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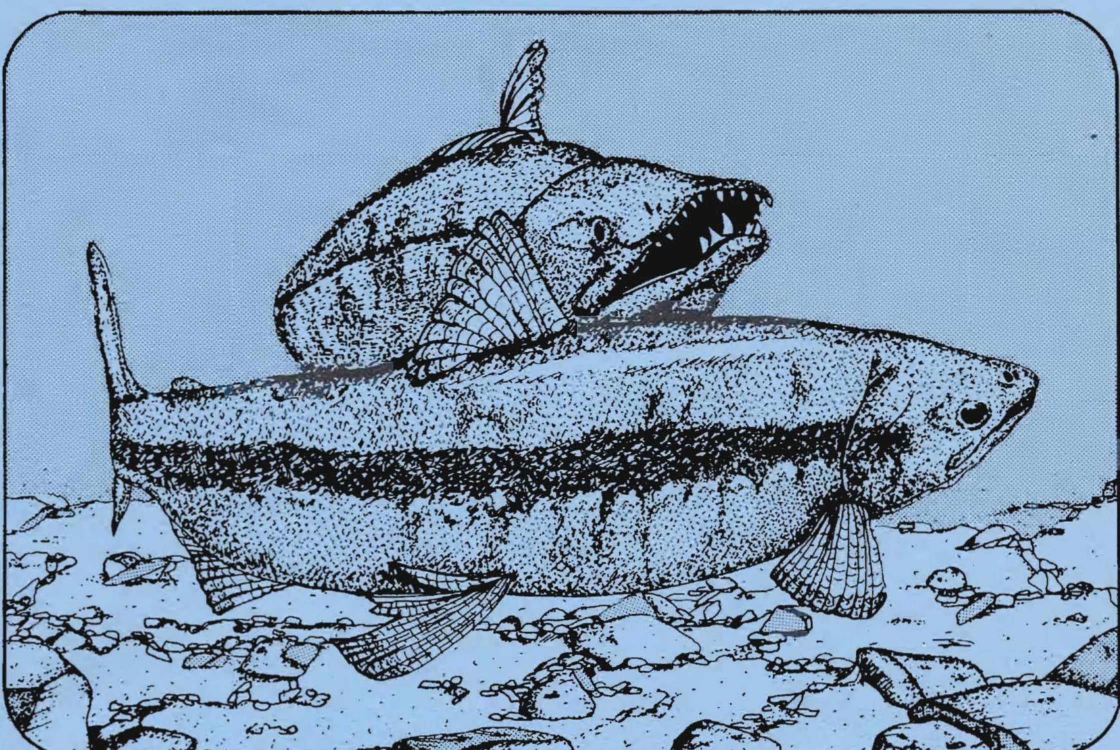
HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: CHUM SALMON



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MODEL EVALUATION FORM

Habitat models are designed for a wide variety of planning applications where habitat information is an important consideration in the decision process. However, it is impossible to develop a model that performs equally well in all situations. Assistance from users and researchers is an important part of the model improvement process. Each model is published individually to facilitate updating and reprinting as new information becomes available. User feedback on model performance will assist in improving habitat models for future applications. Please complete this form following application or review of the model. Feel free to include additional information that may be of use to either a model developer or model user. We also would appreciate information on model testing, modification, and application, as well as copies of modified models or test results. Please return this form to:

Habitat Evaluation Procedures Group
or
Instream Flow Group
U.S. Fish and Wildlife Service
2627 Redwing Road, Creekside One
Fort Collins, CO 80526-2899

Thank you for your assistance.

Species ______________ Geographic Location ________________________________

Habitat or Cover Type(s) ____

Type of Application: Impact Analysis ____ Management Action Analysis _____
Baseline _____ Other ____

Variables Measured or Evaluated ____
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____
____

Was the species information useful and accurate? Yes ____ No ____

If not, what corrections or improvements are needed?______________________
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____
____

Were the variables and curves clearly defined and useful? Yes ____ No ____

If not, how were or could they be improved? ______________________________

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Were the techniques suggested for collection of field data:

Appropriate? Yes ____ No ____

Clearly defined? Yes ____ No ____

Easily applied? Yes ____ No ____

If not, what other data collection techniques are needed? ______________

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Were the model equations logical? Yes ____ No ____

Appropriate? Yes ____ No ____

How were or could they be improved? ______________________________

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Other suggestions for modification or improvement (attach curves, equations, graphs, or other appropriate information) ______________________

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Additional references or information that should be included in the model:

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Model Evaluator or Reviewer ______________________ Date ______________

Agency ____

Address ____

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Telephone Number Comm: ____________________ FTS ____________________

Biological Report 82(10.108)
August 1985

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

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PREFACE

The Habitat Suitability Index (HSI) models and Instream Flow Suitability Index (SI) curves presented in this publication aid in identifying important variables that determine the quality of chum salmon habitat. Facts, concepts, field data, and opinions obtained from published and unpublished reports are synthesized and presented in a format that can be used for habitat impact assessment and development of management alternatives.

