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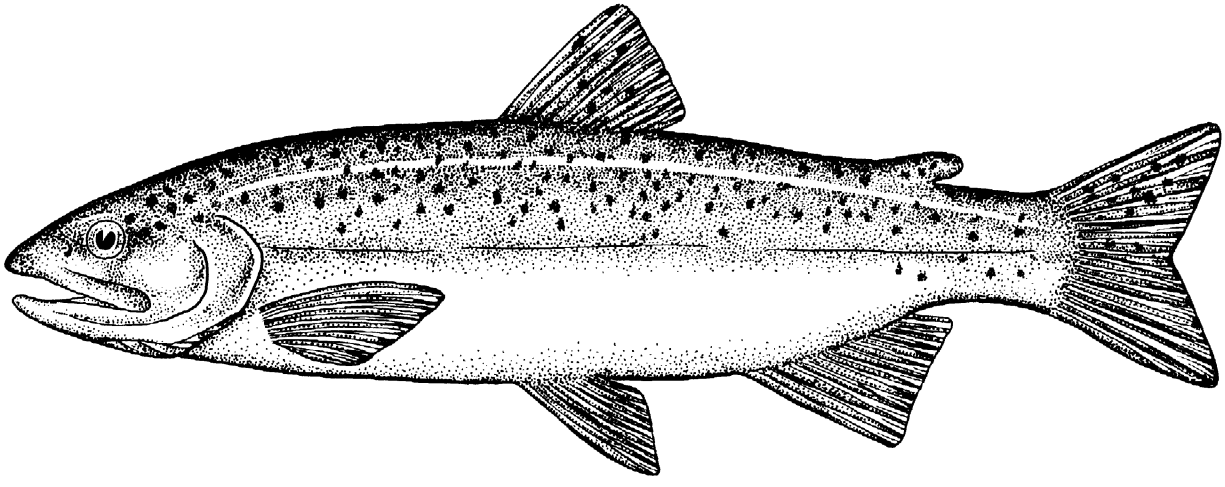
SEPTEMBER 1983

HABITAT SUITABILITY INDEX MODELS: COHO SALMON



Fish and Wildlife Service

U.S. Department of the Interior

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HABITAT SUITABILITY INDEX MODELS: COHO SALMON

by

Thomas E. McMahon
Habitat Evaluation Procedures Group
Western Energy and Land Use Team
U.S. Fish and Wildlife Service
2627 Redwing Road
Ft. Collins, CO 80526

Western Energy and Land Use Team
Division of Biological Service
Research and Development
Fish and Wildlife Service
U.S. Department of the Interior
Washington, DC 20240

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PREFACE

The habitat use information and Habitat Suitability Index (HSI) models presented in this document are intended for use in impact assessment and habitat management activities. Literature concerning a species, habitat requirements and preferences is reviewed and then synthesized into subjective HSI models, which are scaled to produce an index between 0 (unsuitable habitat) and 1 (optimal habitat). Assumptions used to transform habitat use information into these mathematical models are noted and guidelines for model application are described. Any models found in the literature which may also be used to calculate an HSI are cited. A section presenting Instream Flow Incremental Methodology (IFIM) will be included in this series in the near future. The IFIM section will include a discussion of Suitability Index (SI) curves, as are used in IFIM and a discussion of SI curves available for the IFIM analysis of coho salmon habitat.

Use of habitat information presented in this publication for impact assessment requires the setting of clear study objectives. Methods for modifying HSI models and recommended measurement techniques for model variables are presented in Terrell et al. (1982).[1] A discussion of HSI model building techniques is presented in U.S. Fish and Wildlife Service (1981).[2]

The HSI model presented herein is the combination of hypotheses of species-habitat relationships, not statements of proven cause and effect relationships. Results of model performance tests, when available, are referenced; however, models that have demonstrated reliability in specific situations may prove unreliable in others. For this reason, the U.S. Fish and Wildlife Service encourages model users to send comments and suggestions to help increase the utility and effectiveness of this habitat-based approach to incorporate the coho salmon in fish and wildlife planning. Please send comments to:

Habitat Evaluation Procedures Group
Western Energy and Land Use Team
U.S. Fish and Wildlife Service
2627 Redwing Road
Fort Collins, CO 80526

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[1]Terrell, J. W., T. E. McMahon, P. D. Inskip, R. F. Raleigh, and K. L. Williamson. 1982. Habitat suitability index models: Appendix A. Guidelines for riverine and lacustrine applications of fish HSI models with the Habitat Evaluation Procedures. U.S. Dept. Int., Fish Wildl. Serv. FWS/OBS-82/10.A. 54 pp.

[2]U.S. Fish and Wildlife Service. 1981. Standards for the development of habitat suitability index models. 103 ESM. U.S. Dept. Int., Fish Wildl. Serv., Div. Ecol. Serv. n.p.

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COHO SALMON (*Oncorhynchus kisutch*)

HABITAT USE INFORMATION

General

The coho salmon (*Oncorhynchus kisutch*) is native to the northern Pacific Ocean, spawning and rearing in streams from Monterey Bay, California, to Point Hope, Alaska, and southward along the Asiatic coast to Japan. Its center of abundance in North America is from Oregon to Alaska (Briggs 1953; Godfrey 1965; Hart 1973; Scott and Crossman 1973). Coho salmon have been successfully introduced into the Great Lakes and reservoirs and lakes throughout the United States to provide put-and-grow sport fishing (Scott and Crossman 1973; Wigglesworth and Rawson 1974). No subspecies of coho salmon have been described (Godfrey 1965).

Age, Growth, and Food

Coho salmon typically return to spawn in freshwater at ages III or IV at lengths and weights ranging from 45 to 60 cm and 3.5 to 5.5 kg, respectively (Shapovalov and Taft 1954; Godfrey 1965; Scott and Crossman 1973). Coho from Alaska tend to be older and larger at spawning than those further south due to a longer period of freshwater residence (Drucker 1972; Crone and Bond 1976). A significant percentage of spawning runs, particularly in the southern portion of the coho's range, may consist of precocious males (jacks) that mature and return to spawn after only 6 to 9 months in the ocean (Shapovalov and Taft 1954).

Growth rate of coho during freshwater rearing is variable both between and within streams (Drucker 1972; Crone and Bond 1976) and is probably determined, to a large extent, by food availability and temperature. Size, as a function of growth, may play an important role in escapement and survival rate in coho populations; larger seaward migrant coho (smolts) have a higher probability of returning as adults and are larger and more fecund than smaller individuals of a cohort (Crone and Bond 1976; Bilton 1978).

Young coho feed mainly on drifting aquatic and terrestrial insects (Demory 1961; Mundie 1969; Scott and Crossman 1973). As they grow, coho become increasingly piscivorous, preying primarily on salmonid fry (Scott and Crossman 1973). In the ocean or in lakes and reservoirs, coho feed on fish and crustaceans (Grinols and Gill 1968; Hart 1973; Scott and Crossman 1973; Healey 1978). Coho do not feed during spawning migrations.

Reproduction

Coho salmon return to natal streams to spawn from midsummer to winter, depending on latitude. In the southern part of the range, spawning occurs in December and January (Briggs 1953; Shapovalov and Taft 1954). In Alaska, spawning occurs in October (Drucker 1972; Crone and Bond 1976) and, in the Great Lakes, in early September - October (Scott and Crossman 1973). Coho in North America migrate upstream during a single fall run, unlike other salmon, which may migrate upstream in multiple runs throughout the year (Scott and Crossman 1973). Entry into freshwater often coincides with rises in streamflow, particularly in streams with low summer flows (Shapovalov and Taft 1954).

