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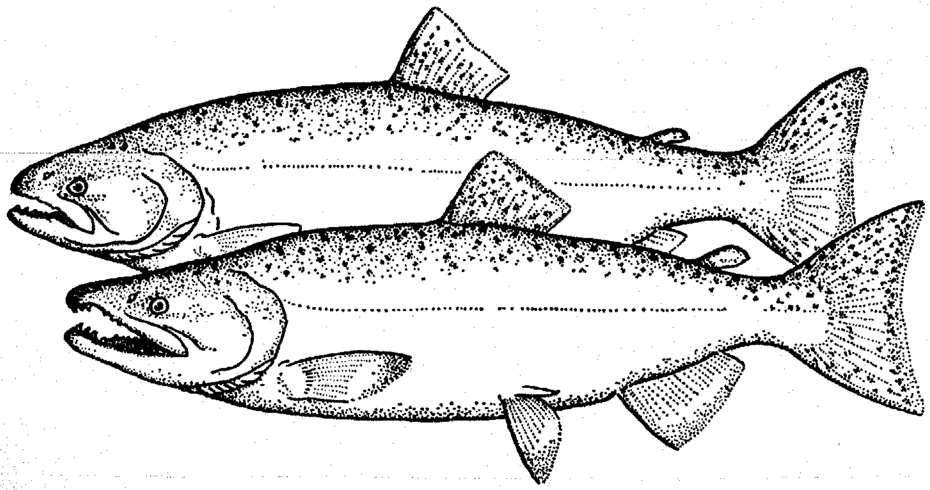
HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: CHINOOK SALMON



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HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: CHINOOK SALMON

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PREFACE

Information presented in this document is for use with the Habitat Evaluation Procedures (HEP) and the Instream Flow Incremental Methodology (IFIM). The information also should be useful for impact assessment and for developing management recommendations and mitigation alternatives for the species using methodologies other than HEP or IFIM. The comparison and recommendations for use of HEP and IFIM presented by Armour et al. (1984)[1] should help potential users of these two methodologies determine the most efficient way to utilize the information in this publication.

The Suitability Index (SI) curves and graphs and Habitat Suitability Index (HSI) models presented in this report are based primarily on a synthesis of information obtained from a review of the literature concerning the habitat requirements of the species. The HSI models and SI curves are scaled to produce an index between 0 (unsuitable habitat) and 1 (optimal habitat). Assumptions used to transform habitat use information into an index are noted, and guidelines for application of the curves and models are described. A discussion of IFIM and chinook salmon SI curves available for use with IFIM is included.

The SI curves and HSI models are starting points for users of HEP or IFIM to develop their own curves and models. Use of the SI curves and HSI models within project-specific applicational constraints is likely to require modification of the SI curves or graphs and HSI models to meet those constraints and to be applicable to local habitat conditions. Users of the SI graphs and/or HSI models with HEP should be familiar with the standards for developing HSI models (U.S. Fish and Wildlife Service 1981)[1] and the guidelines for simplifying HSI models and recommended measurement techniques for model variables (Terrell et al. 1982; Hamilton and Bergersen 1984).[1] Users of the SI curves with IFIM should be familiar with the Guide to Stream Habitat Analysis (Bovee 1982)[1] and the User's Guide to the Physical Habitat Simulation System (Milhous et al. 1984).[1]

The HSI models and SI curves are hypotheses of species-habitat relationships, not statements of proven cause and effect relationships. The curves and models are based on the literature and professional judgment. They have not been applied in the field. For this reason, the U.S. Fish and Wildlife

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[1] Citation included in References.

Service encourages model users to convey comments and suggestions that may help us increase the utility and effectiveness of this habitat-based approach to fisheries planning. Please send comments to:

Habitat Evaluation Procedures Group

or

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ACKNOWLEDGMENTS

We gratefully acknowledge R. Behnke, Colorado State University, T. Bjorn, Idaho Cooperative Fishery Research Unit, F. Everest, Pacific Northwest Research Station, M. Healey, R. Lauzier, W. Knopp, S. Samis, C. Clarke, and S. Macdonald, Canada Department of Fisheries and Oceans, G. Hartman, Pacific Biological Station, Nanaimo, B. C., A. Lowes Blackwell, University of Texas at Arlington, and M. Odemar, California Department of Fish and Game, for review comments which improved the quality and accuracy of this report. The reader should not construe reviewer assistance as an endorsment of the Suitability Index curves or the habitat model. The initial literature reviews were conducted by the Alaska Department of Fish and Game personnel, and T. Tatom. J. Zuboy provided editorial assistance and C. Solomon coordinated the reviews and manuscript production. Word processing was by E. Barstow, P. Gillis, and D. Ibarra. The cover figure is from Freshwater Fishes of Canada, Bulletin 184, Fisheries Research Board of Canada, by W. B. Scott and E. J. Crossman.

CHINOOK SALMON (Oncorhynchus tshawytscha)

INTRODUCTION

This publication contains habitat models constructed and information compiled for two distinctly different purposes. The Habitat Suitability Index (HSI) model by Raleigh and Miller contains 17 habitat variables for chinook salmon by life stage. The HSI model provides an objective quantifiable method of assessing the existing habitat conditions for chinook salmon within a study area by measuring how well each habitat variable meets the habitat requirements of the species by life stage. The model thus provides an objective basis for predicting probable project impacts, documenting post project impacts, and guiding habitat protection, mitigation, enhancement, and management decisions.

The section by Nelson contains habitat criteria curves for five flows-related variables for use in the Instream Flow Incremental Methodology (IFIM) (Bovee 1982; Milhouse et al. 1984). The IFIM model is intended to provide an objective method of assessing the effects of changes in water flow on habitat of chinook salmon by life stage. The HSI model is presented first followed by the IFIM section. Comments on model assumptions or performance, should be addressed to the appropriate author of each section. A brief overview of the HSI modeling procedures and IFIM curves follow.

The HSI model was constructed by searching the available technical literature, agency data files, and individual study progress reports for information on the habitat requirements of chinook salmon. This information was used to derive Suitability Index (SI) graphs for each habitat variable identified from the information base. As many habitat variables as were located were included to enable the user to evaluate a wide variety of habitat conditions useful in evaluating, managing, or improving chinook salmon habitat, or in assessing project impacts. The HSI model is flexible enough to utilize from one to all of the available variables to suit the needs of the user.

The SI graphs for the HSI model were constructed by quantifying field and laboratory information on the effect of each habitat variable (e.g., temperature, dissolved oxygen, spawning gravel size, siltation) on the growth, survival, or biomass of the species, by life stage. The graphs are based on the assumption that increments of growth, survival, or biomass plotted on the y-axis can be directly converted into an index of suitability from 0.0 to 1.0 for the species, with 0.0 indicating unsuitable conditions and 1.0 optimal conditions. Measurements of each habitat variable taken at the proper time in the field can be applied to the SI graphs to obtain an estimate of the suitability of the variable in meeting the habitat requirements of the species.

Instream flow SI graphs may be based on literature, professional judgment, lab studies, or field observations of the frequency of use of a habitat variable (e.g., gravel size), within an available range of conditions, by individuals of a species. The premise with field data is that individual fish will select and occupy the best habitat conditions available to them. Optimal conditions for a variable are considered to be those conditions under which most individuals are observed. Range limits for a variable are the conditions outside of which no individuals are observed. The Physical Habitat Simulation System (PHABSIM) component of the IFIM uses four variables: water velocity, depth, substrate composition, and cover. Wherever individuals of a species are observed in a stream, measurements are taken on the above four variables. In most cases to date SI curves have not been tested for cross-correlations among variables, and only univariate curve functions have been developed. If multivariate SI functions are not available for use with IFIM, then each variable is treated independently of the others. It is also assumed that a full range of preferred and tolerated variable values were available for selection by individuals of the species at each study stream and data collection site. If this assumption is not true, bias may occur in the frequency analysis method, unless habitat availability limitations are factored out (Bovee 1986).

It is sometimes difficult to determine if the full range of usable conditions for a particular variable have been included in field and laboratory studies. For example, spawning adults may have been observed using gravel ranging from 0.3 to 10 cm in size. Studies of the effects of siltation on embryo survival for the species may indicate that the lower limit of 0.3 cm appears acceptable. If different streams had been included in the studies, however, the upper gravel size limit may have been greater than 10 cm.

Laboratory tests used in constructing the HSI model SI graphs can often add more certainty to upper, lower, and optimal suitability values, especially for variables such as temperature, dissolved oxygen, and pH. Both laboratory and field results, must be considered in light of test conditions, e.g., acclimation conditions, handling, exposure times, control test results for laboratory tests, and observation and data collection procedures and conditions for field studies. For these reasons, some judgment is often necessary in constructing SI graphs for both IFIM and HSI models, and some variability may exist in the shape of the SI graphs.

The data base and SI graphs were reviewed by biologists familiar with the ecology of chinook salmon, and suggested changes not at variance with published study results were incorporated. The user is advised, however, to review each SI graph to determine how well it represents known regional requirements for the species. Changes should be made if warranted, but the reasons for each change should be fully documented.

HABITAT USE INFORMATION (HSI MODEL)

General Distribution and Life Cycle

The information included in this chinook salmon model is restricted to the freshwater habitat variables used by prespawning and spawning adults, incubating embryos, preemergent fry, and postemergent juveniles. The ocean habitat requirements of chinook salmon are not included.

Chinook salmon have the most diverse life history of any of the Pacific salmon. Among the various recognized races of chinook salmon (spring, summer, fall, and winter) there is diversity in time of entry into the river systems, time of spawning, distance from the sea of spawning areas, length of freshwater and ocean residence, and average size and age at maturity. The model contains a synoptic overview of the life history and known freshwater habitat requirements of each race.

Chinook salmon are the largest in average size of the five species of Pacific salmon. The largest known weight for a chinook salmon is 57.2 kg. Chinook salmon ranging from 6 to 23 kg are common in sport and commercial catches.

The original range of chinook salmon in North America was from the Ventura River, California, to Point Hope, Alaska, with 13 specimens reported from the Coppermine River about 1,600 km east of Point Barrow, Alaska (Hart 1973; Major et al. 1978; Behnke 1985). In the Far East, chinooks occur from the Anadyr River in the U.S.S.R., southward along the Kamchatka Penninsula and into Hokkaido, Japan (Major et al. 1978; Behnke 1985). Viable populations of chinook salmon have been established in New Zealand and in the Great Lakes in the United States. Attempts to establish chinook runs in other parts of the world have not been successful.

Chinook salmon spawn in about 640 streams along the Pacific Coast of the United States and Canada, but major populations are concentrated in only a few of the larger river systems: the Sacramento, Columbia, Copper, Nushagak, Kuskokwim, and Yukon Rivers in the United States, and about 14 rivers in Canada (Aro and Shepard 1967). Vronskii (1972) attributes more than 90% of the U.S.S.R. commercial catch to the Kamchatka River (Major et al. 1978).

As stated earlier, there is a large amount of life history diversity within the chinook salmon species. Four races of chinook salmon are recognized from the Sacramento River system (Erkkila et al. 1950; Hoopaugh 1978; Behnke 1985). The fall run enters the Sacramento River in late summer and spawns from late October into December. The eggs overwinter and the emergent fry begin their seaward migration in the early spring within a few weeks of hatching. The late fall run enters the river beginning in October, spawning peaks in February, and seaward migration begins at the time of emergence from the gravel. The winter run enters the river in winter and early spring. Spawning begins in April and peaks in May to early June. The fry spend a year in freshwater before smolting. The spring run enters the river primarily in May and June, and spawning occurs in September and October. The eggs overwinter and seaward migration occurs in the early spring.

There are three races of chinook salmon in the Columbia River recognized by their time of entry, time of spawning, and age and time of smolt migration. Spring chinook adults enter the river from February through May, summer chinook June through August, and fall chinook from mid-August through October (Fulton 1968; Major et al. 1978). Spawning occurs from late July into December, with the order of spawning being loosely related to the time of entry into the river (Fulton 1968).

From southern to northern latitudes of the chinook salmon range there appears to be a tendency for: (1) the number of races to decrease from four in the Sacramento to three in the Columbia, Fraser, and Nanaimo Rivers, to two in lower Alaska, to one in northern Alaska rivers; (2) spawning to occur earlier in the year with spawning peaks in late August through October in the southern areas and in July and August in the northern portion of the range; (3) length of freshwater residence by juveniles to increase from a few weeks to 1 year in the southern portion of the range, to an average of 1 to 2 years and occasionally 3 years (Meehan and Siniff 1962) in the northern portion of the range; and (4) average age at spawning to increase from 3 to 6 years in California rivers to 5 to 8 years in central to northern Alaska rivers.

Spawning adults may use all available suitable sections over the entire river system for spawning. Spawning may occur in chinook salmon rivers from within a few miles of saltwater intrusions to as far as 3,000 km upstream from the ocean in the Yukon River. Both the mainstem river and tributaries are used by spawning chinook salmon. In general, fall run chinook tend to spawn in larger mainstem rivers and the emergent fry tend to begin their seaward migration with a few weeks after emergence, whereas spring chinook tend to utilize smaller tributaries and upstream reaches of principal tributaries and the young spend the first year in freshwater prior to smolting (Raleigh and Ebel 1967; Fulton 1968).

Fecundity of chinook salmon varies by size and to some extent by race. In general, fecundity varies from a few thousand to as many as 20,000 eggs per female (Vronskii 1972). The demersal eggs are buried in two or more large pockets excavated in the substrate gravel by the female. The fertilized eggs are covered by gravel dislodged upstream of the redd by the female and carried downstream by the river current. The length of time from fertilization to hatching varies with average stream temperature, but requires roughly 900 to 1,000 thermal units (Seymour 1956). There is one thermal unit for each degree Celsius above freezing for a 24 hour period. After hatching, the yolk sac fry typically spend several more weeks in the gravel prior to emergence. Emergence from the gravel occurs in early spring, generally from February to June, depending on latitude, temperature, and time of spawning. The Sacramento River winter chinook run is an exception. Winter chinook spawn in the spring and the fry hatch and emerge from the gravel in midsummer.

Specific Habitat Requirements, Sources, and Assumptions

Chinook salmon adults stop feeding when they enter a river to spawn and they die after spawning. Adult holding habitat in the form of large, deep, pools is important to prespawners, some races of which may spend several weeks in freshwater before spawning. The productive potential of the river system is not important to the adults, but it is to the juveniles, which may spend from a few weeks to as much as 3 years in freshwater prior to migrating to sea. In addition, juvenile summer and winter rearing habitat is a major factor in the survival and production of chinook salmon. The HSI model includes the freshwater habitat requirements of all life stages, but is most concerned with embryo and juvenile habitat requirements.

Headwaters of high-gradient, coastal salmonid streams are relatively unproductive. Most energy inputs to the stream are in the form of allochthonous materials, such as terrestrial vegetation and terrestrial insects (Idyll 1942; Chapman 1966; Hunt 1971). Aquatic invertebrates are most abundant and diverse in downstream, moderate-gradient riffle areas with rubble substrate and on submerged aquatic vegetation (Hynes 1970; Binns and Eiserman 1979). Optimal substrate for maintenance of a diverse invertebrate population, however, consists of a mosaic of mud, gravel, rubble, and boulders, with rubble dominant. A pool-to-riffle ratio of about 1:1 (approximately a 40% to 60% pool area) appears to provide an optimal mix of food-producing and rearing areas for salmonids (Needham 1940). In riffle areas, the presence (>10%) of coarse (≤3.0 mm) fines reduces the production of invertebrate fauna (adapted from Cordone and Kelly 1961; Crouse et al. 1981). The gradient, water velocity, and substrate size tend to decrease downstream, whereas the pool to riffle ratio, temperature, productivity, and species diversity tend to increase.

Canopy cover is important in maintaining shade for stream temperature control and in providing allochthonous materials in small to moderate sized streams. Too much shade, however, can restrict primary productivity in a stream (Chapman and Knudsen 1980). Shading becomes less important as stream gradient and size increase. About 50% to 75% midday shade appears optimal for most small salmonid streams (adapted from Chapman and Knudson 1980, and Oregon/Washington Interagency Wildlife Conference 1979). In addition, a well vegetated riparian area helps control watershed erosion. The presence of fines in riffle-run areas can adversely affect embryo survival, food production, and escape cover for juveniles. In low to moderate gradient terrain, a buffer strip about 30 m wide on each side of the stream, 80% of which is either well vegetated or has stable rocky stream banks, provides adequate erosion control and maintains undercut stream banks characteristic of good salmonid habitat.

There is a definite relationship between the annual flow regime and the quality of salmonid riverine habitat. Adequate flows must be maintained to meet the needs of the developing embryos and yolk sac fry in the gravel, but abnormally low or high flows can be destructive. Significant mortalities to salmon embryos and yolk sac fry have been reported due to dessication or freezing of redds caused by too-low, late fall-winter flows, and from natal gravel movement and downstream displacement of newly emerged fry during abnormally high freshets (Andrew and Geen 1960). Bustard (1973) listed three major factors contributing to overwinter losses of juvenile chinook and coho salmon and steelhead in the Morice River: (1) stranding and freezing, (2) low dissolved oxygen, and (3) predation. All three factors were correlated with too-low winter flows. An annual base flow ≥50% of the average annual daily flow is considered excellent for salmonid production, a base flow of 25% to 50% is considered fair to good, and a base flow of <25% is considered poor (adapted from Tennant 1976; Binns and Eiserman 1979; Wesche 1980). Nehring and Anderson (1982, 1983) consider a peak flow of about five times the magnitude of an excellent base flow, or about 2½ times the average annual daily flow (Lister and Walker 1966) to be acceptable for good salmonid production. Peak flows exceeding these limits are considered progressively more destructive. Peak and base flow volumes that are controlled in dam tailwater salmon and trout habitats can enhance production of chum, coho, and chinook juveniles (Lister and Walker 1966) and trout (Nehring and Anderson 1982, 1983), or give a competitive edge to spring or fall spawning stocks dependent upon timing and amplitude of flow releases.

Optimal value and range for pH were not located for chinook salmon. Since chinooks are sympatric with other salmonid species, however, we accept the average salmonid pH range of 5.5 to 9.0, with an optimal range of 6.8 to 8.0 (Behnke and Zarn 1976), as applicable to chinook salmon.