This report contains four major parts: (1) a Habitat Use Information section which provides a general summary of the life history of chum salmon; (2) a Specific Habitat Requirements section which provides a detailed discussion of habitat needs for each life stage in freshwater; (3) a HSI Model section which presents hypothesized relationships between various environmental variables and habitat quality for chum salmon; and (4) an Instream Flow Incremental Methodology (IFIM) section which discusses use of Suitability Index Graphs from the HSI model with IFIM and provides additional SI graphs developed specifically for analysis of chum salmon habitat via the IFIM.

Use of the HSI models with the Habitat Evaluation Procedures (HEP) or the SI curves with the Instream Flow Incremental Methodology (IFIM) requires project scoping, including the setting of clear study objectives. Armour et al. (1984)[1] present comparisons of the uses of HEP and IFIM for impact assessment and helpful recommendations for selecting the method most appropriate for achieving study objectives. If HEP is to be used, HSI model building techniques presented by the U.S. Fish and Wildlife Service (1981)[1] and the general guidelines for modifying HSI models presented by Terrell et al. (1982)[1] may be useful for simplifying and applying the HSI models to specific chum salmon habitat assessment problems. Users of the SI curves for IFIM analyses 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, and users should recognize that the degree of veracity of the models, curves, and assumptions will likely vary according to geographical area and to the extent of the data base for each of the individual variables. The models and curves have not been tested against field data. Therefore, the U.S. Fish

[1]Citations listed in REFERENCES section.

and Wildlife Service encourages users of the models or curves to send comments, suggestions, and field results that may help increase the utility and effectiveness of this habitat-based approach to impact assessment. Please send comments to:

Habitat Evaluation Procedures Group or
Instream Flow and Aquatic Systems Group
Western Energy and Land Use Team
U.S. Fish and Wildlife Service
2627 Redwing Road
Fort Collins, CO 80526-2899

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We thank C. Burger, U.S. Fish and Wildlife Service and J. Helle, U.S. National Marine Fisheries Service, for review comments which improved the quality and accuracy of this report. Helpful comments were also provided by various staff of the Susitna River Aquatic Studies Program of the Alaska Department of Fish and Game. The reader should not construe reviewer assistance as an endorsement of the Suitability Index curves and habitat models, which are an independent synthesis and interpretation of the literature. T. Rosenthal provided editorial assistance and J. Terrell coordinated manuscript production. Word processing was by C. Gulzow, D. Ibarra, and E. Graf. The cover figure was drawn by S. Donovan, Alaska Department of Fish and Game, based on a photograph by J. Helle.

CHUM SALMON (*Oncorhynchus keta*)

HABITAT USE INFORMATION

General

Chum salmon have the widest distribution of the Pacific salmons, occurring in the northern North Pacific Ocean, the Bering Sea, the Chukchi Sea, and along the Arctic Ocean coasts of Siberia, Alaska, and northwest Canada (Bakkala 1970). Spawning occurs in North America from the Sacramento River in California to the MacKenzie and Anderson Rivers on the Arctic coast of Canada (Hart 1973), and in Asia, from the Nakdong River in Korea and the Tone River in Japan to the Lena River in Siberia (Bakkala 1970). Spawning has been recorded in at least 1,270 streams in the United States (Atkinson et al. 1967). Along the North American coast, chum salmon populations are relatively small south of central Oregon or north of Kotzebue Sound, Alaska (Helle 1979). Detailed descriptions of their distribution in Alaska were given by Alaska Department of Fish and Game (1978) and Hale (1981).

Summaries of the life history and freshwater habitat requirements of chum salmon were presented in Bakkala (1970) and Hale (1981). The freshwater habitat requirements for Pacific salmon in general have been summarized by Nicola et al. (1966) and Reiser and Bjornn (1979).

Age, Growth, and Food

Chum salmon typically mature at ages III or IV in Oregon and Washington and III, IV, or V in British Columbia and Alaska (Bakkala 1970; Fulton 1970; Helle 1979). Mature fish in North America generally range from 53 to 92 cm long and weigh 0.8 to 13.4 kg (Bakkala 1970).

Some chum salmon fry migrate seaward soon after emergence from redds (Hoar 1953; Neave 1966), whereas others remain in freshwater or intertidal areas for as long as several weeks to feed (Sparrow 1968; Bakkala 1970; Scott and Crossman 1973; Mason 1974). Fry remaining in freshwater feed on drifting terrestrial insects or aquatic forms such as immature chironomids, blackflies, caddisflies, mayflies, and stoneflies (Disler 1953; Sparrow 1968; Bakkala 1970). Those that stay in intertidal reaches feed on amphipods, copepods, and insects (Mason 1974).

