could emerge. Compare 1981 to 1982; the incubation discharge was slightly lower but because the spawning flows were also low the reduction in fry production probably did not occur. The spawning and incubation flows in 1985 were good but the main point is that the incubation flow was not too much lower than the spawning flow. The expected result in 1985 is a larger than average production in fry which caused a larger than expected production of juveniles a year later.

6.4 Little Deschutes River, Central Oregon

Habitat versus population data for the Little Deschutes River in Central Oregon are presented in Figure 11. The factor causing the scatter in the data is the habitat for benthic invertebrates and the competition from other fishes. The population data and the data used to calculate the habitat area are from Lorz

(1974).

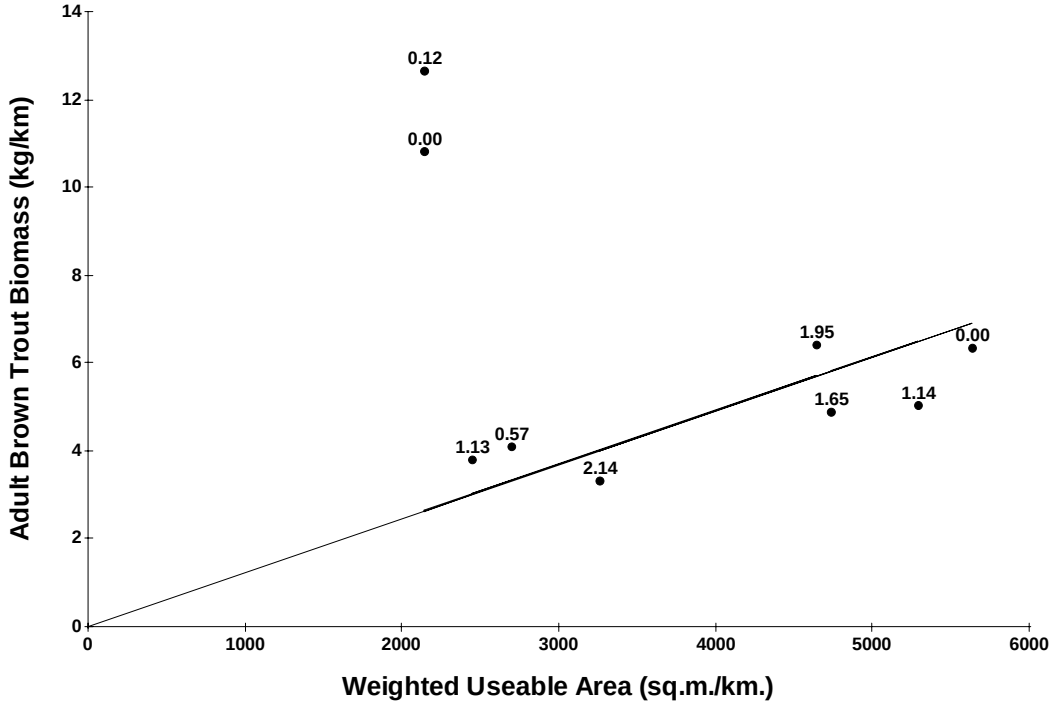

Figure 11. The habitat versus population data for the Little Deschutes River in Central Oregon. Data used is from Lorz, 1974. The numbers are the non-trout biomass in kg/km.

Excluding the two outliers, the average number of fish per unit area is 1.23. The line on Figure 11 has a slope of 1.23. The expected number of fish at both locations with higher than expected populations (Gulick's and Old Mill) is 2.63 instead of the 5.90 at Gulick's and 5.05 at Old Mill. Two factors appear to cause this anomaly, one is the existence of larger than average habitat for benthic invertebrates and the second is lower than average competition from other species of fish. There are programs in PHABSIM that can be used to investigate competition between species. Information on the benthic habitat area and the non-trout biomass are given in Table 4.

Table 4. The adult trout biomass per unit of weighted usable area compared to the non-trout biomass and the weighted usable area for benthic biomass. Little Deschutes River, Oregon.