Adult stage. Chinook salmon enter North American streams to spawn nearly year around. With the wide diversity in times and places of spawning it is not surprising that spawning temperatures also range widely from 4.4 to 18 °C (Mattson 1948; Burner 1951), although temperatures >12.8 °C resulted in increased mortality to females prior to spawning (Andrew and Geen 1960). Spawning and embryo rearing temperatures for winter run chinook salmon are within the above range, but appear to be more restrictive. Information for winter run chinook will be reported in the embryo section that follows. No further distinctions in chinook racial spawning requirements for water velocity, depth, or substrate size will be made in the adult section, since these variables appear to be size, not racially, related.

Chambers (1956) stated that the gravel used in constructing the redd must be of a size that can be moved by the fish and the current. Therefore, the water velocity and the maximum size of the spawning gravel utilized is related to the size of the fish. Chinook, the largest species of Pacific salmon, tend to use slightly higher water velocities and larger gravel for spawning than other salmon. Burner (1951) reported that spring chinook redds in the Columbia River consisted of about 6% fines, 59% to 86% gravel ≤15 cm in diameter, and 8% to 35% rubble >15 cm; summer chinook redds were about 5% to 8% fines, 85% to 95% gravel ≤15 cm, and 0 to 7% rubble >15 cm; and fall chinook redds were about 3% to 5% fines, 56% to 89% gravel ≤15 cm, and 6% to 41% rubble >15 cm. Summer chinook are smaller in average size (6.4 kg average) than fall chinook (8.2 kg average) in the Columbia River (Fulton 1968). Chambers (1956) lists percentages of gravel sizes for chinook salmon redds of about 21% for 0.3 to 1.25 cm; 41% for 1.25 to 6 cm; 24% for 6 to 10 cm; and 14% for 6 to 15 cm. Briggs (1953) gives a mean spawning gravel size of 4.2 cm for chinook salmon in California. Chambers (1956) lists an average size range of 3 to 15 cm for Canadian chinook, and Hobbs (1937) reports that most New Zealand chinook use gravel ≥7.7 cm in diameter. An upper size limit on gravel would depend upon the size of fish and was not reported for chinook salmon; however, since gravel size of >15 cm composed only 0 to 7% of summer chinook redds, we assume that spawning gravel 15 cm in diameter may be approaching the upper usable size limit for average size chinook salmon. Huntington (1985) reported that the most heavily used, prime spawning gravel beds of salmon tend to develop parallel bands of elevated gravel. Bands 0.6 to 2.4 m amplitude with a periodicity of 6.0 to 18.0 m have been reported. Huntington (1985) believes the presence of these bands indicates prime spawning areas for salmon.

McNeil (1968) reported that while coarse bed materials allow better water flow and oxygen levels in the redds, they also allow better access to eggs and yolk sac fry by predators than smaller gravel sizes. McNeil (1968) attributed a 32% greater egg loss from the coarsest gravel areas to probable predation by sculpins. From the above information we conclude that suitable spawning gravel for chinook salmon ranges in size from about 0.3 to 15 cm. The upper size being dependent upon size of spawner. The optimal size range is estimated to be about 2 to 10.6 cm.

Water velocity and minimal depth appear to be factors influencing spawning site selection and survival of embryos. Velocity appears to be a major factor and minimal depth a secondary factor. Spawning in productive chinook salmon streams has been observed at depths of ≤0.2 m (Briggs 1953) to ≥7 m (Chambers 1956). Sockeye salmon have been reported spawning in lakes at depths >21 m (Canada Department of Fisheries 1959). Andrew and Geen (1960), after a 3-year study on the Chilko River, reported that, beyond a minimal figure, depth per se did not appear to exert a major influence on the selection of spawning sites, but velocity did. Shallow gravel beds that go dry and are exposed to freezing in the winter were never heavily populated, nor were they the first choice of spawning salmon. Divinin (1952) observed that when the distribution of salmon spawners over the spawning grounds was optimum, there was no spawning in waters shallower than 0.2 m. At high spawner densities, however, salmon have been reported to spawn on sand and silt substrates (Semko 1939) and at depths of ≤0.1 m (Divinin 1952). Embryo mortalities would likely be excessive under such extreme conditions. We conclude that spawning of chinook salmon can successfully take place over a wide range of depths, but that depth per se, beyond a minimal level required to protect the embryos from drying or freezing, does not significantly affect the selection of spawning sites or the survival of embryos. An acceptable minimal spawning depth for chinook salmon depends upon the amount of flow fluctuation, but in rivers with relatively stable flow regimes (base flow ≥50% of the average annual daily flow), we conclude that an acceptable minimal spawning depth for chinook salmon would be ≥0.2 m.

The major functions of water velocity during spawning and embryo incubation are to: (1) move displaced substrate materials downstream during redd construction, (2) carry dissolved O_2 to the developing embryos, and (3) remove metabolic wastes from the redd. Andrew and Geen (1960) list spawning velocity ranges of 0.45 to 0.76 m/s for spring chinook and 0.35 to 1.15 m/s for fall chinook salmon. Few chinook were observed spawning in velocities >1.15 m/s. Smith (1973) reported mean spawning velocities of 0.43 and 0.50 m/s for spring and fall chinook salmon, respectively. In an Idaho stream with uncompacted gravel, a velocity of 0.2 m/s was considered adequate for chinook spawners. Gravel permeability affects the suitability of low velocity levels, whereas fish size, swimming ability, and average substrate size dictate the suitability of upper velocity ranges. From the above information we conclude that the usable spawning and embryo incubation velocity range is about 0.2 to 1.15 m/s with an optimal range of about 0.30 to 0.9 m/s, dependent upon gravel permeability, average substrate size, and average size of spawning adult. It is conceivable that chinook stocks spawning in colder, northern latitudes may select slightly lower velocity water for spawning.

Embryo and yolk sac fry: the intergravel stage. With the exception of winter run chinook that spawn in the spring, the developing embryos of spring, summer, and fall runs spend the fall and winter months in the gravel. High survival of developing eggs and intergravel yolk sac fry is primarily dependent on the interactions of four variables: temperature, dissolved oxygen, water velocity, and gravel permeability. Studies have indicated usable ranges and optimal values for each of the above variables under a variety of conditions, but some judgement is necessary in developing and using the SI graphs developed for the model. Obviously, lower water velocities are more acceptable with higher gravel permeability than with low permeability. Also, O_2 saturation and fish metabolism vary with temperature. Thus, as temperatures increase the biological demand for O_2 increases, but the available O_2 supply decreases. The habitat variables of water velocity and spawning gravel particle size were discussed in the adult section. This section will contain information on the effects of fines, dissolved O_2, and temperature on survival of chinook embryos.

Burner (1951) observed that chinook salmon redds averaged about 6 m^2 in size, and that chinook spawners tend to select areas relatively free of silt, under normal to low spawning densities. When spawning densities are high or suitable spawning gravel is scarce, however, chinook salmon have been reported to spawn on sand and silt substrates (Major et al. 1978). In the Kamchatka River, Vronskii (1972) reported that about 95% of the chinook redds were located on the gravel transition areas between pools and riffles. He expressed the opinion that subsurface flows were ideal and the gravels relatively silt-free in these areas.

It is well known that the presence of fines in redds can impede water flow and cause impairment of water quality for salmonid embryos (Cordone and Kelly 1961; McNeil 1968). Other studies show that fines can impede the emergence of fry (Koski 1966; Bjornn 1969; Phillips et al. 1975). The size of the fines appears important. McNeil and Ahnell (1964) reported that survival of pink salmon embryos and intergravel yolk sac fry significantly decreased as fines (≤ 0.833 mm) exceeded 5% and approached 15% of the redd particulate materials. Bjornn (1969) recorded a 28% average survival of steelhead embryos implanted in a mixture of 30% sand and 70% gravel. Of the 28% that hatched, only 74% emerged. Suitable incubation substrate for chinook embryos appears to be gravel that is about 0.3 to 15 cm in size that is relatively free of fines. Optimal gravel conditions are assumed to include ≤ 5% small fines (≤0.8 mm) and <10% large fines (≤3.0 mm); amounts greater than these are assumed to result in increasingly low survival of embryos and emerging yolk sac fry.

While spawning may occur over a wide range of water temperatures (4.4 to 18 °C), suitable temperature regimes for incubating embryos are more restrictive. Chambers (1956) reported that spring chinook usually spawned at declining temperatures ranging from 12.8 to 4.5 °C, whereas fall chinook spawned during temperatures of 13.4 to 5.0 °C. Seymour (1956) observed high chinook egg and fry survival rates at constant temperatures of 10, 7.2, and 4.5 °C, but very low survivals at temperatures >16 °C. Seymour (1956) also reported no survival among chinook eggs incubated at a constant temperature of 1.0 °C. Eggs incubated at 12.8 °C for 3.5 weeks and thereafter at 1.0 °C suffered only a 3% loss while eggs incubated at 12.8 °C for only 2 weeks and then at 1.0 °C suffered a 42% mortality (Seymour 1956). It appears that a period of incubation >2 but ≤3.5 weeks at temperatures ≥4.5 °C but ≤12.8 °C is necessary for good survival of late summer to fall spawned chinook embryos. Winter run chinook from the Sacramento River and any spring spawning stocks in the Great Lakes, however, would spawn in the spring while water temperatures are increasing. The limited information available indicates that winter run chinook in the Sacramento River system usually spawn at temperatures of about 5.9 to 14.2 °C, and that temperature suitability and survival is limited on both the low and high side of this range (Slater 1963). We assume that this temperature data would also apply to any spring spawners in the Great Lakes.

Survival of chinook eggs from fertilization to fry emergence ranged from 90% to 100% at constant O_2 concentrations of 3.5, 5.0, 7.3, and 10.5 mg/l at a water temperature of 10.5 °C. Survival dropped to 0 at a constant temperature of 15 °C (Eddy 1972). From these temperature data (here and above) it appears that a temperature ≥15 °C may be lethal to chinook embryos. Eddy (1972) also reported that embryo to fry survival was highest at 10.5 mg/l O_2 and lowest at 3.5 mg/l for all temperatures tested (10.5, 12.0, 13.5, and 15.0). Gangmark and Bakkala (1960) found that survival of chinook salmon embryos in a cold stream (4 to 9 °C) was highest at O_2 concentrations of 13 mg/l and lowest at 5 mg/l. The greatest increase in survival occurred between 5 and 7 mg/l. In another study, mean length of sac fry was greatest at 11.7 mg/l O_2 and least at 2.5 mg/l. These tests were conducted at a temperature of 11 °C (Silver et al. 1963). Davis (1975), after reviewing the dissolved O_2 requirements for several Canadian fishes, suggested a minimum concentration of 8 mg/l for developing salmonid embryos. From the above we conclude that the lower limit of O_2 concentration for survival with short term exposures is ≥2.5 mg/l at water temperatures ≤7 °C with optimal levels of ≥8 mg/l at temperatures ≥7 but ≤10 °C and ≥12 mg/l at temperatures >10 °C.

Juvenile stream resident stage. There are two general freshwater life history patterns for juvenile chinook salmon: (1) juveniles from stocks that spawn primarily in larger mainstem rivers or close to the ocean and tend to begin their seaward migration within a few weeks after emergence from the gravel; and (2) juveniles from stocks that spawn in smaller tributary streams and in more distant upstream areas that tend to spend one or more years in the freshwater environment before smolting. In North America, both age-at-migration patterns are present in the southern portion of the range, but only the second pattern is found in the northern or Alaskan portion (Major et al. 1978). Migration for both groups begins in the spring, primarily April through June, but the peak of migration occurs later in northern latitudes. Seaward migration of chinook smolts tends to be nocturnal and near the stream surface (Gauley et al. 1958; Meehan and Siniff 1962; Major and Mighell 1969; Durkin et al. 1970).

The following synoptic freshwater life history for juveniles that spend one or more years in the freshwater environment is taken from Everest and Chapman (1972). Their study was conducted on spring chinook in two tributary streams in Idaho. Spawning occurs in August and September. The embryos overwinter in the stream gravel. Fry emerge in March; feed and grow through the summer and fall months; re-enter the gravel-rubble substrate in the late fall as temperatures decline from 8 to ≤4 °C; overwinter in the gravel; emerge in the spring; and begin the seaward migration in late May through early June. From time of egg fertilization until smolting the juvenile chinook spend about 14 to 16 months in freshwater. About 50% of that time is spent in a dormant to semidormant condition in the stream substrate during the cold weather months. The 7 to 8 months of active stream life, however, are extremely important. This same pattern would apply to summer chinook juveniles that spend a year in freshwater prior to smolting. Some variations in timing would be expected due to racial and average temperature differences.

Upon emergence from the gravel, greatest densities of newly emerged chinook were observed by Everest and Chapman (1972) some distance from shore at depths ≥15 cm in pools and eddies at velocities <50 cm/s. They observed lesser densities in faster (≥60 cm/s) water where the fish behaved territorially. As the young chinook increase in size they move to faster and deeper water with larger size substrate where they occupy and defend feeding stations (Edmundson et al. 1968; Lister and Genoe 1970; Everest and Chapman 1972). Everest and Chapman (1972) state that the shift from shallow to deeper water may be both food and cover related. Over the period of freshwater residence juvenile chinook tended to select low-focal-point velocity water (0.0 to <40 cm/s) above silt to >40 cm sized substrate.

Juvenile chinook use water depth (deep, low-velocity pools and bank eddies), surface turbulence, instream structures, and substrate (primarily 10 to 40 cm in size) as cover, with substrate being a major source of escape and winter cover (Hartman 1965; Everest 1969). Platts (1974) found greatest densities of juvenile chinook associated with large, deep, low-velocity pools with abundant instream cover, overhanging banks and vegetation, and rubble substrate. Studies that estimated the amount of cover needed to support average densities of chinook juveniles could not be found. We estimate that about ≥20% of the stream area should provide cover as described above. For juvenile chinook stocks that overwinter in the stream habitat, we estimate that ≥15% of the stream area should be cover in the form of relatively silt-free 10 to 40 cm substrate.

Rainbow-steelhead fry have been observed at depths of 15 to 30 cm in the substrate during the winter. Everest and Chapman (1972) report that both steelhead and chinook juveniles either move downstream in the fall or enter the substrate for the winter. This observation was confirmed by Edmundson et al. (1968) and Chapman and Bjornn (1969). Bjornn (1971) found that late fall downstream movement of juvenile steelhead and chinook salmon did not occur if adequate overwinter habitat in the form of class 1 and 2 pools and relatively silt-free substrate was locally available. Silt deposits >5% to 30% in gravel-rubble areas tend to impair and eventually prevent the use of the gravel-rubble substrate for escape and winter cover by juvenile chinook salmon.

In summary, we conclude that young-of-the-year chinook salmon tend to select water velocities 0 to 60 cm/s with an optimal range of 0 to <40 cm/s at depths of ≥15 cm. Substrate occupied by juvenile chinook ranges from silt to >40 cm in size, but optimal size substrate for escape and winter cover is 10 to 40 cm in diameter. Sand and silt deposits in the 10 to 40 cm size substrate should be ≤5% for optimal use; substrate use becomes increasingly marginal as sand and silt deposits approach and exceed 30%. We estimate that ≥20% of the stream area with an average water column velocity <60 cm/s at depths ≥15 cm is needed to provide suitable habitat area for an average density juvenile chinook population. In addition, we estimate that ≥15% of the stream area must have a 10 to 40 cm sized, relatively silt free, gravel-rubble area in order to provide adequate escape and winter cover for juvenile chinook salmon. Most relatively silt-free chinook streams with a 40% to 60% pool area will provide adequate juvenile habitat area.

Temperature data are scarce for chinook salmon juveniles. Brett (1952), Black (1953), McAfee (1966), and Bidgood and Berst (1969) report a temperature range of 0 to 25 °C for salmonids, primarily rainbow-steelhead trout. Because juvenile chinook are often sympatric with rainbow-steelhead trout and range from coastal areas to hundreds of miles inland at elevations up to 1,200+ m, we assume that they have a fairly wide temperature tolerance range, similar to rainbow-steelhead trout. Brett et al. (1972) reported excellent growth of juvenile chinook occurred at test temperatures ranging from 15-19 °C. Growth slowed significantly at temperatures ≥19 °C and mortality was excessive at 24.8±.4 °C. From these limited data we suggest a temperature range of 0-24 °C with an optimal range of 12-18 °C for chinook. Northern stocks may have a lower overall and optimal range (Behnke, review comments).

Bustard (1983) reported juvenile chinook winter mortalities occurred when O_2 levels were between 2-3 mg/l, but juveniles survived at O_2 levels ranging from 3-7 mg/l. He noted that there is growing evidence that natural oxygen depression to levels below 5 mg/l in late winter is widespread in northern environments. These data concur with oxygen data on chinook embryos. We conclude that chinook juveniles can survive short term exposures to 3 mg/l O_2 at temperatures ≤5 °C, but optimal levels are ≥9 mg/l at ≤10 °C and 13 mg/l at >10 °C.

HABITAT SUITABILITY INDEX (HSI) MODELS

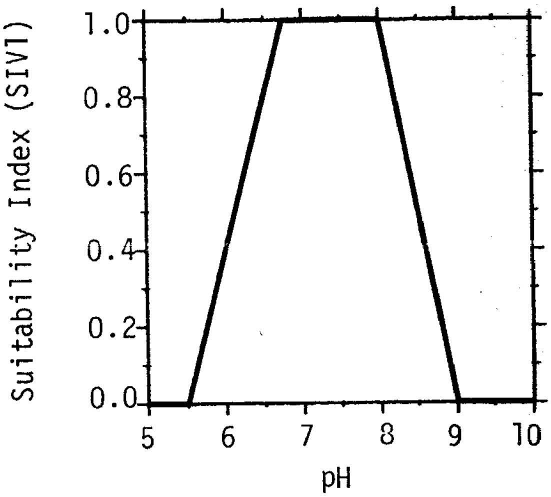
Suitability Index (SI) Graphs for Model Variables

This section contains SI graphs for 18 chinook salmon riverine habitat variables. Instructions on where and when to take the habitat measurements to obtain valid SI scores are included with each SI graph. The habitat measurements and SI graph construction are based on the premise that extreme, rather than average, values of a variable most often limit the productivity of a habitat. Thus, extreme conditions, such as maximum temperatures and minimum dissolved oxygen levels, are often used in the graphs to derive SI values for the model. Other premises are discussed in the Habitat Use Information section. Instructions for obtaining an HSI score for chinook salmon habitat from SI scores are included.

