A Review of Habitat Capacity for Salmon Spawning and Rearing

Prepared for:

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1. Introduction

The guiding principle which underlies fish habitat conservation, restoration, and development in Canada is to achieve no net loss of the productive capacity of aquatic habitats. Application of the no net loss policy is particularly challenging in the province of British Columbia, where 5 species of Pacific salmon are widely dependent upon freshwater and estuarine spawning and rearing habitats. The Aquatic Task Force of the B.C. Resources Inventory Committee (RIC) is currently reviewing and establishing standards for the collection and interpretation of aquatic inventory information. One of the objectives of the Task Force is to develop a strategy for province-wide application to determine the habitat capacity for fisheries resources, and to review appropriate parameters for determining the quantity and quality of freshwater spawning and' freshwater and estuarine rearing habitat for the five species of salmon. This study was undertaken in 1993 during a 20-day contract period by Levy Research Services Ltd. to support the work of the Task Force.

The terms "productive capacity" and "productivity" have been defined in a 1988 DFO document "Draft Procedures for Achieving No Net Loss of the Productive Capacity of Fish Habitat" and are further discussed by Patterson (1988). For the present review, the following definitions will be adopted: *productive capacity* is the maximum natural ability of a habitat to support healthy fish or grow aquatic organisms upon which fish depend, and *productivity* is a measure of a habitat's current yield of fish and other biological material such as fish food organisms or organic matter which are necessary to support fish production. Following Shirvell (1986), Patterson (1988) defined fish habitat as a combination of its usable area (space) and its productive capacity (factors affecting metabolism and behavior). A change in streamflow, for example, can modify the usable area (depth, velocity) but the population will also be directly or indirectly affected by other parameters, such as DO, temperature, pH, food production, protection from predators etc. Shirvell (1986) demonstrated the importance of these variables in a stream where the fish biomass varied, even though there was no change in the percent usable habitat. It is therefore not only the physical space provided by a habitat, but also its quality (ability to produce) that determines fish distribution and abundance. This "productive capacity" to grow fish is what must be maintained under the no net loss policy. Translation of this concept into meaningful, practical and justifiable empirical field procedures is a crucial requirement under the "no net loss" policy. As an operational definition for the present study, the term "habitat capacity" represents the maximum number of fish per unit area that can be supported by the available physical and biological resources.

Measurements can be justified by existing hypotheses or models which relate habitat parameters to fish productivity parameters. Therefore, a major focus of the present review is to examine the ability of existing habitat models to predict salmon abundance or biomass in aquatic areas where habitat alterations will occur and where decisions must be made. The goal is to develop consensus on which parameters trained habitat personnel can measure in the field to assess spawning and rearing habitats for Pacific salmon. This review is particularly timely in view of possible future increased involvement of outside parties and agencies in the co-management of fish habitats.

2. DFO Policy for the Management of Fish Habitat

Canada's policy for the management of fish habitat is contained in a paper that was presented to Parliament by the Minister of Fisheries and Oceans in 1986 (DFO 1986). The policy objective is to achieve a net gain of habitat for Canada's fisheries resources. There are 3 basic goals: fish habitat conservation, fish habitat restoration, and fish habitat development. The guiding principle which underlies the fish habitat conservation goal is to achieve no net loss of the productive capacity of habitats. Under this principle the Department strives to balance unavoidable habitat losses with habitat replacement on a project-by-project basis so that reductions to Canada's fisheries resources due to habitat loss or protection may be prevented. The second goal (fish habitat restoration) involves rehabilitation of the productive capacity of fish habitats in selected areas where economic and social benefits can be achieved through the fisheries resource. The third goal (fish habitat development) involves the improvement and creation of fish habitats in selected areas where the fisheries resources can be increased for the social or economic benefit of Canadians.

There are 8 DFO implementation strategies for fish habitat management:

1. *Protection and compliance* – fish habitats are protected by administering the *Fisheries Act* and incorporating fish habitat protection requirements into land and water use activities and projects.

2. *Integrated resource planning* – DFO participates in and encourages resource planning and management to incorporate fish habitat priorities into air, land and water use plans.

3. *Scientific research* – DFO conducts a broad program of basic scientific research to provide the information and technology necessary for the conservation, restoration and development of fish habitats.

4. *Public consultation* – Consultations with the public are undertaken on major or controversial fish habitat issues and on the development of new policies and legislation for fish habitat management.

5. *Public information and education* – This is undertaken to promote public awareness in the conservation, restoration and development of fish habitats.

6. *Cooperative action* – Involvement by government agencies, public interest groups and the private sector to conserve, restore and develop fish habitats is encouraged and supported.

7. *Habitat improvement* – Projects are initiated and advice is provided to other interested groups to restore and develop fish habitats, in support of the net gain objective.

8. *Habitat monitoring* – Evaluations are undertaken to determine the effectiveness of decisions taken and techniques used to conserve, restore and develop fish habitats.

Procedures that are routinely implemented to apply the "no net loss" principle include notification by a development proponent and government sources, examination of the development proposal by DFO (often in consultation with other agencies), decision making (proceed as proposed, proceed with conditions, or reject proposal), and lastly enforcement to correct any habitat problems, or prosecution if required.

Application of the DFO Habitat Policy is particularly challenging in British Columbia due to the presence of five species of Pacific salmon with high sensitivity to freshwater and estuarine habitat modifications. The questions being considered during the present review are directly relevant for five out of the eight DFO implementation strategies: integrated resource planning, scientific research, cooperative action, habitat improvement, and habitat monitoring.

3. Habitat Management Goals and Objectives

A preliminary task in any habitat assessment is to establish the spatial and temporal scales to be considered. The review by Hall and Knight (1981) indicates that temporal and spatial variation in the population size of stream salmonids can be as high as several orders of magnitude in the extreme, and are sufficient to mask significant perturbations caused by non-point source habitat alterations or pollutants. This natural variability will undermine efforts to understand functional relationships between fish habitat and fish production.

A working group at the Habitat Alteration Workshop (Meerburg 1989) considered fish habitat effects on three different scales: (1) the "small impact" project level, (2) the "large impact" project level, and (3) the synoptic level. In addressing the question of habitat capacity, it is important at the outset to clarify whether one is interested in habitat relationships at a small scale (i.e. what is the effect of installing a highway culvert?) or a large spatial scale (i.e. how will global warming affect salmon production in the Fraser River watershed?). Both levels of enquiry are justifiable approaches, but the mechanics of measurement and assessment of fish habitat would be very different in the two cases.

Similarly, the requirements for short-term decision-making (e.g. response to agency referrals), will be different than those involved in long-term (years or decades) strategic planning for habitat protection and enhancement (e.g. Fraser River Green Plan).

A discussion of the strategies for setting goals and objectives for managing salmonid habitats is provided by Kershner et al. (1991). In their terminology, ***goals*** describe the ultimate state that a program is designed to achieve, and should be both realistic and achievable. As an example, a specific goal for stream habitat may involve maintenance of adequate habitat to support a population of 5000 coho spawners in a particular watershed. By contrast, ***objectives*** describe the discrete projects needed to achieve a stated goal. The projects can be undertaken either sequentially or simultaneously. In all cases, objectives should be measurable and quantifiable. Additionally, recommended goals and objectives for salmonid habitats should be periodically revised, as shown in Figure 1.

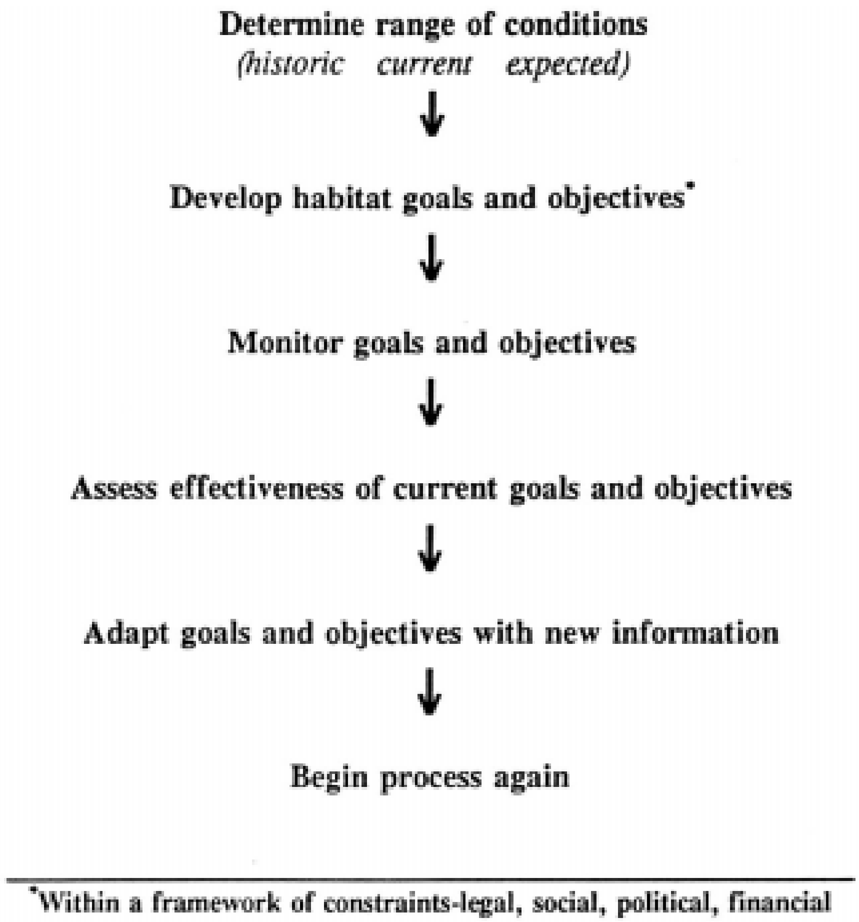

Figure 1. A procedural strategy to establish goals and objectives for salmonid habitats. Reproduced from Kershner et al. (1991).

Effective planning is a prerequisite for successful salmonid stream habitat assessment projects. In order to minimize the risk of failure, detailed program planning must precede the implementation of habitat-related work. Everest et al. (1991) review and discuss planning frameworks based on both *Program Planning* which involves coordination of financial resources, selection of subbasins, selection of species, selection of personnel and coordination of evaluation programs, and *Project Planning* which involves preimprovement inventory, analysis of limiting factors, site selection, selection of techniques and materials, selection of implementation procedures, and project evaluation.

Careful monitoring and critical evaluation provides the essential feedback to managers on whether goals and objectives are actually being met. Three types of monitoring can be distinguished (Kershner et al. 1991): (1) implementation monitoring, (2) effectiveness monitoring, and (3) validation monitoring. Implementation monitoring is the most straightforward, and addresses the question: "Were the prescribed activities for an objective implemented correctly on the ground?" Effectiveness monitoring addresses whether an objective was actually achieved. Validation monitoring is undertaken to test the hypotheses or judgments associated with a project to improve the formulation of future goals and objectives.

As an example, the stated goal of a habitat manager may be to protect a coho population within a stream from environmental impacts associated with logging. A temperature objective, to maintain the stream water temperatures below 200C, would be consistent with the overall goal, and could be achieved by maintaining a 30m buffer strip adjacent to the stream banks. Implementation monitoring would involve establishing whether the buffer strip was left as prescribed, perhaps by random sampling of the buffer width and assessment of tree damage. Effectiveness monitoring would involve measuring stream temperatures during late summer low flow periods to ensure that temperature actually remained below 20*C. Validation monitoring would involve a research program to establish that the prescribed results were the result of the management action (use of a buffer strip) and not the result of influence from some unmeasured parameter (i.e. the stream remains below 200C because of strearnside vegetation or groundwater inflows). Successful validation monitoring of this type can provide an important feedback mechanism in the overall strategy for adapting and revising goals and objectives.

4. Habitat Requirements for Paciftc Salmon

Aquatic habitats utilized by the five species of salmon encompass headwater streams, lakes, mainstem rivers, estuaries, marine foreshore areas, and the North Pacific Ocean. The present review focuses primarily on freshwater environments because of their high utilization as spawning and rearing habitats by Pacific salmon (Figure 2). Freshwater habitats include streams, which provide spawning habitats for all five species, and which are extensively utilized by both chinook and coho salmon for juvenile rearing (Table 1). For sockeye salmon, lakes provide primary rearing habitats, both in littoral areas (Morton and Williams 1990) and pelagic environments (Narver 1970). Certain coho populations also utilize lakes as juvenile rearing habitat. Sockeye also spawn within certain B.C. lakes, including Cultus Lake, Great Central Lake, and lakes of the upper Skeena River drainage (Burgner 1991).

Estuaries and marine foreshore areas also provide rearing habitat for certain salmon species, notably chinook and chum. Recent reviews of Pacific salmon habitat utilization of estuaries, as well as habitat evaluation procedures, are provided by Levings (1990) and Williams (1989) respectively.

A thorough understanding of Pacific salmon life history is a prerequisite for determining habitat requirements. Most species of salmon show impressive variation in life history features between, and within watersheds (e.g. Healey 1991). Such life history variation must be explicitly recognized and understood by habitat managers in order to determine meaningful habitat parameters within particular watersheds; this issue is especially relevant for the protection and preservation of threatened stocks (Nehlsen et al. 1991). Acquisition of life history information for species and stocks of interest will not be obtained easily or at low cost; habitat managers must be committed to obtaining this information if meaningful habitat programs are to be developed.

A detailed review of the habitat requirements of salmonids is provided by Bjornn and Reiser (1991). The following discussion and data are abstracted largely from this source.

4.1 Upstream Migration of Adults

Adult salmon require adequate flows and temperature conditions in rivers and streams to permit upstream migration. For salmon protection in B.C. rivers and streams, the DFO Habitat Management Unit have adopted a flow velocity value of 1.0 m/sec as a guideline for defining maximum flow discharges suitable for upstream salmon migration. Due to temperature-related prespawning mortality problems experienced by early migrating sockeye salmon stocks (Table 1), Gilhousen (1990) recommends a temperature value below 15°C for maximum survival of maturing sockeye during their river migration.