Spawning behavior of coho has been summarized by Morrow (1980). Spawning occurs primarily in moderate-sized coastal streams and tributaries of larger rivers. Coho do not utilize main channels of large rivers for spawning as heavily as do chinook (O. tshawytscha) or intertidal reaches as heavily as do chum (O. keta) and pink (O. gorbuscha) salmon (Scott and Crossman 1973). Supplementation of declining runs of wild spawning stocks with hatchery fish is increasing in the Northwest (Fulton 1970; Korn 1977).

Incubation period varies inversely with temperature and usually lasts 35 to 50 days (Shapovalov and Taft 1954). Fry emerge 20 to 25 days after hatching (Mason 1976a).

Freshwater Residence

Coho fry emerge from the gravel from early March to mid-May. Newly emerged fry aggregate along stream margins, in shallow pools, and in backwaters and eddies (Lister and Genoe 1970; Stein et al. 1972). Fry gradually move into deeper pools, where they become aggressive and territorial. Fry unable to hold a territory emigrate downstream into the ocean (Hartman et al. 1982) or elsewhere in the stream system (Shapovalov and Taft 1954) because of intraspecific competition for food and space (Chapman 1966a). Coho that emigrate in their first spring or summer of life as age 0 fish [usually < 40 mm fork length (FL)] often constitute a major portion of the seaward migrants, but their probability of returning as adults is extremely low (Crone and Bond 1976; Hartman et al. 1982). Otto (1971) demonstrated that age 0 coho are poorly equipped physiologically to survive and grow in the high salinities encountered in the ocean.

Scales from returning adults indicate that the vast majority of coho reside in freshwater for at least 1 year prior to seaward migration. In the southern part of the range, coho commonly remain in freshwater for 1 to 2 years (Shapovalov and Taft 1954; Godfrey 1965). In Alaska, freshwater residence lasts from 2 to 4 years (Drucker 1972; Crone and Bond 1976).

Smoltification

Myriad processes and factors initiate, control, and affect parr-smolt transformation (smoltification) in coho and other anadromous salmonids. An important requirement of hatchery or naturally produced coho juveniles is that

the resulting smolts be fully able, behaviorally and physiologically, to migrate to the sea, grow, develop normally, and return to their native stream and successfully spawn. Among the environmental factors that influence smoltification, photoperiod, temperature, and flow are especially critical (Parry 1960; Hoar 1965; Clarke et al. 1978; Clarke and Shelbourn 1980; Wedemeyer et al. 1980).

Smoltification and seaward migration in coho occurs in the spring (Shapovalov and Taft 1954; Drucker 1972; Crone and Bond 1976), with some exceptions (Chapman 1962). Migration often follows periods of rapid temperature warming (Shapovalov and Taft 1954). Coho smolts in California are reported to migrate to sea in April - May (Shapovalov and Taft 1954); in southeast Alaska, migration peaked in mid-June (Crone and Bond 1976).

Parr-smolt transformation is primarily a function of size, rather than of age. Minimum size for successful smoltification in coho is near 100 mm FL (Shapovalov and Taft 1954; Drucker 1972; Crone and Bond 1976). This size corresponds closely to the 90 mm threshold size of coho for maximum salinity tolerance (Conte et al. 1966). Smaller coho may show signs of transformation to smolts (e.g., silvery color, increased buoyancy, and salinity tolerance), but other critical aspects of the process are usually lacking (e.g., migratory behavior), and they do not develop fully until the threshold size is attained (Wedemeyer et al. 1980).

Due to the reduction in spawning habitat and spawning runs, natural reproduction of coho salmon is increasingly supplemented by release of hatchery-reared smolts. However, a perennial problem in the use of hatchery-produced juvenile salmonids is that ocean survival is often below estimated survival of naturally produced smolts. The failure to produce good quality smolts centers on the release of fish at a size, age, and time unsuitable for their ocean survival and on their exposure to environmental conditions that adversely affect growth and survival. Wedemeyer et al. (1980) have reviewed this problem in depth and propose guidelines for rearing and release of hatchery smolts to maximize the number returning as adults.

Specific Habitat Requirements

Coho salmon utilize a variety of freshwater habitats and tolerances and requirements change with season and age. Although most developmental changes and movements to different habitats are gradual, it is useful to delineate the freshwater life cycle into four distinct life stages and to specify factors assumed to affect habitat quality for each life stage. These life stages are defined as follows:

1. Adult. Sexually mature coho migrating from the ocean to natal stream to spawn.

2. Spawning/embryo/alevin. From period of egg deposition to hatching and emergence of fry from redds (Alevins = yolk-sac fry).

3. Parr. Fry (age 0) and juvenile (age I+) coho residing in rearing streams.

4. Smolt. Seaward migrant juveniles undergoing parr-smolt transformation.

Adult. Accessibility of the spawning stream and water quality appear to be the major factors affecting coho during upstream migration. Dams may completely block upstream passage, and other physical features may become impossible to cross at low (e.g., debris jams or waterfalls) or high (e.g., excessive velocities) flows (Reiser and Bjornn 1979). Thompson (1972) recommended a minimum depth of 0.18 m and a maximum velocity of 244 cm/sec as criteria for successful upstream migration of adult coho.

Water quality can affect upstream migration of coho through direct mortality, increasing the susceptibility of the coho to diseases, or adversely altering the timing of the migration and rate of maturation (Holt et al. 1975). Temperatures ≥ 25.5° are lethal to migrating adults (Bell 1973). Sublethal temperatures may result in major prespawning mortalities through activation of latent infections (Wedemeyer 1970). Disease infection rates in coho increase markedly at temperatures above 12.7° C (Fryer and Pilcher 1974; Holt et al. 1975; Groberg et al. 1978). Temperatures ≤ 13° C have been recommended to minimize prespawning mortality of coho during upstream migration (Wedemeyer, pers. comm.).

Dissolved oxygen (D.O.) levels > 6.3 mg/l are recommended for successful upstream migration of anadromous salmonids (Davis 1975). Lower D.O. concentrations adversely affect upstream migration by reducing the swimming ability of migrants and by eliciting avoidance responses. Maximum sustained swimming speed of coho is sharply reduced at D.O. levels < 6.5 mg/l at all temperatures (Davis et al. 1963). It is assumed that adult coho respond to low D.O. levels in a fashion similar to juveniles and avoid waters with D.O. concentrations < 4.5 mg/l (Whitmore et al. 1960).

Spawning/embryo/alevin. Coho salmon construct redds in swift, shallow areas at the head of riffles (Burner 1951; Briggs 1953; Shapovalov and Taft 1954). Preferred redd construction sites in riffle areas have velocities of 21 to 70 cm/sec and minimum depths ≥ 15 cm (Smith 1973). Gravel and small rubble substrate with low amounts of fine sediments is optimum for survival, growth, and development of embryos and alevins and for later emergence of fry (Platts et al. 1979). Percent composition of various size classes of substrate resulting in high survival of embryos and alevins has not been established. Reiser and Bjornn (1979) estimated that redds with 1.3 to 10.2 cm diameter substrate sizes and a low percentage of fines result in high survival of embryos. An inverse relationship between percent fines < 3.3 mm and emergence of fry has been well established in field (Koski 1966; Hall and Lantz 1969; Cloern 1976) and laboratory (Phillips et al. 1975) experiments. In all studies, emergence of coho fry was high at < 5% fines but dropped sharply at ≥ 15% fines.