Location	Trout Biomass/WUA (kg/sq m)	Non-trout Biomass (kg/km)	Benthic WUA (sq m/km)
Cow Camp	1.13	0.00	1003
Gulick's	5.90	0.12	4020
Old Mill	5.05	0.00	3133
Crescent	1.52	0.57	6059
Rocky Reach	1.55	1.13	7309
Willows	1.39	1.95	1838
Larson's	1.02	2.14	600
Conifers	0.95	1.14	1817
Crider's	1.04	1.65	786

The possible cause of the outliers is the joint existence of above average benthic habitat and low non-trout biomass. At Cow Camp the non-trout biomass is zero but the benthic habitat low, the result is average trout biomass. In contrast, at Crescent and Rocky Reach the benthic habitat is above average but the non-trout biomass is above the threshold that appears to cause a reduction of trout biomass below that which could be supported by the expected benthic production.

6.5 THE USE OF PHABSIM IN WEDGE MODELING

If physical habitat is only one of a number of factors limiting the numbers of individuals or the biomass of aquatic animals then the physical habitat is a necessary but not sufficient condition. That is to say, the physical habitat is a limiting factor and the population cannot, on a long term basis, be larger than the physical habitat can support. The population could be smaller than the physical habitat can support but not larger. In this case, a wedge-shaped pattern of variation of the population would be expected (Terrell et al, 1996, and Cade et al, 1997). An example of the wedge-shaped pattern was given in Figure 9 for Little Prickly Pear Creek where the stock of trout is limited by the physical habitat and by the cover available in the stream. The fact the limit line shown on Figure 9 is above many of the points suggest there are other factors limiting the benthic biomass but not to the same degree as the cover and physical habitat.

Another example is given in Figure 12 for twenty streams in Newfoundland (Clarke and Scruton, 1997). Nitrate would be expected to be a limiting factor (Terrell et al, 1995). The four points with a nitrate concentration of 0.01 ueq/l are shown on Figure 12 and may be a limiting factor but clearly not the only one. The other limiting factors are the concentration of organic anions (related to the allochthonous materials entering the stream) and the possibility of perdition by salmonids because some of the rivers were better trout habitat than others. In general, the four factors limiting the habitat were 1) the physical habitat (correlation coefficient, r, of 0.63), 2) organic anions (r of 0.53), 3) the nitrate (r of -0.24), and the trout physical habitat (r of 0.62).