A summary of water temperatures, depths and velocities that enable upstream migration of adult salmon are shown in Table 2. In addition to these parameters, water quality conditions, in particular dissolved oxygen and turbidity conditions, need to be maintained at levels which do not compromise upstream migration ability. Barriers in streams (both man-made and natural) can prevent or delay upstream migration, and -are generally related to the jumping abilities of different salmon species (Table 3).

4.2 Spawning

Various habitat parameters mentioned by Bjorrn and Reiser (199 1) as being important before and during spawning include substrate composition, cover, water quality and water quantity. The number of spawners in a stream is a function of the total area available for spawning and the average area required for each redd (Table 4). In the absence of specific spawner-recruitment information for a specific salmon stock, the latter data are also useful for establishing optimum spawning escapement targets (Healey 1993).

A variety of techniques have been used to quantify the relationships between spawning area and flow discharge within a stream, including the instream flow incremental methodology (IFIM). In most cases, there is an exponential or sinusoidal relationship which peaks at a level which defines the optimum spawning flow (Figure 2). The actual timing of spawning is thought to provide a synchronizing mechanism associated with differences in the incubation temperatures experienced by developing embryos (Burger et al. 1985; Salo 1987). Favourable temperatures for spawning salmon (Table 5) are considerably narrower than the range, which extends between 1 to 20°C.

Most salmon spawn in transitional areas between pools and riffles. This results in favourable percolation of water through the incubation gravel, and enhanced water flow to the developing eggs (Figure 3). Additionally, salmon frequently select spawning sites which contain upwelling groundwater, thus contributing to efficient water exchange between developing eggs and interstitial water.

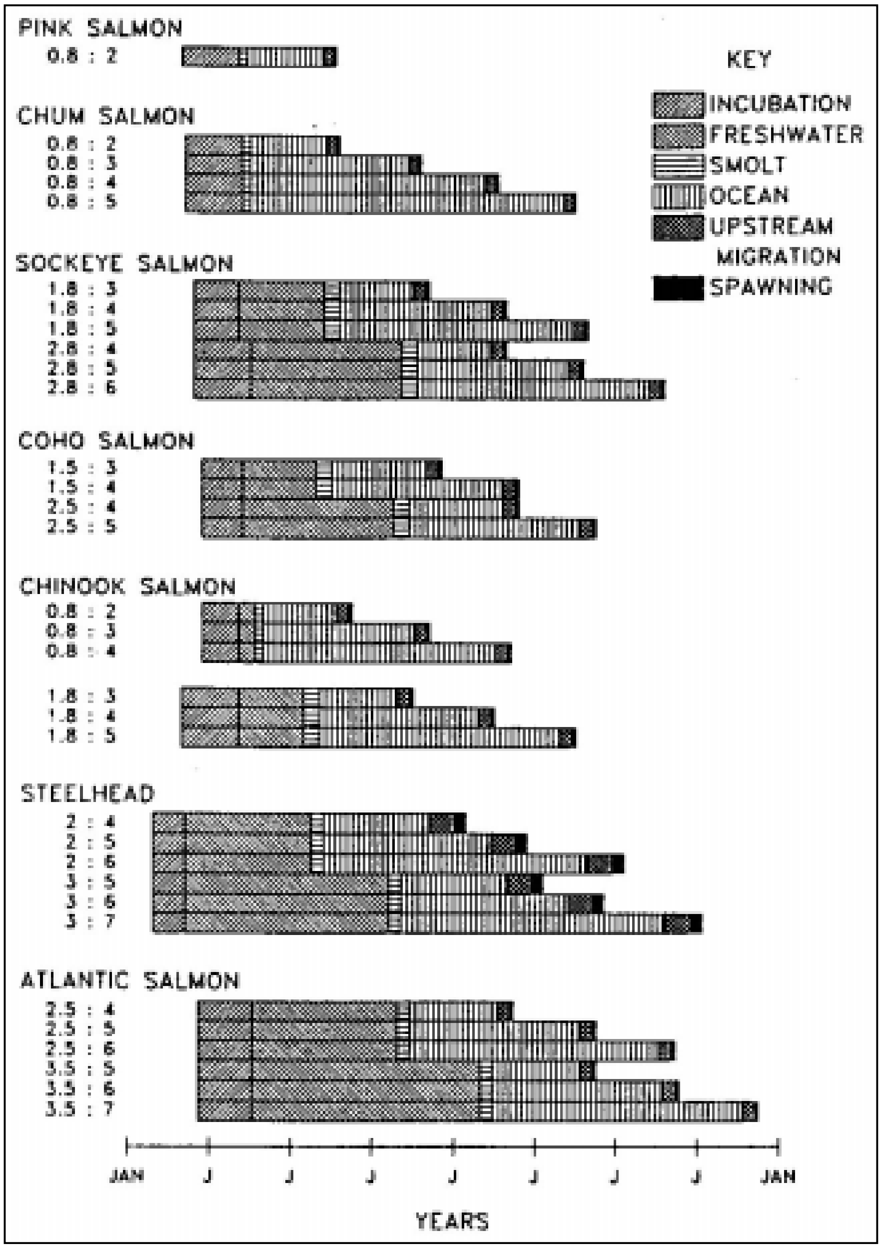

Figure 2. Typical lengths of time that representative anadromous salmonids spend in various developmental stages. Numbers under the species names are age keys indicating years spent rearing in freshwater, in relation to the total age of the fish. For example, 2.5:5 indicates a fish in its fifth year of life that had spent 2.5 years incubating and rearing in fresh water before migrating to sea. Reproduced from Meehan and Bjornn (1991).

Table 1. Stream utilization by Pacific salmon during different life history stages. Modified from Northcote (1974).

			Type and Time of Stream Utilization					
Degree of Use	**Saknonid form**	**Indirect**	**Adult mign.**	**Spawn**	**Egg inc. alevin dev.**	**Juvenile mign.**	**Juvenile rearing, feeding**	**Adult feeding**
Indirect	kokanee lake spawners	year round						
Low	sockeye lake spawners	year round	summer-autumn			spring		
Moderate	pink salmon		summer-autumn	late summer-autumn	winter	early spring		
Moderate	chum salmon		autumn-winter	autumn-winter	winter-early spring	spring		
Moderate	sockeye salmon	year round	summer-autumn	autumn	winter	spring		
Moderate	kokanee	year round	summer-autumn	autumn	winter	spring		
Moderate to high	chinook salmon		spring-summer	summer-autumn	winter	spring	year round	
Moderate to high	coho salmon		late summer-winter	autumn-winter	winter-spring	spring	year round	

Table 2. Water temperatures, depths, and velocities that enable upstream migration of adult salmon and trout.
Reproduced from Bjornn and Reiser (1991).

Species of fish	**Tempemture mnge (°C)**	**Minimum depth (m)**	**Maximum velocity (m/s)**
Fall chinook salmon	10.6-19.4	0.24	2.44
Spring chinook salmon	3.3-13.3	0.24	2.44
Summer chinook salmon	13.9-20.0	0.24	2.44
Chum salmon	8.3-15.6	0.18	2.44
Coho salmon	7.2-15.6	0.18	2.44
Pink salmon	7.2-15.6	0. 18a	2.13
Sockeye salmon	7.2-15.6	0.18	2.13
Steelhead		0.18	2.44
Large trout		0.18	2.44
Trout		0.12	1.22

* Estimate based on fish size.

Table 3. Swimming and jumping abilities of average-size adult salmonids. Reproduced from Bjornn and Reiser (1991).

	Swimming speed (m/s)			Maximum jumping height (m)
Taxon	**Cruising**	**Sustained**	**Darting**	
Chinook salmon	0-1.04	1.04-3.29	3.29-6-83	2.4
Coho salmon	0-1.04	1.04-3.23	3.23-6.55	2.2
Sockeye salmon	0-0.98	0.98-3.11	3.11-6.28	2.1
Steelhead	0-1.40	1.40-4.18	4.18-8-08	3.4
Trout	0-0.61	0.61-1.95	1.95-4.11	
Brown trout	0-0.67	0.67-1.89	1.89-3.87	0.8

Table 4. Average area of salmonid redds and area recommended per spawning pair of fish in articial spawning channels. Reproduced from Bjornn and Reiser (1991).

Species	Average area of redd (M^2)	Area recommended per spawning pair[a] (M^2)	Source
Chinook salmon	9.1-10.0		Neilson and Banford (1983)'
Spring chinook salmon	3.3	113.4	Burner (1951)
Spring chinook salmon	6.0		Reiser and White (1981 a)
Fall chinook salmon	5.1	20.1	Burner 0 95 1)
Summer chinook salmon	5.1	20.1	Burner (1951)
Summer chinook salmon	9.4		Reiser and White (1981a)
Coho salmon	2.8	11.7	Burner (1951)
Chum salmon	2.3	9.2	Burner (1951)
Sockeye salmon	1.8	6.7	Burner (195 1)
Pink salmon	0.6	0.6	Hourston and MacKinnon (1957)
Pink salmon	0.6-0.9		Wells and McNeil (1970)
Steelhead	5.4		Orcutt et al. (1968)
Steelhead	4.4		Hunter (1973)
Steelhead	4.4		Reiser and White (198 1 a)
Rainbow trout	0.2		Hunter (1973)
Cutthroat trout	0.09-0.9		Hunter (1973)
Brown trout	0.5		Reiser and Wesche (1977)

[a] Modified from Clay (1%1).

Table 5. Recommended temperatures for spawning and incubation of salmonid fishes. Reproduced from Bjornn and Reiser (1991).		
	Temperature (°C)	
Species	**Spawning**	**Incubation**[a]
Fall chinook salmon	5.6-13.9	5.0-14.4
Spring chinook salmon	5.6-13.9	5.0-14.4
Summer chinook salmon	5.6-13.9	5.0-14.4
Chum salmon	7.2-12.8	4.4-13.3
Coho salmon	4.4-9.4	4.4-13.3
Pink salmon	7.2-12.8	4.4-13.3
Sockeye salmon	10.6-12.2	4.4-13.3
Kokanee	5.0-12.8	
Steelhead	3.9-9.4	
Rainbow trout	2.2-20.0	
Cutthroat trout	6.1-17.2	
Brown trout	7.2-12.8[b]	

[a] The higher and lower values are threshold temperatures beyond which mortality increases. Eggs survive and develop normally at lower temperatures than indicated, provided initial development of the embryo has progressed to a stage that is tolerant of cold water.

[b] From Hunter (1973).

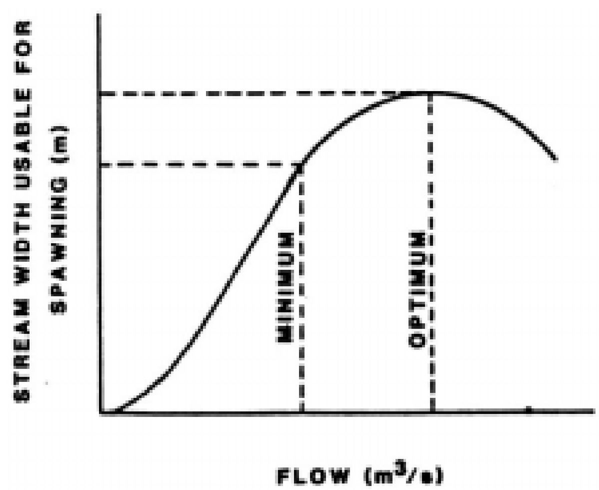

Figure 2. Usable width technique for determining spawning flow. Reproduced from Bjornn and Reisser (1991).

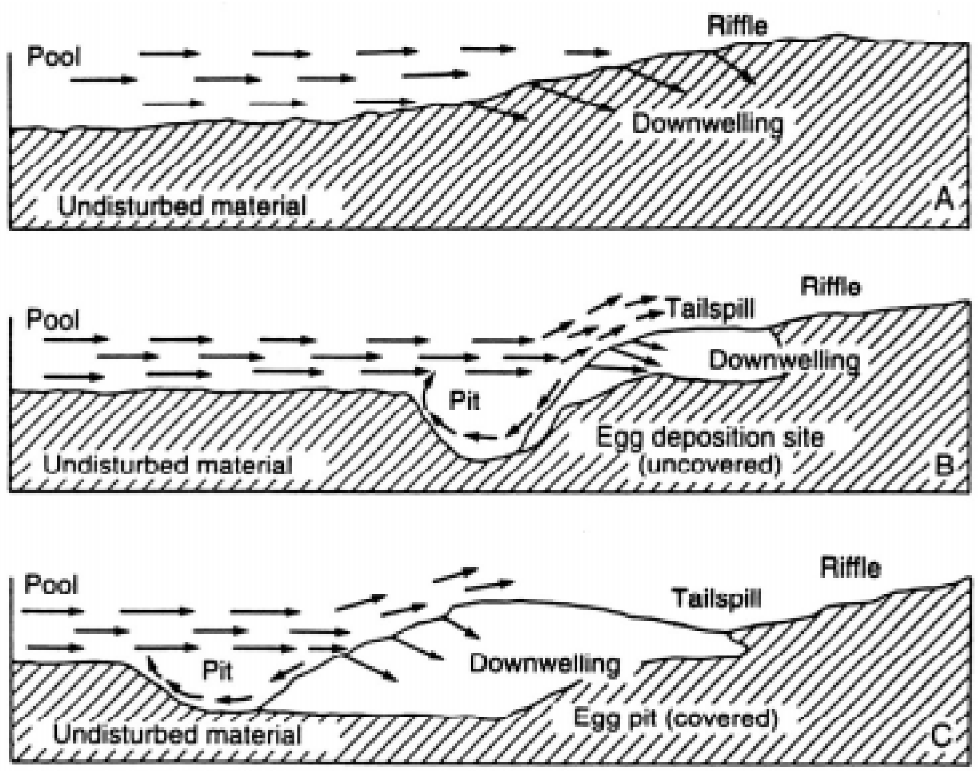

Figure 3. Longitudinal sections of spawning area. A. pool/riffle relationship results in percolation of water through gravel; B. excavation of nest increases flow rate through gravel and creates back eddy in pit; C. when the eggs are covered with gravel a second pit is created and water flow to the eggs is enhanced. Reproduced from Sandercock (1991).