Survival and emergence of embryos and alevins is greatly influenced by D.O. supply within the redd (Mason 1976a). D.O. concentrations ≥ 8 mg/l are required for high survival and emergence of fry. Embryo survival drops significantly at levels ≤ 6.5 mg/l; concentrations < 3 mg/l are lethal (Coble 1961; Shumway et al. 1964; Davis 1975). D.O. supply available to coho in redds is determined primarily by the interrelationship of gravel permeability, water velocity, and D.O. concentration. When any of these factors, acting alone or in combination, reduces the intragravel O_2 supply below saturation, hypoxial stress occurs, resulting in delayed hatching and emergence, smaller size of emerging fry, and increased incidence of developmental abnormalities (Alderice et al. 1958; Coble 1961; Silver et al. 1963; Shumway et al. 1964; Mason 1976a). D.O. concentrations at or near saturation, with temporary reductions no lower than 5 mg/l, are recommended as criteria necessary for successful reproduction of anadromous salmonids (Reiser and Bjornn 1979).

Burner (1951) observed coho spawning in Oregon at temperatures of 2.5 to 12.0° C. Temperatures of 4.4 to 9.4° C are considered suitable for spawning (Bell 1973). Temperatures in the 4.4 to 13.3° C range are considered optimum for embryo incubation; survival decreases if these thresholds are exceeded (Bell 1973; Reiser and Bjornn 1979).

Parr. Coho parr require an abundance of food and cover to sustain fast growth rates, avoid predation, and avoid premature displacement downstream to the ocean in order to successfully rear in freshwater and migrate to the sea as smolts (Mundie 1969). Mason and Chapman (1965) found that the number of coho parr remaining in stream channels is dependent on the amount of food and cover available; if food or cover is decreased, emigration from the area subsequently is increased. Mason (1976b) substantially increased summer carrying capacity of a coho stream by supplemental feeding; however, these gains were largely lost because numbers exceeded winter carrying capacity. Dill et al. (1981) found that territory size in coho is inversely related to the amount of available food. Low levels of food result in larger and fewer territories per unit area, increased emigration of resident fry, and slower growth rate of remaining fish. Small, slow growing parr may remain in freshwater for longer periods (with an attendant high mortality rate) until threshold size for smolting is reached or may migrate to the sea at a time when chances for survival are slim (Chapman 1966a).

Substrate composition, riffles, and riparian vegetation appear to be the most important factors influencing production of aquatic and terrestrial insects as food for coho (Mundie 1969; Giger 1973; Reiser and Bjornn 1979). Highest production of aquatic invertebrates is found in stream substrates comprised of gravel and rubble (Giger 1973; Reiser and Bjornn 1979). Pennak and Van Gerpen (1947) reported that the production of benthic invertebrates is greater in rubble > bedrock > gravel > sand. Because substrate size is a function of water velocity, larger substrate sizes are associated with faster currents. Thus, food production is also high in riffles (Ruggles 1966; Waters 1969). Pearson et al. (1970) found that coho production per unit area in Oregon streams is higher in pools with larger riffles upstream. However, increased fines in riffles can reduce production of benthic food organisms (Phillips 1971). Crouse et al. (1981) reported that coho production is lowest in laboratory stream channels when embeddedness of the rubble substrate is

high (80 to 100%) and the percent (by volume) of fines (≤ 2.0 mm) exceeds 26%. Lastly, riparian vegetation along coho streams acts as habitat for terrestrial insects, as well as a source of leaf litter utilized by stream invertebrates as food (Chapman 1966b; Mundie 1969).

Coho parr are most abundant in large, deep [generally > 0.30 m (Nickelson, pers. comm.)] pools, where they congregate near instream and bank (overhead) cover of logs, roots, debris, undercut banks, and overhanging vegetation (Ruggles 1966; Lister and Genoe 1970; Mason 1976b). Nickelson and Reisenbichler (1977) and Nickelson et al. (1979) found positive correlations between standing crop of age 0+ coho and pool volume. Studies in Oregon by Nickelson (pers. comm.) suggest that pools of 10 to 80 m^3 or 50 to 250 m^2 in size with sufficient riparian canopy for shading are optimum for coho production. A pool to riffle ratio of 1:1 provides optimum food and cover conditions for coho parr. Ruggles (1966) found that the greatest number of coho fry remained in stream channels consisting of 50% pools and 50% riffles; numbers of fry remaining in channels of either 100% pools or 100% riffles could be 39% and 20% lower, respectively.

As water temperatures decrease below 9° C, coho fry become less active and seek deep (≥ 45 cm), slow (< 15 cm/sec) water in or very near (< 1 m) dense cover of roots, logs, and flooded brush (Hartman 1965; Bustard and Narver 1975a). Beaver ponds and quiet backwater areas, often some distance from the main stream channel and dry during summer low flow periods, are also utilized as winter habitat (Narver 1978). Several studies indicate that the amount of suitable winter habitat may be a major factor limiting coho production (Chapman 1966a; Mason 1976b; Chapman and Knudsen 1980). Swimming ability of coho is decreased as the water temperature drops; therefore, winter cover is critical for protection from predation, freezing, and, especially, displacement by winter freshets (Bustard and Narver 1975b; Mason 1976b; Hartman et al. 1982). Chapman and Knudsen (1980) found a very low winter biomass of coho in channelized and grazed sections of streams in Washington, which they attributed to the reduced pool volumes and amount of instream and bank cover present in those areas.

Several studies have shown a positive relationship between stream carrying capacity for coho and streamflow (McKernan et al. 1950; Mathews and Olson 1980; Scarnecchia 1981). Strong positive correlations have also been found between total stream area and measures of coho biomass (Pearson et al. 1970; Burns 1971). Lowest returns of adult coho coincide with low summer flows coupled with high winter floods (McKernan et al. 1950). Burns (1971) found that highest mortality of coho and other salmonids in the summer occurred during periods of lowest flows. Higher streamflows during rearing appear to provide more suitable habitat for growth and survival through increased production of stream invertebrates and availability of cover (Chapman 1966a; Giger 1973; Scarnecchia 1981). Stabilization of winter flows and increases in summer flows have led to increased production of coho (Lister and Walker 1966; Mundie 1969). Narver (1978) suggested that stream enhancement techniques aimed at reducing displacement downstream during winter floods and at providing deep pools during summer low flows could substantially increase stream rearing capacity for coho.

Growth rate and food conversion efficiency of coho fry is optimum at D.O. concentrations above 5 mg/l. Below 4.5 mg/l, growth and food conversion rapidly decreases to the point where growth ceases or is negative (below 3 mg/l) (Herrmann et al. 1962; Brett and Blackburn 1981). Swimming speed decreases below the saturation level, especially below 6 mg/l (Dahlberg et al. 1968). D.O. concentrations < 4.5 mg/l are avoided (Whitmore et al. 1960). Upper incipient lethal temperatures for coho fry range from 22.9 to 25.0° C (acclimation temperatures of 5 to 23° C) (Brett 1952). Significant decreases in swimming speed occur at temperatures > 20° C (Griffiths and Alderice 1972), and growth ceases at temperatures above 20.3° C (Bell 1973). Stein et al. (1972) found that the growth rate of coho fry was high in the 9 to 13° C temperature range, but slowed considerably at temperatures near 18° C. Brungs and Jones (1977) reported that growth of coho occurred from 5 to 17° C.

Streamside vegetation plays an important role in regulating the temperature in rearing streams. Cooler winter water temperatures may occur if the stream canopy is absent or reduced, adversely affecting egg incubation (Chapman 1962). Where streamside vegetation is intact but the surrounding watershed has been logged, warmer winter water temperatures may result, shifting the period of emergence of fry and downstream movement of smolts to earlier, and less favorable, periods (Hartman et al. 1982). In areas where the stream canopy has been reduced, the resultant warmer summer temperatures may make the habitat unsuitable if the temperature exceeds 20° C (Stein et al. 1972) or may increase the mortality of fry from disease (Hall and Lantz 1969). However, too much stream canopy can also reduce habitat suitability for coho fry. For example, Chapman and Knudsen (1980) found reduced coho biomass in stream sections where the canopy was very dense. Pearson et al. (1970) reported that coho fry appear to avoid areas of dense shade; they suggested that stream canopy enclosing > 90% of the sky may exceed the optimum level.