Growth in freshwater is negligible in fry that migrate to sea soon after emergence, but may be considerable for those that remain in freshwater for several weeks. Chum fry in the Tokachi River of Japan showed up to a 30%

increase in length and up to a 310% increase in weight during April and May (Kaeriyama et al. 1978). Freshwater feeding and growth of chum salmon fry have also been demonstrated in the Satsunai River (Kaeriyama and Sato 1979) and in the Yurappu River (Kobayashi and Abe 1977). In the Susitna River, Alaska, emerging chum salmon fry that were marked with a coded wire tag and subsequently recaptured, showed a steady increase in length from a mean of 40 mm to a mean of 49 mm, 22 to 28 days later, an increase in length of 22.5%, which would correspond to an even larger percentage increase in weight (Roth, pers. comm.). Many chum fry from the upper reaches of the spawning areas in the Susitna River move downstream at lengths not much longer than their emergence length (< 40 mm), but there are also many that spend several weeks in freshwater and attain lengths of > 60 mm, an increase of over 20 mm.

Reproduction

The timing of the return of adult chum salmon to natal streams to spawn varies with location. Summer runs are characteristic in Alaska and other northern parts of the range, spawning in these areas occurring in August and September (Alaska Department of Fish and Game 1978; Morrow 1980). In lower southeast Alaska and southward, fall spawning runs of chum salmon are more common (Hunter 1959; Neave 1966; Fulton 1970). Chum salmon may spawn over a prolonged period; both summer and fall runs occur in many streams, particularly large rivers. In the Yukon and other large river systems, fish in the summer run spawn in lower sections of the river and those in the fall run spawn in areas much farther upstream (Scott and Crossman 1973).

Spawning occurs primarily in short coastal streams and in the lower 200 km of large rivers (Neave 1966; Fulton 1970), but chum salmon migrate upstream over 1900 km in the Amur River (Bakkala 1970) and over 2,500 km in the Yukon River (Bakkala 1970; Morrow 1980). Like pink salmon (*O. gorbuscha*), chum salmon frequently spawn in intertidal areas. In general, they are less likely to surmount waterfalls and other barriers than other salmon (Neave 1953, 1966; Bakkala 1970; Thorsteinson et al. 1971).

Eggs incubate in gravel redds 50 to 130 days (depending on temperature) before hatching. Newly hatched fry (alevins) remain in the gravel until spring, when their yolk sacs are nearly or completely absorbed (Bakkala 1970; Scott and Crossman 1973). Mortality during incubation is high; survival from egg deposition to fry emergence typically averages < 10% (Hunter 1959).

Rearing and Downstream Migration of Fry

Fry emerge from the gravel in March to May (Sano 1966; Bakkala 1970). Timing of downstream migration of chum fry in Carnation Creek, British Columbia over a 13-year period (1971-1983) is presented in Andersen (1983, 1984). After leaving the gravel, many fry soon migrate downstream to the ocean (Hoar 1956; Neave 1966) but, in some systems at least, a considerable number remain in streams [Scott and Crossman 1973; Kobayashi and Abe 1977; Roth et al. 1984; personal observation (McMahon) in Carnation Creek, British Columbia] and intertidal areas (Mason 1974) for at least several weeks. In the Fraser River system, Beacham and Starr (1982) found that 80% of the downstream migrants were < 40 mm FL, but that the proportion of fry > 40 mm increased with time, suggesting that later migrants had spent more time feeding in freshwater. Mason (1974) found that the fry have complex behavioral responses that delay seaward movement and allow the fish to feed in freshwater and intertidal areas before entering the ocean. It is unknown if those fry that rear in freshwater for longer periods have higher survival rates than those that migrate to the ocean soon after emergence, as found for coho salmon (*O. kisutch*) fry (Crone and Bond 1976).

Chum salmon fry migrate downstream primarily at night (Andersen 1983), and hide in the streambed (Neave 1966) or feed (McMahon personal observation) during the day. In large, turbid rivers at more northern latitudes where there is little darkness in June, such as the Susitna River in south-central Alaska, migration occurs during the day as well (Roth et al. 1984). Preference for higher salinities increases as the fry grow (Houston 1961; McInerney 1964), and migration to seawater within the first summer is considered mandatory for survival (Houston 1961). Environmental factors that control downstream migration include temperature, photoperiod, light intensity, size of fish, and level of river discharge (Brannon and Salo 1982).

Specific Habitat Requirements

Tolerances and requirements of chum salmon change with season and age. Although most developmental changes and movements to different habitats are gradual, factors assumed to affect habitat quality can be specified most effectively if the freshwater life cycle is divided into three distinct stages: (1) upstream migrants - sexually mature chum salmon migrating from the ocean upstream to spawn; (2) spawning, embryo, and alevins (yolk-sac fry) - period from egg deposition to hatching and emergence of fry from redds; and (3) downstream migrant - young fish from the time of emergence from gravel to entry into the ocean.

Upstream migration. Adult chum salmon must arrive at the spawning grounds within a relatively restricted seasonal period and in good health if spawning is to be successful. The habitat needs are relatively broad during this phase, which lasts for only a few weeks or less for stocks that spawn in short coastal streams or within a few kilometers from the stream mouth. This phase lasts for a month or more for stocks that spawn upstream in larger rivers such as the Yukon.