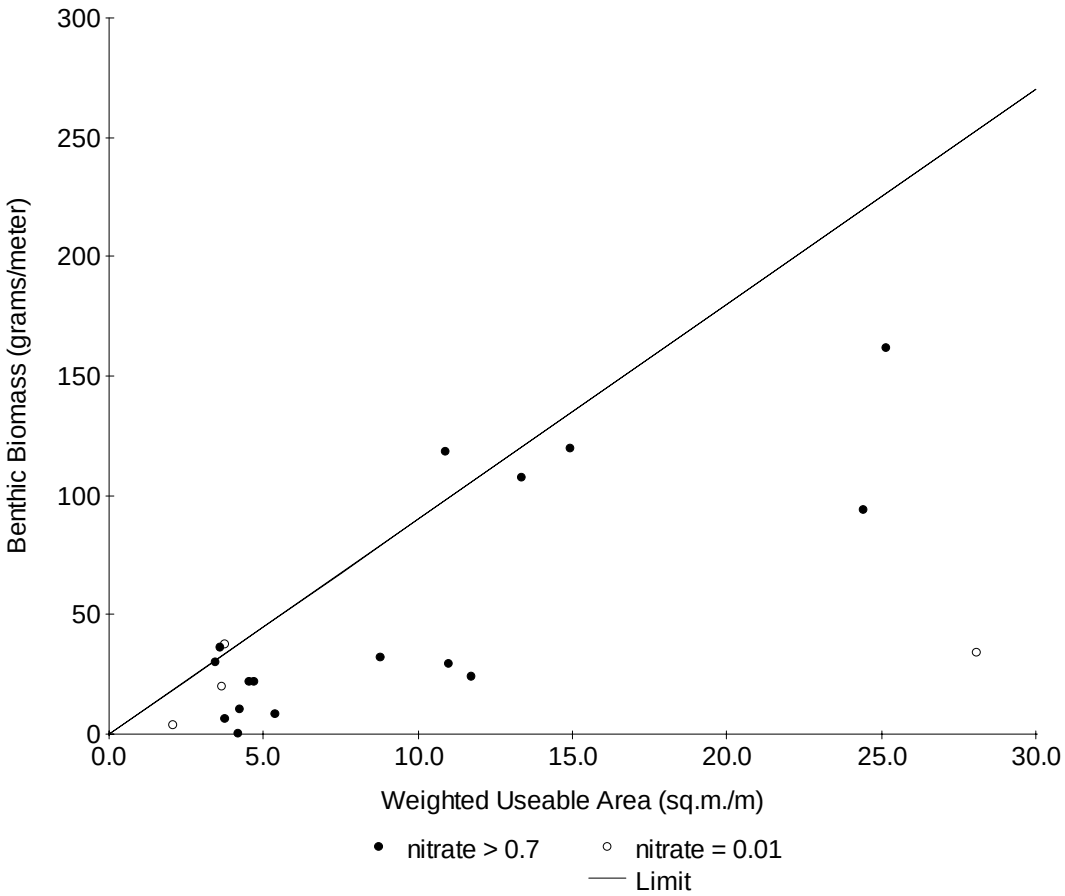

Figure 12. The weighed usable area compared to benthic biomass for the twenty Newfoundland streams. The weighted usable area versus benthic data with a line representing the upper bound. Date used from Clarke and Scruton (1997).

7.0 NEW DEVELOPMENTS NEEDED IN PHYSICAL HABITAT ANALYSIS

There are many needed improvements to the simulation of physical habitat. Two of these are improvements to the simulation of habitat at high flows and the modeling of physical habitat during periods of low flows (either because of drought or because it is winter). The modeling of both winter and high flow physical habitat needs to be improved. Drought is another factor that should be considered and species survival criteria curves developed.

It was shown in a previous paper (Milhous, 1999) that velocities in the Animas River of southwestern Colorado are too high for optimal adult trout habitat when the streamflows are high during spring runoff. When the velocities are high the fish must seek velocity shelters and other ways of reducing their expenditure of energy. In such situations, the fish is considered to be under stress caused by a lack of appropriate physical habitat. An index to habitat stress has been developed and is described in detail by Milhous (1998b). The index is a measure of the stress on the fish that may be caused by the higher velocities. The results of a simulation of the time series of the stress index are given in Figure 13. The larger the absolute value of the stress index the more high flows may be limiting the population of trout.

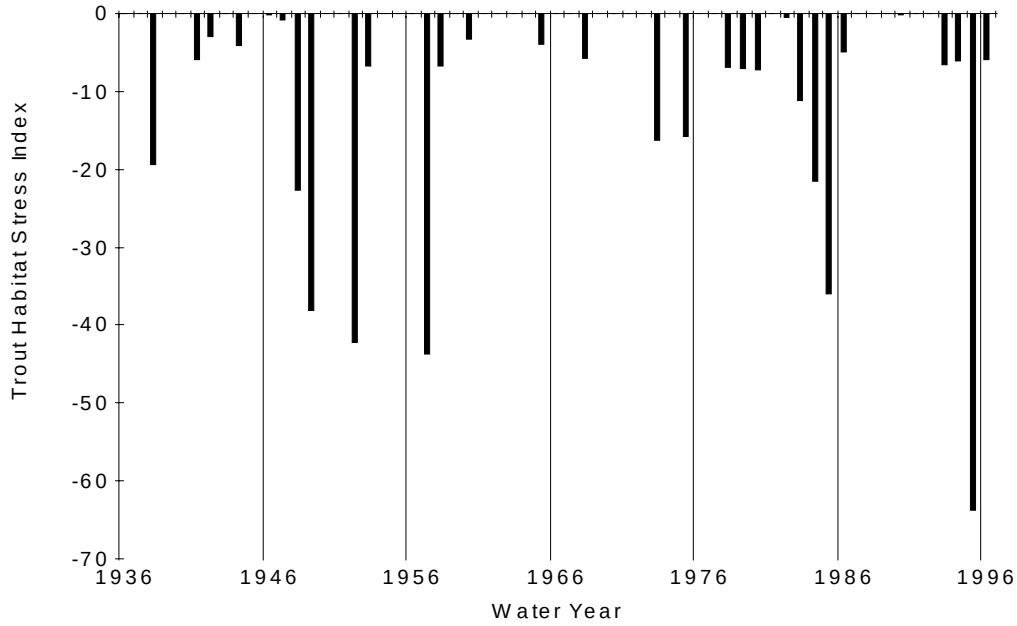

Figure 13. The annual index to the habitat stress introduced to the trout in the Animas River, Colorado by high velocities during high flow periods.