Measurements of water depth and velocity at redds vary by species and size of fish, ranging between 6 to 300 cm. In general, water depths are at least sufficient to cover the fish during spawning, and many salmon spawn in water deeper than necessary to submerge them (Table 6). Water velocities shown in Table 6 refer to the water velocity at 0.6 x depth from the surface to the stream bed. A general rule of thumb for preferred sustrate size suggests that gravel substrate should range between 1.3 to 10.2 cm in diameter. Additionally, the suitability of gravel substrate is a function of fish size – large chinook spawners generally utilize much coarser gravel than pink salmon, for example.

4.3 Incubation

Survival of embryos within spawning gravel depends upon many chemical, physical, and hydraulic variables (Chapman 1988): dissolved oxygen, temperature, biochemical oxygen demand of material carried in the water and deposited in the redd, substrate size, sediment concentration, channel gradient, channel configuration, water depth (head) above the redd, surface water discharge and velocity, permeability and porosity of gravel in the redd and surrounding streambed, and velocity of water through the redd. Salmon alevins generally experience difficulties with emergence when the percentage of fine sediments exceed 20% of the substrate volume (Figure 4).

Effects of low dissolved oxygen on salmon egg survival and embryo development has been addressed in a number of studies (e.g. Shumway et al. 1964). A number of developmental effects of low dissolved oxygen concentration have been documented, including smaller size at hatching, delayed or premature hatching, as well as morphological anomalies. Bjornn and Reiser (1991) recommend that during egg development, DO concentration remain at, or near saturation, and that temporary reductions should drop to no lower than 5.0 mg/L for anadromous salmonids.

Within limits, temperature has a direct effect on embryo development rate such that higher temperatures result in shorter incubation periods and more rapid development. Coho salmon require the least time for egg development, while sockeye require the most. At extremely low temperatures, anchor or frazil ice can result in egg mortality due to a reduction in water interchange between the stream and the redd.

4.4 Freshwater Rearing

For stream rearing salmon (e.g. chinook and coho), there is likely an asymptotic relationship between fry number and smolt output. At high fry density, the production of smolts is thought to be stable at an upper limit, often termed the carrying capacity. Density-independent factors (e.g. amount of suitable habitat, quality of cover, productivity of the stream, and certain types of predation) set an upper limit on juvenile abundance, and the population is held to that level by density-dependent processes (competition and some types of predation). Carrying capacity may also differ between seasons, for example between winter and summer (Nickleson et al. 1992A) and may also vary with stage of development.

Table 6. Water depth, velocity, and substrate size criteria for anadromous and other salmonid spawning areas. Reproduced from Bjornn and Reiser (1991).

Species	Depth (cm)	Velocity (cm/s)	Substrate size (cm)	Source
Fall chinook salmon	≥24	30-91	13-10.2[a]	Thompson (1972)
Spring chinook salmon	≥24	30-91	1.3-10.2[a]	Thompson (1972)
Summer chinook salmon	≥30	32-109	1.3-10.2[a]	Reiser and White (1981[a])
Chum salmon	≥18	46-101	1.3-10.2[a]	Smith (1973)
Coho salmon	≥18	30-91	1.3-10.2[b]	Thompson (1972)
Pink salmon	≥15	21-101	1.3-10.2[a]	Collings (1974)
Sockeye salmon	≥15	21-101[b]	1.3-10.2[a]	[b]
Atlantic salmon	≥25	25-90		Beland et a]. (1982)
Kokanee	≥6	15-73		Smith (1973)
Steelhead	≥24	40-91	0.6-10.2[c]	Smith (1973)
Rainbow trout	≥18	48-91	0.6-5.2	Smith (1973)
Cutthroat trout	≥6	11-72	0.6-10.2	Hunter (1973)
Brown trout	≥24	21-64	0.6-7.6[c]	Thompson (1972)

[a] From Bell (1986).
[b] Estimated from criteria for other species.
[c] From Hunter (1973).

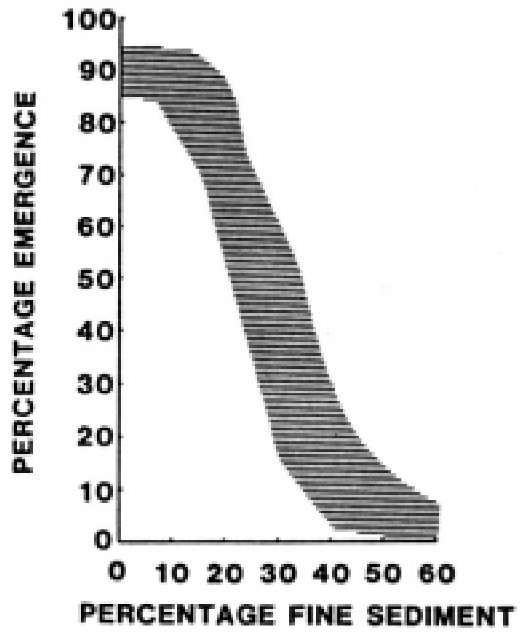

Figure 4. Percentage emergence of swim-up fry placed in gravel-sand mixtures in relation to the percentage of sediment smaller than 2-6.4 mm. The stipled area includes data from eight tests on brook trout, steelhead, and chinook and coho salmon. Reproduced from Bjornn and Reiser (1991).

Bjornn and Reiser (1991) consider the following factors as being important in affecting the distribution and abundance of juvenile salmon in streams: temperature, productivity, suitable space, water quality (turbidity, DO etc.), water velocity, depth, substrate, cover, predators and competitors. A summary of lower and upper lethal temperatures and preferred temperatures for salmon are shown in Table 7. A number of studies have shown that the preferred temperature of fish often coincides with temperatures that optimize physiological function (Levy 1992).

Davis (1975) reviewed information on incipient DO response thresholds of Pacific salmon and developed oxygen criteria related to concentration, water temperature, and percent saturation. Salmonids are not impaired by DO concentrations of 8 mg/L (76-93% saturation), and initial symptoms of DO deprivation occur at about 6 mg/L (57-72% saturation). Although salmonids can survive at DO concentrations below this concentration, this occurs at the expense of growth, food conversion efficiency and swimming performance.

The productivity of a stream determines the amount of food available to stream rearing salmonids, and is determined largely by nutrients and available energy. A review of stream energy sources and production processes is provided by Murphy and Meehan (1991).

The space available to stream rearing juvenile salmon is a function of streamflow, channel morphometry, gradient, water depth and velocity, and instream and riparian cover. Food abundance, predators and competitors also influence what portion of the available suitable space an individual fish uses. The amount of space needed by fish generally increases with age and size.

Space is also a function of streamflow. In principle, the relationship between streamflow and fish production is constrained through the origin (i.e. no flow, no fish). Thereafter, fish production should increase with streamflow (the relationship could be linear, non-linear, or discontinuous) up to a maximum level, and thereafter level off or decline if flows become excessive. The instream flow incremental methodology (IFIM) is a procedure designed to evaluate the effect of different strearnflows on fish production. The method generates relationships between weighted usable area (Y*IUA) and streamflow which can be related, at least in principle, to biological parameters of interest e.g. fish standing crop. However, by reviewing 11 studies which related WUA to fish biomass or abundance, Shirvell (1986) found that statistical relationships were poor, most likely because of faulty assumptions, and the fact that WUA doesn't incorporate any aspect of habitat capacity.

Stream rearing salmonids also have specific velocity and depth requirements which can vary seasonally and are also related to fish size (Everest and Chapman 1972). The depth of water which juvenile salmonids use, in turn depends upon the amounts and type of cover, and the perceived threat from predators. Additional parameters which directly influence the distribution and abundance of stream salmonids include substrate particle size, cover in the form of boulders, large woody debris and over-head cover, and the presence of other fish species.

Table 7. Lower lethal, upper lethal, and preferred temperatures (*Q for selected species of salmon, trout, and ch ar based on techniques to determine incipient lethal temperatures (ILT) and critical thermal maxima (CTM).					
	Lethal temp. (°C)				
Species	**Lower lethal**[a]	**Upper lethal**[b]	**Preferred temp. (°C)**	**Source**	**Technique**
Chinook salmon	0.8	26.2	12-14	Brett (1952)	ILT
Coho salmon	1.7	26.0 28.8[c]	12-14	Brett (1952) Becker and Genoway (1979)	ILT CTM
Sockeye salmon	3.1	25.8	12-14	Brett (1952)	ILT
Chum salmon	0.5	25.4	12-14	Brett (1952)	ILT
Steelhead	0.0	23.9	10-13	Bell (1986)	
Rainbow trout		29.4 25.0		Lee and Rinne (1980) Charlon et a[. (1970)	CTM ILT
Brown trout		29.9 26.7		Lee and Rinne (1980) Brett (1952)	CTM ILT
Gila trout		29.6		Lee and Rinne (1980)	CTM
Apache trout		29.4		Lee and Rinne (1980)	CTM
Brook trout		29.8 25.8	 14-16	Lee and Rinne (1980) Brett (1952) Graham (1949)	CTM ILT
Cutthroat trout	0.6	22.8		Bell (1986)	
Atlantic salmon		27.1 27.8		Brett (1952) Garside (1973)	ILT ILT
Lake trout		25.0		Brett (1952)	ILT

[a] Acclimation temperature was 10°C; no mortality occurred in 5,500 min.
[b] Acclimation temperature was 20°C unless noted otherwise; 50616 mortality occurred in 1,000 min.
[c] Acclimation temperature was 15°C.

4.5 Juvenile Downstream Migration

In some cases, juvenile salmon migrate from an incubation site or a rearing site directly to the ocean. In others, downstream migration can be discontinuous, with time spent rearing in non-natal streams (Murray and Rosenau 1989). Much attention has focussed on the downstream migration of juvenile salmon in the Columbia River system in the U.S., because of the mortality problems associated with fish passage around hydro facilities (Raymond 1988). Recently, coordinated studies in the U.S. have beeh undertaken on predation-induced mortality on downstream migrant smolts by virtue the increased piscivore populations associated with reservoir installations (Nigro 1989).

5. Approaches for Determining Salmon Habitat Capacity

5. 1 Theoretical

There is a growing body of academic knowledge that has important implications for determining the habitat capacity of living organisms in aquatic environments. As an example, Werner and Gilliam (1984) developed an optimal-control model (based on a standard model of life history strategies) of the trade-off between food consumption and the risk of predation in different lake habitats. Their model is capable of explaining many observed patterns of ontogenetic shifts in habitat preference. The insights generated by this theoretical study have important implications for the determination of fish habitat capacity within the systems analysed by Werner and Gilliam (in this case, bluegill sunfish habitat shifts from the littoral zone to a pelagic zone of a lake).

Other theoretical studies more closely related to the determination of habitat capacity in salmonids include the papers by Ryder and Kerr (1989) and Shuter and Regier (1989) which were prepared for the National Workshop on Effects of Habitat Alteration on Salmonid Stocks (Levings et al. 1989). While the latter paper is essentially a theoretical development, it is guided by a practical question, namely: Can "salmonid habitat" be defined and measured quantitatively? Shuter and Regier assume that the answer to this question is a qualified yes and that the real issues of interest are issues of methodology: how and with what precision can these measurements be made? Thus the focus of this theoretical analysis is very consistent with the present review project.

While the direct benefits of theoretical assessments of habitat capacity cannot be determined directly, it will be useful for habitat managers to keep abreast of theoretical developments as they occur, and to concentrate on the applications of meaningful theoretical advances.

5.2 Pure Research

Certain academic-type research may involve tests of habitat switching theories, and is therefore closely related to development of theory. Examples of both field and laboratory experimental studies designed to test habitat selection theory include studies by Werner et al. (1983) and Gilliam and Fraser (1987), respectively. As with theoretical development, this type of work may not provide direct applied habitat management implications, however, it may lead to conceptual breakthroughs which support practical applications.

5.3 Applied Research

Most recent effort within the Salmon Habitat Section of the Biological Sciences Branch (DFO) falls within the category of applied research. Considerable effort has been expended to obtain a better understanding of the impacts of urban/industrial activities on salmon populations and the habitats on which they depend. Typical examples include the influence of forest harvesting practices on salmon populations (e.g. Holtby and Scrivener 1989) and research to determine the importance of estuarine habitats for chinook salmon (e.g. Levings et al. 1989). Much of this applied research is extremely useful for evaluating development proposals, assessing stock status, and restoring and developing fish habitat. However, such research is relatively costly and time consuming, and answers to important habitat questions can only be obtained through the investment of substantial resources. Moreover, it is often difficult or impossible to generalize or extrapolate the results from an intensive applied research project to other areas. This limits the utility of applied research information for ongoing habitat decision-making.

It is clearly desirable for DFO to continue to support applied research on relevant habitat issues. Attention should also address the utility of ongoing research programs to support the requirements of habitat managers. Projects, such as the present habitat capacity review, can be designed to foster a closer association between research activities and management requirements.

5.4 Descriptive Measurements

5.4. 1 Physical features

A review of stream habitat evaluation techniques is provided by Platts et al. (1983). The report was written to standardize the way that physical and biological attributes of streams are measured and quantified, and to shed light on the strengths and weaknesses of those attributes. The report covers sampling design, parameters useful for stream habitat evaluation, riparian zone assessment and fish population evaluation. Several investigators have developed diagramatic mapping techniques to characterize and quantify stream habitats of fish (Oswood and Barber 1982; Barber et al. 1982).

A listing of physical habitat parameters that are often measured during stream assessment programs was compiled by Osborne et al. (1991). Many of the parameters are measured on different spatial scales i.e. transect, reach, watershed. The following variables were measured by at least some agencies in the North Central Division of AFS: channel morphology, depth, velocity, discharge, percent pools, instream cover, substrate type, substrate size, substrate embeddedness, cover surface area, channel alterations, streambank erosion, streambank vegetation condition, riparian vegetation condition, width of the riparian zone, riparian vegetation quality, riparian management, percent shading, vegetation overhang, percent bank slope, undercut banks, nearness to dam, channel gradient, channel sinuosity, watershed land use, watershed geology, watershed soils, and flow stability. Most agencies that were censused undertook some spatial (reach) replication within their habitat assessment programs and integrated their programs with water chemistry measurements. However, none undertook significant temporal replication, contributing to a static perception of habitat quality.