Temperature can adversely affect migrating salmon by altering the timing of migration and rate of maturation, by increasing the susceptibility to diseases, and by causing direct mortality (Holt et al. 1975; Reiser and Bjornn 1979). Chum salmon usually enter streams as temperatures fall below 15° C (Bakkala 1970), and most upstream migration occurs in the range of 8 to 14° C (Hunter 1959; Sano 1966; Barrett et al. 1984). In Alaska, the observed temperature range during upstream migration was 5.0 to 12.8° C in the Kuskokwim River (Alaska Department of Fish and Game 1980), 10.0 to 16.7° C in the Anvik River (Trasky 1974), and 8.9 to 14.4° C (during peak migration) in the Traitors River (Mattson and Hobart 1962). Bell (1973) suggested that the temperature range of 8.3 to 15.6° C would allow successful upstream migration of chum salmon, and that temperatures near 10° C were optimum. Temperatures above about 15° C are likely to result in increased susceptibility to disease (Wedemeyer 1970; Fryer and Pilcher 1974; Holt et al. 1975; Groberg et al. 1978) and to delay upstream migration (Bell 1973). Temperatures ≥ 25.5° C are lethal to migrating Pacific salmon (Bell 1973). The effects of low temperatures are less clear. Although most migration occurs above 7° C, Mattson and Hobart (1962) observed upstream migration at temperatures as low as 4.4° C; it is not known if upstream migration occurs at even lower temperatures.

Dissolved oxygen (DO) levels > 6.3 mg/l are recommended for successful upstream migration of anadromous salmonids (Davis 1975). Lower DO concentrations are likely to inhibit upstream movement by reducing swimming ability and eliciting avoidance responses. Davis et al. (1963) found that the maximum sustained swimming speed of coho salmon was sharply reduced at DO levels < 6.5 mg/l. Whitmore et al. (1960) reported that juvenile coho salmon avoided waters where DO was < 4.5 mg/l. About 300 pre-spawn pink and chum salmon died in Porcupine Creek, southeastern Alaska, in 1981 when their upstream migration was blocked by low flows, crowding them into a pool where the DO level dropped to < 2.0 mg/l (Murphy 1985). Edgington (pers. comm. in Krueger 1981) reported high mortalities of ripe pink salmon in southeast Alaska streams where DO had dropped below 4 mg/l.

Chum salmon are less inclined to surmount rapids, waterfalls, and other barriers than other species of Pacific salmon; thus, accessibility of the spawning stream is probably a very important variable determining the success of upstream migration. The maximum height of surmountable barriers for chum salmon has not been determined.

Low flow can also be a barrier. Adult chum salmon travel upstream in shallow riffles with the upper part of their bodies above water (personal observation, Hale), but the distance that can be traversed in such shallow water is unknown. In southeast Alaska, where the streams without a snow pack generally have low reservoir capacity and the flow depends heavily on rainfall, migrating chum salmon often have difficulty moving upstream during dry periods. A similar situation has been reported in British Columbia (Wickett 1958). High mortality of pre-spawn salmon caused by high water temperatures and low DO levels during low flow conditions is not uncommon in southeastern Alaska; up to 30,000 pink and chum salmon died in one stream (Murphy 1985). Thompson (1972) suggested that the maximum water velocity for successful upstream migration of adult chum salmon was 2.44 m/sec and that the minimum water depth required was 18 cm. Blakely et al. (1985), who observed successful and unsuccessful attempts by chum adults trying to reach spawning grounds at 85 passage reaches in the Susitna River, stated that the threshold depth for successful passage was 15.2 cm. This depth increases as the passage reach becomes longer than one or two meters.

The timing of upstream migrations is often correlated with flow conditions. Lister and Walker (1966) observed chum salmon delaying at the mouth of the Big Qualicum River, British Columbia, during extremely low discharges and then moving upriver when discharge increased. Similar observations have been made in Carnation Creek, British Columbia (Scrivener, pers. comm.) and in the Chitose River, Japan (Mayama 1978). High levels of discharge can also slow upstream migration. Barrett et al. (1984) observed chum salmon milling in the Susitna River during discharge peaks when the catch rate in fish wheels declined. High suspended sediment loads may also inhibit upstream migration. In Prince William Sound, chum salmon did not spawn in a glacier-fed stream until after the flow and silt load had decreased (Helle 1960). In the Delta River, Alaska, chum salmon did not enter the stream until after freeze-up when glacial run-off had ended and the only source of water was upwelling groundwater (Geiger, pers. comm. in Hale 1981).

Spawning. Temperature, water velocity, substrate composition, and salinity appear to be the major factors determining the suitability of an area for spawning. Chum salmon spawn at temperatures of 5.1 to 6.7° C in the tributaries of the Columbia River; at 4.0 to 16.0° C for British Columbia in general (Neave 1966); at a mean temperature of 12° C in Hooknose Creek, British Columbia (Hunter 1959); at ≤ 13° C in Sashin Creek, southeast Alaska (McNeil 1964); at 6.5 to 9.0° C in the Kizhuyak River and 9.0 to 12.5° C in the Terror River on Kodiak Island (Wilson et al. 1981); and at about 4.5 to 13.0° C in the Susitna River (Vincent-Lang et al. 1984). Schroder (1973) noted that there was some inhibition of spawning by chum salmon in Washington at temperatures < 2.5° C. Bell (1973) recommended 7.2 to 12.8° C as optimum for successful spawning.