Variable

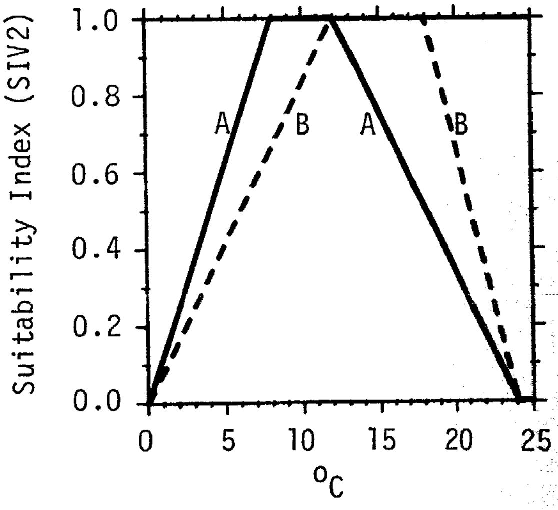
Suitability graphs

V_1 Annual maximal or minimal pH. Measure during the summer to fall season. Use the measurement with the lowest SI value.



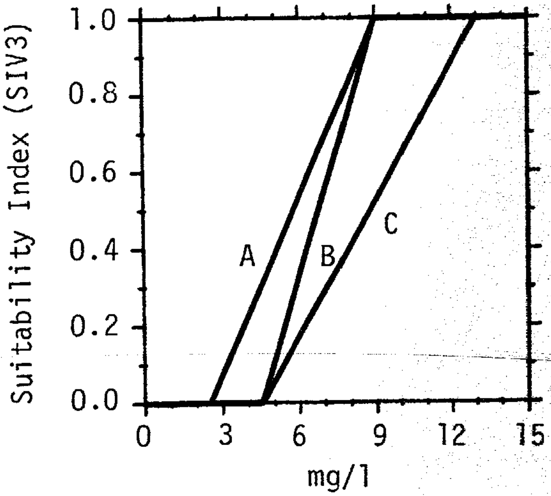
V_2 Maximum temperature during warmest periods when adults or juveniles are present. Measure at locations where problems may exist. Down-river, migration block areas and stream resident locations.

A = prespawning adults
B = juveniles

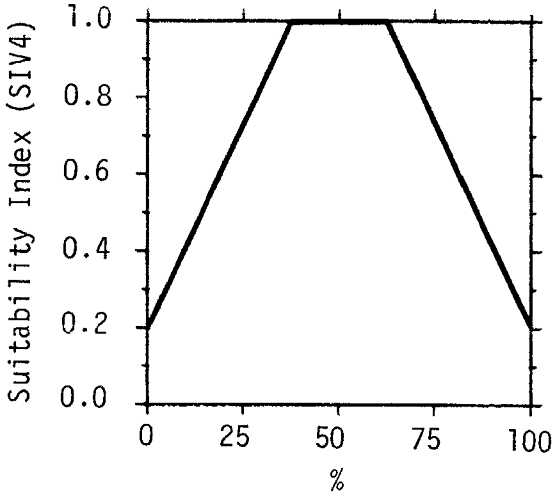


V_3 Minimum dissolved O_2 level during egg and preemergent yolk sac fry period, and during periods of occupation by adults and juveniles.

A. ≤5 °C
B. >5 - ≤10 °C
C. >10 °C

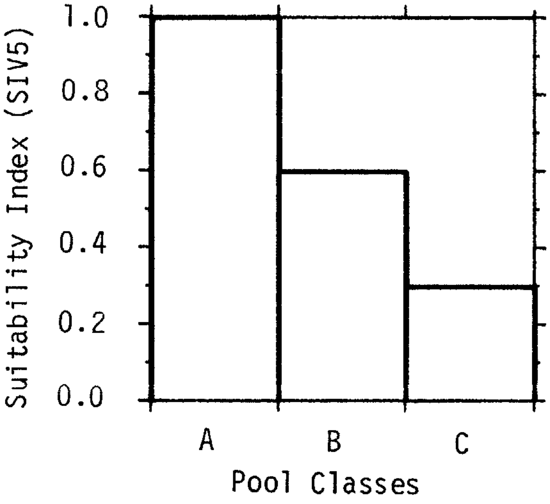


V_4 Percent pools during the late growing season low water period.



V_5 Pool class rating during the late growing season low flow period.

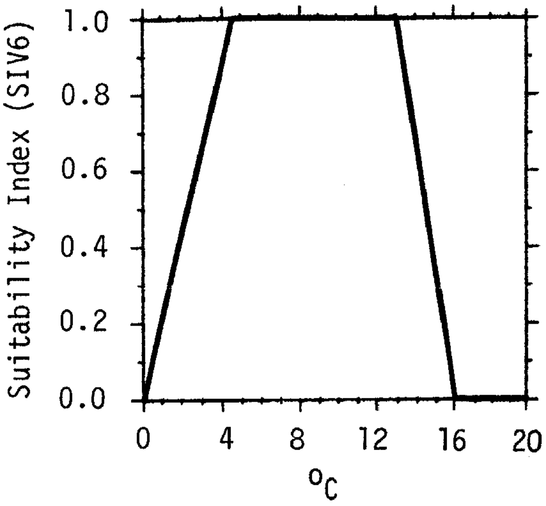
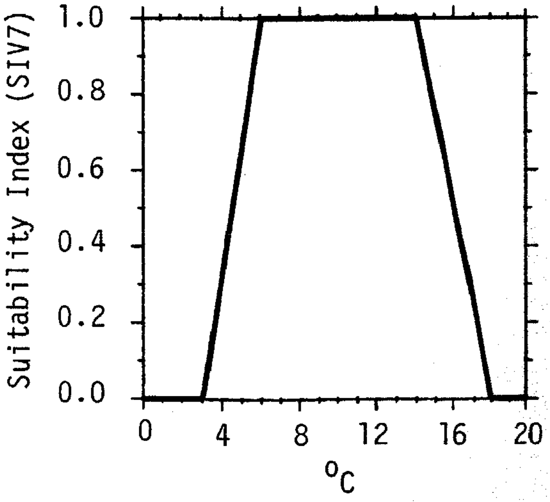
A. ≥30% of the habitat classified as pools is composed of 1st class pools.
B. ≥10% but <30% of the habitat classified as pools is composed of 1st class pools or ≥50% is 2nd class or better pools.
C. <10% of the habitat classified as pools is composed of 1st class pools and <50% is 2nd class pools.



First-class pool: Large and deep. Pool depth and area are sufficient to provide a low velocity resting area for several adult chinook. More than 30% of the pool bottom is obscure due to surface turbulence, turbidity, or the presence of structures such as logs, boulders, or overhanging objects. Or, the greatest pool depth is ≥1.5 m in streams ≤5 m wide or ≥2 m in streams >5 m wide.

Second-class pool: Moderate size and depth. Pool depth and area are sufficient to provide a low velocity resting area for a few adult chinook. From 5 to 30% of the bottom is obscured by surface turbulence, turbidity, or the presence of structures. Typical 2nd class pools are large eddies behind boulders and low velocity moderately deep areas beneath overhanging banks and vegetation.

Third-class pool: Small in area, or shallow, or both. Pool depth and area are sufficient to provide a low velocity resting area for one to very few adult chinook. Cover, if present, is in the form of shade, surface turbulence, or very limited structure. Typical 3rd class pools are wide, shallow areas of streams or smaller eddies behind boulders. The entire bottom of the pool may be visible.

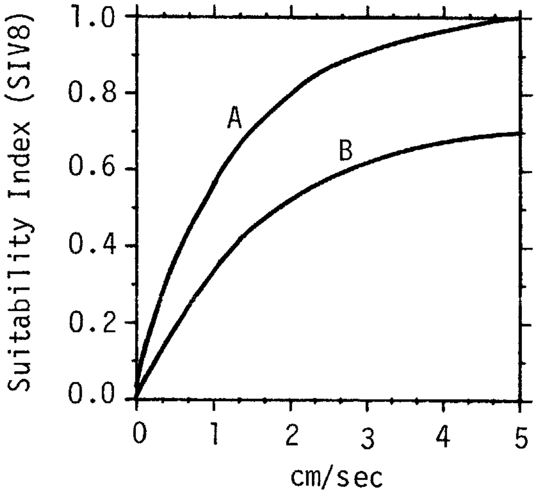
Variables		Suitability graphs
V_6	Maximum or minimum temperature at beginning and end of first month of spawning of late summer or fall spawning stocks. Use the temperature that yields the lowest SI. Minimum temperature must remain ≥4.5 °C for ≥3.5 weeks after fertilization.	
*V_7	Maximum or minimum temperature at beginning and end of embryo incubation period. Use the temperature that yields the lowest SI. *Use for spring spawning stocks only.	

V_8

Percentage of spawning gravel in each of two classes: A. 2-10.6 cm B. 0.3-≤2, and ≥10.6-15 cm. Measure during or within 30 days after spawning.

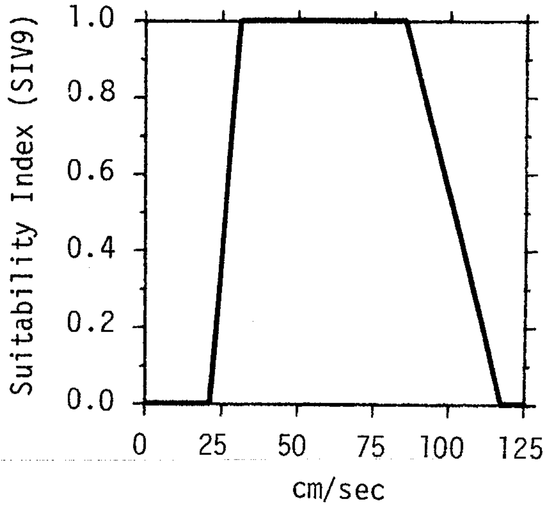
Record total area (m²) of gravel in each class. To derive an SI score, use the best substrate (class A) until the sample contains an area equal to 5% of the entire chinook habitat area sampled. If class B substrate must be included to obtain a 5% sample, derive an arithmetic mean SI score from the two individual SI scores obtained from the graph.

$$V_8SI = \frac{SIA + SIB}{2}$$



V_9

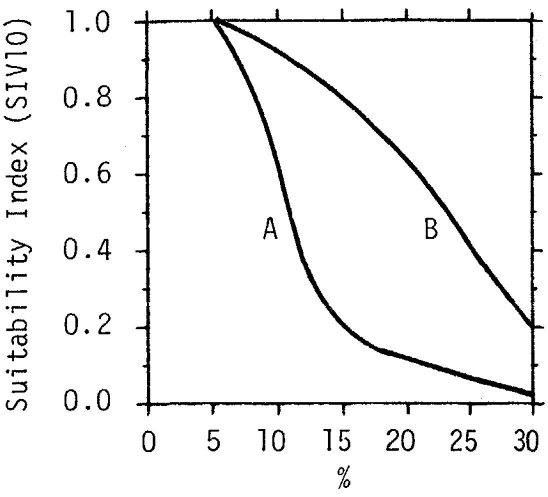
Average water column velocity (cm/s) over areas of spawning gravel used by chinook salmon during period of spawning and embryo development. Measure only at depths ≥20 cm and at same location as gravel (V_8).



V_{10}

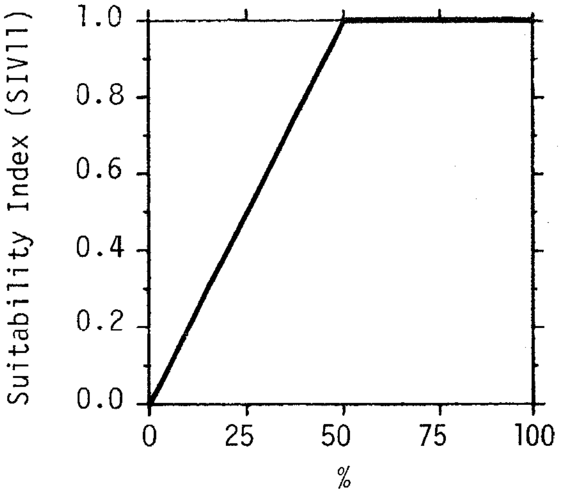
Average percentage of fines in spawning gravel in major spawning areas. Measure within 30 days after spawning is over and at the same sites as V_8.

A. Fines ≤0.8 mm in size (silt).
B. Fines >0.8 to 30 mm in size (sand).



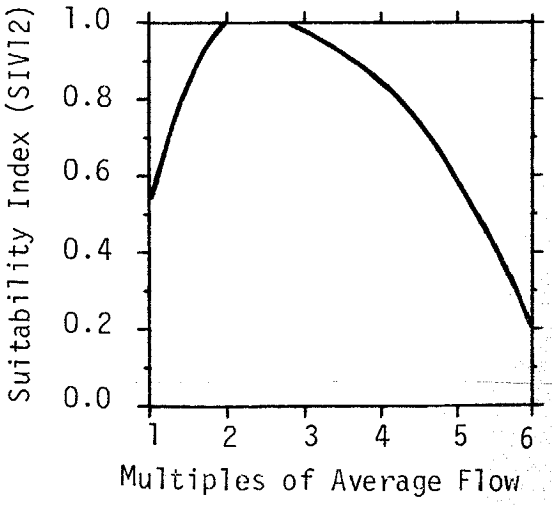
V_{11}

Average annual base flow during the late summer to winter low-flow period as a percentage of the average annual daily flow. For embryo and preemergent fry use the average and low flows that occur during intergravel occupation period.



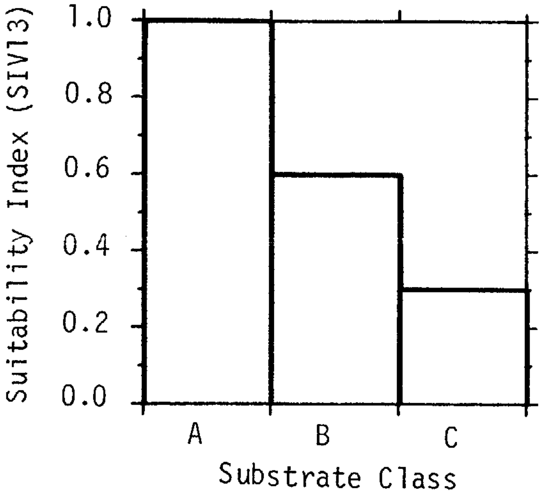
V_{12}

Average annual peak flow as a multiple of the average annual daily flow. For embryo habitat suitability use the peak flow measurment that occurs from time of egg deposition until two weeks after fry emergence from the gravel.

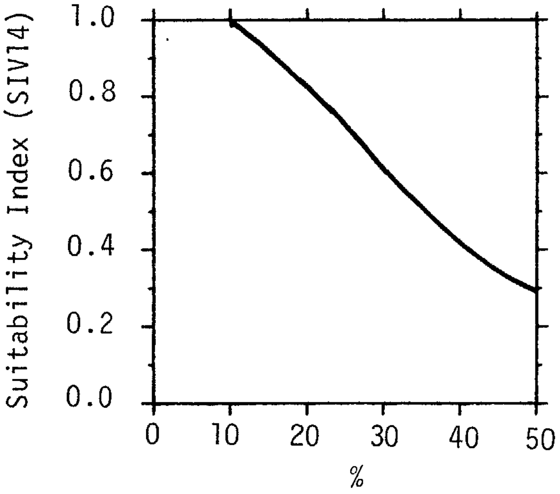


V_{13} Predominant (≥50%) substrate type in riffle-run areas for food production indicator. Measure in juvenile rearing and upstream areas.

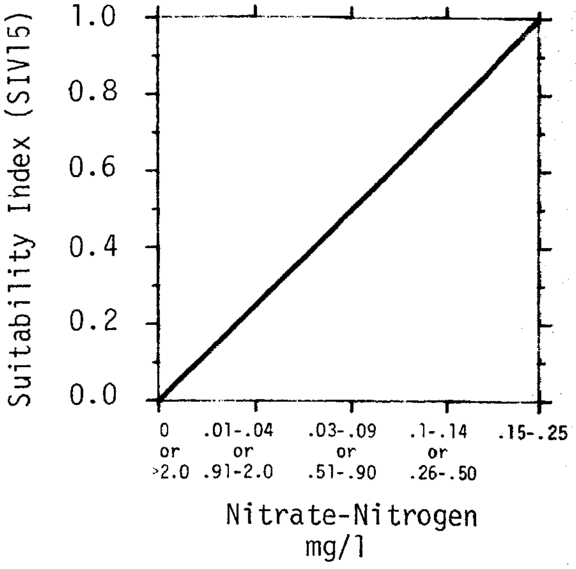
A. Rubble or small boulders (or aquatic vegetation in spring areas) dominate; limited amounts of gravel, large boulders, or slab rock may be present.
B. Rubble, gravel, and boulders occur in roughly equal amounts, or gravel or small boulders predominant. Fines, large boulders, or slab rock may be present in moderate quantities (≤25%).
C. Fines, slab rock, or large boulders predominate. Rubble or gravel are insignificant (≤25%).



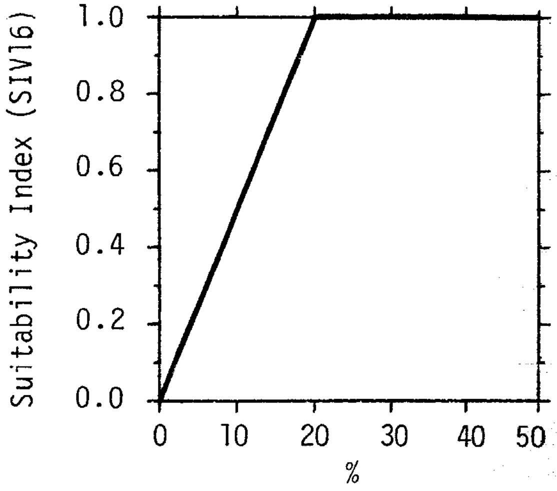
V_{14} Average percentage of fines (<3 mm) in riffle-run areas. Measure in juvenile rearing areas during average flow period.



V_{15} Levels of late summer nitrate-nitrogen (mg/l). Measure after spawner die off.



V_{16} Percentage of stream area providing escape cover. Measure during late summer-fall average to low flow period at depths ≥ 15 cm and with bottom velocities ≤ 40 cm/s.



*V_{17} Percentage of stream area with 10 to 40 cm average sized boulders. Measure at same time and areas as V_{16}.

*Use only for juveniles that overwinter in the freshwater.