The Fish Habitat Inventory and Information Program is a joint federal (DFO) and provincial (MOE) program designed to standardize the compilation of a comprehensive inventory of the quality, quantity and productive capacity of fish habitats in freshwater, estuarine and marine environments of British Columbia. A Stream Survey Form is provided in the Stream Survey Field Guide which contains instructions for the recording of fish habitat data. A detailed description of inventory approach, pre-inventory activities (e.g. reach identification), field methods and post-field activities (e.g. data analysis, mapping) are described in a separate reference document entitled Stream Survey Manual (currently in preparation). The following parameters (highlighted in the Stream Survey Forms in dark blue) are considered mandatory for completing the Stream Survey Form:

Stream Name
Watershed Code
Location
Map #
Reach Number
Site Number
Length Surveyed
Fish Card (Y/N)
Field, Historical
Date
Time
Agency
Crew
Average Channel Width
Average Wetted Width
Gradient
Pool, Riffle, Run and Other
Side Channel
Debris
Bed Material
Obstructions
Stage
Fish Summary (only species, life phase and method/ref.)

While the Stream cards have been widely applied throughout the province, the utility of the system is unknown. Information contained on the cards has never been adequately analysed or evaluated. Completed stream cards are stored -at MOELP in Victoria, and there has been no co-ordinated effort to code the information for computer analysis purposes, and the data remain unprocessed.

There is also a perception among habitat researchers that the information requirements are more complicated than necessary. In other words, it should be feasible to revise and simplify the system with little loss of information content. This would provide at least one practical advantage; field crews could cover greater stream lengths in discrete sampling periods and potentially place more emphasis on fish sampling.

A similar data collection format has been prepared for public sponsored habitat improvement projects for trout and salmon in Eastern Canada (Scruton et al. 1992). While this manual provides a logical rationale and guide for habitat measurements in streams, it is unclear how the information relates to fish production, or how the information can or will be utilized.

Recently, Hankin and Reeves (1988) described methods of estimating total fish abundance and total habitat area in small streams based on rapid visual estimation procedures (diving in the case of the fish estimates). When compared with more accurate methods of field measurement, the estimation techniques compared well, and correlations between visually estimated habitat unit areas and accurately measured areas exceeded 0.93. Hankin and Reeves emphasize the importance of assigning estimation responsibility to a single experienced observer. These habitat assessment procedures are now being applied routinely in the U.S. (e.g. Nickelson et al. 1992A).

5.4.2 Stream and watershed classification systems

The primary purpose of a stream and/or watershed classification is to stratify the existing habitat into ecologically meaningful sub-units, and to estimate the relative amount of habitats in each class. When the information is effectively quantified and mapped, it can serve as an inventory of habitat within a watershed which can be used for decision-making and evaluations of habitat status for a given species.

A secondary purpose of stream and watershed classification is to estimate the productive capacity of fish stocks of interest. This latter function requires an empirical model between measurable habitat parameters and biological variables of interest (e.g. fish standing stock, abundance). Existing models and their effectiveness are reviewed in Section 5.5.

A review of factors which impede habitat classification (Hawkins et al. 1993) include:

1. stream environments consist of so many independent and interacting factors known to influence biota that distinguishing habitats based on a single criterion is impractical;

2. environmental heterogeneity varies considerably both within and among streams, which makes the number of habitat classes required for adequate description of a given stream unclear;

3. environmental variation is often gradual rather than discrete at several different spatial and temporal scales, further confounding identification of habitat classes; and

4. the type and resolution of classification needed may vary with specific research or management objectives.

A small stream classification system, developed by Bisson et al. (1982), has guided much of the stream habitat classification work for salmonids in the Pacific Northwest during the past decade. The salmonid habitat classification is based on naturally occurring channel units and the hydraulic processes that formed them. The classification -system divides stream habitat into riffles, pools, and glides. Riffles are further divided into the following categories: low gradient riffles, rapids, and cascades. Pools are divided into six types: secondary channel pools, backwater pools, trench pools, plunge pools, lateral scour pools, and dammed pools. Glides are intermediate in many characteristics between riffles and pools. An example of a scale map, illustrating many of the habitat types classified by Bisson et al. (1992), is shown in Figure 5.

An application of the Bisson et al. (1982) classification system is provided by Nickelson et al. (1992A). These investigators modified the previous classification system as follows. First, they added a midchannel scour pool to the lateral scour pool and identified both as a single category (scour pool). Second, they classified secondary channels by habitat type, and treated them the same as main channel habitats. Third, they classified backwater pools during winter into two types: 1. those with low current velocity, even at high flows, which were termed "alcoves", and 2. those with moderate to high current velocity during high flow, which were termed "backwater pool". A list of stream habitat types defined by Nickelson et al. (1992A) is shown in Table 7. Application of the classification system, combined with estimates of coho population density in the respective habitat categories at different times of the year, provided the basis for estimating the potential populations of coho salmon which could be supported in

Oregon coastal streams. Critical limiting factors for Oregon coho production (off-channel winter habitat) were identified.

A recent approach to stream habitat classification is provided by Hawkins et al. (1993). The approach is based on a hierarchical classification of channel units designed to alleviate problems encountered with earlier classification systems and to- produce subdivisions which are ecologically relevant (Figure 6). The system provides a consistent means for either collapsing or splitting data sets, thus enhancing a managers ability to make comparisons.

At the most coarse level of resolution are riffles and pools. To avoid confusion associated with the definition of subcategories of these two basic stream habitat types, Hawkins et al. (1993) refer to the broad categories of riffle and pool habitat as fast-water and slow-water channel units respectively. Fast-water units are divided into either high-turbulent or low-turbulent classes based on differences in gradient, bed roughness, and step development (distinct breaks in bed slope which occur within a channel unit). Two types of pool categories are recognized: scour pools and damned pools. The latter tend to accumulate and retain sediment and organic debris to a greater extent than scour pools, and also often have greater amounts of cover than scour pools, because they are usually formed behind wood, debris, or large substrates.

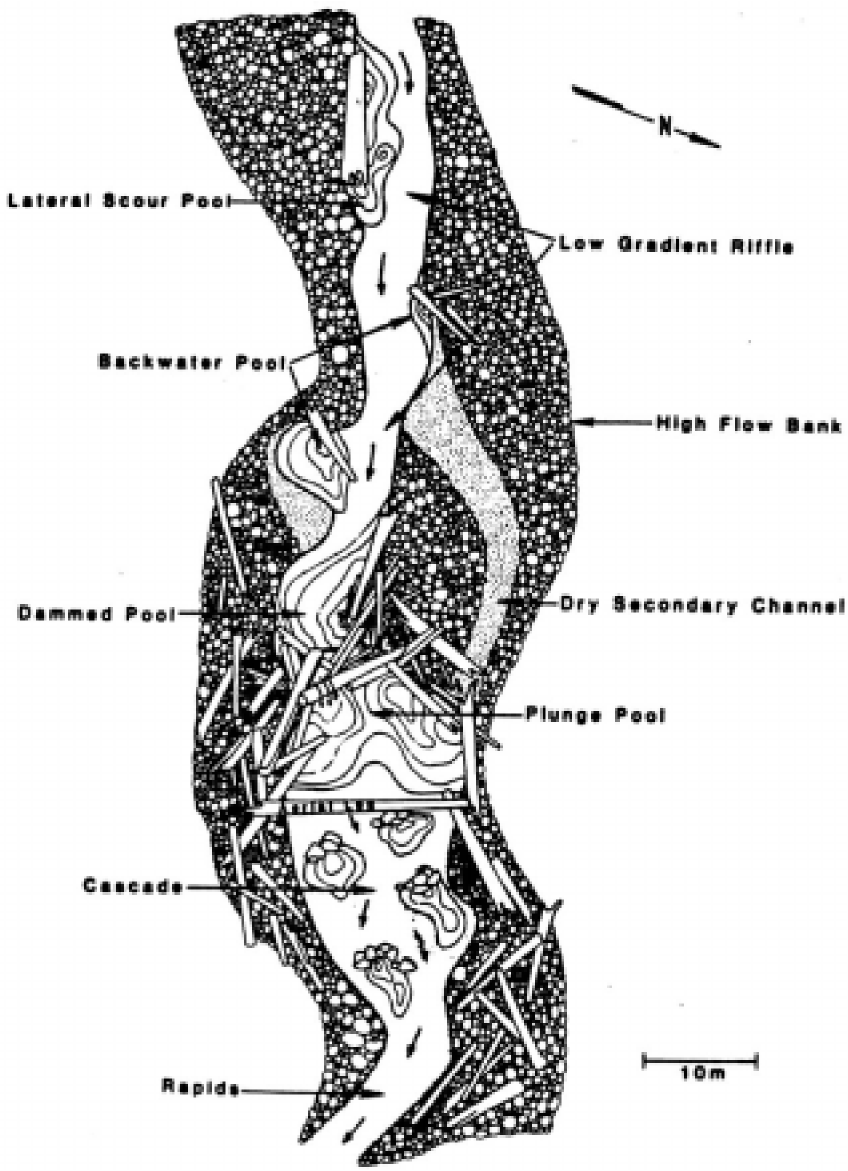

Figure 5. An example of a stream channel map showing locations of various habitat types. Reproduced from Bisson et al. (1982).

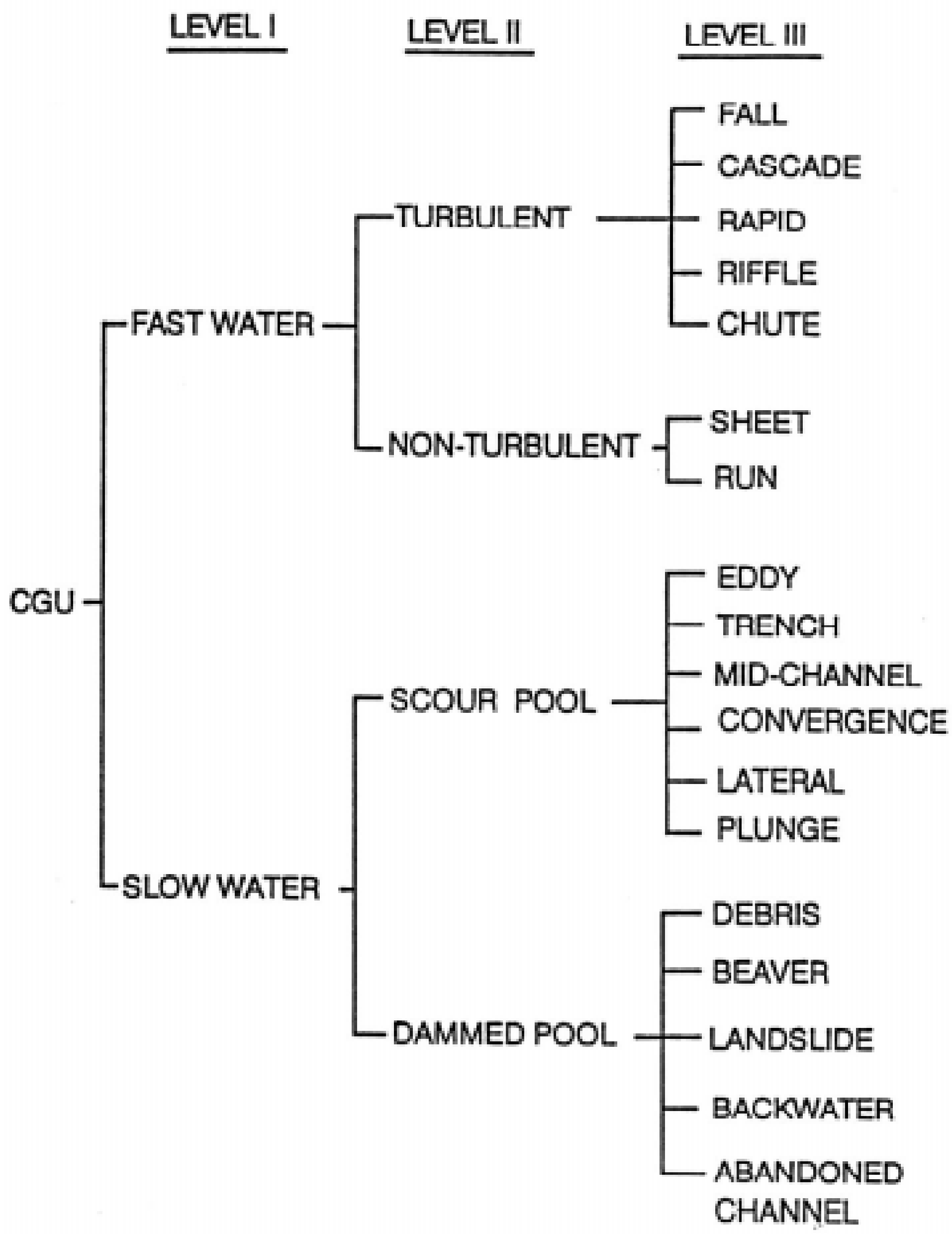

Figure 6. similarity dendogram illustrating how channel geomorphic units (CGU) can be classified with increasing levels of resolution. Three levels of classification are shown that can be used to distinguish classes. Reproduced from Hawkins et al. (1993).