In summary, optimum rearing habitat for coho parr consists of a mixture of pools and riffles, abundant instream and bank cover, water temperatures that average between 10 to 15° C in the summer, D.O. near the saturation level, and riffles with low amounts of fine sediment (Reiser and Bjornn 1979). Streamside vegetation is an important component of coho habitat because it provides food, cover, temperature control, and bank stabilization (Narver 1978).

Smolt. The radical physiological and behavioral changes that occur during smoltification make this stage particularly sensitive to environmental stress factors. Blockage and delay of migration by dams, unfavorable stream flows and temperatures, fluctuations in food supplies, predation, gas supersaturation below dams, activation of latent infections due to environmental stress, interference with saltwater adaptation in estuaries because of gill infestations, and handling stress and descaling during transportation around dams are major sources of mortality and reduced ocean survivability of coho smolts (Wedemeyer et al. 1980).

Elevated water temperatures can accelerate the onset of smoltification and shorten the smolting period and may result in seaward migration of smolts at a time when conditions are unfavorable (Wedemeyer et al. 1980). Zaugg and McLain (1976) reported that the period of high gill ATPase activity (indicative

of high salinity tolerance and other adaptations necessary for parr-smolt transformation) in coho smolts held at 20° C occurred from mid-March to early April; at 15° C, it occurred from mid-March to early May; and, at 10° C, a normal pattern resulted with a peak in ATPase activity from mid-March to early July. By shortening the duration of smolting and accelerating desmoltification, sublethal temperatures can lead to parr-reversion of coho smolts in estuaries where exposure to predation and risk of infection is high, thereby diminishing the number of coho smolts entering the ocean (Wedemeyer et al. 1980). Wedemeyer et al. (1980) recommend that temperatures follow a natural seasonal cycle as closely as possible to those present in the coho's native range to ensure optimum conditions for smoltification and timing of seaward migration. Specifically, temperatures should not exceed 10° C in late winter to prevent accelerated smolting; temperatures should not exceed 12° C during smolting and seaward migration in the spring to prevent shortened duration of smolting and premature onset of desmoltification and to reduce the risk of infection from pathogens (see Adult section).

Exposure to pollutants can have a major deleterious impact on smoltification and early marine survival of anadromous salmonids (see review by Wedemeyer et al. 1980). For example, Lorz and McPherson (1976) found that, at very low levels of copper (20 to 30 µg/l), migratory behavior and gill ATPase activity in coho smolts was greatly suppressed and high mortalities resulted from exposure to saltwater. Low concentrations of herbicides have also been found to inhibit smolt function and migratory behavior (Lorz et al. 1978).

The lethal threshold for gas supersaturation in coho smolts is 114.5%. No deaths were reported at 110% supersaturation, but the majority of fish exhibited symptoms of gas-bubble disease (Rucker and Kangas 1974; Nebeker and Brett 1976).

Specific D.O. requirements for coho smolts are unknown, but are probably similar to those for parr.

HABITAT SUITABILITY INDEX (HSI) MODEL

Model Applicability

Geographic area. The model was developed from information gathered on habitat requirements of coho salmon throughout its native and introduced range. This general model is designed to be applicable to all the above areas but is limited to the freshwater stage of the life cycle: upstream migrant; embryo; parr; and smolt.

Season. The model is structured to account for changes in seasonal as well as life stage requirements of coho salmon during those parts of the life cycle when they inhabit freshwater. Because rearing streams are utilized year-round, the model is developed to measure the suitability of a given habitat to support parr for the entire year and to support embryos during the spawning and incubation period.

Cover types. The model is oriented primarily to small coastal streams and tributaries of larger rivers, which are the major spawning and rearing areas of coho salmon. Habitat requirements of coho in large rivers, where some spawning and rearing occurs and which serve as "highways to the sea" for upstream and downstream migrant wild and hatchery-reared coho, are less well-known and are not adequately addressed in this model. Water quality variables are the only variables in this model that may be applicable when coho inhabit large rivers. Variables that measure habitat suitability for adult coho in lakes, reservoirs, estuaries, or the ocean are not included in this model.

Water quality. The model has limited utility in areas where water quality variables (e.g., toxic substances and gas supersaturation) are major factors limiting coho populations. If toxic substances are being discharged into a river, Wedemeyer et al. (1980) should be consulted for information on the types of substances that can adversely affect survival of smolts.

Verification level. The model represents the author's interpretation of how specific environmental factors combine to determine overall habitat suitability for coho salmon. The model has not been field tested.

Model Description

The HSI model that follows is an attempt to condense information on habitat requirements for coho into a set of habitat evaluation criteria, structured to produce an index of overall habitat quality. A positive relationship between HSI and carrying capacity of the habitat is assumed (U.S. Fish and Wildlife Service 1981), but this relationship has not been tested.

As a consequence of their homing to natal streams to spawn, coho and other anadromous salmonids commonly form local races and stocks, exhibiting adaptations to the particular set of environmental conditions present in the spawning streams (Larkin 1981; MacLean and Evans 1981). The generalized HSI model presented does not take into account the different stocks or subpopulations. The model was developed, and should be applied, with the following statement by Banks (1969:131) in mind: "... the consequences of man-made changes (on anadromous salmonids) ...can be predicted in general terms from the existing literature, but (due to the formation of local stocks) each situation is unique ... and requires studies of the special needs of each river system as well as the flexible application of general principles".

The model consists of those habitat variables that affect the growth, survival, abundance, distribution, behavior, or other measure of well-being of coho, and therefore can be expected to have an impact on the carrying capacity of a habitat. Coho salmon habitat quality, in this model, is based on parameters assumed to affect habitat suitability for each of four life stages of coho salmon during residence in freshwater (Fig. 1). Variables affecting habitat suitability for parr are further delineated into the life requisite components of: water quality; food; and cover. It was assumed that the most limiting factor (i.e., lowest SI score) defines the carrying capacity for coho salmon; thus,