In slightly more than 50% of the years there is no real habitat stress on the trout

populations caused by high streamflows but during about 20% of the years the habitat stress could be important. For the remaining 30% of the years, some habitat stress occurs but it is probably not all that important. This suggests that there could be variation in the trout population caused by variation in the streamflows alone.

The way trout adjust to higher velocities is to use velocity shelters where the velocity is significantly lower than in the surrounding water. In many rivers the most important velocity shelters are pools, root wads and undercut banks on the sides of the stream, and large bed elements such as cobbles and boulders on the stream bed (Raleigh, 1982). Most, but not all, of the velocity shelters in the Animas River are cobbles and boulders. The size of fish that can be sheltered by boulders and cobbles is related to the size of the armour on the bed surface. The percent of the bed surface with sizes in the range of 100 to 400 mm is the amount of the stream bed that can be used as velocity shelters (Raleigh, 1982). The size of material on the bed surface in the range of 100 to 400 mm is given in Table 4.

Table 4. The percent of the stream surface that are velocity shelters and the maximum size of the surface layer at four locations in the Animas River between Eureka and Silverton. The percent shelters is the difference between the percent of the surface less than 400 mm and more than 100 mm. D/S is downstream of Howardsville and U/S is upstream.

Location of shelters	% surface shelters	Median size (mm)	Maximum Size (mm)
U/S 1	34	123	145
U/S 2	0	----	95
D/S 1	60	142	220
D/S 2	78	171	430

The winter streamflows in the Animas River are very low and little physical habitat is available. Any trout in the river would be expected to be under stress caused by the winter conditions. The location of winter habitat is similar to the velocity shelters during spring runoff with two exceptions: 1) the river has essentially no edge (root wads and undercut banks) either because of ice and snow, or the edge of the water is away from the banks, and 2) the substrate (bed material) can be a shelter during the winter.

Voids in the substrate are used by wintering trout as resting locations to avoid expending energy (Meyer and Griffith, 1997). The specific weight and porosity for samples collected from two rivers are presented in Table 5. Fines (sediment less than 3 mm) are considered to be undesirable in the bed material used as trout habitat (Raleigh, 1982). The percent of fines in the bed material is also given in Table 5. The data for the Animas River show it has less voids than the two other unregulated rivers but the percent of fines is similar to Soda Butte Creek. The habitat value of the substrate in the Animas River is probably lower than in the

other rivers because the mixture of low porosity and relatively high percent of fines means the bed material is firmer than the other two rivers. The observations that the substrate of the Animas River has a low porosity and has significant fines suggests the substrate of the Animas River is not good habitat for wintering trout.

Table 5. Specific weight, specific gravity, porosity, and percent less than 3 mm of the bed material of two unregulated Rocky Mountain rivers.

Stream	specific weight (lb/ft3)	specific gravity	porosity	%≤3 mm
Soda Butte Creek, WY-MT				
upstream	108	2.65	0.35	16
downstream	104		0.37	23
Animas River, Colorado				
above Howardsville	135	2.80	0.22	20

Metals in some streams may limit the populations of aquatic animals. An example of one suitability function for metals in rivers is presented as Figure 14. The curve is based on data in Woodward et al (1997),and in Besser and Leib (1999). Woodward et al showed the avoidance concentration of zinc is 28 ug/l for fish in the Coeur d'Alene basin in Idaho. The assumption for the suitability criteria is that the chronic limit had a suitability of 0.1 and any concentration of zinc larger that the acute limit has a suitability zero. The values used are from Besser and Leib for a hardness of 120 mg/l (the chronic limit for cutthroat is assumed to be the same as for rainbow trout).