Table 7. Stream habitat types defined by Nickelson et al. (1992A), as modified from Bisson et al. (1982).	
Habitat type	**Characteristics**
Pools:	
Dammed pool	a pool impounded'upstream from a complete or nearly complete channel blockage- (including beaver ponds).
Backwater pool	an eddy or slack water along the channel margin separated from the main current by a gravel bar or small channel obstruction.
Alcove	a slack water along the channel margin separated from the main current by streambanks or large channel obstructions such that it remains quiet even at high flows.
Scour pool	a scoured basin either (1) near the channel margin caused by flow being directed to one side of the stream by a partial channel obstruction, or (2) near the center of the channel usually caused by a channel constriction high gradient rapid.
Plunge pool	a basin scoured by a vertical drop over a channel obstruction.
Trench pool	a long, usually deep slot in a stable substrate (often bedrock).
Glide	a moderately shallow reach with an even flow and no pronounced turbulence.
Riffles:	
Riffle	a shallow reach of gradient <4% with moderate current velocity and moderate turbulence.
Rapid	a shallow reach of gradient >4% with high current velocity and considerable turbulence.
Cascade	a series of small steps of alternating small waterfalls and small pools.

The Level III terminology (Figure 6) is largely consistent with Bisson et al. (1982). with the exception of several categories which were collapsed or added (e.g. sheet: units with shallow water flowing over smooth bedrock). Individual pool types within the scour and dammed groups differ in terms of their location within the flood channel, cross-sectional depth profile, substrate characteristics, and the constraining feature which contributes to their formation. As with any classification system, difficulties occur with transitional areas between defined habitat categories, and when habitat sub-units vary seasonally under different flow regimes.

The Hawkins et al. (1993) classification system is based on the experience of numerous investigators in attempting to carry out objective and accurate habitat inventories. Following refinement and validation, the system may prove useful in depicting the physical and biological reality of stream habitats.

5.5 Statistical Models

Mathematical models in population biology can be evaluated in terms of 3 general characteristics (Levins 1966): precision, generality, and realism. Any model will represent a compromise in these characteristics, and will tend to be weak in terms of at least one of the 3 general characteristics (precision, generality or realism). These issues are very relevant to the requirements of habitat managers who frequently seek quantitative predictions which relate measurable parameters and habitat capacity. According to Levins (1966), it would be erroneous to expect any single model to simultaneously deliver precise, generalizable, and realistic results.

A review of the performance of 99 available models (Fausch et al. 1988) as predictors of standing crop of stream fish (number or biomass per unit area or length of stream) from measurable habitat variables revealed that certain parameters were most significant when similar variables were grouped. Measures of instream, overhead cover were most frequently significant (22 models) followed by depth (20 models), alkalinity/hardness/conductivity (15 models), mean stream flow (14 models), width (14 models), surface area (12 models), and dissolved oxygen (11 models). A summary of independent variables found significant in the best models (model quality determined by means of coefficient of determination, sample size, and degrees of freedom) is shown in Table 8.

Fausch et al. (1988) discuss several problem areas among the models which were reviewed, including:

1. *Inadequate sample size*: many data sets were collected at too few locations on too few dates, resulting in small degrees of freedom and low predictive power,

2. *Error in measuring habitat variables*: most investigators assume that independent variables are measured without error, when in fact, a sensitivity analysis is required to determine how much the model slope and intercept change when habitat variables are altered by an amount corresponding to measurement error,

3. *Choosing the best model*: stepwise multiple regression procedures are unsuitable when the order of variable entry affects the model performance; there are currently more objective procedures which are statistically preferable,

4. *Testing models*: there are relatively few examples of model validation, and where these occur, the models generally performed poorly (Shirvell 1989),

5. *Using models to predict standing crop*: many models involve observational rather than experimental data, forcing investigators to make inductive leaps because habitat variables are rarely under experimental control (other unmeasured but correlated variables may be functionally important in controlling fish standing crop),

6. *Estimating standing crop of stream fish*: many commonly-applied fish enumeration methods are poor estimators of fish population size, and

7. *Major biological assumptions*: all models assume that the fish population is limited by the habitat variables under consideration, and unaffected by other important parameters (e.g. fishing, interspecific competition, predation) which profoundly affect fish populations in streams.

Table 8. Independent variables found significant in the best models reviewed by Fausch et al. (1988).			
Abbreviation	**Variable**	**Abbreviation**	**Variable**
DRAINAGE BASIN (A)[a]			
AR	Annual rainfall	MBL	Mean basin length
BID	Basin perimeter	MBS	Mean basin slope
DA	Drainage area	RE	Elevation rating
DAO	Distance from Atlantic Ocean	RG	Gradient rating
DD	Drainage density	RMBE	Mean basin elevation rating
E	Reach elevation	FIR	Relief ratio
FA	Forested area	so	Stream order
G	Reach gradient from map	TSL	Total stream length
MBE	Mean basin elevation	WC	Watershed condition
CHANNEL MORPHOMETRY (B)			
ADW	Area of deep water > 1.5 ft	RNW	Minimum width rating
CW	Channel width at bankful flow	RPP	Percentage of pool rating
FD1	Frequency of depth 46-60 cm	RPR	Percentage of riffle rating
FD2	Frequency of depth >60 cm	RPRU	Percentage of run rating
MD	Mean depth	RSW	Stream width rating
MPD	Mean pool depth	RW	Riffle width
MW	Mean width	RWDR	Rating of width-to-depth ratio
PA	Pool area	RXW	Maximum width rating
PPO	Percentage of pool	SA	Surface area
PRI	Percentage of riffle	SG	Section gradient measured in field
PV	Pool volume	V	Channel volume
PW	Pool width	WDR	Width-to-depth ratio
RA	Riffle area	XD	Maximum depth
RMD	Mean depth rating	XPD	Maximum pool depth
RMW	Mean width rating		
FLOW[b] (B)			
AFV*	Annual flow variation	MSPF	Mean song Now
CPF:MF	Critical period flow as percent of mean flow	MV	Mean velocity
		MWF	Mean winter Bow
F	Flow	NSF	Minimum summer flow
F11P	Flow 11 days previous	NSPFIP	Minimum spring flow I year previous
DVVF3P	Difference between 7-day maximum and 7-day minimum winter flows 3 years previous	NSPF2P	Minimum spring flow 2 years previous
		RAFV	Annual flow variation rating
		RLSF	Late summer flow rating
MFA	Mean flow per unit area	RV	Velocity rating
MMF	Mean monthly flow	VI	Velocity index
MPV	Mean pool velocity	XPv	Maximum pool velocity
MSF	Mean summer flow	XSF	Maximum summer flow
MSF2P	Mean summer flow 2 years previous	XSFIP	Maximum summer flow I year previous
		XSPF	Maximum spring flow
HABITAT STRUCTURE (C)			
AAV	Area of aquatic vegetation	LUB	Length of undercut bank
AC	Area of all cover	NR	Number of rocks
AOV	Area of overhanging riparian vegetation	NR>30	Number of rocks>30 cm
		PAC	Percentage of area as cover
AOV-c1	Area of overhanging riparian vegetation <1 m above water	PAV	Percentage of area as aquatic vegetation
		P8	Percentage of pool area as brush cover
AOVI-2	Area of overhanging riparian vegetation 1-2 m above water	PBL	Percentage of area as boulder and log cover
Footnotes are at and of table.			

Table 8. Independent variables found significant in the best models reviewed by Fausch et al. (1988) (continued).

Abbreviation	**Variable**	**Abbreviation**	**Variable**
HABITAT STRUCTURE (C) (continued)			
ARBV	Area of rubble, boulder, and aquatic vegetation substrate	PEB	Percentage of eroding bank
		PF	Pool feature
AUB	Area of undercut bank	PIBV	Percentage of area as instream bank vegetation
AWW	Area of water willow	PIC	Percentage of area as instream cover
BS	Bank stability rating	POV	Percentage of zero velocity
CD	Channel debris	PRA	Pool rating
DS	Deep slow area	PTC	Pool and turbulence cover
FC>5	Frequency of cover in water >5cm deep	RC1	Rock cover <0. I m^2
FOC>5	Frequency of overhanging cover in water >5 cm deep	RC2	Rock cover >0.3 m^2
		RCO	Rating of cover
FT>5	Frequency of turbulence in water >5 cm deep	REB	Rating of eroding banks
		SBC	Streambank condition
FVR>5	Frequency of velocity refuge in water >5 cm deep	SS	Shallow slow area
		TCR	Total cover rating
BIOLOGICAL (C)			
DAY	Days from June 1	NFS	Number of fish species
DVP	Depth and velocity preference factors	PRBV	Preference factor for rubble, boulder, and aquatic vegetation
ED	Estimate of eggs deposited per m^2	PUB	Preference factor for undercut bank
		PSC	Previous standing crop
ID	Invertebrate drift abundance	R	Species range
PHYSICAL (C) – SUBSTRATE			
AB	Area of boulder substrate	PG	Percentage of gravel substrate
ACS	Area of cobble substrate	PR	Percentage of rubble substrate
D90	90th percentile substrate size	PS<1	Percentage of fine sediment <1 mm
MRPS	Mean riffle particle size	PS 16-256	Percentage of area of 16-256 mm substrate
PBS	Percentage of boulder substrate	RS	Substrate rating
PE	Percentage of substrate embeddedness	SSA	Area with suitable spawning substrate
		SSC	Substrate score
PFS	Percentage of fine substrate		
PHYSICAL (C) – TEMPERATURE			
FFD	Frost-free days	NT5P	Minimum water temperature of 5 previous days
MAT	Mean annual air temperature		
MAWT	Mean annual water temperature	RVVT	Water temperature rating
MAXT	Mean annual maximum water	RXST	Maximum summer water temperature rating
	temperature	XST	Maximum summer water temperature
CHEMICAL (C)			
C	Conductivity	NDO	Minimum dissolved oxygen
DOR	Dissolved oxygen range	NN	Nitrate nitrogen
MAL	Mean alkalinity	RCH	Calcium hardness rating
MBOD5	Mean annual 5-day biochemical oxygen demand	RMH	Magnesium hardness rating
		RNN	Nitrate nitrogen rating
MC	Mean conductivity	RPH	pH rating
MPCC	Mean platinum-cobalt color	RPO	Phosphate rating
MTH	Mean total hardness	RSU	Sulfate rating
MTOC	Mean total organic carbon	RT	Turbidity rating
MTP	Mean total phosphorus	RTA	Total alkalinity rating
MTU	Mean turbidity	SU	Sulfate

[a] Letters refer to categories of variables defined In the appendix heading and text.
[b] Flows for specific months were grouped by season

Fausch et al. (1988) conclude by re-iterating that models developed for specific areas with relatively few variables may be precise but difficult to apply outside of the region the data were collected in. Conversely, more robust models may be developed with greater numbers of variables, but will suffer from lack of precision. A key area for model improvement involves effective stratification of land areas into homogeneous ecoregions (e.g. Hawkes et al. 1986).

Another review of the performance of six published habitat models (Shirvell 1989) showed that while existing models performed well in accounting for the variation in the data sets Ihey were generated from (% explained variation = 50 - 96%; μ = 76%), they performed poorly when applied to new data sets (% explained variation = 7 - 50%; μ = 24%). Out of the entire set of (15) habitat variables, water depth was significant in 4 out of 6 models, water velocity, substrate, cover, width, and TDS were significant in 3 out of 6 models, fish food abundance or diversity, water temperature, and turbidity were significant in 2 out of 6 models, and annual streamflow variation, bank erosion, nitrogen (NO_2), water yield, dissolved oxygen, and altitude had significance in only one of the habitat models. Shirvell (1989) stresses that since the same habitat variable(s) is not limiting all populations, habitat models cannot routinely be transferred to new situations without recalibration or verification.

A simple regression model relating coho smolt yields in the Pacific Northwest (expressed as numbers or biomass) and rearing space (expressed as length or area of stream accessible to spawners) was generated by Marshall and Britton (1990):

$$\text{Smolt numbers} = 9.31\ (\text{km of stream}) + 17028$$
$$N=24;\ r^2 = 0.89$$

This type of simple relationship, beyond a reflection of the obvious fact that large streams produce more coho smolts than small streams, provides a useful prediction of the coho production associated with a given length of fish habitat. In view of the goodness-of-fit of the derived regression, one could enquire whether similar production constraints (i.e. limiting factors) may be operating in different coho populations within the sample population. Additionally, it may be informative to analyse the outlying data points on similar regressions derived over large spatial scales, to determine the influence of site-specific habitat constraints on fish production.

A recent salmonid production model developed by Ptolemy (1993),for application within B.C. relates fish density, fish size, and nutrient indices from B.C. streams. Maximum density of six salmonid species declined (in a non-linear fashion) as a function of mean weight, reflecting fish territorial behavior. Multiple regression equations were obtained to relate fish density to measured alkalinity, fish size, and the suspended sediment concentration (non-filterable residue). The models have potential practical value for predicting salmonid population densities in streams with unaltered water chemistry.

5.6 Habitat Evaluation Procedures

The Habitat Evaluation Procedures (HEP) were developed by the U.S. Fish and Wildlife Service in the early 1980's in order to develop numerical ratings of habitat, by means of a Habitat Suitability Index (HSI), to determine the sensitivity of individual species to environmental impacts. HSI models have been developed for over 100 animal species, including birds, fish and invertebrates (referenced in Anon. 1990). Guidelines for the riverine and lacustrine applications of fish HSI models under the Habitat Evaluation Procedures are described by Terrel et al. (1982). There are three types of fish models that have been developed for application as HSI models: 1. regression models, 2. descriptive models, and 3. mechanistic models. Most HSI models are mechanistic models which provide a way to display and integrate a wide variety of assumed cause and effect relationships between variables when determining habitat suitability.

A review of HEP procedures is provided by McMahon (1987). The HEP method consists of a basic accounting procedure that combines habitat quality, defined as the HSI index, with habitat area to calculate Habitat Units (HUs) which are sensitive to changes in both the amount and quality of available habitat. Model variables are parameters which affect the survival, distribution, abundance, behavior, growth, or some other measure of a species well-being. Each model variable is related to habitat suitability through the use of Suitability Index (SI) curves. These curves depict the hypothesized relationship between levels of a particular variable and the Suitability Index scale of 0 to 1 (0 = unsuitable, 1 = optimum). The shape of the curve is based on empirical measurement, literature information, or expert opinion.