$$HSI = \text{minimum value for suitability indices } V_1 \text{ to } V_{15}.$$

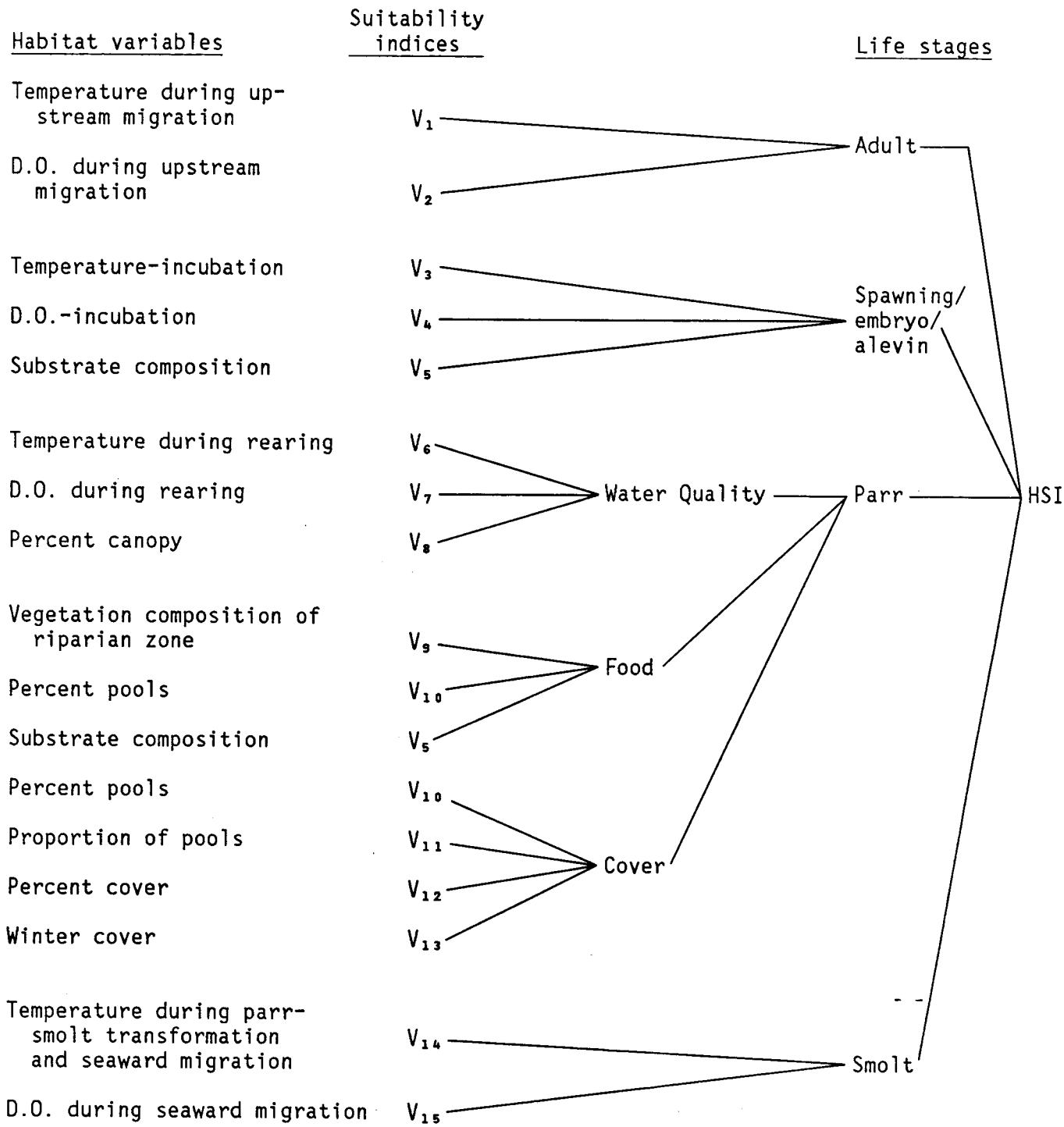


Figure 1. Diagram showing habitat variables included in the HSI model for coho salmon and the aggregation of the corresponding suitability indices (SI's) into an HSI. HSI = the lowest of the fifteen suitability index ratings.

Adult component. V_1 was included in this component because temperature can result in direct mortality, can increase coho susceptibility to infectious diseases, or can alter the timing of migration and rate of maturation of coho salmon during migration from the ocean to the spawning stream. Because D.O. levels below saturation can elicit avoidance behavior and reduce the swimming ability in coho, D.O. (V_2) also was included as a variable that affects habitat suitability for upstream migrants.

No specific variables were included in this component as measures of the accessibility of the spawning stream. Nevertheless, physical features encountered by coho while migrating upstream should be considered when evaluating habitat suitability. Features that impede or delay migrants from moving upstream (see Adult section) would make suitable habitat, as defined by the model, less useable.

Spawning/embryo/alevin component. V_3 was included in this component because embryo survival decreases when temperatures during incubation exceed the optimum temperature boundary of 13.3° C. V_4 was included because D.O. levels below the saturation level induce hypoxial stress in embryos and alevins and lead to decreased quantity and quality of emerging fry. V_5 was included because percent emergence of fry is related to substrate composition of spawning redds.

Parr component. Water quality: V_6 was included because temperature affects swimming speed, growth, and survival of coho parr. V_7 was included because D.O. concentration affects growth, food conversion, swimming speed, and avoidance behavior of parr. V_8 was included because coho numbers (or biomass) are related to the quantity of stream canopy cover.

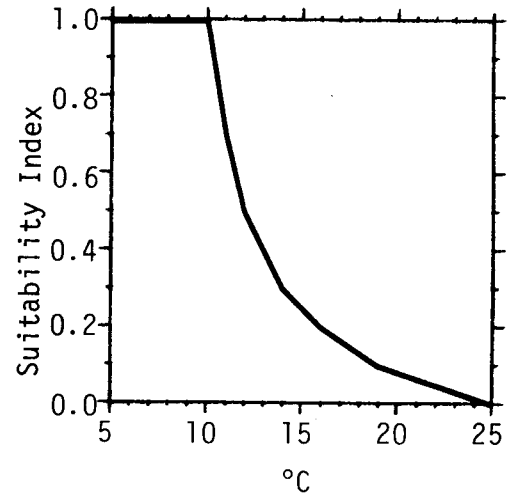
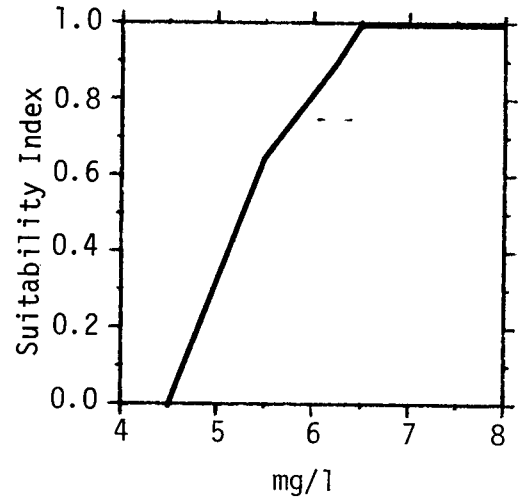
Food: V_9 was included because it was assumed that the direct (terrestrial insects) and indirect (leaf litter as food for aquatic insects) production of food utilized by coho parr varies with the amount and type of riparian vegetation present. V_{10} was included because the production of aquatic insects, as well as coho parr, has been related to the amount of riffle areas present in a stream. V_5 was included because the production potential of aquatic insects is related to the substrate composition.

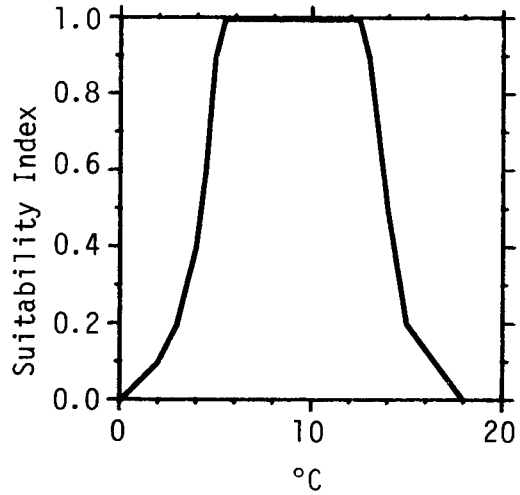
Cover: V_{10} and V_{11} were included because the abundance of coho parr varies with the amount (V_{10}) and type (V_{11}) of pools present in a stream. V_{12} was included because coho parr are commonly associated with instream and bank cover. V_{13} was included because the amount of suitable winter cover may be a major factor affecting coho production.

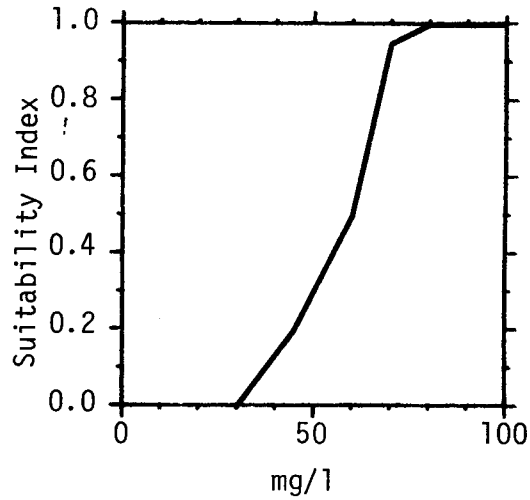
Smolt component. V_{14} was included because temperature greatly affects the timing and duration of parr-smolt transformation, can alter the timing of seaward migration, and can affect the susceptibility of smolts to infection. Although specific data are lacking, V_{15} was included because D.O. concentration could potentially impact smolt migration through its effects on swimming ability, by eliciting avoidance behavior, or by resulting in the direct mortality of smolts.