Chum salmon spawn over a wide range of water velocities; surface water velocity may be less important than the presence of upwelling groundwater (Kogl 1965; Sano 1967; Helle 1979; Vincent-Lang et al. 1984). Surface water velocities (cm/sec) measured at spawning sites in different areas were: 0 to 60 in the Chena River, Alaska (Kogl 1965); 0 to 118.9 in the Terror and Kizhuyak Rivers (Wilson et al. 1981); a range of 46 to 97 (Thompson 1972) and a mean of 73 cm/sec over 214 redds in Oregon (Smith 1973); and 21 to 101 (12 cm above chum salmon redds) in Washington (Collings 1974). The range of water velocities at 333 chum salmon redds in the Susitna River, Alaska, examined by Vincent-Lang et al. (1984) was from 0 to about 130 cm/sec; the velocity at most redds ranged from 0 to 30 cm/sec. In a spawning channel in Washington, velocities ranging from 0 (at high tide) to 22.5 cm/sec had no apparent effect on spawning behavior (Schroder 1973). In the Memu River, Japan, redds were most abundant in areas where the velocity was 15 to 20 cm/sec (Sano and Nagasawa 1958). Sano (1967) stated that chum salmon spawn in water with surface velocities of less than 15 cm/sec provided there is groundwater seepage through the gravel. Smith (1973) recommended velocities of 46 to 101 cm/sec for successful spawning of chum salmon in Oregon. A chum salmon spawning channel at Jones Creek, British Columbia, was designed for velocities of 31 to 76 cm/sec (MacKinnon et al. 1961).

Tautz and Groot (1975) suggested that chum salmon prefer to spawn in areas where rocks protruding above the substrate create an upwelling, accelerating current. The current at the boundary between pools and riffles is also favorable. Such irregularities are conducive to a good flow of intragravel water (Reiser and Bjornn 1979). Streamflow during spawning, relative to the flow during the incubation period, can be an important factor affecting survival. Eggs deposited in shallow water during high flow stages are subject to desiccation or freezing during low flow stages. Kogl (1965) found that chum salmon dug redds in the Chena River at water depths of 5 to 120 cm; the fish spawned at the greater depths (> 100 cm) in areas where upwelling spring water or groundwater seepage was lacking. Eggs deposited in areas where the water was < 100 cm deep and where there was no upwelling were subject to freezing in winter. Chum salmon spawned at depths of 61 to 92 cm in the Delta River (Francisco 1976) and 7.6 to 106.7 cm in the Terror and Kizhuyak Rivers (Wilson et al. 1981). In the Susitna River, water depths at chum salmon redds ranged from about 5 to 90 cm; most were in the range of 10 to 60 cm (Vincent-Lang et al. 1984). Water depths over chum salmon redds were 5.1 to 76.2 cm (mean 25 cm) in tributaries of the Columbia River (Burner 1951); averaged 30 cm in five Oregon streams (Smith 1973); and ranged from 15 to 53 cm in Washington streams (Collings 1974). A minimum water depth of 18 cm was recommended by Thompson (1972) and Smith (1973).

Chum salmon excavate redds in gravel beds with particles of 2 to 3 cm in diameter, but they also construct redds in substrates with larger rocks, including bedrock covered with small boulders (Scott and Crossman 1973; Morrow 1980). Duker (1977) reported that spawning females given a choice of substrates preferred particle sizes 0.7 to 7.6 cm in diameter over larger or smaller ones.

Salinity may interfere with fertilization of eggs spawned in the intertidal zone. Rockwell (1956) found that salinities of ≥ 18 ppt inhibit fertilization of chum salmon eggs, although some fertilization occurred in salinities as high as 30 ppt.

The outlet of a tidal lagoon in Prince William Sound, Alaska, drained saline water after the 1964 earthquake that uplifted the area about 6 ft. Salinity of the outlet stream ranged from 4 to 8 ppt. Chum and pink salmon spawned in this stream and redd excavations yielded no live eggs. The eggs had not imbibed water to separate the membranes, i.e., they did not "waterharden" (Helle, pers. comm.).