During an impact assessment, the procedure for applying HSI models is to: 1. measure model variables, 2. determine the SI value for each model variable from the SI curves, 3. aggregate the individual SIs into an overall HSI for the study site, 4. determine the total area of the study site, and 5. multiply the area of the study site by the HSI to obtain the total HUs. Comparison of pre- and post-project HSIs and HUs provides a basis for estimating the magnitude and direction of habitat change associated with a proposed project, which can then provide a.basis for mitigation plans or project alterations.

There are different procedures that can be applied to aggregate the model variables into an overall HSI. These include the Average Value Method (AVM) which is the same as the geometric mean, and the Interactive Limiting Factor (ILF), which weights low SIs heavily in determining overall habitat suitability. The AVM and ILF are calculated as:

$$AVM = (SI_1 \text{ x } SI_2 \text{ x } ... \; SI_n)^{1/n}$$

$$ILF = (SI_1 \text{ X } S1_2 \text{ x } ... \; SI_n)$$

where SI is the suitability index of the i^{th} variable, and n is the total number of variables. Lastly, there is the Lowest SI (LSI) approach which assumes that the most limiting factor determines the upper limit of habitat suitability. Thus:

$$LSI = \min(SI_1, SI_2, ... \; SI_n)$$

An example of a generic HSI model involving 18 variables is shown in Figure 7. HSI models have been developed for salmon by Raleigh et al. (1986; chinook), McMahon (1983; coho), Raleigh and Nelson (1985; pink), and Hale et al. (1985; chum). HSI models for these species are shown in Figures 8-11 respectively.

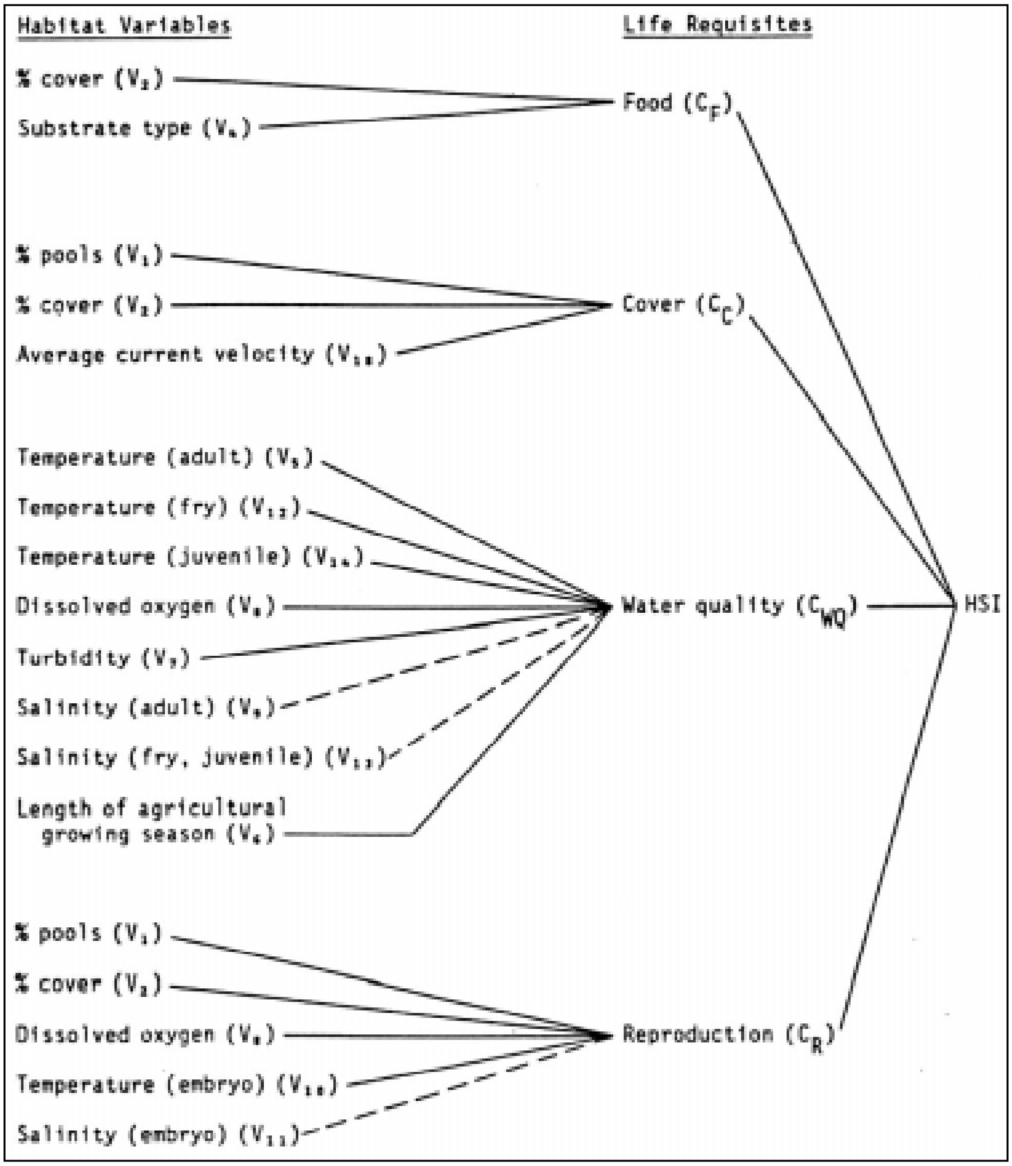

Figure 7. Example of model structure to show how variables combine to determine an HSI. Dashed lines indicate optional variables. Reproduced from Terrell et al. (1982).

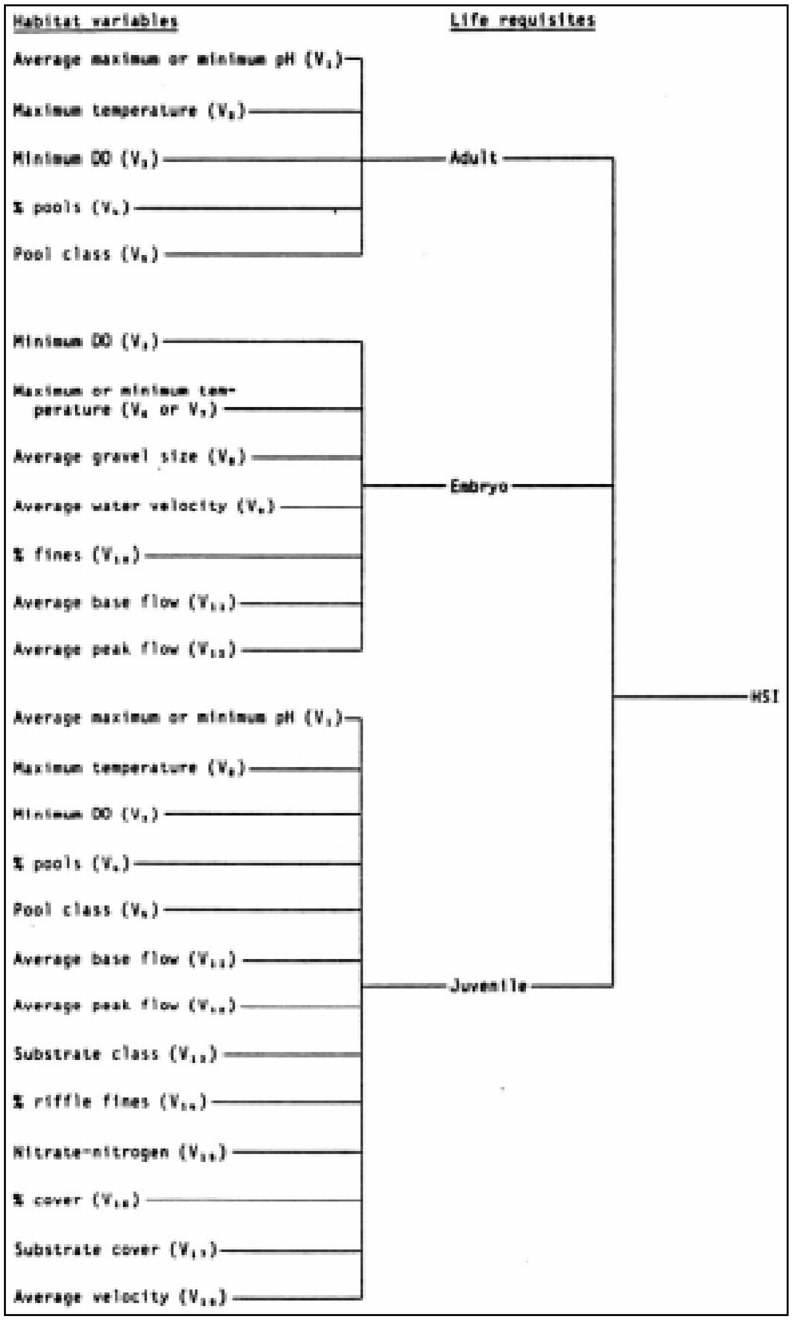

Figure 8. Diagram showing habitat variables included in the HSI model for chinook salmon and the aggregation of the corresponding suitability indices (SIs) into an HSI. Reproduced from Raleigh et al. (1986)

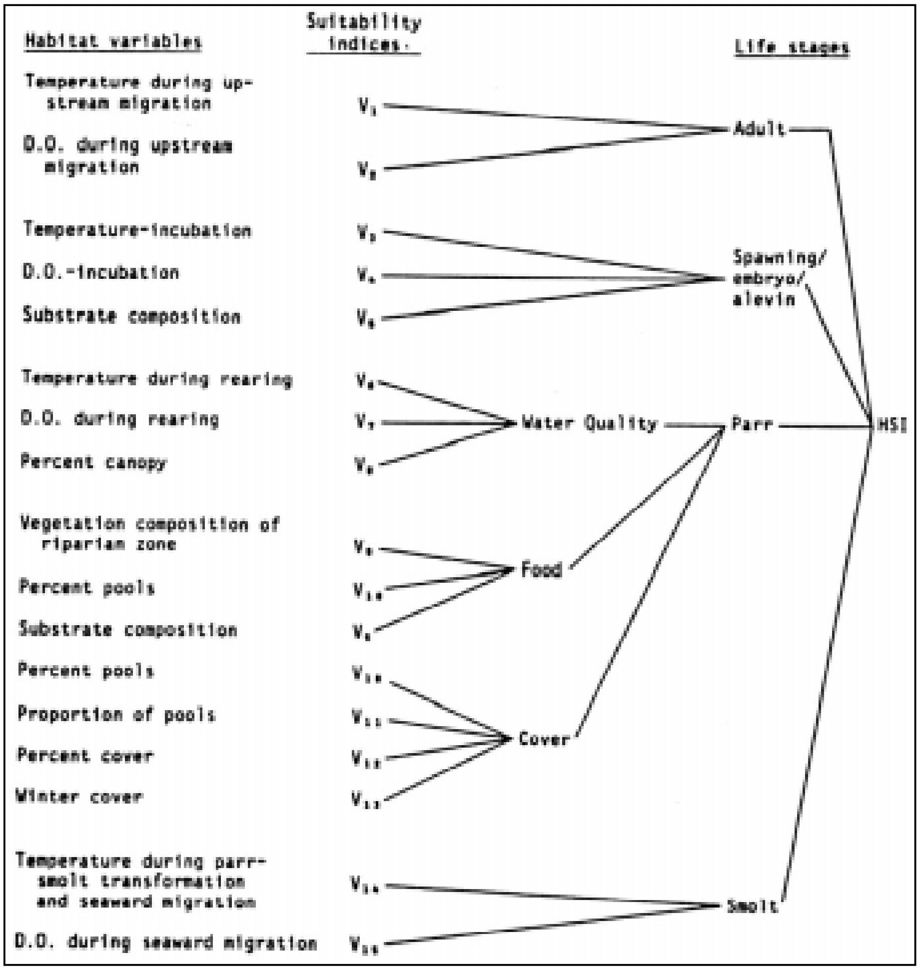

Figure 9. Diagram showing habitat variables included in the HSI model for coho salmon and the aggregation of the corresponding suitability indices (SIs) into an HSI. Reproduced from McMahon (1983).

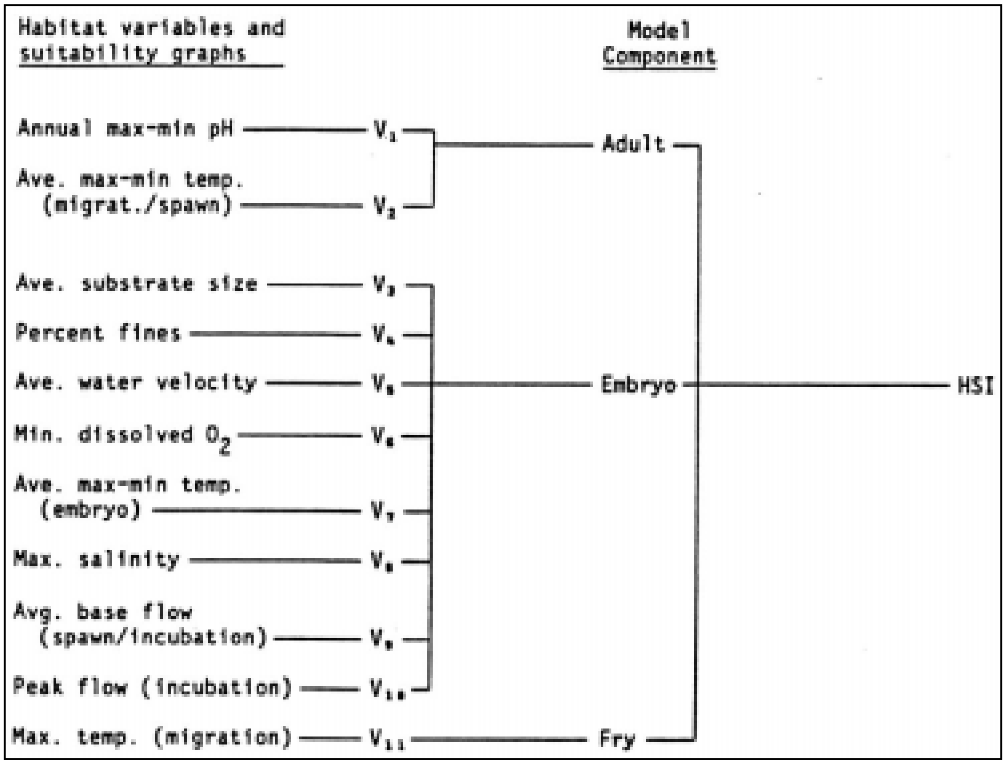

Figure 10. Diagram showing habitat variables included in the HSI model for pink salmon and the aggregation of the corresponding suitability indices (SIs) into an HSI. Reproduced from Raleigh and Nelson (1985).