Woodward et al states: 'Avoidance of metals contaminated habitats by cutthroat trout may, in part, be responsible for reduced fish populations.' In many rivers the fish can escape - in the Animas River upstream of Silverton there are no uncontaminated alternatives and fish are found in places with significant concentrations of zinc.

The discussion above suggests future improvements in physical habitat simulation can be made by considering the time series of habitats that may limit the populations of aquatic animals, improvements in the use of substrate information in the simulation of physical habitat, and that suitability criteria for metals and other chemicals in the stream environment should be developed.

9.0 LIMITATIONS OF PHABSIM

There are many limitations to the Physical Habitat Simulation System. The first should be obvious now - physical habitat is a necessary but not a sufficient condition for the existence of a species, or a collection of species. The second is that there are many interactions between species, between life stages, and between many other factors that will influence the state of the ecosystem that are not modeled by PHABSIM.

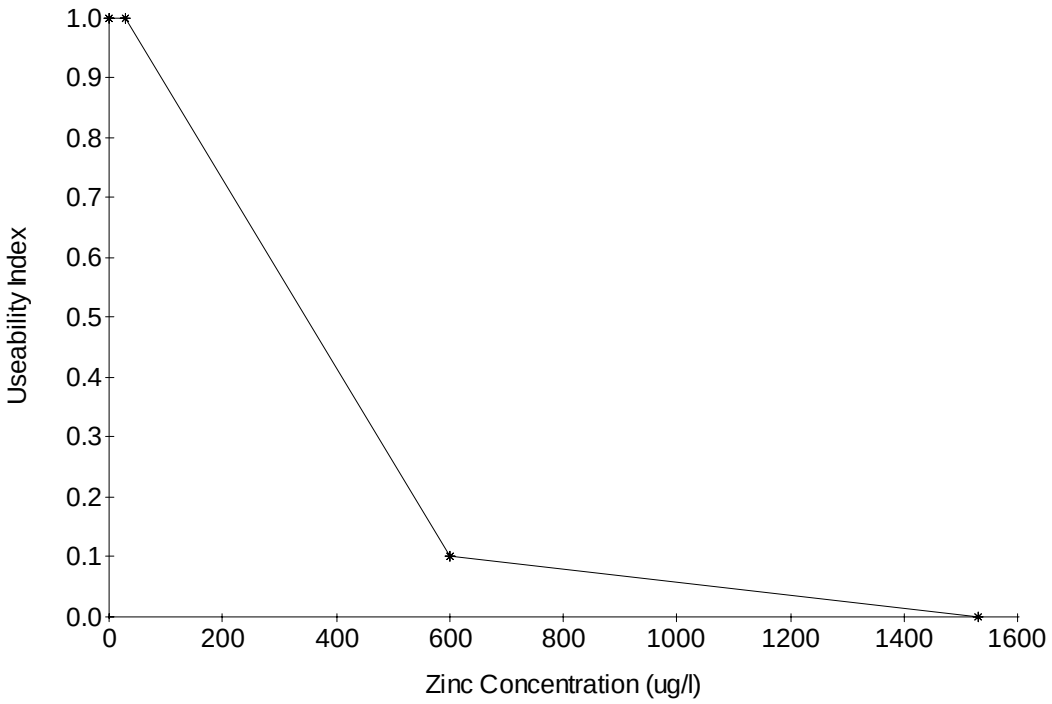

Figure 14. A cutthroat trout suitability curve for zinc concentrations in streams.

Never-the-less, PHABSIM results do help in understanding the ecosystem and in the development of instream (i.e. environmental) flow needs because PHABSIM does simulate the impact of the changes made in the management of water.

Perfect knowledge of the habitat as a function of discharge will not necessarily give knowledge of the animal population in a stream. The basic assumption is that a population of aquatic animals must have the required physical habitat conditions but the existence of the physical habitat for an animal does not guarantee the animal will be found in the stream. In other words, physical habitat is necessary but it is not sufficient as the discussion in the section linking habitat and population demonstrates.

A principle of environmental flow analysis is that the analyst must first understand the stream. This understanding includes, but is not limited to, an understanding

of the hydraulic nature of the stream, the hydrology of the stream and its watershed, and the aquatic biology of the stream.

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