Embryos and alevins. Temperature, streamflow, dissolved oxygen, salinity, and especially substrate composition are important factors affecting survival of chum salmon embryos and alevins. Stream water temperatures from 0° C to as high as 15° C have been observed during incubation (McNeil 1966; Koski 1975). Intragravel temperatures in chum salmon redds in the Susitna River, Alaska, ranged from 12.5° C in September to 0.0° C in December (Vining et al. 1985). Chum salmon prefer to spawn in upwelling areas of the Susitna, where intragravel temperatures remain about 3 to 4° C all winter. Embryos in redds where the temperature was less than 3° C hatched two to three months later than those in the upwelling areas (Vining et al. 1985). In northern Japan, Sano (1966) found that fall chum salmon preferred to spawn in spring areas where water temperatures did not decrease below 4° C. In Alaska, observed intragravel temperatures during incubation were 0.5 to 4.5° C in the Chena River (Kogl 1965); 6.1 to 10.0° C in early October to 0.2 to 3.3° C in March in the Noatak River (Merritt and Raymond 1982); 0.6 to 6.7° C in the Delta River (Francisco 1977); and 4° C in October, near 0° C in December-January, and 1° C in mid-March before fry emergence in Olsen Creek (Bailey 1964). Long-term exposure to temperatures < 4.4° C reduces survival of chum salmon embryos (Schroder 1973; Koski 1975; Wangaard and Burger 1983; Alaska Department of Fish and Game 1983). Schroder et al. (1974) reported that the percent survival to emergence of chum salmon in Washington was decreased if the embryos were exposed to water temperatures < 1.5° C during the early stages of embryonic development. In a hatchery in Alaska, Raymond (1981) found that mortality (fertilization to emergence) was higher (38%) when incubation temperatures were 2.0 to 4.2° C than when they were at 3.6 to 4.5° C (18%). Wangaard and Burger (1983), in a laboratory experiment, observed an increase in mortalities and abnormalities in Susitna River chum embryos and alevins when the average incubation temperature was < 3.4° C. Kirkwood (1962) found that survival of Prince William Sound chum salmon embryos was higher in the upper intertidal zone than farther upstream, due to the higher intertidal temperatures. Similarly, Hartman and Leahy (1983) found that intragravel temperatures in chum spawning areas in British Columbia during winter were up to 2° C higher than stream temperatures and that these differences were most pronounced in the upper intertidal zone. Koski (1975) found that exposure of Washington chum salmon embryos to water temperatures < 4.4° C before gastrulation caused high mortalities. McNeil and Bailey (1975) suggested that temperatures in Pacific salmon hatcheries should be maintained above 4.4° C for at least 10 days, and preferably for 20 to 30 days, after fertilization. After this period, Bailey and Evans (1971) found that pink salmon embryos can tolerate temperatures as low as 0° C, provided that freezing does not occur.

Water temperatures can also cause significant changes in the time of emergence of fry from the substrate. Koski (1975) found that annual water temperature variations in a Washington stream caused the time required to reach 50% emergence of chum fry to vary as much as 30 days during a 3-year period. The time to hatching of fry is about 50 days at 7.0 to 15.0° C, but 130 days at 0.0 to 5.0° C (Bakkala 1970). Raymond (1981) reported that chum salmon eggs taken from the Delta River and incubated at 2.0 to 4.2° C in a hatchery emerged from the gravel 7 weeks later than fry from the same stock exposed to a higher mean temperature (3.9° C) in the natural spawning area. Incubation of chum salmon embryos was studied at three sloughs with upwelling ground water (3.5 to 4.0° C) in the Susitna River (Alaska Department of Fish and Game 1983). One of these sloughs was flooded with cold (~ 0° C) mainstem water when an ice jam caused the head of the slough to be overtopped. Chum embryos and alevins in this slough experienced a higher mortality rate and a delayed emergence as compared to the other sloughs which remained at 3.5 to 4.0° C. In a controlled laboratory experiment, Wangaard and Burger (1983) found that complete yolk sac absorption of Susitna River chum fry was delayed by up to 2 months when the average incubation temperature was 2.1° C, as compared to 3.9 and 4.0° C. Kirkwood (1962) stated that chum salmon embryos in Prince William Sound that had not hatched before January or February did not survive. Clear-cut logging in the Carnation Creek, B.C., watershed resulted in a 2° C rise in winter stream temperatures (Holtby and Newcombe 1982; Hartman et al. 1982; Holtby, pers. comm.) and a shift in chum fry migration of up to 6 weeks earlier (Andersen 1983, 1984). Since ongoing work indicates that emergence timing in chum salmon is genetically controlled, it is possible that earlier emergence of Carnation Creek chum salmon could have significant, deleterious effects on early fry survival in the ocean and may be a factor in the declines in adult returns to Carnation Creek that occurred after logging (Holtby, pers. comm.).