Suitability Index (SI) Graphs for Model Variables

All variables pertain to riverine (R) habitat. Table 1 lists the information sources and assumptions used in constructing each SI graph.

Habitat	Variable		Suitability graph
R	V_1	Maximum temperature during upstream migration.	
R	V_2	Minimum dissolved oxygen concentration during upstream migration.	

R	V_3	Maximum temperature from spawning to emergence of fry.	

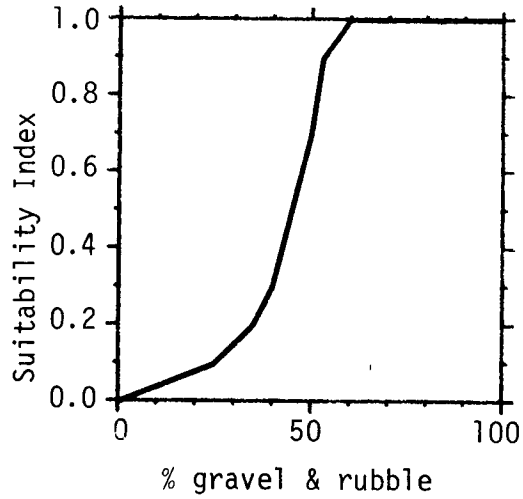
R	V_4	Minimum dissolved oxygen concentration from spawning to emergence of fry.	

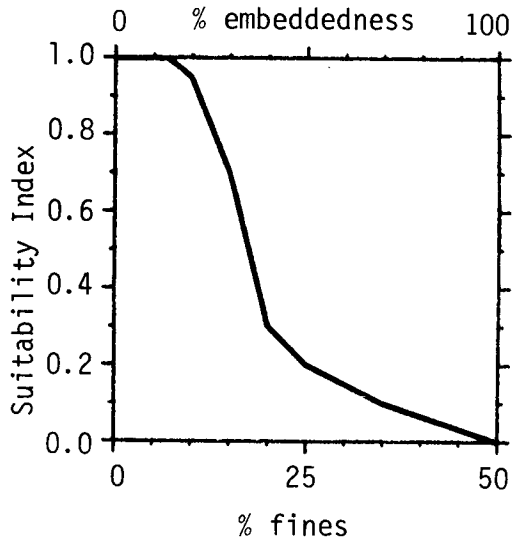
R V_5 Substrate composition in riffle/run areas.

A. Percent of gravel (10 to 60 mm) and rubble (61 to 250 mm) present.
B. Percent fines (< 6 mm) or percent embeddedness of substrate.

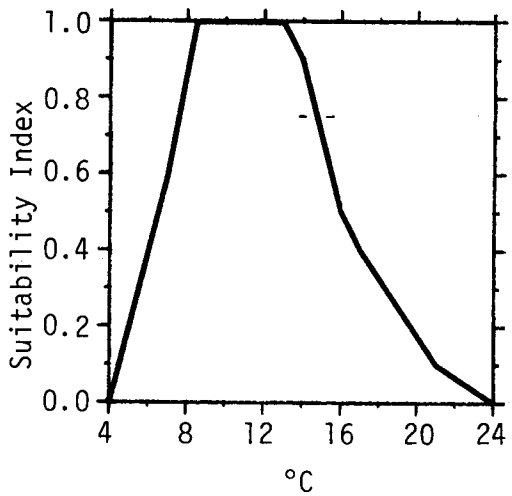
$$SI = \frac{A + B}{2}$$, where B = % fines

or % embeddedness, whichever is lower.

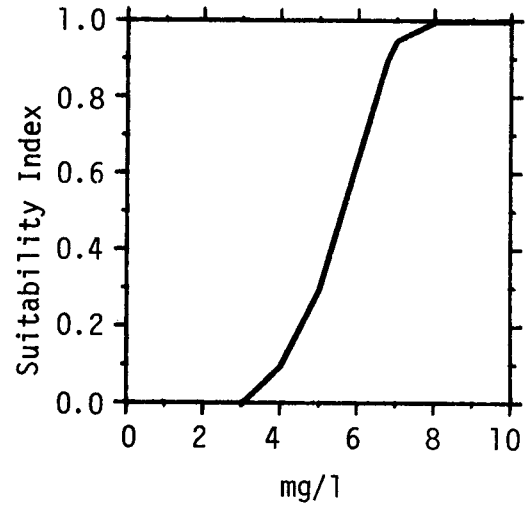




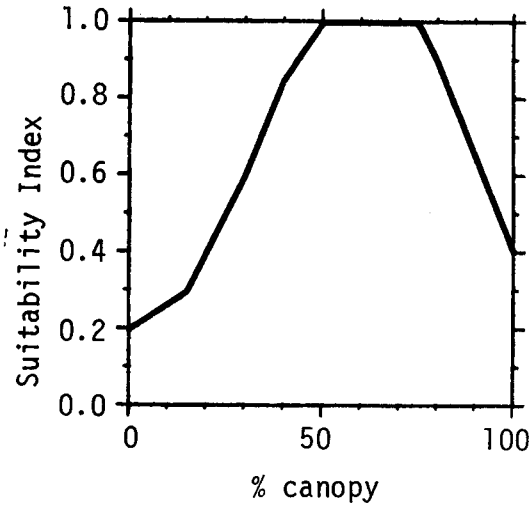
R V_6 Maximum temperature during rearing (parr).



R V_7 Minimum dissolved oxygen concentration during rearing (parr).