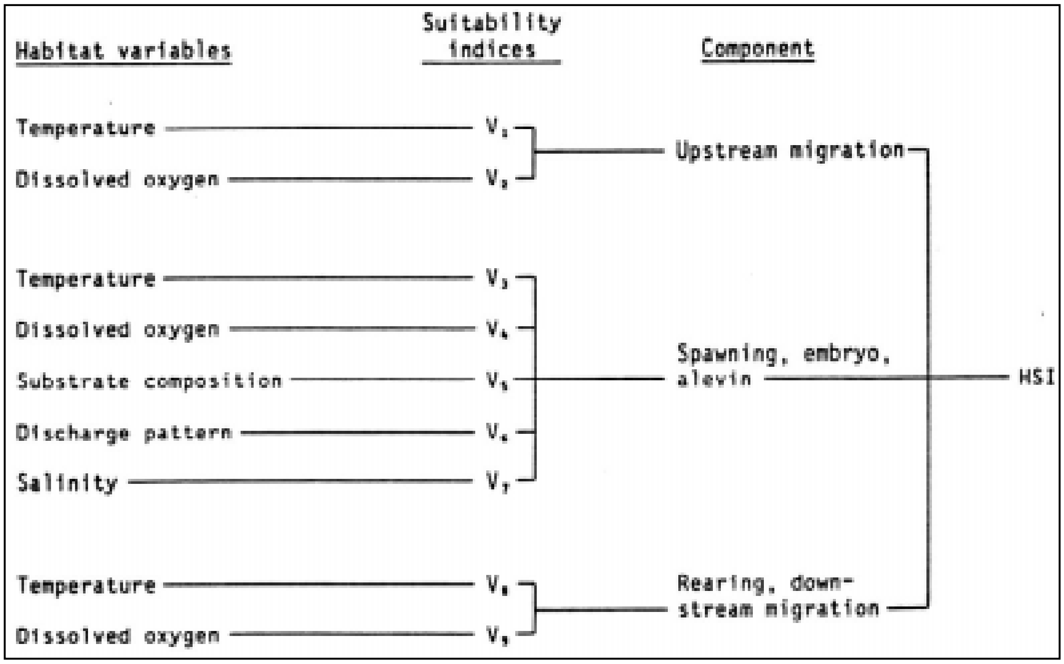

Figure 11. Diagram showing habitat variables included in the HSI model for chum salmon and the aggregation of the corresponding suitability indices (SIs). Reproduced from Hale et al. (1985).

The applicability of existing HSI models for salmon in B.C. has been evaluated by McMahon (1987) and Lister (1988). For both coho and chum salmon, the HSI mdels performed reasonably well when tested with the Carnation Creek data set (McMahon 1987). Streambed gravel quality declined for chum salmon, and this was shown by calculated HSIs which were positively correlated with adult recruitment. For coho salmon, the HSI was not positively correlated with fall population numbers, fall biomass, fall density, smolt numbers or adult returns and model component SIs were not positively correlated with coho population abundance parameters. McMahon suggested that a model emphasizing winter habitat would be more valid in B.C., than the existing coho, model which emphasized summer conditions (for use in Washington and Oregon).

Lister (1988) modified the HSI models developed for chinook and coho by dropping those variables that did not relate directly to the summer-fall juvenile rearing phase. Application -of the HSI models to chinook and coho data for the Coldwater River was only moderately successful: correlations between fish density and HSI were poor and the existing models (developed in the U.S.) could not be transferred directly to B.C. Additionally, for both chinook and coho, 1 or 2 variables accounted for all or most of the HSI's effectiveness to predict fish density, suggesting that the models were more complicated than necessary. Lister (1988) cautions that the coho and chinook HSI models were developed for application in coastal streams, and that neither model should be applied without modification to the mainstems of larger streams such as the North Thompson, Thompson, and Fraser Rivers. In the chinook model, spatial variation in juvenile recruitment also obscured relationships between fish density and habitat quality.

5.7 Identification of Limiting Factors

A recent study by Nickelson et al. (1992A) compared the habitat use by juvenile coho salmon in Oregon coastal streams. Because of the strong preference of alcove and beaver pond habitat .during winter, and the rarity of that habitat in coastal streams, the investigators concluded that coho salmon in this area of the coast are probably limited by the availability of winter habitat. Provided that spawning escapement is adequate in these systems, the number of coho smolts is limited by this "habitat bottleneck". A graphical representation of this concept is shown in Figure 12. Such information has direct relevance for the design and effectiveness of different stream improvement techniques and structures (Nickelson et al. 1992B).

There are indications that similar processes may operate in coho populations in B.C. streams. Within Carnation Creek, in spite of considerable variation in September juvenile numbers, the smolt output from the Creek was relatively constant (Figure 13). Such a pattern can be explained by a winter habitat bottleneck operating within this population.

For habitat assessment purposes, knowledge of limiting factors is a critical pre-requisite to determine habitat capacity. If such information was available a priori, it would greatly simplify the choice of parameters for the determination of habitat capacity.

Unfortunately, the identification of limiting factors is not easily accomplished. In a recent essay, Bisson (1992) summarized a number of potential barriers to identifying important limiting factors. These include:

1. *Excessive reliance on professional judgement in the absence of site-specific data*. Bisson identifies limited budgets, insufficient time, and personal biases which all contribute to excessive reliance on professional judgement. Additionally, reliance on inappropriate models incorporating incomplete or inconclusive data, may lead to mis-identification of the factors limiting smolt yield.

2. *Extrapolation in space and time*. Bisson cautions investigators about inappropriate extrapolations, and provides several examples indicating high variation in stream fish population size (also documented by Hall and Knight 198 1) which may be related to a succession of limiting factors within a single stream. Bisson concludes that out of four long-term (> 15 yr) studies of salmonids in small streams (Alsea Watershed Study, Carnation Creek Study, Shelligan Bum Study and Black Brow Beck in the U.K.), none have conclusively identified important limiting factors with certainty. One British investigator states that: "The major weakness of the present investigation is that data are available for only 18 years." Although such a perspective is inconsistent with management requirements, it does point out that brief and cursory studies are inadequate to provide scientific documentation of limiting factors.

3. *Oversimplification of complex ecological situations*. Bisson questions an untested assumption which often underlies habitat enhancement programs, namely that fish populations are linearly related to the amount of rearing habitat space. Several studies suggest that this assumption is incorrect; due to territoriality, the relationship between fish length and average area of stream bed per fish is curvilinear (larger fish require larger territories). Moreover, rearing space is known to fluctuate with food availability, the presence of competitors, predators etc. further increasing the difficulty of relating rearing area and population density.

4. *Focusing exclusively on one aspect of life history*. This point suggests that even if limiting factors are identified at a particular life history stage, this may be an inadequate basis for production increases due to mangerial intervention. Rather, it is appropriate to consider multiple limiting factors that potentially come into play at different life history stages, and the necessity to consider the entire life cycle of the fish species of interest.

5. *Failure to consider critically important factors*. Bisson identifies several areas where the understanding of stream salmonid life history information is poor, including such factors as predation, nocturnal habitat preference, use of winter refuges etc. A further complication is introduced by salmonids which are migratory (all anadromous Pacific salmon) and capable of both short- and long-term movements.

While Bisson's essay is a somewhat sobering reflection on the difficulty of identifying limiting factors, it does point out the need for rigorously designed and executed scientific studies of testable hypotheses that may be profitably addressed through applied research.

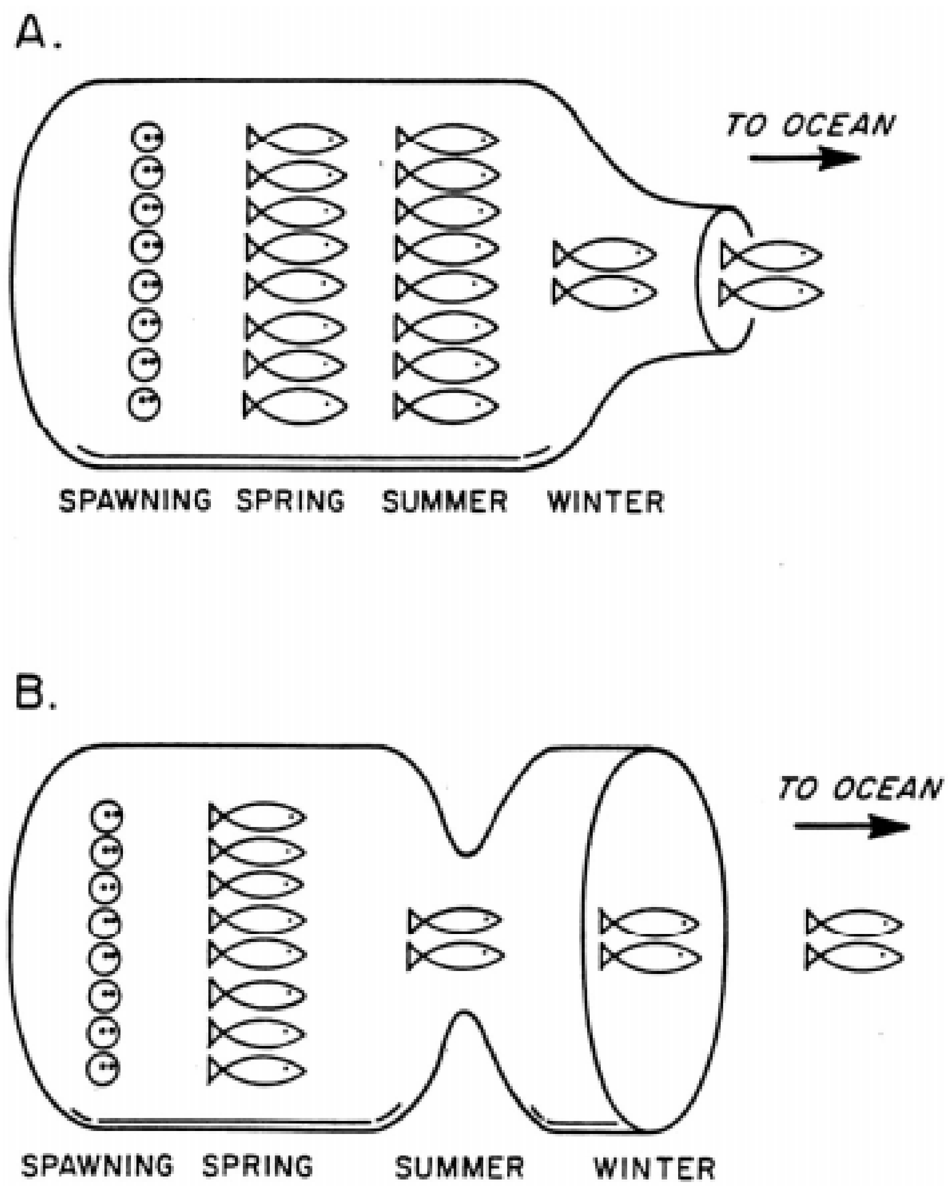

Figure 12. Examples of habitat bottlenecks occurring during (A) the winter, and (B) the summer. Reproduced from Nickelson et al. (1993).

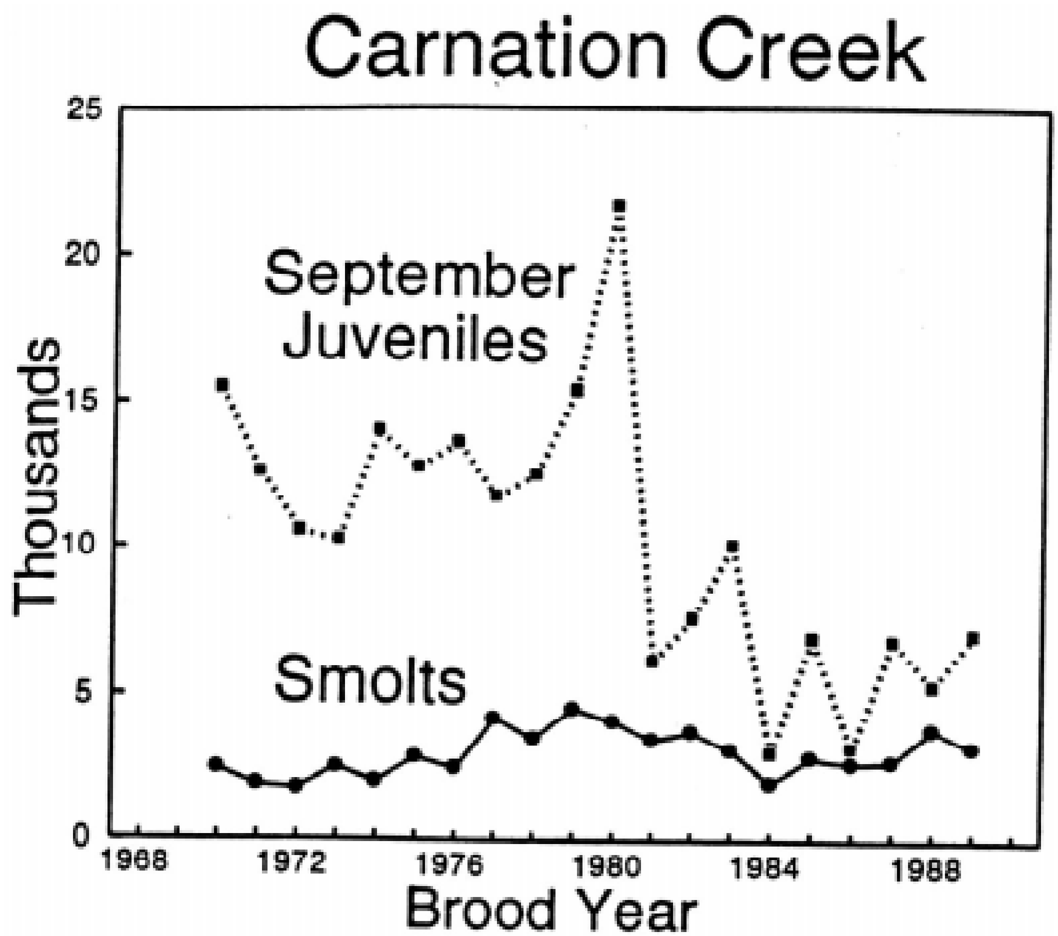

Figure 13. A comparison of number of coho juveniles residing in the main-channel of Carnation Creek in late summer, and corresponding smolt production for 1970 to 1989 brood years. Data courtesy T.G. Brown (PBS, unpublished data).