Because chum salmon frequently spawn in streams where runoff is highly variable, embryo mortality during freshetting may be severe (Hunter 1959; McNeil 1966; Neave 1966). High flows cause increased mortality by directly scouring redds or by depositing fine sediments over the redds which, in turn, reduces substrate permeability and inhibits emergence of fry (Neave 1953; Wickett 1958; McNeil 1966, 1969; Scrivener and Brownlee 1982, in prep.). Conversely, low flows can lead to desiccation of eggs, low DO, high temperatures, or freezing (Neave 1953; Levanidov 1954; Wickett 1958; McNeil 1966; Sano 1966; Vining et al. 1985). McNeil (1966, 1969), who observed that survival to emergence varied in relation to stream discharge during the winter, found that mortality of chum and pink salmon eggs and alevins was four to five times greater in a stream with a 500-fold difference in average daily stream discharge (0.11 to 55.0 m^3/sec) than in a nearby stream where this difference was only 80-fold (0.34 to 28.0 m^3/sec). Cederholm and Koski (1977) reported that 55% of chum salmon redds in a channelized section of a Washington stream were scoured out or covered by sediment due to streambed shifting during frequent and severe freshets. Also, Lister and Walker (1966) found an inverse relation between percent survival of chum salmon eggs to the fry stage and the peak daily discharge of the Big Qualicum River, British Columbia. On the Noatak River, low adult returns appear to be correlated with high water levels (Bird, pers. comm. in Hale 1981). Gallagher (1981) found that low flows during the incubation period were correlated with good adult returns for streams in the Puget Sound area. Beacham and Starr (1982) determined that freshwater survival (based on fry escapement) from the Fraser River system was due to interactions of temperature, rainfall (= flow), and egg abundance. Survival was highest in years when winters were dry and warm and lowest in years when winters were cold and wet. On the other hand, Wickett (1958) showed a direct relationship between an index of production and discharge for Hooknose Creek in November. In summary, the effect of varying discharge is not constant between streams and may depend on other conditions in the selected stream.

The size and shape of substrate particles influence many factors that are important to the successful incubation of embryos and alevins. Some of these factors -- several of them interrelated--are permeability, porosity, flow of intra-gravel water, dissolved oxygen concentration, concentration of waste metabolites such as carbon dioxide and ammonia, the "armoredness" or resistance to abrasion of the substrate surface, and the degree of embeddedness of large particles in the substrate surface. Ideal substrate conditions for incubation of eggs and alevins of chum salmon are hard to specify because different investigators have used various methods and definitions, making comparisons difficult. Hunter (1959) found that chum salmon in Hooknose Creek, B.C., spawned in gravel 13 to 130 mm in diameter that contained unspecified amounts of sand and silt. Sano (1959) reported that chum salmon redds in Japan consisted of > 30% gravel (particle diameter > 31 mm). Burner (1951) wrote that redds in the Columbia River were composed of 81% gravel (particles < 152 mm in diameter but larger than sand); 6% mud, silt, and sand; and 13%

cobble (≥ 152 mm diameter). The substrate in chum salmon redds sampled in the Susitna River, Alaska, was mainly composed of particles 2 to 76 mm in diameter; particles < 2 mm comprised 6 to 25% of the total (Vining et al. 1985). Percent survival of embryos in in situ Whitlock-Vibert boxes was zero at percent fines > 18%.

Sedimentation during the incubation period can be a major source of egg mortality (Neave 1953; Levanidov 1954; Wickett 1954; McNeil 1966; Rukhlov 1969; Scrivener and Brownlee 1982, in prep.). In one year in the early 1950's, siltation in the River Khor in Siberia killed all of the embryos in 42 chum salmon redds (Levandov 1954). However, inasmuch as chum salmon often spawn in areas of upwelling ground water, they may be able to tolerate a higher percentage of fines if intra-gravel flow is maintained by such upwelling (Sano and Nagasawa 1958; Helle, pers. comm. in Hale 1981; Vining et al. 1985).

Dill and Northcote (1970) found that survival to emergence for chum salmon in experimental containers was nearly 100% in large gravel (51 to 102 mm) but only 31% in small gravel (10 to 38 mm). Koski (1975) found a highly significant inverse relation between percent sand (fines < 3.327 mm but > 0.105 mm) and percent survival to emergence of chum salmon in Washington. Increased percent sand also resulted in earlier emergence, reduced yolk conversion efficiency, and smaller fry. Furthermore, ≥ 45% silt (fines < 0.105 mm) reduced survival; this effect was masked by a changing percentage of sand. Koski also observed a significant inverse relation between DO concentration and percent sand and silt.

Scrivener and Brownlee (1982, in prep.) reported that after intense logging in the Carnation Creek watershed, British Columbia: (1) fine sand particles significantly increased; (2) intragravel DO decreased from a mean of 6.8 mg/l prior to logging to 3.2 mg/l after logging; (3) gravel permeability declined 50 to 68% to levels below the threshold cited as limiting chum fry production (3,000 cm/hr); and (4) chum salmon egg-to-fry emergence rates ranged from 16.3 to 25.0% ($\bar{x}$ = 20.95%) in the 6 years before logging to 4.6 to 23.5% ($\bar{x}$ = 12.3%) in the 5 years after logging.