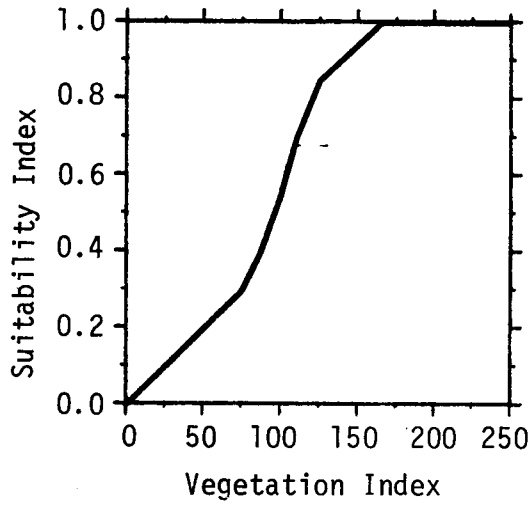


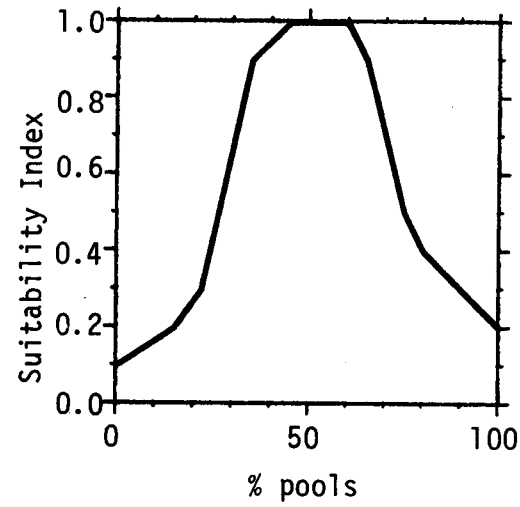
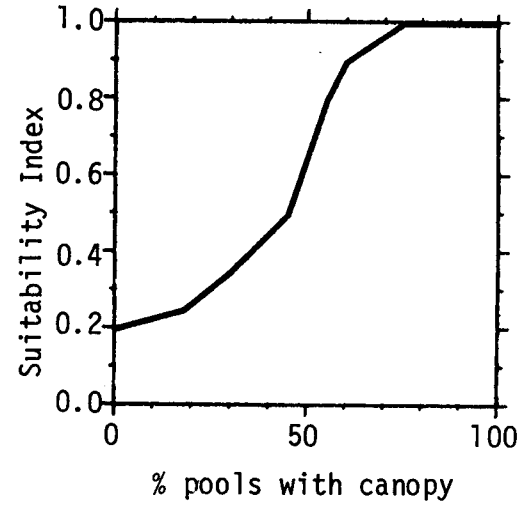
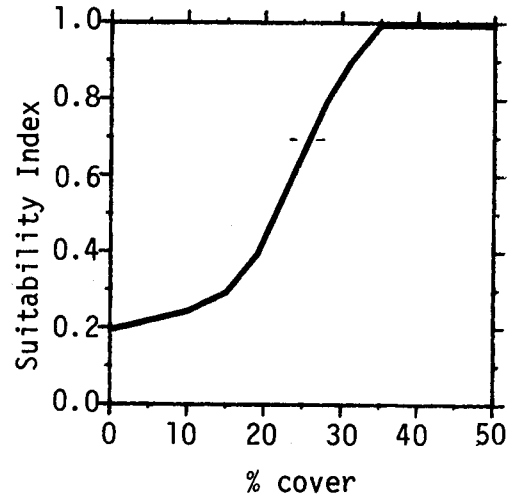
R V_8 Percent vegetative canopy over rearing stream.



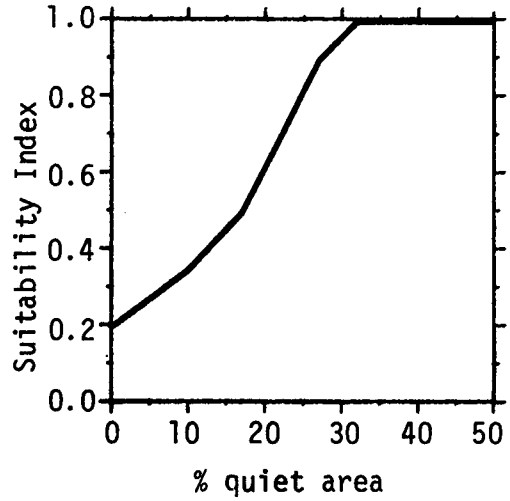
R V_9 Vegetation index of riparian zone during summer.

Vegetation Index = 2 (% canopy cover of deciduous trees and shrubs) + (% canopy cover of grasses and forbs) + (% canopy cover of conifers). For measurement techniques, see Terrell et al. (1982), p. A.19 and A.37.



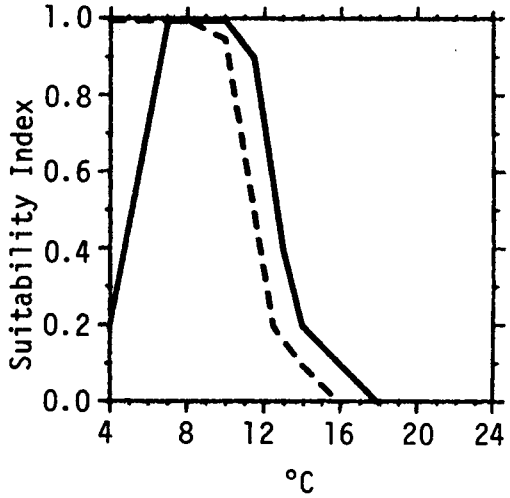
R	V_{10}	Percent pools during summer low flow period.	
R	V_{11}	Proportion of pools during summer low flow period that are 10 to 80 m^3 or 50 to 250 m^2 in size and have sufficient riparian canopy to provide shade.	
R	V_{12}	Percent instream and bank cover present during summer low flow period.	

R V_{13} Percent of total area consisting of quiet backwaters and deep (≥ 45 cm) pools with dense cover of roots, logs, debris jams, flooded brush, or deeply-undercut banks during winter.



R V_{14} Maximum temperature during (A) winter (Nov.-March) in rearing streams and (B) spring-early summer (April-July) in streams where seaward migration of smolt occurs.

A. - - - -
B. _____



R V_{15} Minimum dissolved oxygen concentration during April-July in streams where seaward migration occurs.

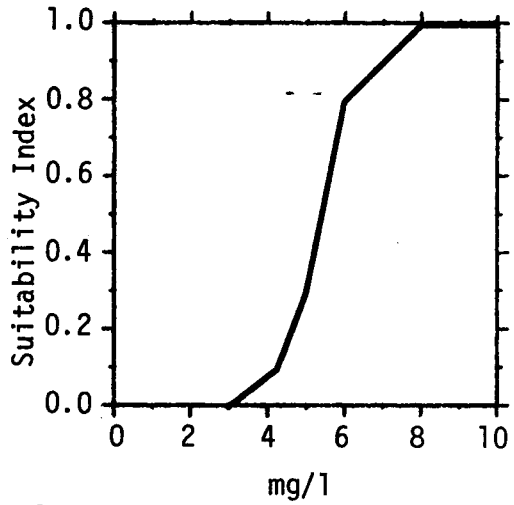


Table 1. Sources of information and assumptions used in construction of the suitability index graphs are listed below. "Excellent" habitat for coho salmon was assumed to correspond to an SI of 0.8 to 1.0, "good" habitat to an SI of 0.5 to 0.7, "fair" habitat to an SI of 0.2 to 0.4, and "poor" habitat to an SI of 0.0 to 0.1.

Variable	Assumptions and sources
V_1	Temperatures that are lethal or that correspond to high mortality rates in infected coho are poor (Bell 1973; Fryer and Pilcher 1974; Holt et al. 1975). Temperatures where mortality of infected coho is moderate or where activation of latent infections begins to increase are fair (Fryer and Pilcher 1974; Groberg et al. 1978). Temperatures that correspond to low disease mortality (Fryer and Pilcher 1974; Holt et al. 1975) and that are recommended for minimizing prespawning mortality are excellent (Wedemeyer pers. comm.).
V_2	D.O. levels that correspond to undiminished swimming ability (Davis et al. 1963) and that are recommended for successful upstream migration (Davis 1975) are excellent. Levels where swimming speed is greatly reduced (Davis et al. 1963) and avoidance is high (Whitmore et al. 1960) are poor.
V_3	Temperature ranges corresponding to those recommended as optimum for spawning and for incubation of embryos (Bell 1973) are excellent. Temperatures outside of this range are less suitable.
V_4	D.O. levels at or near the saturation level corresponded to the highest survival and emergence of fry and, therefore, are excellent. Levels that correspond to reduced emergence, delays in hatching or emergence, smaller size of fry, or increased incidences of developmental abnormalities (Alderice et al. 1958; Cobel 1961; Silver et al. 1963; Shumway et al. 1964; Mason 1976a) are fair. D.O. levels below 5 mg/l (Reiser and Bjornn 1979) or that approach lethal conditions (3 mg/l) (Coble 1961; Shumway et al. 1964; Davis 1975) are poor.

Table 1. (continued).