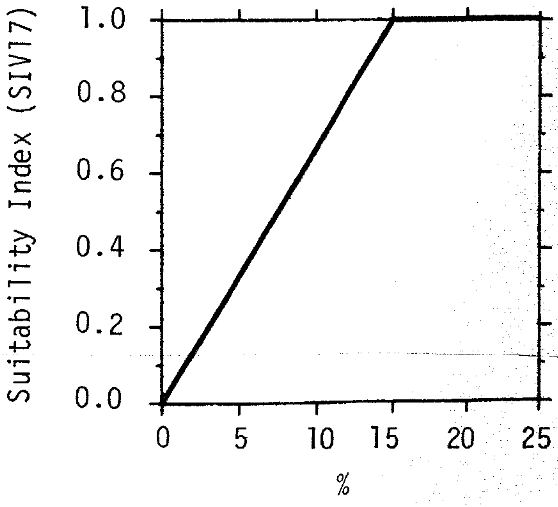


Table 1. Literature sources and assumptions for chinook salmon suitability index graphs.

Variable	and source	Assumptions
V_1	Behnke and Zarn 1976	We assumed that an acceptable pH range and optimal values were similar to other sympatric salmonid species.
V_2	Mattson 1948 Burner 1951 Brett 1952 Black 1953 McAfee 1966 Bidgood and Berst 1969 Behnke 1986 (review comment)	Because chinook salmon are often sympatric with rainbow-steelhead trout, range from coastal areas to elevations of 1200+ m, and from California to Northern Alaska, we assumed they would have a fairly wide temperature tolerance range, similar to rainbow-steelhead, but with a lower maximum and optimal range. Northern and high elevation stocks may have a more restricted range.
V_3	Gangmark and Bakkala 1960 Eddy 1972 Davis 1975 Bustard 1983	Dissolved oxygen concentrations below minimum levels associated with temperature thresholds affect the development and survival of chinook salmon embryos and juveniles.
V_4	Needham 1940 Hartman 1965 Edmundson et al. 1968 Lister and Genoe 1970 Everest and Chapman 1972 Platts 1974	A pool to riffle ratio of about 1:1 (about 40%-60% pools) provides an optimal mix of prespawning adult holding area, juvenile cover and resting area, and stream food-producing habitat for chinook salmon.
V_5	Hartman 1965 Edmundson et al. 1968 Lister and Genoe 1970 Everest and Chapman 1972 Platts 1974	Pools differ in their ability to provide cover and adequate resting habitat. Pool classes utilized by prespawning adults, schools of juveniles, and as summer and winter cover by chinook salmon were considered essential.

Table 1. (Continued)

Variable and source		Assumptions
V_6	Chambers 1956 Seymour 1956 Gangmark and Bakkala 1960 Eddy 1972 Brett et al. 1982 Behnke (correspondence)	Temperatures associated with high survival of spring spawning stocks were considered optimal. Those associated with poor survival were considered suboptimal.
V_7	Slater 1963	Temperatures during the first 3.5 weeks of embryo development associated with high embryo survival were assumed optimal. Temperatures associated with developmental abnormalities and poor survival were considered suboptimal.
V_8	Hobbs 1937 Burner 1951 Chambers 1956 Fulton 1968 McNeil 1968	Gravel size ranges selected for spawning by chinook salmon were used to set the size range. The optimal size range was those gravel sizes associated with the best permeability, survival of embryos, and emergence of yolk sac fry.
V_9	Andrew and Geen 1960 Smith 1973	Average water column velocities selected by spawning adult chinook salmon and associated with high survival of embryos were considered in selecting velocity ranges and optimal values.
V_{10}	Burner 1951 Cordone and Kelly 1961 McNeil and Ashell 1964 Koski 1966 McNeil 1968 Bjornn 1969 Phillips et al. 1975	The percentages of fines in spawning gravel areas associated with high embryo survival and emergence of yolk sac fry were considered optimal. Suitability decreased as the percent fines and embryo mortality increased.
V_{11}	Andrew and Geen 1960 Tennent 1976 Binns and Eiserman 1979 Wesche 1980 Nehring and Anderson 1982, 1983	Base flows as a percentage of the average annual daily flows that were associated with high embryo survival and high standing crops of juvenile salmonids were considered optimal.
V_{12}	Lister and Walker 1966 Nehring and Anderson 1982, 1983	Average annual peak flows as a multiple of the average annual daily flows that were associated with high embryo survival and high standing crops of salmonids were considered optimal.

Table 1. (Concluded)

Variable and source		Assumptions
V_{13}	Hynes 1970 Binns and Eiserman 1979	The predominant substrate type containing the greatest numbers and kinds of aquatic insects was considered optimal.
V_{14}	Cordone and Kelly 1961 Crouse et al. 1981	The percentage of fines in riffle-run areas associated with the highest standing crops of aquatic food organisms was considered optimal.
V_{15}	Binns and Eiserman 1979	Nitrate nitrogen levels in rivers that are associated with the highest standing crops of aquatic food organisms and fishes are considered optimal.
V_{16}	Hartman 1965 Everest 1969 Platts 1974	The percentage of instream and bank cover in juvenile rearing areas associated with the highest standing crops of juveniles are optimal.
V_{17}	Hartman 1965 Everest 1969 Chapman and Bjornn 1969 Everest and Chapman 1972	The size range of substrate selected most often by juvenile chinook as escape and winter cover was considered optimal. Percentages needed were estimated.

HSI Model Applicability

Geographic area. The following models are applicable over the entire North American freshwater geographic range of chinook salmon.

Season. The models rate the freshwater habitat of chinook salmon by season of occupation for each model component: prespawning and spawning adult, intergravel embryo and yolk sac fry, and stream resident juvenile.

Cover types. The models are applicable to freshwater riverine habitat.

Minimum habitat area. Minimum habitat area is the minimum area of contiguous habitat that is required by a species to live and reproduce. Because chinook salmon can travel considerable distances to spawn or locate suitable summer or winter rearing habitat, no attempt has been made to define a minimum amount of habitat for the species, except that spawning adults often utilize about 6 m^2 of spawning gravel with a minimum width of 1 m.

Verification level. An acceptable level of performance for this chinook salmon model is for it to produce variable SI scores between 0 and 1 that the author and other biologists familiar with chinook salmon ecology believe is positively correlated with the habitat requirements of chinook salmon for each variable. Model verification consisted of observing the model outputs from sample data sets developed by the author and model review by chinook salmon experts.

Model Description

The chinook salmon HSI model consists of three components: spawning adults (C_A), developing embryos (C_E), and stream resident juveniles (C_J). Each component contains variables specifically related to that component.

Two models are presented. The first model uses a simple limiting factor theory. The model assumption is that all variables can have a significant effect on chinook salmon survival and production, and that the high SI scores of one or more variables cannot compensate for low SI scores of other model variables.

The second model uses a partial compensatory limiting factor theory. This method assumes that some compensation can occur among dependent variables, such as water velocity, spawning gravel size, and percent fines.

Adult component. Variables pH (V_1), maximum temperature (V_2), minimum dissolved oxygen (V_3), percent pools (V_4), and pool class (V_5) affect the ability of chinook salmon adults to enter the spawning streams, to find suitable holding habitat until time to spawn, and to survive and spawn successfully in freshwater, riverine habitats.

Embryo component. Variables minimum dissolved oxygen (V_3), maximum or minimum temperature (V_6 or V_7), average spawning gravel size (V_8), average water column velocity (V_9), percent fines (V_{10}), average base flow (V_{11}), and average peak flow (V_{12}) all affect the ability of the developing embryos and intergravel yolk sac fry to develop, hatch, and emerge from the gravel successfully.

Juvenile component. Variables pH (V_1), maximum temperature (V_2), and minimum dissolved oxygen (V_3) are water quality variables that directly affect the ability of the juveniles to survive in the riverine environment. Variables percent pools (V_4), pool class (V_5), average base flow (V_{11}), average peak flow (V_{12}), percent riffle-run fines (V_{14}), percent cover (V_{16}), and percent substrate cover (V_{17}), all affect the quantity and quality of the juvenile rearing habitat. Variables substrate class (V_{13}), percent riffle-run fines (V_{14}), and nitrate-nitrogen concentration (V_{15}) are indicators of stream productivity and food supply necessary to sustain juvenile chinook stocks during the period of freshwater residence.

Model Use and Interpretation

The primary purposes of aquatic HSI models are to: (1) provide reliable information on the known habitat requirements of a species by life stage, (2) provide an extensive list of specific habitat variables for a species along with brief instructions on when and where to measure them, (3) provide an objective method of estimating how well specific habitat variables meet the habitat requirements of a species by life stage, and (4) thus, provide an objective, measurable basis for predicting or documenting project impacts, guiding habitat management decisions, and habitat improvement procedures.

The field measurements of variables for HSI models can be as simple as foot surveys and ocular estimates over small study sections, or as complex and detailed as frequent transects using measuring tapes, velocity meters, and substrate screens over the entire range of the species in a river system. The importance of the decisions to be made, along with time and financial constraints, will dictate methods selected. The information derived is limited by the accuracy of the sampling methods and to the area sampled.

In practice, the habitat variables are measured in the selected study area. The data collected for each variable are compiled and analyzed, SI scores derived by use of the SI graphs provided, and the information arranged in a matrix similar to Table 2. This will provide quantified information on the relative condition of the habitat from which habitat management decisions can be made. For project impact analysis purposes, habitat variable measurements should be done prior to project initiation to document existing habitat conditions and as a basis for projecting probable project impacts. Such information is extremely valuable in negotiating project design features and conditions and timing of construction phases. The habitat variables are measured again after construction is completed to document changes in specific habitat variable suitabilities to guide post project mitigation and habitat enhancement efforts.

For project impact analysis purposes it is often sufficient to measure the selected habitat variables only in the project impact area. For species management purposes, however, it may be desirable to collect habitat data over the entire range of the species within a river system. For example, individuals may move for considerable distances within the drainage to locate suitable spawning, rearing, or overwintering habitat. Hence, the lack of such habitat within any one study section would not necessarily mean that it is in short supply or species limiting. The habitat character of the entire range of the species in the drainage system would have to be considered before this kind of decision would be warranted. The user must be judicious in interpreting the outputs of the model.

We believe that the data base and SI graphs are reasonably accurate. We have done a fairly thorough job of reviewing the currently available data base, and the model has received excellent peer review. The individual variable SI scores can be reasonably relied on to indicate the relative suitability of each variable in meeting the habitat requirements of the species, if the habitat measurments were correctly taken. We recognize the correlation between habitat condition and stock density, but past attempts to produce HSI model equations that yielded life stage or species HSI scores correlated with stock density have not been successful. Tests of the cutthroat trout model HSI against cutthroat trout stocks in Yellowstone Park streams yielded a correlation coefficient of 0.37. Goertler, Wesche, and Hubert (1985) tested an early brown trout HSI model score against brown trout stocks in 10 Wyoming streams. They found that using all 19 of the brown trout variables in model equations only accounted for 10% of the variation in brown trout population size in the test streams. They produced a three variable model that accounted for 63% of the variations in brown trout standing stocks. Models that estimate standing stocks of fishes are useful management tools. Such models typically use a minimum number of variables identified by regression analysis as accounting for significant percentages of variability in stock size. Models with a limited number of variables have limited usefulness in evaluating a wide variety of possible project impacts. We provide guidance on how to derive life stage and species HSI scores for chinook salmon. We assume that there is some correlation between species HSI scores and population size, especially when carefully selected key variables are used. Tests to date, however, using the whole array of variables, have indicated only weak, insignificant correlations.

The aquatic HSI models are not intended to be standing stock predictive models. They are models offering the user a maximum number of habitat variables for a species, which are useful in providing an objective method of assessing a wide variety of project impacts and in guiding management decisions. We advise the use of the individual variable SI scores rather than life stage or species HSI scores as the most reliable guides in this process.

Table 2 displays hypothetical data sets for each chinook habitat variable and SI scores derived for these data from the appropriate suitability index graphs. Table 2, Figure 1, and the preceding life stage discussions in the narrative section indicate the relationships among model habitat variables and chinook salmon freshwater life stages. A single HSI score can be obtained for the species or for any life stage in the sample area as desired by the user. We suggest selecting the lowest SI score of key variables as the species or life stage HSI (Table 2).

Model 1, Limiting Factor

The limiting factor model assumes that each variable in the model can significantly affect the ability of the habitat to produce chinook salmon; therefore, high SI values in some variables cannot compensate for low SI values in other variables and, hence, the species HSI cannot exceed the lowest SI value for any variable. The limiting factor model yields component SI scores of 0.7 for adults, 0.5 for embryos, and 0.6 for juveniles with a species HSI of 0.5 for the habitat represented by the SI values shown in Table 2.

Model 2, Compensatory Limiting Factor

The compensatory limiting factor model also assumes that each variable can significantly affect the ability of the habitat to produce chinook salmon. This model, however, assumes that low SI scores of dependent variables can be partially compensated for by high SI scores of other dependent variables in the set. An SI score ≤ 0.3 cannot be compensated for. Two examples using the compensatory limiting factor model follow:

1. Adult and juvenile components. It is assumed that the variables percent pools (V_4) and pool class (V_5) are dependent and compensatory in their effect on chinook salmon habitat suitability ($V_4 = 0.7$, $V_5 = 1.0$, Table 2).

$$\text{Lowest SI} = \frac{0.7 + 1.0}{2} = 0.85$$

The percent pool variable (V_4) SI for both adults and juveniles would increase from 0.7 to 0.85. The adult component SI would now be dissolved oxygen limited so the adult component SI score (lowest) would now be 0.8.

The juvenile component SI would still be limited by V_{12} and V_{13} and would remain 0.6.

The species HSI would not change since the embryo component SI score is still the lowest component SI score.

Table 2. Suitability indices (SI) scores for chinook salmon habitat variables by life stage.[a]

	Variables	Adult		Embryo		Juvenile	
		Data	SI	Data	SI	Data	SI
V_1	pH	6.8	1.0	-	-	6.8	1.0
V_2	Maximum temperature (°C)	19 °C	0.82	-	-	19 °C	0.82
V_3	Minimum dissolved oxygen O_2 (mg/l)	10B	0.8	9A	1.0	10B	0.8
V_4	% pools	30	0.7	-	-	30	0.7
V_5	Pool class	A	1.0	-	-	A	1.0
V_6	Maximum temperature (embryo)	-	-	8.0	1.0	-	-
V_7	Maximum or minimum temperature (embryo)[b]	-	-	-	-	-	-
V_8	Average substrate size (embryo)	-	-	1.5	0.5	-	-
V_9	Average velocity (embryo)	-	-	40	1.0	-	-
V_{10}	% fines (embryo)	-	-	12B	0.9	-	-
V_{11}	Average base flow[c]	-	-	40	0.8	40	0.8
V_{12}	Average peak flow[c]	-	-	1.5	1.0	3.5	0.6
V_{13}	Substrate class	-	-	-	-	B	0.6
V_{14}	% riffle-run fines	-	-	-	-	8	1.0
V_{15}	Nitrate-N concentration	-	-	-	-	0.12	0.75
V_{16}	% cover	-	-	-	-	35	1.0

Table 2. (Concluded)

Variables	Adult		Embryo		Juvenile	
	Data	SI	Data	SI	Data	SI
V_{17} Substrate cover	-	-	-	-	20	1.0
HSI = lowest SI score for the life stage or species		0.7		0.5		0.6

[a] The data sets are from hypothetical measurements. The corresponding SI scores are from the chinook salmon SI graphs.

[b] Use variable V_7 for spring spawning chinook only.

[c] Use base and peak flow data for embryos only if the embryos and yolk sac fry are still in the gravel during base and peak flow periods. If base or peak flow occur after emergence, then use the minimum and maximum flows that occur during the intergravel stage for variables V_{11} and V_{12} for the embryo component.

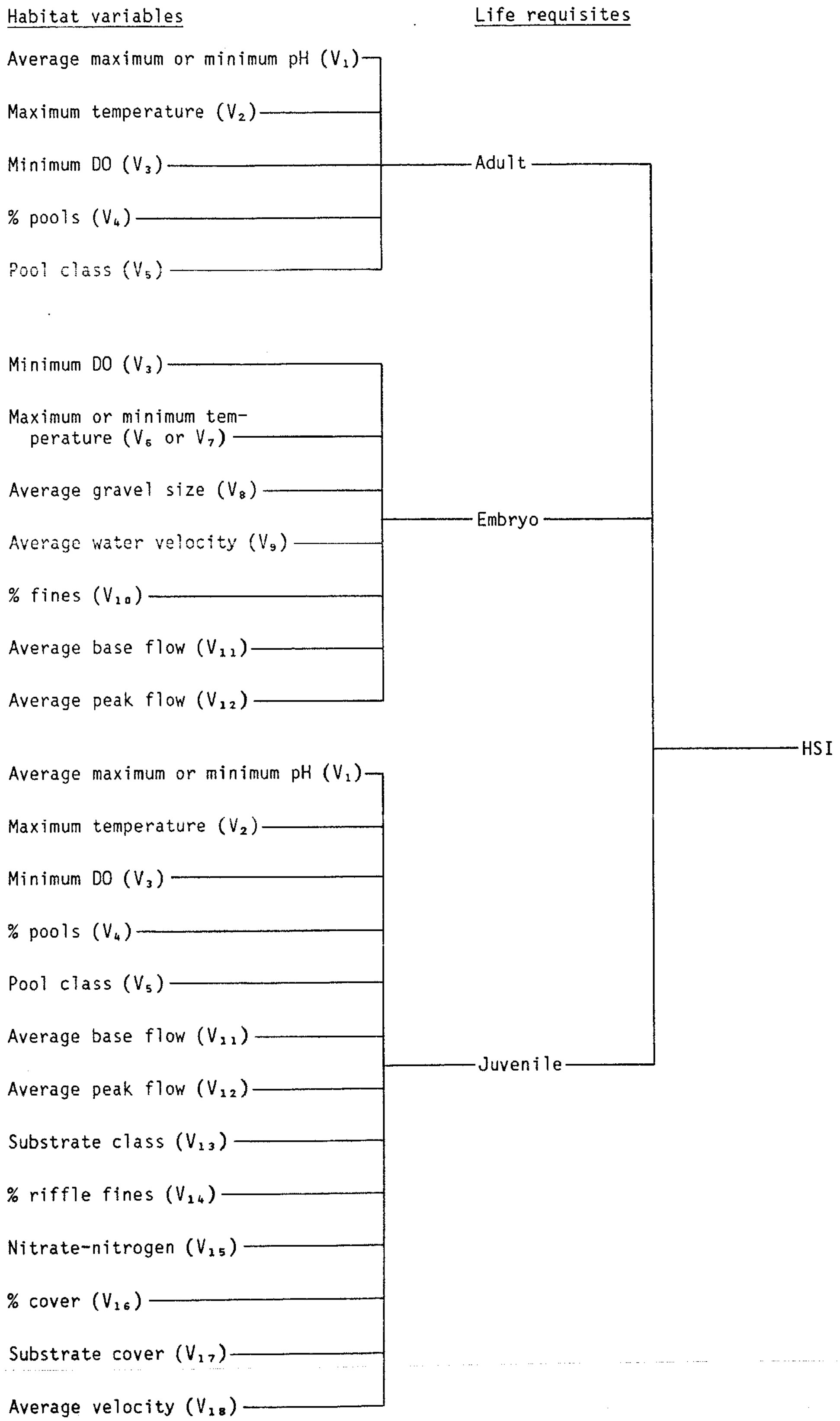


Figure 1. Diagram illustrating the relationship among model variables, components, and HSI.