6.0 Workshop Results

Following the preparation of a preliminary draft of Sections 1- 5 of this report, a workshop was held to review the techniques and approaches in the light of Departmental needs. The workshop was held March 25, 1993 at the Pacific Biological Station and was attended by the following DFO and MELP personnel whose activities included measurements of habitat capacity:

List of Workshop Participants	
Bryan Allen	DFO Comox Valley Habitat Pilot Project, Courtenay
Bruce Anderson	DFO Biological Sciences Branch, Nanaimo
Tom G. Brown	DFO Biological Sciences Branch, Nanaimo
Tom J. Brown'	DFO Biological Sciences Branch, Nanaimo
Peter Delaney	DFO Habitat Management , Vancouver
Kim Hyatt	DFO Biological Sciences Branch, Nanaimo
Jim Irvine	DFO Biological Sciences Branch, Nanaimo

Lidia Jaremovic	DFO Fraser River Action Plan, Vancouver
Tom Johnston	MELP Fisheries Research Section, Vancouver
Colin Levings	DFO Biological Sciences Branch, West Vancouver
Gary Logan	DFO SEP Resource Restoration Unit, Vancouver
Carey McAllister	DFO Biological Sciences Branch, Nanaimo
Brad Mason	DFO Habitat Management Division, Vancouver
John Patterson	DFO Fraser River Action Plan, Vancouver
Tom Pendray	DFO Habitat Management, Prince Rupert
Ron Ptolemy	MELP Fisheries Branch, Victoria
Bruce Reid	DFO Habitat Management, New Westminster
Cole Shirvell	DFO Biological Sciences Branch, Nanaimo
Tim Slaney	Aquatic Resources Limited, Vancouver
Dave Tredger	MELP Fisheries Branch, Victoria
Ian Williams	DFO Biological Sciences Branch, Nanaimo

6. 1 Objectives

One of the biggest problems encountered during the workshop lay in establishing explicit and generalizable goals for inventory work. This problem was identified early in the day and remained unresolved at the end of the workshop. As the end use has major implications both in terms of detail and approach, DFO needs to clearly establish the purpose and users of inventory work. Once the DFO requirements are clearly established, information needs of other users can be considered as outlined in the RIC process. The RIC process was established to deal with two critical issues concerning land and resource inventories (FITF 1992):

a. What information is vital for effective land management, at what levels of detail and for what purposes?

b. How can this information most effectively be acquired in a manner that minimizes duplication, promotes co-operative data collection, and encourages broad application and long term relevance?

The problem is that the Habitat Management Division (HMD) has a formal mandate (DFO 1986) and has also assumed a number of administrative responsibilities for habitat evaluation. As a result, the RIC objectives do not quite mesh with those already in place and the workshop participants had a great deal of difficulty fesolving the types of inventories which should be discussed.

Workshop participants identified the potential uses of habitat information as follows:

Protection of environmental integrity	
Resource planning	Varying scales. (Includes non fisheries issues such as water extraction).
Impact assessment	Usually site specific.
Stock management	Long term planning. Identification of production constraints.
Enhancement	Production constraints and potential capacity.
Land claims	
Research	

6.2 Definitions

Habitat capacity can be defined either in terms of production rates or in terms of standing stock. Habitats have both the capacity to produce "grams of fish per unit area" and to support fish populations of a certain size. This is further complicated in that physical constraints and human activities have resulted in a large number of habitats which are under used or under used. There was general acceptance that the range of objectives could best be met by an operational definition of habitat capacity as "numbers of fish per unit area" and that habitat capacity should include potential habitats which may not be occupied at the present time.

6.3 Level of Information

Various geographic scales and levels of analysis can be used in estimating habitat capacity. Their use depends on both the detail of the survey data available and the end use of the work. For example, the Marshall and Britton (1990) model provides a rough estimate of potential smolt production from streams of varying sizes. There was some suggestion that this model be redone with a contemporary data base and that geographic variability should be examined.

To better support a range of model applications, local or site specific information needs to be applied over a wide range of scales and applications. To accomplish this, there is a need to standardize information formats (terms and definitions) for data collection.

6.4 Minimum Data

Several of the workshop participants suggested that the most immediate need is for systematic mapping of currently used fish habitats (presence/absence of fish). The water bodies do not need to be surveyed in great detail but their locations must be mapped accurately. This problem is particularly acute amongst habitat managers who are forced to assess development issues and often have no way of knowing whether or not a given water course needs to be rigorously protected. This is particularly true of areas such as the lower

Fraser Valley where many streams have been channelized and where it is often difficult to distinguish between recent drainage ditches and channelized streams. In some cases both may support fish populations.

There were varying ideas on how presence/absence information should be reported or stored. These ranged from a simple listing (species, location) to a GIS. The GIS would start from the Stream Atlas and would include corrections to the stream locations as well as the addition of missing watercourses.

6.5 Habitat Units

The workshop participants generally agreed that methods exist for assessing the capacity of individual habitat units. Although each species and life stage may have alternate uses for each unit, standard methods could be adopted for survey and inventory at this level. It was recognized that a great deal of regional variation exists and that it may be necessary to develop a regionalized approach to assessment. The problem is that habitat units on the Bisson et al. (1982) level can be relatively small: such units require careful survey techniques and there are a large number of units in any watercourse.

6.6 Linkage

Habitat capacity within a watershed may be assessed on a species-specific basis with varying levels of precision. However, the relative importance of these units is less well understood. In some species, such as sockeye, where there is a discrete movement between habitat types at various life stages, it may be possible to assess a system's habitat capacity as that of the habitat type with the lowest capacity. But in other species, such as coho which tend to move throughout a water course depending on season and life stage, it is still possible to assess the capacity of individual habitat units, but it is far more difficult to evaluate a particular unit's importance to the overall system capacity.

There was general agreement that this aspect of system wide capacity assessment is poorly understood. However, there was less agreement on how it might best be tackled. Several participants felt that the RIC objective of broad application required a modeling approach. Others felt that the preferred approach would be to develop a watershed by watershed understanding of life history and habitat utilization.

Some of the biggest concerns were in regard to the uninformed application of standardized methods and models. As noted in Section 5.5, a certain amount of professional judgment is required for model selection and may include factors such as geographic area, species, limiting factors, and acceptable error. The widespread use of models would be effective only if. a) the models were locally validated or calibrated, and b) they were accompanied by some strict protocols on where or how each should be employed. For example, the application of models may be misleading where unconsidered limiting factors (e.g. barriers, over-wintering habitats) operate.

6.7 FHIIP survey

There was a general agreement that the Fish Habitat Inventory and Information Program (FHIIP) survey process was not providing much information in return for the large amount of effort expended on it. Some of the problems include:

Lack of a centralized data base. Most cards completed in the field are used for one project and there is no further information transfer.

Interpretive problems. There is no formal way to interpret the cards. They do not lead to a model or evaluation procedure.

Inconsistency. The present cards were designed to be used over several levels of detail, as a result there is often confusion. Fish collection and riparian measurement problems are inadequately covered.

Quality control. There is no way of knowing whether the information is valid.

In many ways the problems stem from the fact that the cards were intended only as a first component in an inventory system but the originally envisioned data base, display, and interpretive components have never been completed.

The cards do however, provide an effective means of collecting the basic descriptive habitat information which is a part of almost every habitat investigation. The advantage of the card is that it formalizes inputs and prompts the user. It was generally agreed that some effort should be expended on trying to put the FHIIP cards to better use. Some of the areas that need to be investigated include:

- use of FHIIP data for stream classification or predictive capacity models.
- development of an audit program for FHIIP surveys.
- development of a standardized database format and display/reporting system.
- development of similar standardized cards for lakes and estuaries.

6.8 Communication

The federal/provincial FHIIP is planning to develop an overview fisheries resource inventory data base. Many of the workshop participants stated that information transfer is essential. At present there is often little information available to field personnel. The RIC ob ectives of co-operative data collection and broad application would suggest that some form of standardized information transfer is necessary, if not an open-access data base system. Some of the ideas expressed included a habitat information database which would parallel the salmon escapement data base (SEDS).

6.9 Future Work

The workshop ended without a formal resolution however the discussion suggested several topics which HMD should examine in order to develop an inventory strategy and procedures.

(a) Inventory objectives must be clearly defined in terms of the end users 'and uses to be served. Is it practical to meet all needs in a standardized way?

(b) Bio-geographic variability was discussed in several contexts. How much region specific information is already available to develop standards and is there a need for some type of eco-region classification?

(c) If we can not recommend the wholesale adoption of a modeling or classification approach to drive survey design and analysis, can we define a series of instances in which they may be useful?

(d) If a modeling approach is to be used, can it include a validation process which would incorporate both bio-geographic and temporal elements?

(e) How can the existing FHIIP card system and information be put to best use?

(f) Can we develop a self prompting system like the FHIIP card for lakes and estuaries?

(g) What is the best way to communicate inventory information and can it be done in a manner which supports users at varying scales and levels of detail?

(h) How can a quality control or audit element be included in inventory procedures?

7. Conclusions and Recommendations

An objective of the Aquatic Task Force is to develop a strategy for province-wide application to determine the habitat capacity for aquatic resources, and to review appropriate parameters for determining the quantity and quality of freshwater and estuarine habitat for the five species of salmon. Based on the preceding review and the workshop results, it can be safely concluded that this objective will not be achieved easily. The objective of the Task Force is based on an underlying premise, namely that there is a stable, quantifiable relationship between fish habitat and fish production. It is unlikely that the Task Force objective will be achieved if this premise is false. Indeed, in reviewing the literature, one is impressed more by the spatial and temporal variability in freshwater fish production (e.g. Hall and Knight 1981), than the occurrence of predictable habitat relationships involving fish populations.

On both theoretical grounds and in certain closed, stable environments (e.g. Bjornn 1978; McNeil 1964), the concept of habitat capacity for spawning and rearing salmonids is well proven and is measurable. Within open systems subject to natural levels of variability, however, the concept becomes difficult to operationalize.

From a qualitative perspective, our ability to identify habitat requirements (e.g. presence/absence of spawning grounds) is adequate. Unfortunately, the "no net loss" policy requires more than simply qualitative information on which to base habitat management decisions. Additionally, with the fast pace of ongoing habitat alterations, definition of precise habitat relationships may be a luxury that we can collectively no longer afford.

Quantification of spawning habitat appears to be more straightforward compared to the quantification of rearing habitat. Additionally, in terms of habitat requirements, the 5 species of Pacific salmon differ considerably. Due to short freshwater residency, pink and chum habitat requirements are relatively straightforward. Likewise, sockeye spawning habitats can be assessed directly and there are presently some effective sockeye rearing habitat models (e.g. Koenings and Burkett 1987). Chinook and coho salmon present a worst case in terms of habitat models, due to significant difficulties in the understanding and modelling of freshwater rearing.

A productive line of enquiry appears to lie with the stratification of spatial areas into "ecoregions". If fish habitat models are not widely generalizable, what is the scale of their spatial applicability? One could develop habitat relationships for a watershed, and successively test and apply them within the same watershed, within neighbouring watersheds, between watersheds etc. Are habitat relationships applicable over wide spatial areas (e.g. the coastal, interior plateau, and Rocky Mountain slope ecoregions within the Fraser River system)?

Scientific answers to questions related to fish habitat capacity may elude the research community for considerable time periods. In the interim, there will be increased pressure on fish habitats and habitat management decisions cannot be deferred. We therefore recommend a parallel process whereby new guidelines are developed for habitat protection purposes, at the same time as focussed research is undertaken to field test and validate fish habitat capacity models.

From a management perspective, the challenge is to rapidly develop habitat management guidelines based on the best information available. Habitat protection and evaluation guidelines can be developed based on syntheses of existing information. As an example, Toews and Brownlee (1981) published a handbook for fish habitat protection on forest lands in British Columbia. While many of the recommendations are based on consensus and less-than-perfect information, they provide a valuble set of recommendations for protecting stream habitats from logging damage. If such guideline documents were regularly and periodically revised, new information could be included and the guideline manuals would remain current. Moreover, by regularly reviewing the guidelines, this will ensure that management procedures are based on sound, defensible information.

A number of habitat protection guideline documents are urgently required. For example, within British Columbia, long-term (10 year) power exports from small-scale facilities (<20 KW) are now permitted, and there are more than 250 licence applications on file in Victoria. The existing environmental review procedures will consider impact analyses from individual proponents. Under this system, there is no guidance provided on cumulative impacts within watersheds, nor any systematic guidelines available for the protection of anadromous salmonids in affected freshwater environments. The availability of a guideline document would greatly assist both fish habitat managers and power proponents. It should be feasible for the Habitat Management Division to rapidly assign priorities for developing habitat guideline documents which could be drafted (either in-house, or by consultants) and completed in 1993.

Strategies for measuring habitat capacity need to be also refined and validated with empirical data. Within B.C., priority application of fish habitat capacity models should be undertaken in aquatic environments adjacent to rapidly developing areas, e.g. the lower Fraser River and the east coast of Vancouver Island.

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