Variable	Assumptions and sources
V_5	(Embryo) Substrate composition that corresponds to high embryo survival and high emergence of fry is excellent. Compositions that contribute to reduced emergence (high percentage of fines, high embeddedness) are good-poor depending on the severity of the impact on survival and emergence (Koski 1966; Hall and Lantz 1969; Phillips et al. 1975; Cloern 1976; Platts et al. 1979; Reiser and Bjornn 1979). (Parr-Food) Gravel-rubble substrate composition corresponds to a high production of aquatic invertebrates (Giger 1973; Reiser and Bjornn 1979) and, therefore, is excellent in providing food for coho. Other substrates produce decreasing amounts of invertebrates in this order: rubble > bedrock > gravel > sand (Pennak and Van Gerpen 1947). It is assumed that the higher the percentage fines or percent embeddedness, the lower the production of aquatic invertebrates (Phillips 1971; Crouse et al. 1981).
V_6	Temperatures that correspond to high growth (9 to 13° C) (Stein et al. 1972) are excellent. Temperatures that correspond to reduced growth (Stein et al. 1972) are fair. Temperatures that are lethal or where growth of parr ceases are poor.
V_7	D.O. levels that correspond to the highest growth and food conversion rates (Herrmann et al. 1962; Brett and Blackburn 1981) are excellent. Levels that correspond to greatly reduced swimming speed (Dahlberg et al. 1968), avoidance behavior (Whitmore et al. 1960), and cessation of growth are poor.
V_8	It is assumed that 50 to 75% canopy enclosure is excellent. Other percentages are less suitable because cooler winter and warmer summer temperatures, associated with low canopy cover, result in decreased survival of embryos and fry (Chapman 1962; Hall and Lantz 1969; Stein et al. 1972). Lower biomass of coho corresponds to a high percent (> 90%) of canopy closure (Pearson et al. 1970; Chapman and Knudson 1980), so percentages ≥ 90% are fair.
V_9	Based on the work of Chapman (1966b), deciduous trees and shrubs are excellent as habitat for terrestrial insects and in providing high amounts of leaf litter used as food for aquatic invertebrates. Grasses/forbs and conifers are less suitable. The equation was formulated so that no riparian vegetation rates poor and so that ≥ 75% deciduous trees and shrubs rates excellent. It was based on the assumption that deciduous trees and shrubs provide twice the amount of terrestrial insects and leaf litter per unit area as do grasses/forbs and conifers.

Table 1. (continued)

Variable	Assumptions and sources
V_{10}	(Food-Cover) A pool to riffle ratio of 1:1 in streams is excellent in providing both food and cover for coho parr because: (1) food production is highest in riffles (Ruggles 1966; Waters 1969); (2) coho fry are most abundant in pools (Ruggles 1966; Lister and Genoe 1970; Mason 1976b); and (3) the highest number of coho fry remained in stream channels with a 1:1 ratio (Ruggles 1966). Higher or lower percentages of pools are less suitable because fewer coho fry remain in the stream channels (Ruggles 1966). This variable should be measured during summer low flow because this is the critical summer period for parr (Burns 1971).
V_{11}	The graph is based on studies on Oregon streams by Nickelson and colleagues where: (1) positive correlations were found between standing crop of age 0+ coho and pool volume (Nickelson and Reisenbichler 1977; Nickelson et al. 1979); and (2) coho fry biomass was highest in pools 10 to 80 m^3 or 50 to 250 m^2 in size (Nickelson pers. comm.). It is assumed that a positive relationship exists between proportion of pools 10 to 80 m^3 or 50 to 250 m^2 in size and habitat suitability (= carrying capacity) for coho fry. If such pools are absent from the reach, it is assumed that some other pool habitat would exist but would be poor, capable of supporting parr in relatively small numbers (therefore, SI = 0.2 at 0%).
V_{12}	Because there is a positive relationship between number of coho parr remaining in an area and amount of instream cover (Mason and Chapman 1965) and, because parr are most abundant near instream and bank cover (Ruggles 1966; Lister and Genoe 1970; Mason 1976b), it is assumed that habitat suitability is proportional to the amount of instream or bank cover present in a reach. Zero percent cover is assigned an SI of 0.2 because the stream may still be able to support coho parr, although at a greatly reduced level.
V_{13}	It is assumed that quiet backwaters and deep pools with dense cover are excellent winter habitat for coho parr because parr are most abundant in these areas during the winter (Hartman 1965; Bustard and Narver 1975a). Because several studies infer that the amount of suitable winter habitat may be a major factor limiting rearing capacity and smolt production (Chapman 1966a; Mason 1976b; Chapman and Knudsen 1980), it is assumed that habitat suitability is proportional to the amount of suitable winter habitat available. Zero percent winter cover has an SI rating of 0.2 because it is assumed that other potential sites can still support some overwintering parr. Thirty percent and above has an SI of 1.0, because it is assumed that optimum values of this variable are obtainable in conjunction with optimum riffle-pool ratios (V_{10}).

Table 1. (concluded).

Variable	Assumptions and sources
V_{14}	Temperatures that correspond to a long and normal pattern of gill ATPase activity during smoltification (Zaugg and McLain 1976) are excellent, as are temperatures recommended for optimum smoltification and timing of seaward migration; i.e., ≤ 10° C during winter and ≤ 12° C during spring (Wedemeyer et al. 1980; Wedemeyer pers. comm.). It is assumed that the shorter the duration of gill ATPase activity, the less suitable the temperature. Also, temperatures > 12° C are considered fair-poor because the risk of infections from pathogens is assumed to be higher than at lower temperatures (Fryer and Pilcher 1974; Holt et al. 1975).
V_{15}	It is assumed that D.O. requirements for smolts are similar to those of parr, thus the same assumptions and sources used in developing the D.O. graph for parr (V_7) were used in constructing the SI graph for V_{15}.

Interpreting Model Outputs

The model described above is a generalized description of habitat requirements for coho salmon and, as such, the output is not expected to discriminate among different habitats with a high resolution at this stage of development (see discussion in Terrell et al. 1982). Each model variable is considered to have some effect on habitat quality for coho, and the suitability index graphs depict what the measurable response is assumed to be. However, the graphs are derived from a series of untested assumptions, and it is unknown how accurately they depict habitat suitability for coho salmon. The model assumes that each model variable alone can limit coho production, but this has not been tested. A major potential weakness in the model is that, while the model variables may be necessary in determining suitability of habitat for coho, they may not be sufficient. Species interactions and other factors not included in this model may determine carrying capacity to a greater degree than the variables included in this model. Data describing measurable responses for additional factors are, however, scarce or nonexistent and, therefore, the variables do not meet the standards for consideration as variables in HSI model development (U.S. Fish and Wildlife Service 1981).

I recommend interpreting model outputs as indicators (or predictors) of excellent (0.8 to 1.0), good (0.5 to 0.7), fair (0.2 to 0.4), or poor (0.0 to 0.1) habitat for coho salmon. The output of the generalized model provided should be most useful as a tool in comparing different habitats. If two study areas have different HSI's, the one with the higher HSI is expected to have the potential to support more coho salmon. The model also should be useful as a basic framework for formulating revised models that incorporate site specific factors affecting habitat suitability for coho salmon and more detailed variable measurement techniques on a site-by-site basis.

ADDITIONAL HABITAT MODELS

No other habitat models that could be utilized in habitat evaluation for coho salmon were located in the literature. The user is referred to Terrell et al. (1982) and U.S. Fish and Wildlife Service (1981) for techniques to modify this model to meet project needs.

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A review and synthesis of existing information were used to develop a riverine habitat model for Coho Salmon (Oncorhychus kitsutch) an anadromous species. The model is scaled to produce an index of habitat suitability between 0 (unsuitable habitat) and 1 (optimally suitable habitat) for riverine areas of the continental United States. Habitat suitability indices (HSI's) are designed for use with Habitat Evaluation Procedures previously developed by the U.S. Fish and Wildlife Service.

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