2. Embryo component. It is assumed that the variables average gravel size (V_8), average water column velocity (V_9), and percent fines (V_{10}) are interacting compensatory variables ($V_8 = 0.5$, $V_9 = 1.0$, and $V_{10} = 0.9$, Table 2).

$$\text{Lowest SI} = \frac{0.5 + 1.0 + 0.9}{3} = 0.8$$

The SI for variable V_8 would increase from 0.5 to 0.8 and the embryo component SI would now be gravel (V_8) and base flow (V_{11}) limited. The embryo component SI would increase from 0.5 to 0.8.

The species HSI would increase from 0.5 to 0.6 (V_{12} and V_{13}) this being the lowest remaining SI score for any model component.

Model users are encouraged to devise other models or to make model alterations based on their knowledge of chinook salmon ecology. Alterations to the models, however, should be fully documented.

INSTREAM FLOW INCREMENTAL METHODOLOGY

The Instream Flow Incremental Methodology (IFIM) was designed to quantify changes in the amount of habitat available to different species and life stages of fish (or macroinvertebrates) under various flow regimes (Bovee 1982). The IFIM can be used: to help formulate instream flow recommendations, to assess the effects of altered streamflow regimes, on habitat improvement projects, for mitigation proposals, for fish stocking programs, and to assist in negotiating releases from existing water storage projects. The IFIM has a modular design, and consists of several autonomous models that are combined and linked as needed by the user. One component of the IFIM is the Physical Habitat Simulation System (PHABSIM) (Milhous et al. 1984). The output from PHABSIM is a measure of physical microhabitat availability as a function of discharge and channel structure for each set of habitat suitability criteria (SI curves) entered into the model. The output can be used for several IFIM habitat display and interpretation techniques, including:

1. Habitat Time Series. Determination of impact of a project on a species' life stage habitat by imposing project operation curves over baseline flow time series conditions and integrating the difference between the corresponding time series;

2. Effective Habitat Time Series. Calculation of the habitat requirements of each life stage of a single species at a given time by using habitat ratios (relative spatial requirements of various life stages); and

3. Optimization. Determination of flows (daily, weekly, and monthly) that minimize habitat reductions for a complex of species and life stages of interest.

Suitability Index Curves as Used in IFIM

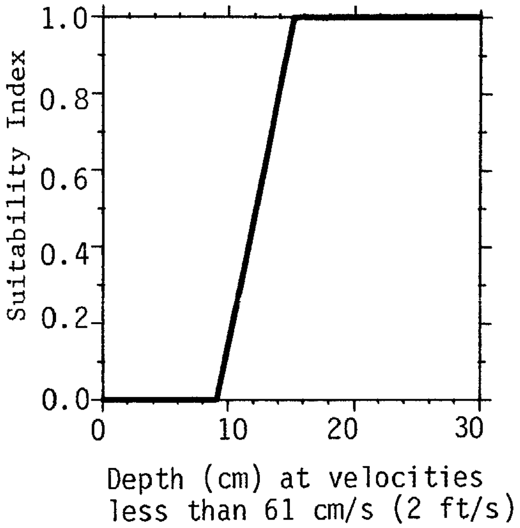
PHABSIM utilizes Suitability Index (SI) curves that describe the instream suitability of the habitat variables most closely related to stream hydraulics and channel structure (e.g., velocity, depth, substrate, and cover) for each major life stage of a given fish species (e.g., spawning, egg incubation, larval, juvenile, and adult). The National Ecology Center has designated four categories of curves and standardized the terminology pertaining to the curves (Armour et al. 1984). Category one curves are based on literature sources and/or professional opinion. Category two (utilization) curves, based on frequency analyses of field data, are fit to frequency histograms. Category three (preference) curves are utilization curves with the environmental bias removed. Category four (conditional preference) curves describe habitat requirements as a function of interaction among variables. The designation of a curve as belonging to a particular category does not imply that there are differences in the quality or accuracy of curves among the four categories.

Availability of SI Curves for Use in IFIM

The SI curves available for IFIM analyses of chinook salmon habitat are category one and two (Figures 2-19), based on combinations of judgement, information derived from the literature, and field data. Investigators are encouraged to review the curves carefully and verify them before use in IFIM analyses. Any discrepancies in the curves reproduced here are a result of misinterpretation by the authors, and not attributable to the studies cited.

At the time of this writing, numerous investigators were collecting data for chinook salmon SI curve development. Curve users may wish to contact the Instream Flow and Aquatic Systems Group to determine the latest in available criteria before undertaking an instream flow study.

Coordinates x cm	 x ft	 y SI
0.0	0.0	0.0
9.1	0.3	0.0
15.2	0.5	1.0
3048.0	100.0	1.0



x °C	x °F	y SI
0.0	32.0	0.0
2.0	35.6	0.0
7.0	44.6	1.0
13.0	55.4	1.0
16.0	60.8	0.0
30.0	86.0	0.0

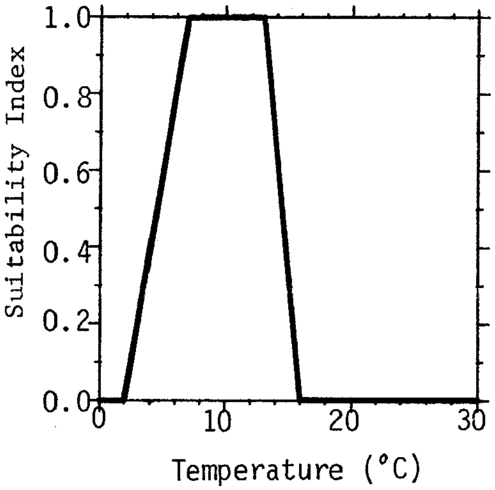
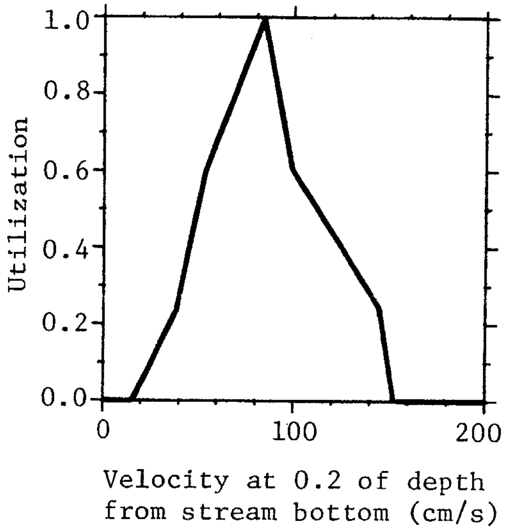


Figure 2. Category one SI curves for chinook salmon passage depth and temperature suitability (from Sautner et al. 1984; Meyer et al. 1984).

Coordinates x cm/s	x ft/s	y SI
0.0	0.00	0.00
15.2	0.50	0.00
22.9	0.75	0.08
38.1	1.25	0.24
53.3	1.75	0.60
83.8	2.75	1.00
99.1	3.25	0.60
129.5	4.25	0.36
144.8	4.75	0.24
152.4	5.00	0.00
3048.0	100.00	0.00



x cm	x ft	y SI
0.0	0.0	0.00
30.5	1.0	0.00
45.7	1.5	0.10
106.7	3.5	0.38
137.2	4.5	0.81
198.1	6.5	0.90
228.6	7.5	1.00
289.6	9.5	0.38
350.5	11.5	0.10
365.8	12.0	0.00
3048.0	100.0	0.00

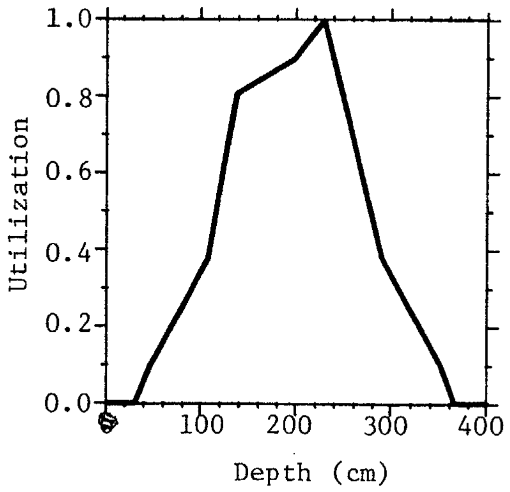
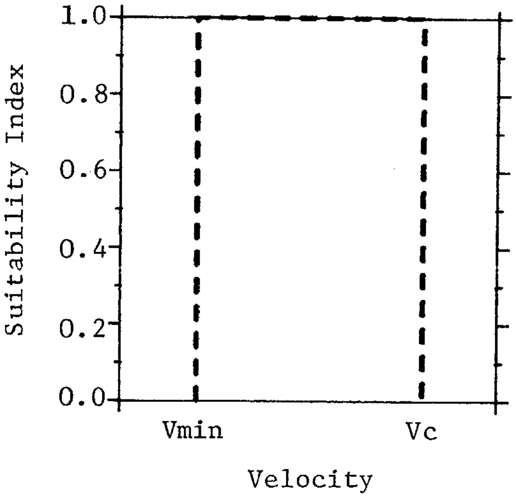


Figure 3. Category two SI curves for migrating chinook salmon spawners; velocity and depth utilization during migration holding (from Burger et al. 1982).

Coordinates

x	y
0	0
Vmin-.001	0
Vmin	1
Vc	1
Vc+.001	0
100	0

Vmin is the minimum velocity necessary to prevent siltation of spawning sites; Vc is the critical velocity, above which scouring of spawning sites will occur.



x	y
0	0
Dmin-.001	0
Dmin	1
100	1

Dmin is either the minimum depth required for egg incubation (≥ 0.0) or ice depth (when ice is present during egg incubation).

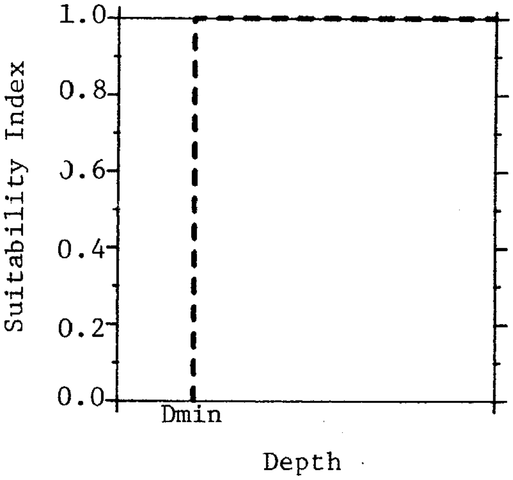
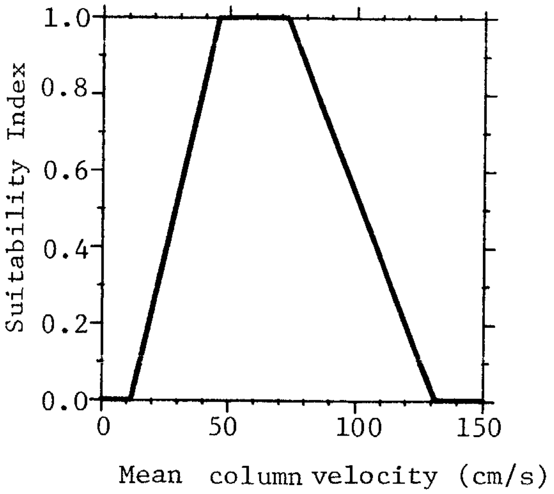
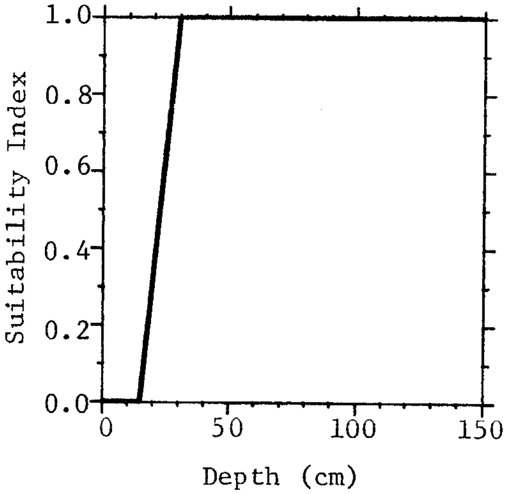


Figure 4. SI curves for spawning/egg incubation velocity and depth, for effective spawning habitat analyses.

Coordinates		
x cm/s	x ft/s	y SI
0.0	0.0	0.0
12.2	0.4	0.0
45.7	1.5	1.0
73.2	2.4	1.0
131.1	4.3	0.0
3048.0	100.0	0.0



x cm	x ft	y SI
0.0	0.0	0.0
15.2	0.5	0.0
30.5	1.0	1.0
3048.0	100.0	1.0



x cm	x inches	y SI
0.0	0.00	0.0
0.4	0.16	0.0
2.0	0.79	1.0
11.0	4.33	1.0
13.0	5.12	0.7
15.0	5.91	0.2
17.0	6.69	0.0
100.0	39.37	0.0

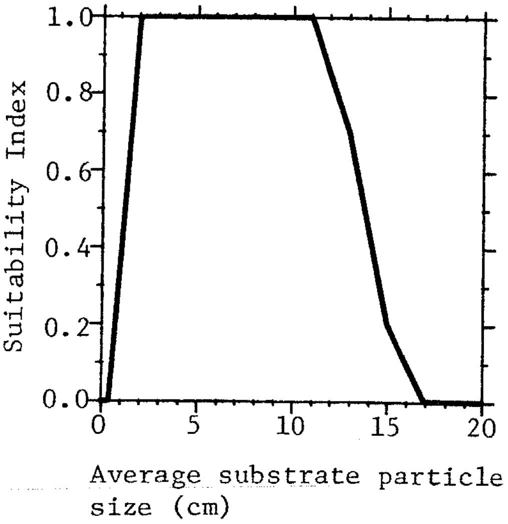
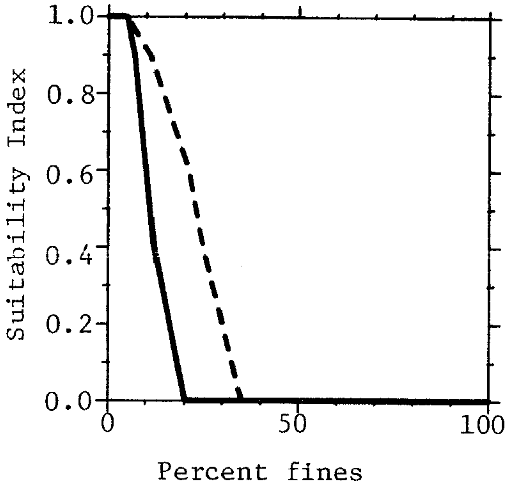


Figure 5. Category one SI curves for chinook salmon spawning, egg incubation, and intergravel fry velocity, depth, substrate, percent fines, and temperature suitability.

Coordinates		
x Fines ≤ 0.8 mm or 0.03 inches (solid line)	x Fines > 0.8 mm or 0.03 inches (broken line)	y SI
0.0	0.0	1.0
5.0	5.0	1.0
7.0	11.0	0.9
10.0	21.0	0.6
12.0	25.0	0.4
20.0	35.0	0.0
100.0	100.0	0.0



x Spawning (solid line) °C (°F)	x Egg incubation and intergravel fry (broken line) °C (°F)	y SI
0.0 (32.0)	0.0 (32.0)	0.0
0.5 (32.9)	-	0.0
-	3.0 (37.4)	0.0
4.4 (39.9)	-	1.0
-	6.0 (42.8)	1.0
12.8 (55.0)	-	1.0
-	14.0 (57.2)	1.0
15.0 (59.0)	-	0.0
-	18.0 (64.4)	0.0
30.0 (86.0)	30.0 (86.0)	0.0

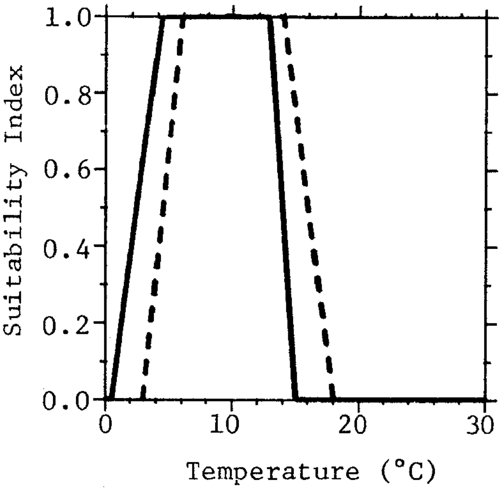
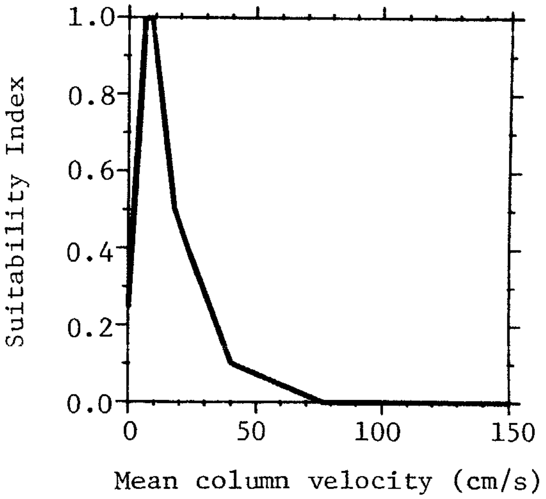
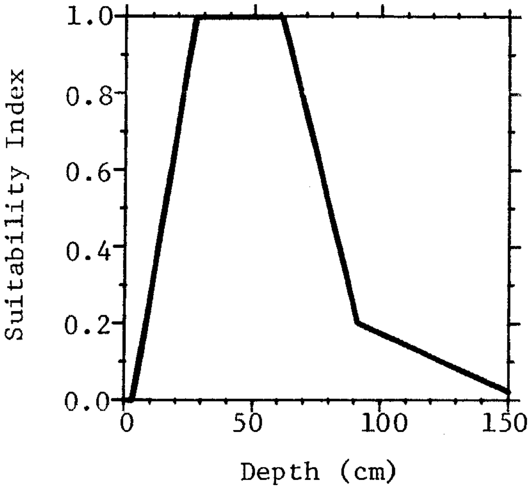


Figure 5. (concluded).

	Coordinates	
x cm/s	x ft/s	y SI
0.0	0.0	0.25
6.1	0.2	1.00
9.1	0.3	1.00
18.3	0.6	0.50
39.6	1.3	0.10
76.2	2.5	0.00
3048.0	100.0	0.00



x cm	x ft	y SI
0.0	0.0	0.0
3.0	0.1	0.0
27.4	0.9	1.0
61.0	2.0	1.0
91.4	3.0	0.2
152.4	5.0	0.0
3048.0	100.0	0.0



x °C	x °F	y SI
0.0	32.0	0.0
2.0	35.6	0.0
7.0	44.6	1.0
14.0	57.2	1.0
16.0	60.8	0.0
30.0	86.0	0.0

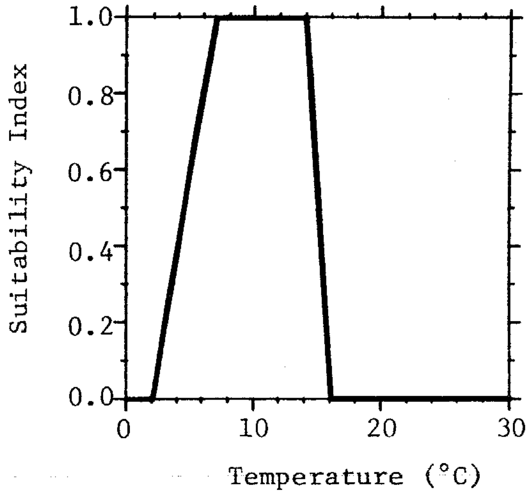
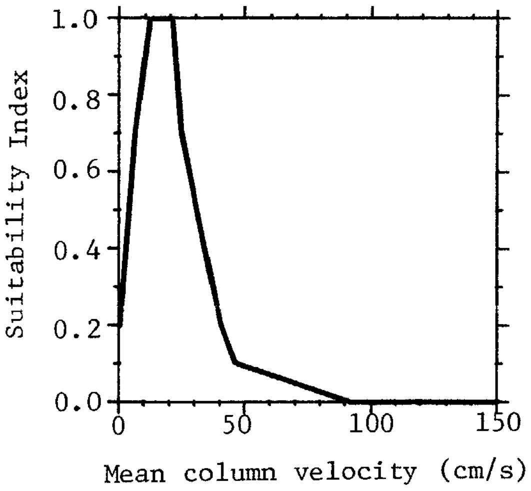


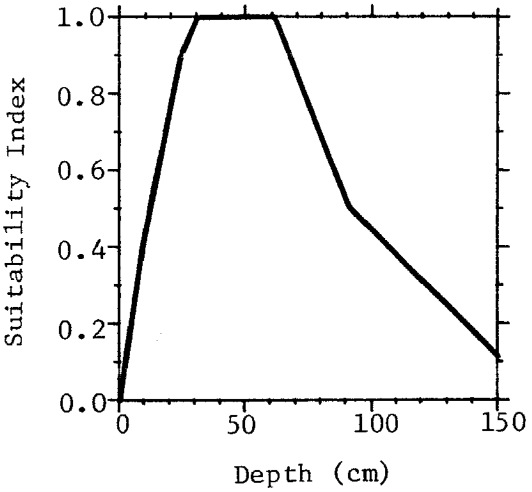
Figure 6. Category one SI curves for chinook salmon fry velocity, depth, and temperature suitability.

Coordinates

x cm/s	x ft/s	y SI
0.0	0.0	0.2
6.1	0.2	0.7
12.2	0.4	1.0
21.3	0.7	1.0
24.4	0.8	0.7
30.5	1.0	0.5
39.6	1.3	0.2
45.7	1.5	0.1
91.4	3.0	0.0
3048.0	100.0	0.0



x cm	x ft	y SI
0.0	0.0	0.0
9.1	0.3	0.4
24.4	0.8	0.9
30.5	1.0	1.0
61.0	2.0	1.0
91.4	3.0	0.5
152.4	5.0	0.1
3048.0	100.0	0.1



x °C	x °F	y SI
0.0	32.0	0.0
2.0	35.6	0.0
7.0	44.6	1.0
14.0	57.2	1.0
16.0	60.8	0.0
30.0	86.0	0.0

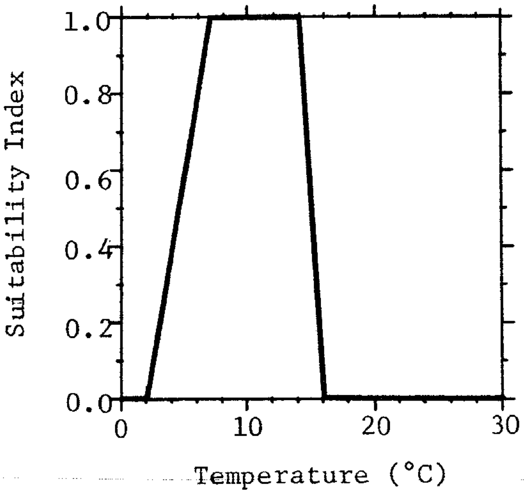
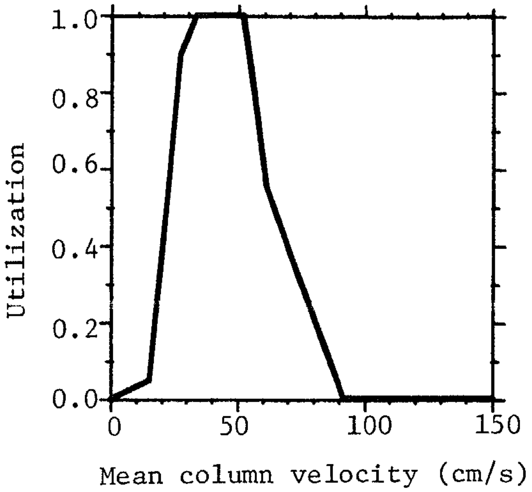


Figure 7. Category one SI curves for chinook salmon juvenile velocity, depth, and temperature suitability.

	Coordinates	
x cm/s	x ft/s	y SI
0.0	0.0	0.00
15.2	0.5	0.05
27.4	0.9	0.90
33.5	1.1	1.00
51.8	1.7	1.00
61.0	2.0	0.55
91.4	3.0	0.00
3048.0	100.0	0.00



x cm	x ft	y SI
0.0	0.0	0.0
9.1	0.3	0.2
24.4	0.8	1.0
36.6	1.2	1.0
42.7	1.4	0.5
61.0	2.0	0.1
3048.0	100.0	0.1

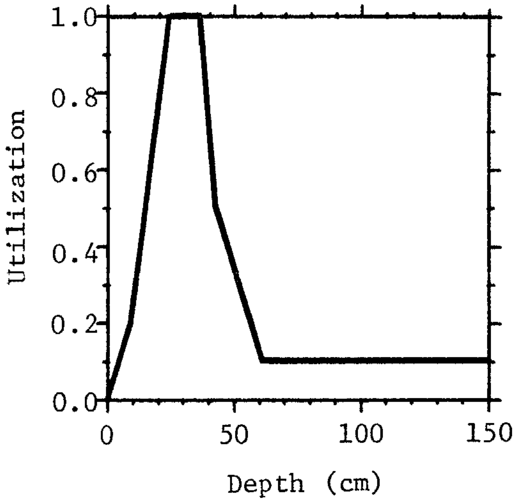
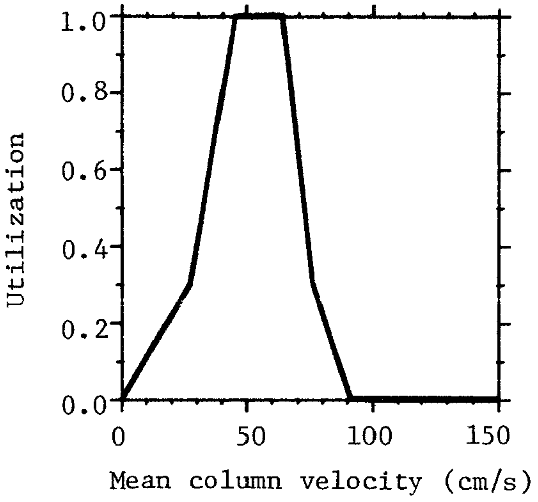


Figure 8. Category two SI curves for spring chinook salmon spawning velocity and depth utilization (n=252; from Sams and Pearson 1963).

	Coordinates	
x cm/s	x ft/s	y SI
0.0	0.0	0.0
27.4	0.9	0.3
45.7	1.5	1.0
64.0	2.1	1.0
76.2	2.5	0.3
91.4	3.0	0.0
3048.0	100.0	0.0



x cm	x ft	y SI
0.0	0.0	0.00
9.1	0.3	0.05
21.3	0.7	1.00
33.5	1.1	1.00
36.6	1.2	0.40
45.7	1.5	0.10
3048.0	100.0	0.10

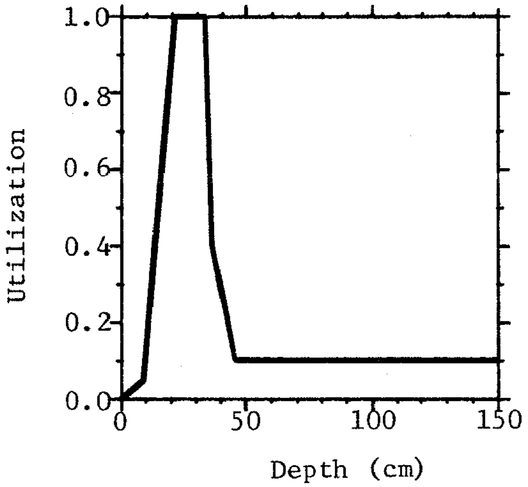
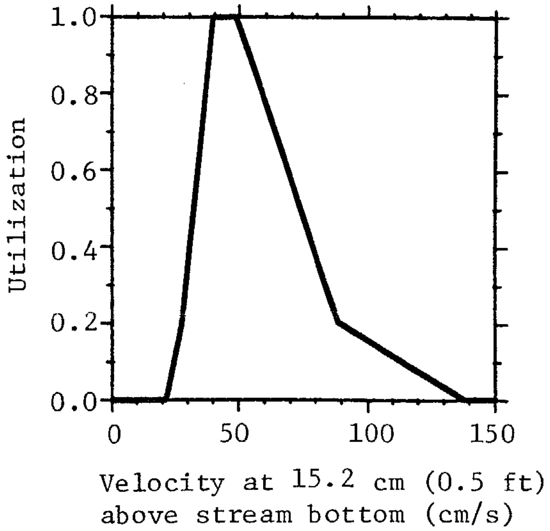


Figure 9. Category two SI curves for fall chinook salmon spawning velocity and depth utilization (n=107; from Sams and Pearson 1973).

Coordinates x cm/s	 x ft/s	 y SI
0.0	0.0	0.0
21.3	0.7	0.0
27.4	0.9	0.2
39.6	1.3	1.0
48.8	1.6	1.0
88.4	2.9	0.2
137.2	4.5	0.0
3048.0	100.0	0.0



x cm	x ft	y SI
0.0	0.0	0.0
9.1	0.3	0.0
18.3	0.6	0.2
24.4	0.8	1.0
54.9	1.8	0.2
67.1	2.2	0.0
3048.0	100.0	0.0

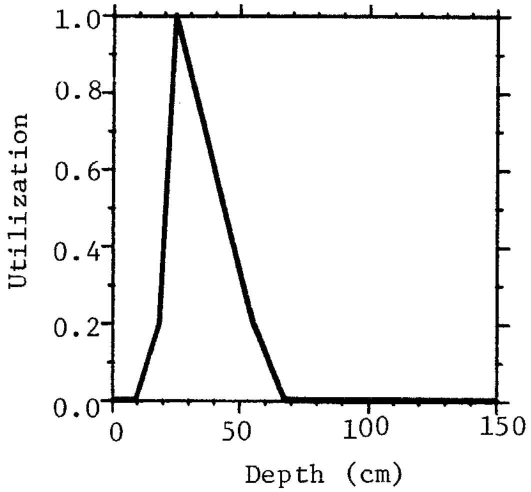
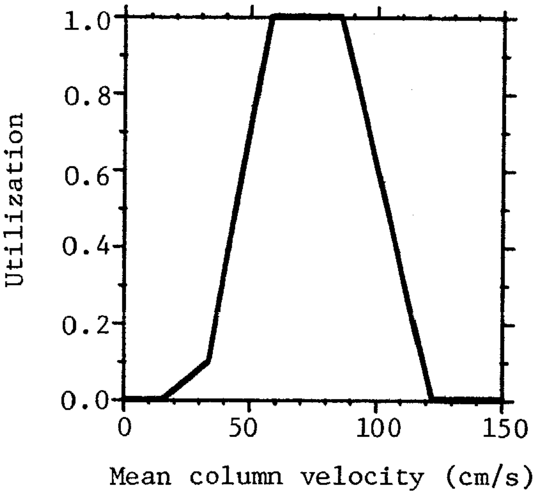


Figure 10. Category two SI curves for fall chinook salmon spawning velocity and depth utilization (n=216; from Vogel 1982).

Coordinates

x cm/s	x ft/s	y SI
0.0	0.0	0.0
15.2	0.5	0.0
33.5	1.1	0.1
57.9	1.9	1.0
85.3	2.8	1.0
121.9	4.0	0.0
3048.0	100.0	0.0



x cm	x ft	y SI
0.0	0.0	0.0
12.2	0.4	0.0
27.4	0.9	1.0
36.6	1.2	1.0
61.0	2.0	0.1
91.4	3.0	0.0
3048.0	100.0	0.0

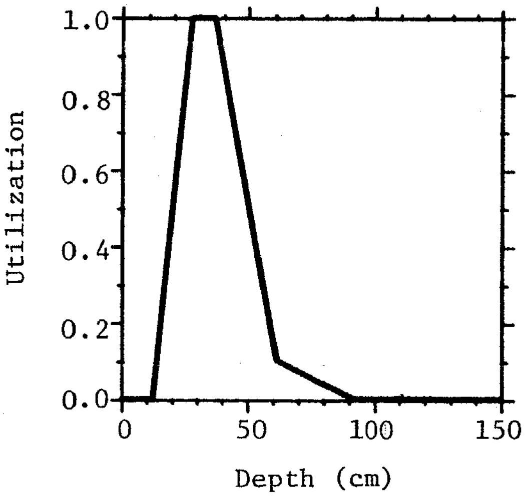
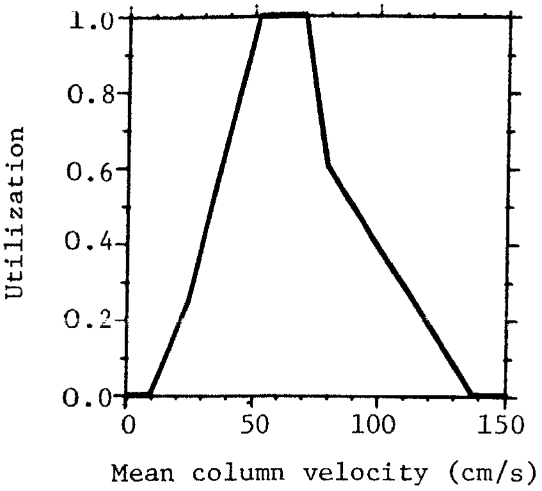


Figure 11. Category two SI curves for spring chinook salmon spawning velocity and depth utilization (n=118; from Stempel 1984).

Coordinates x cm/s	 x ft/s	 y SI
0.0	0.0	0.00
9.1	0.3	0.00
24.4	0.8	0.25
51.8	1.7	1.00
70.1	2.3	1.00
79.2	2.6	0.60
137.2	4.5	0.00
3048.0	100.0	0.00



x cm	x ft	y SI
0.0	0.0	0.0
15.2	0.5	0.0
30.5	1.0	1.0
121.9	4.0	1.0
3048.0	100.0	1.0

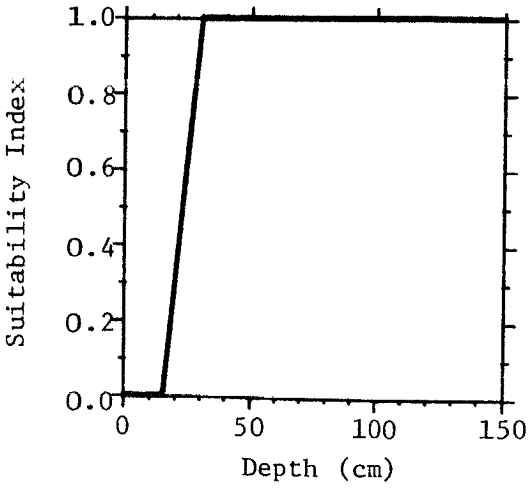
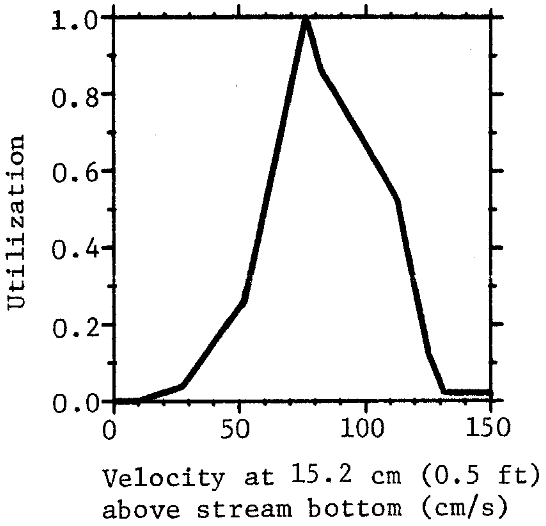


Figure 12. SI curves for chinook salmon spawning velocity (category two) and depth (category one) (n=265; from Vincent-Lang et al. 1984).

Coordinates x cm/s	 x ft/s	 y SI
0.0	0.0	0.00
9.1	0.3	0.00
27.4	0.9	0.04
51.8	1.7	0.26
76.2	2.5	1.00
82.3	2.7	0.86
112.8	3.7	0.52
125.0	4.1	0.12
131.1	4.3	0.02
149.4	4.9	0.02
155.4	5.1	0.00
3048.0	100.0	0.00



x cm	x ft	y SI
0.0	0.00	0.00
15.2	0.50	0.00
22.9	0.75	0.09
53.3	1.75	0.37
68.6	2.25	0.84
99.1	3.25	1.00
114.3	3.75	0.53
160.0	5.25	0.05
216.4	7.10	0.01
219.5	7.20	0.00
3048.0	100.00	0.00

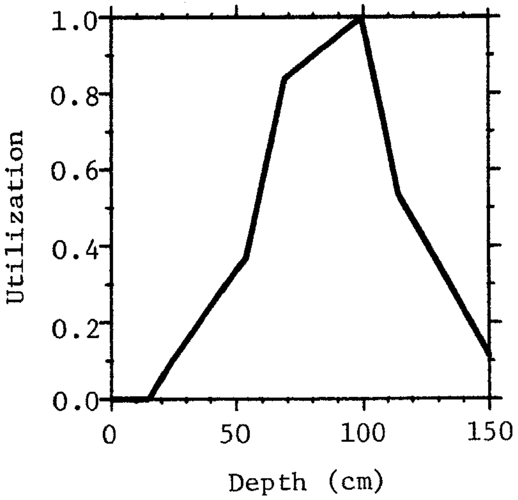
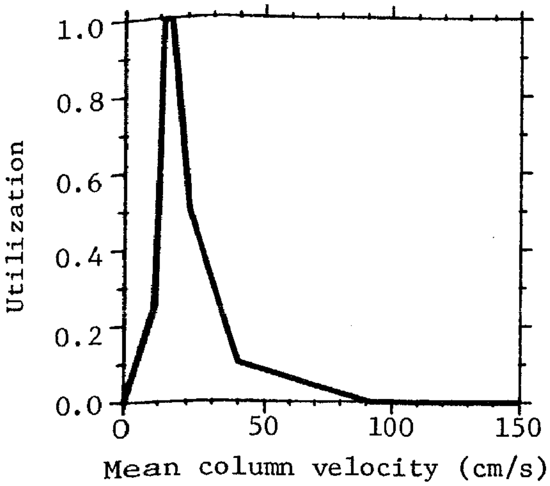


Figure 13. Category two SI curves for chinook salmon spawning velocity and depth utilization (n=436; from Kurko 1977).

Coordinates x cm/s	x ft/s	y SI
0.0	0.0	0.00
9.1	0.3	0.25
12.2	0.4	1.00
15.2	0.5	1.00
21.3	0.7	0.50
39.6	1.3	0.10
91.4	3.0	0.00
3048.0	100.0	0.00



x cm	x ft	y SI
0.0	0.0	0.00
30.5	1.0	0.10
48.8	1.6	0.25
70.1	2.3	1.00
82.3	2.7	1.00
91.4	3.0	0.40
121.9	4.0	0.10
152.4	5.0	0.00
3048.0	100.0	0.00

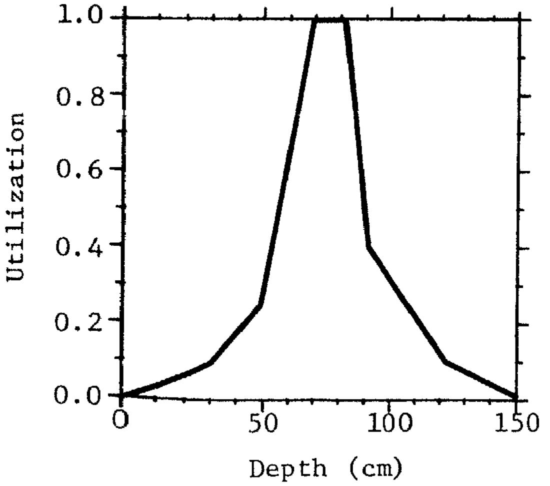
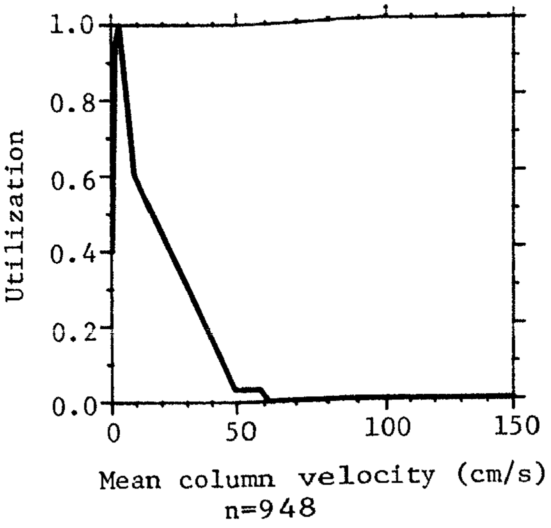


Figure 14. Category two SI curves for chinook salmon fry velocity and depth utilization (n=202; from Stempel 1984).

Coordinates x cm/s	 x ft/s	 y SI
0.0	0.00	0.40
1.5	0.05	0.95
3.0	0.10	1.00
9.1	0.30	0.60
48.8	1.60	0.03
57.9	1.90	0.03
61.0	2.00	0.00
3048.0	100.00	0.00



x cm	x inches	y SI
0.0	0.00	0.00
0.1	0.04	0.40
1.6	0.63	1.00
2.2	0.87	1.00
3.0	1.18	0.20
10.0	3.94	0.30
12.0	4.72	0.05
18.4	7.24	0.10
100.0	39.40	0.10

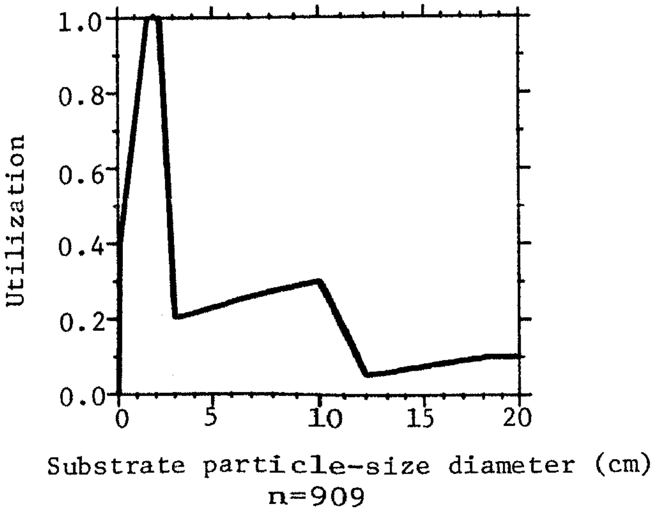
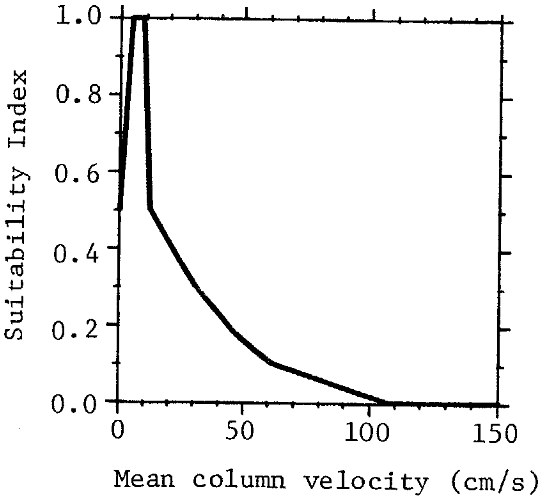


Figure 15. Category two SI curves for chinook salmon fry velocity and substrate utilization (from Burger et al. 1982).

Coordinates		
x cm/s	x ft/s	y SI
0.0	0.00	0.50
4.6	0.15	1.00
9.1	0.30	1.00
12.2	0.40	0.50
30.5	1.00	0.30
45.7	1.50	0.18
61.0	2.00	0.10
106.7	3.50	0.00
3048.0	100.00	0.00



x cm	x inches	y SI
0.0	0.0	0.00
3.0	0.1	0.00
21.3	0.7	1.00
30.5	1.0	1.00
36.6	1.2	0.75
61.0	2.0	0.50
91.4	3.0	0.15
121.9	4.0	0.10
304.8	10.0	0.01
762.0	25.0	0.01
3048.0	100.0	0.00

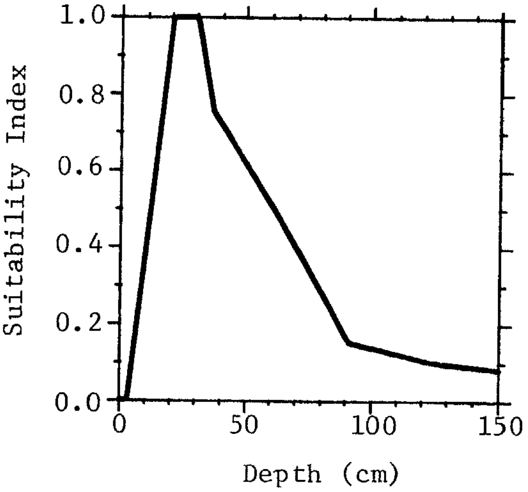
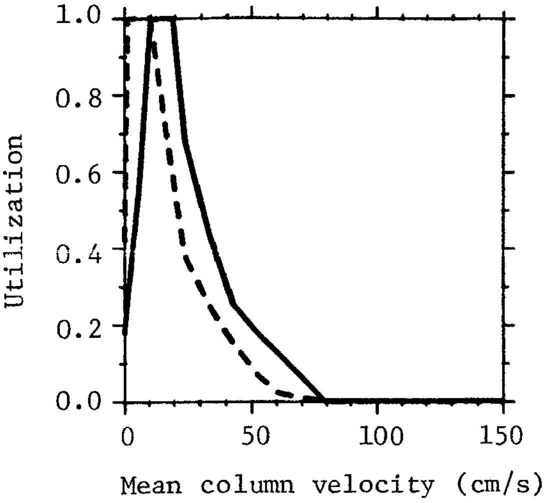


Figure 16. Category one SI curves for chinook salmon fry velocity and depth suitability (from U.S. Fish and Wildlife Service 1985).

x cm/s	x ft/s	Coordinates y SI (clear; solid line)	y SI (turbid; broken line)
0.0	0.00	0.18	0.42
1.5	0.05	-	1.00
6.1	0.20	0.57	-
10.7	0.35	1.00	1.00
15.2	0.50	-	0.80
19.8	0.65	1.00	-
24.4	0.80	0.68	0.38
33.5	1.10	0.44	0.25
42.7	1.40	0.25	0.15
51.8	1.70	0.18	0.07
61.0	2.00	0.12	0.02
70.1	2.30	0.06	0.01
79.2	2.60	0.00	0.00
3048.0	100.00	0.00	0.00



x cm	x ft	y SI (clear; solid line)	y SI (turbid; broken line)
0.0	0.00	0.00	0.00
3.0	0.10	-	1.00
9.1	0.30	0.70	-
16.8	0.55	-	1.00
24.4	0.80	0.85	0.75
32.0	1.05	1.00	-
47.2	1.55	1.00	0.55
54.9	1.80	0.50	-
62.5	2.05	0.30	0.50
91.4	3.00	0.30	0.50
3048.0	100.00	0.30	0.50

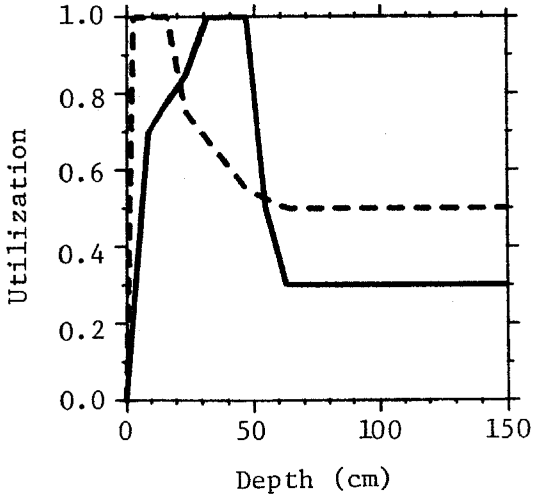
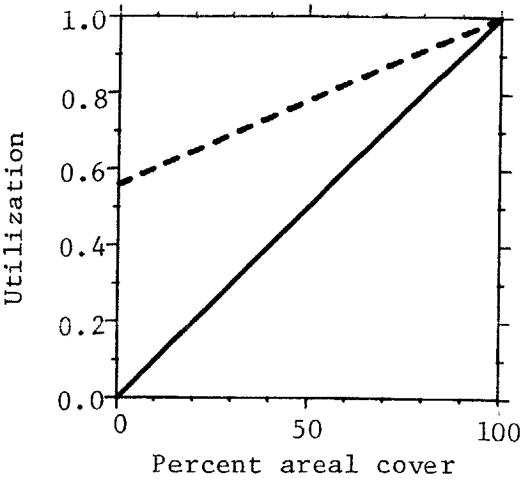


Figure 17. Category two SI curves for chinook salmon juvenile velocity, depth, percent cover, and cover type utilization (from Suchanek et al. 1984).

x	y SI (clear water; solid line)	y SI (turbid; broken line)
	Coordinates	
0	0.0	0.56
50	0.5	-
100	1.0	1.00



x Code	Cover type description	y SI
1	Debris	0.90
2	Undercut bank	1.00
3	Rubble/cobble/boulder	0.20
4	Aquatic vegetation	0.65
5	Large gravel	0.25
6	Overhanging vegetation	0.38
7	Emergent vegetation	0.30
8	No cover	0.01

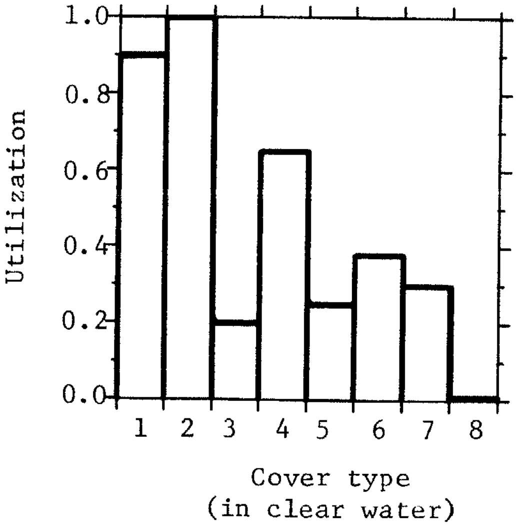
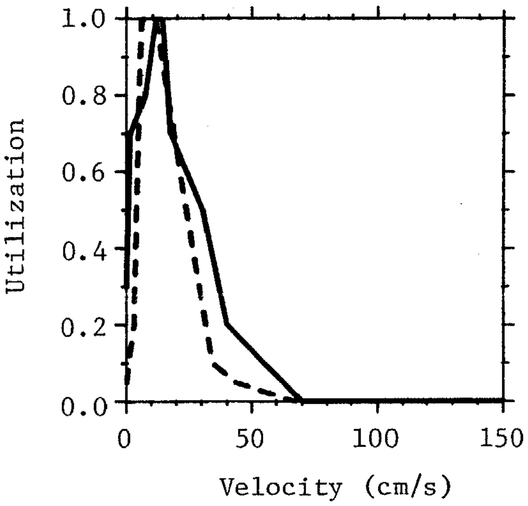


Figure 17. (concluded).

		Coordinates	
x cm/s	x ft/s	y Mean column SI n=947 (solid line)	y Nose SI n=163 (broken line)
0.0	0.00	0.3	0.05
1.5	0.05	0.7	-
3.0	0.10	-	0.20
6.1	0.20	-	1.00
7.6	0.25	0.8	-
12.2	0.40	1.0	1.00
15.2	0.50	1.0	-
18.3	0.60	0.7	-
24.4	0.80	-	0.50
30.5	1.00	0.5	-
33.5	1.10	-	0.10
39.6	1.30	0.2	-
42.7	1.40	-	0.05
67.1	2.20	-	0.00
70.1	2.30	0.0	-
3048.0	100.00	0.0	0.00



x cm	x inches	y SI
0.0	0.00	0.00
0.2	0.08	0.60
1.6	0.63	1.00
2.2	0.87	1.00
2.6	1.02	0.20
9.2	3.62	0.03
10.0	3.94	0.20
18.4	7.24	0.20

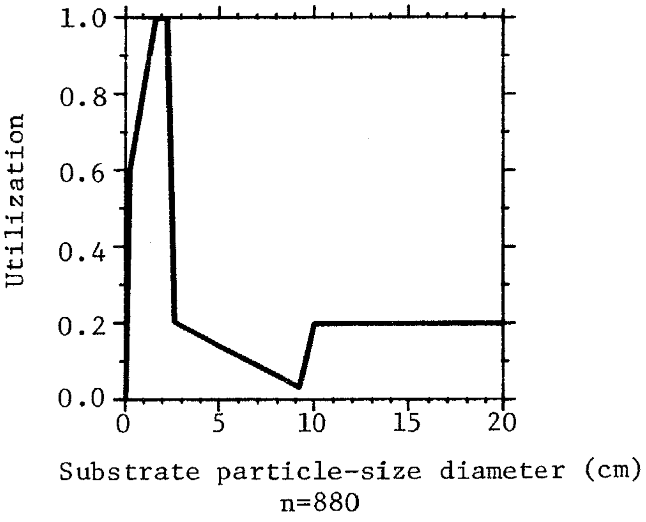
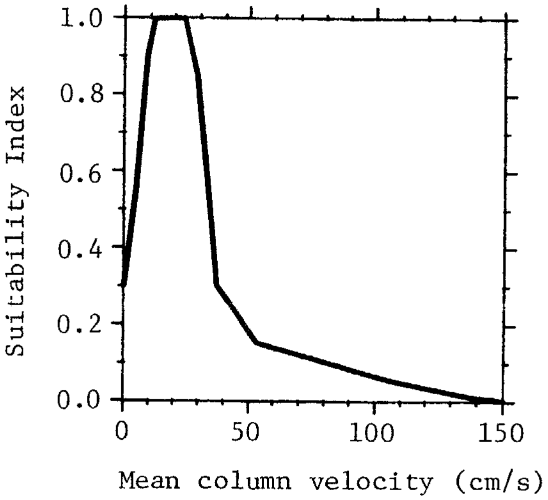


Figure 18. Category two SI curves for chinook salmon juvenile velocity and substrate utilization (from Burger et al. 1982).

	Coordinates	
x cm/s	x ft/s	y SI
0.0	0.00	0.30
4.6	0.15	0.55
9.1	0.30	0.90
12.2	0.40	1.00
24.4	0.80	1.00
29.0	0.95	0.85
36.6	1.20	0.30
53.3	1.75	0.15
106.7	3.50	0.05
137.2	4.50	0.01
152.4	5.00	0.00
3048.0	100.00	0.00



x cm	x ft	y SI
0.0	0.0	0.00
6.1	0.2	0.00
24.4	0.8	0.90
30.5	1.0	1.00
76.2	2.5	1.00
91.4	3.0	0.75
121.9	4.0	0.20
152.4	5.0	0.10
304.8	10.0	0.10
762.0	25.0	0.01
3048.0	100.0	0.01

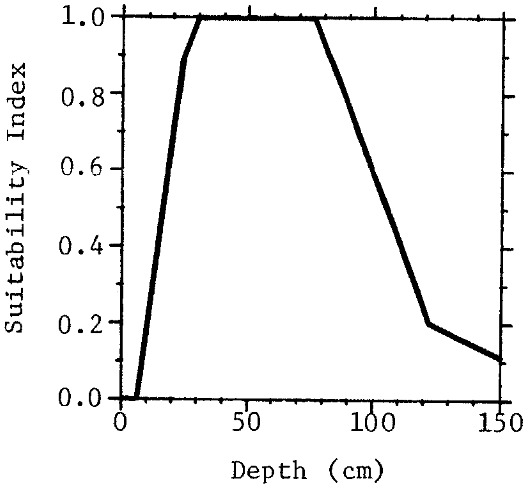


Figure 19. Category one SI curves for chinook salmon juvenile velocity and depth suitability (from U.S. Fish and Wildlife Service 1985).

Spawning migration. The time period during which chinook salmon migrate upstream to spawn is dependent on locale, and the investigator will have to determine the time period and the stream segments within which migration habitat is required. Little information was found in the literature concerning migration habitat requirements of chinook salmon. We assume that the variables that may limit migration in most instances will include depth, velocity, and temperature.

SI curves for adult chinook passage (Figure 2) are category one and were taken from several sources. Sautner et al. (1984) selected chum salmon for development of passage criteria in the Susitna River, Alaska, because chum were determined to be more susceptable to migration obstacles than were other salmon species within the study area. Sautner et al. assumed that the length of a passage reach at limiting water depths was the most important variable in their area. Since passage criteria were not found for chinook salmon, the authors assume that criteria for chum salmon will satisfy chinook migration requirements. Information on maximum water velocities that can be tolerated by migrating chinook adults was not found, and investigators will need to develop their own criteria for use in areas where velocity may be a problem. The SI curve for relative suitability of migration temperatures is based on several studies (Meyer et al. 1984) and may require tailoring for specific spawning runs in areas of interest.

Burger et al. (1982) collected data to characterize migration holding areas in the Kenai River, Alaska. Chinook salmon ranging in length from 74 to 117 cm (29 to 46 inches) were radio-tagged and followed to spawning areas. Depths and velocities were measured at point locations of holding adults (n = 54). Velocities were measured at 0.2 of the total depth from the bottom, the point closest to where the individual fish were assumed to be located. The category two SI curves for migration holding (Figure 3) were developed by connecting the midpoints of frequency histogram class intervals.

Spawning and egg incubation. The time period during which spawning and egg incubation habitat is required for chinook salmon is variable (depending on locale), and should be determined before habitat quantification and simulation are conducted. SI curves available should be tailored to the time period and study sites of interest.

There are two approaches for determining the amount of spawning and egg incubation habitat for a stream reach. One approach treats spawning and egg incubation as separate life stages, each with its own set of criteria, and assumes that weighted useable area (WUA) does not vary by more than 10% during the spawning and egg incubation periods. The other approach measures effective spawning habitat (Milhous 1982) and is recommended when WUA does vary by more than 10% (as a result of streamflow variation), from the onset of spawning to the end of the fry emergence period.

Effective spawning habitat is habitat that remains throughout the spawning, egg incubation, and intergravel fry period. In a given reach, the area of effective spawning habitat is equal to the area of suitable spawning habitat minus the spawning habitat area that was dewatered, scoured, or silted-in during egg incubation. Factors to consider when determining habitat reduction because of dewatering include the depth of the eggs and fry within the streambed, temperature and dissolved oxygen requirements of incubating eggs, and fry emergence requirements. To determine habitat reduction from scouring, the critical scouring velocity (Figure 4) can be determined by:

$$V_c = 22.35 \left(\frac{d_{bf}}{D65}\right)^{1/6} [K_s(S_s - 1)]^{1/2} \ (D65)^{1/2}$$

where V_c = critical velocity in ft/s

d_{bf} = average channel depth (ft) at bankfull discharge

D65 = substrate particle size diameter (ft) not exceeded by 65% of the particles

K_s = 0.080, a constant pertaining to the general movement of the surface particles

S_s = specific gravity of the bed material, and ranges from 2.65 to 2.80

Factors to consider when determining habitat reduction from siltation include suspended sediment concentrations, minimum velocities necessary to prevent siltation (Figure 4), and dissolved oxygen concentrations among the embryos. More detailed information about the analysis of effective spawning habitat is presented in Milhous (1982).

At present there are no standard methods for collecting or analyzing habitat criteria data. Numerous investigators have compiled chinook spawning habitat information and have developed criteria using a variety of techniques (Chambers et al. 1955; Sams and Pearson 1963; Smith 1973; Kurko 1977; Hoffman 1979; Estes et al. 1981; Vogel 1982; Crumley and Stober 1984; Estes 1984; Stempel 1984; Vincent-Lang et al. 1984; U.S. Fish and Wildlife Service 1985). The curves selected for inclusion in this report (Figures 8-13) have two things in common. First, they are all category two (utilization) curves fit to frequency histograms and are based on at least 100 field observations. Second, all of the data represent observations of "active" redds where females were observed fanning or cutting, or where other types of spawning behavior were observed. All depth and velocity measurements were taken on, immediately upstream, or immediately adjacent to each active redd. Criteria developed in cases where spawners were absent were not included because conditions during the survey may have been different from conditions during spawning. Criteria that represented average, and not redd-specific, conditions within a spawning area were not included because they usually desensitize the PHABSIM model. Category one curves were not included only because such curves are developed when field data are unavailable. Category three (preference) curves certainly would have been included, but none were available as of this writing.

The category two curves (Figures 8-13) selected for this report have some differences among them. Most of the differences may be primarily a function of habitat availability. Spawners may select the best available redd sites within the confines of their natal stream, but are unable to select optimal conditions if those conditions are not available. Another possible explanation for differences in the curves may be that species habitat preferences differ among different stocks or in different parts of the country. Differences in data collection, analysis, and interpretation techniques may also have affected the configuration of the curves. In the future, the development of standardized methods for the generation of category three curves may help to answer many of the questions concerning differences often found among category two curves.

All of the utilization curves developed for chinook spawning velocity and depth were based on data collected either from relatively small streams, or from larger streams during low-flow conditions. Sampling deeper, faster water is difficult and often unsafe. Therefore, the curves may be biased towards relatively shallow, low velocity water. Following are brief descriptions of the background for each curve.

Sams and Pearson (1963) collected spawning velocity and depth utilization data from several small streams in Oregon. Depth and mean column velocity measurements were taken either 30.5 cm (1.0 ft) upstream or directly alongside each active redd (where spawners were present). Data for spring chinook redds ($n = 252$) were collected in 1961 from the Little North Santiam River ($n = 59$; 0.7 to 1.0 m^3/s or 25 to 35 cfs during study), and the Molalla River ($n = 52$; 1.0 to 1.3 m^3/s or 35 to 45 cfs during study); and in 1962 from the South Fork McKenzie River ($n = 141$; 6.5 m^3/s or 230 cfs during study). Data for fall chinook redds ($n = 107$) were collected during 1962 from Humbug Creek ($n = 27$), East Humbug Creek ($n = 22$), Tillamook River ($n = 22$), and Moon Creek ($n = 36$). Because of low variance, the 95% confidence limits for the mean spawning velocities and depths were assigned SI values equal to 1.0, and all values outside the 95% confidence limits were normalized to the highest frequency. The curves (Figures 8-9) were then smoothed using professional judgement.

Vogel (1982) collected data in Battle Creek, California, during October 1982. Depth and velocity measurements (at 15.2 cm or 0.5 ft above the substrate) were taken immediately adjacent to active or fresh chinook redds ($n = 216$). Frequency analyses of the data were performed and category two curves (Figure 10) were developed using methods outlined in Bovee and Cochnauer (1977). Velocities available ranged from 0.0 to 137.3 cm/s (0.0 to 4.5 ft/s), and depths available ranged from 0.0 to 67.1 cm (0.0 to 2.2 ft).

Stempel (1984) collected data for spring chinook salmon spawning ($n = 118$) in the upper Yakima and American rivers in south-central Washington during August and October 1983. Snorkeling was used to locate active redds; depth and mean column velocity were measured on or adjacent to each redd. Category two curves (Figure 11) were developed using methods from Bovee and Cochnauer (1977) and smoothed using professional judgement. Velocities available ranged from 0 to 122 cm/s (0 to 4 ft/s), and depths available ranged to 158.6 cm (5.2 ft). Streamflow during data collection was approximately 7.1 m^3/s (250 cfs).

Vincent-Lang et al. (1984) collected data (n = 262) from Portage Creek (n = 137) and the Indian River (n = 125), tributaries of the Susitna River in Alaska, during July and August 1983. Active redds were located by visual observation from the stream bank, and depth and mean column velocity were measured at the upstream edge of each redd. Data were plotted as frequency histograms with various increment sizes and starting values. Curves (Figure 12) were fit to the "best" histograms, i.e., those histograms with the best combination of the lesser sample variances and coefficients of variation for the frequency counts, and the lesser irregular fluctuations and peakedness. The depth curve was modified based on the assumption that depths from 48.8 to 122.0 cm (1.6 to 4.0 ft) will not limit spawning activities.

Kurko (1977) collected data (n = 436) from the upper Skagit River in north-central Washington during September and October 1975 and 1976. Boat surveys were used to locate spawners; velocities (at 15.2 cm or 0.5 ft above the substrate) and depths were measured at the upstream lip of each active redd. Curves (Figure 13) were fit by hand to frequency histograms. Flows during spawning generally ranged from 56.6 to 226.5 m^3/s (2,000 to 8,000 cfs), although observations were made during extreme low-water periods.

Category one curves (Figure 5) for spawning velocity and depth were developed as a composite of the category two curves, in the event that investigators cannot develop their own curves or verify any of the category two curves in this publication. The curves are meant only to represent relative suitability for depth and velocity, not preference. The curves should be considered "interim" until category three curves become available.

The category one curves for chinook spawning substrate suitability (Figure 5) were taken from the HSI model section of this report (V_8 and V_{10}). Literature sources used in developing these curves may be found in Table 1.

No evidence was found in the literature to suggest that cover is utilized by spawning chinook salmon. Therefore, we assume that a cover curve is not necessary for IFIM analyses of spawning habitat.

The category one SI curve for chinook spawning temperature (Figure 5) was taken from the HSI model section of this report (V_6), and it may require modification before use in a specific locale.

Little information was found in the literature concerning velocity, substrate, and depth requirements of incubating embryos. Until further information becomes available, we assume that the SI curves for spawning velocity, depth, and substrate will satisfy habitat requirements for egg incubation. No cover curve is deemed necessary because suitable substrate should provide suitable cover for embryos. The temperature curve for egg incubation was taken from the HSI model section (V_7) and may have to be tailored to each given set of conditions.

Fry. After hatching, fry may remain in the gravel for 4 to 6 weeks (Dill 1968). The habitat requirements for intergravel fry are assumed to be the same as for incubating embryos. Effective spawning habitat analyses may be used to determine how much of the suitable spawning/egg incubation habitat remained suitable for intergravel fry, from the onset of spawning through the end of the fry emergence period.

Upon emergence, some fry may begin seaward migration immediately, whereas others may remain in freshwater for up to 3 years. Postemergent fry are considered to be individuals less than or equal to 5.1 cm (2.0 inches) in length. The category one curves for velocity and depth (Figure 6) developed for IFIM analyses of chinook salmon fry habitat are a composite of category one and two criteria developed by Burger et al. (1982), Stempel (1984), Glova and Duncan (1985), and U.S. Fish and Wildlife Service (1985).

Stempel (1984) used snorkeling to locate fry (n = 202; generally 2.5 to 7.6 cm or 1 to 3 inches in length at age 6 months) in the upper Yakima and American Rivers of Washington. Mean column velocity and depth were measured at each location, and category two curves were developed (Figure 14). See the IFIM section on spawning and egg incubation for further information.

Burger et al. (1982) collected data from the mainstem Kenai River from 1979 through 1981. Chinook fry (n = 948; 3.6 to 5.1 cm or 1.4 to 2.0 inches in length) and juveniles (n = 947; 5.1 to 10.2 cm or 2 to 4 inches in length) were located by direct observation or electroshocking from the river mouth to river kilometer 75 (river mile 45). Sample sites were located every other 1.7 km (1 mile) and were sampled every month from April to October. Mean column velocity, nose velocity (where possible), and substrate were measured at each point location where a fish was observed or captured. Category two curves were developed for fry and juveniles (Figures 15 and 18). Mean annual flow for the Kenai River is 141.6 m^3/s (5,000 cfs). Associated fish species included sockeye salmon, coho salmon, pink salmon, Dolly Varden, sticklebacks, sculpins, and rainbow trout.

The U.S. Fish and Wildlife Service (1985) developed category one SI curves for chinook fry (3.5 to 5.0 cm or 1.4 to 2.0 inches FL) and juvenile (5.1 to 10.2 cm or 2.0 to 4.0 inches in length) velocity and depth suitability. The curves (Figures 16 and 19) were derived from two years of American River field studies, professional judgement, Bovee (1978), and a Sacremento River habitat preference study. All curves were meant to represent habitat preferences in the lower American River of California.

Glova and Duncan (1985) collected data from the Rakaia River and two other braided rivers in New Zealand. Electroshocking was used in wadeable areas; deeper areas were seined. Depth, velocity, and substrate measurements were taken where chinook fry (n = 530; less than or equal to 5.5 cm or 2.2 inches FL) and juveniles (n = 870; greater than 5.5 cm or 2.2 inches FL) were collected. Data were analyzed and curves were developed using methods outlined in Bovee (1978) and Orth and Maughn (1982). The SI curves could not be reproduced because they were too small to take x,y coordinate pairs from them. Glova and Duncan found that chinook fry occurred in shallow, low-velocity areas along the river margin, near vegetation and debris. Juveniles inhabited deeper waters, usually backwaters or pools, with velocities ranging from 20 to 30 cm/s (0.7 to 1.0 ft/s) and depths greater than 50 cm (1.6 ft).

No category one curves were developed for postemergent fry substrate or cover. Burger et al. (1982), Glova and Duncan (1985), and Lister and Genoe (1970) found most fry over gravel and cobble, whereas Everest and Chapman (1972) observed fry associated with silt, sand, and rock. Chinook fry may prefer certain substrate or cover types and amounts, but insufficient quantitative information was available for curve development. The SI curves for fry temperature suitability (Figure 6) were taken from Meyer et al. (1984).

Juvenile. Chinook salmon juveniles are considered to be individuals greater than 5.1 cm (2.0 inches) in length. In areas where fry migrate to the sea immediately after emerging from the gravel, juvenile habitat is not required. In other areas, juvenile habitat may be required year round. The category one SI curves for juvenile velocity and depth suitability (Figure 7) are a composite of curves developed by Burger et al. (1982), Suchanek et al. (1984), Glova and Duncan (1985), and U.S. Fish and Wildlife Service (1985).

Suchanek et al. (1984) collected data from the Susitna River tributaries, sloughs, and side channels between the Chulitna River confluence and Devil's Canyon in Alaska during May through October 1983. Twenty-three sites were sampled from 3 to 7 times and 12 sites were sampled only once or twice. Shoreline and midchannel cells 1.8 m by 15.2 m (6 ft by 50 ft) were sampled at each site using electroshocking in clear water and seining in turbid water. Average depth, velocity, percent cover, and dominant cover type were characterized for each cell. Data were pooled over site and season separated by gear type, and category two curves (Figure 17) were developed for mean column velocity, depth, percent cover, and cover type for both clear (n = 871 cells; less than 30 NTU) and turbid (n = 389 cells; greater than 30 NTU) water. The curves are based on analyses of variance and least squares regressions used to analyze differences in mean catch per cell by habitat attribute values. Over 99% of the fish captured were age 0+ (no size classes defined) and, therefore, the curves may be biased toward smaller juveniles.

A description of data collection and analyses methods used by Burger et al. (1982), Glova and Duncan (1985), and U.S. Fish and Wildlife Service (1985) may be found in the IFIM section on fry in this report. Burger et al. defined juveniles (n = 947) as individuals varying in length from 5.1 to 10.2 cm (2 to 4 inches); Glova and Duncan defined them as greater than 5.5 cm (2.2 inches) FL; and U.S. Fish and Wildlife Service defined them as 5.1 to 10.2 cm (2 to 4 inches). The curves developed (Figures 7 and 17-19) should satisfy juvenile nonwinter habitat requirements, assuming juveniles will migrate out of a system by the time they attain a length of 10.2 cm (4.0 inches). Otherwise, SI curves will have to be developed for larger juveniles.

No category one curves were developed for substrate or cover. Investigators may wish to use curves (Figures 17 and 18) developed by Burger et al. (1982) and Suchanek et al. (1984), or they may want to develop their own. The category one SI curve for juvenile temperature suitability (Figure 7) was taken from Meyer et al. (1984). No curves were developed for smolt outmigration. We assume that spawning migration and passage curves (Figures 2 and 3) will satisfy outmigration requirements.

Summary. There exists a great deal of information pertaining to chinook salmon habitat requirements and preferences that has not been included in this report. Information included here is meant only to assist investigators with instream flow studies. Before approaching an instream flow study, the development of a basin-wide species periodicity chart is recommended, to assist in identifying study-specific research needs and potential habitat vs. development conflicts. Investigators may wish to develop their own SI curves, or select, verify, and/or modify curves contained in this report, for use in their specific study area.

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A review and synthesis of existing information were used to develop a Habitat Suitability Index (HSI) model and instream flow suitability curves for Chinook salmon (Oncorhynchus tshawytscha). The model consolidates habitat use information into a framework appropriate for field application, and is scaled to produce an index between 0.0 (unsuitable habitat) and 1.0 (optimum habitat). HSI models are designed to be used with Habitat Evaluation Procedures previously developed by the U.S. Fish and Wildlife Service.

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