Rukhlov (1969) found that egg mortality of chum salmon on Sakhalin Island increased as sand content exceeded 14%. He found that average survival rates were ≤ 50% in substrates with > 22% sand, 65% in those with 18% sand, and 85% in those with 10% sand. Thorsteinson (1965) stated that spawning grounds in which the percent fines (particles < 0.833 mm) exceeded 12.7 are of poor quality because permeability is greatly reduced. Johnson (1980) showed experimentally that the permeability of spawning gravels decreased as percent fines (particles < 0.5 mm) increased. Wickett (1958) related the average survival of chum and pink salmon eggs and alevins to the permeability of the substrate: percent survival (eggs in female to fry escapement) was only 1.2% at a permeability of 1,914 cm/hr but 7.6% at a permeability of 4,035 cm/hr. Substrate sizes (diameter of particles) suggested for successful spawning and incubation of chum salmon were 13-152 mm (McNeil and Bailey 1975) and 13-102 mm (Bell 1973).

DO affects the survival, fitness, and timing of emergence of chum salmon embryos and fry (Wickett 1954, 1958; Alderdice et al. 1958; Koski 1975). The level of intragravel DO is a function of sediment particle size, rate of intragravel flow, and DO concentration in the free flowing water (Daykin 1965; Koski 1975). Critical oxygen levels (the lowest concentration at which respiration demands are satisfied) for chum salmon eggs at 8 to 10° C ranged from 0.72 mg/l for early developmental stages to 7.19 mg/l just before hatching (Wickett 1954; Alderdice et al. 1958). Wickett (1954, 1957) reported that a DO concentration of 2 mg/l at 5° C was lethal, but Levanidov (1954) and Kogl (1965) found good survival rates at 2.0 mg/l in areas where springs and upwelling groundwater provided good intragravel flow. Koski (1975) found a significant correlation between percent survival to emergence of chum salmon and DO concentration with survival decreasing markedly below 3.0 mg/l. An _in situ_ incubation experiment using chum salmon eggs in 59 Whitlock-Vibert boxes in artificial redds in the Susitna River, Alaska, resulted in good survival rates where the intragravel DO level was > 3.0 mg/l and zero survival where DO was < 3.0 mg/l (Vining et al. 1985). Redds in intertidal areas may be exposed to low DO levels during tidal cycles; during high tide in Prince William Sound, Thorsteinson (1965) observed a drop from 7 mg/l to 4.5 mg/l. Reduced water permeability at one tide level in the Olsen Creek intertidal spawning area led to a low DO level (3.6 mg/l) and a low percent survival to emergence (Bailey 1964). Long dry periods during which stream and intragravel flows are reduced can also result in low DO. Such conditions in the Traitors River, Alaska, led to high mortality of embryos at an intragravel DO level of 1.8 mg/l (Mattson et al. 1964).

Low DO causes reduction in the size of emerging fry and delays hatching and emergence. Kogl (1965) reported that the dry weight of chum salmon alevins in the Chena River, Alaska, decreased from 2.3 mg at 4.5 mg/l DO (average) to 0.1 mg at 2.1 mg/l DO (average). Alderdice et al. (1958) reported that early developmental stages (embryos < 12 days after fertilization) could survive 7 days of exposure to 0.3 mg/l DO but that a high percentage of abnormalities resulted; later developmental stages (> 22 days) did not survive. Furthermore, short-term (7 day) exposures to DO levels below saturation (at 10° C) caused delays in hatching in early and middle developmental stages but caused premature hatching when the exposure to low DO occurred just before hatching. Koski (1975) observed similar delays in emergence of fry when DO was < 3 mg/l. Delays in emergence could place fry in unfavorable conditions in relation to food availability, predation, temperature, or streamflow.

Survival of chum salmon embryos seemingly declines from the upper to lower reaches of intertidal zones, presumably as a result of higher salinity (Bailey 1964; Thorsteinson 1965; Thorsteinson et al. 1971). Thorsteinson (1965) found that egg-to-fry survival was 40 to 50% in the upper section of the intertidal zone in Prince William Sound and 10 to 15% in the middle section; the lower section was not used by chum salmon. In laboratory experiments, Rockwell (1956) found that: (1) constant salinities ≤ 6 ppt had no effect on early developmental stages of chum salmon eggs; (2) significantly retarded development and 67% mortality occured at 11.6 ppt; and (3) > 12 ppt led to 100% mortality. Kashiwagi and Sato (1969) found that percent mortality of chum salmon eggs to hatching was 0 at ≤ 9 ppt, 25 at 18 ppt, 50 at 27 ppt, and 75 at 35 ppt; however, nearly all alevins reared from eggs held at > 9 ppt died within a few days after hatching. Alevins that were hatched in freshwater and then exposed to a seawater mixture survived constant salinities of < 9 ppt but died at higher salinities (Kashiwagi and Sato 1969). Duration of exposure, temperature, dissolved oxygen, and stage of development confound these effects of salinity on chum salmon eggs and alevins (Rockwell 1956; Thorsteinson 1965; McNeil 1966). Also, recent observations by Hartman (pers. comm.) in Carnation Creek, B.C., support McNeil and Bailey's (1975) speculation that Pacific salmon eggs can tolerate periodic inundations of salinities of 15 to 30 ppt; Hartman found viable chum eggs in the Carnation Creek intertidal zone 200 m below the high tide mark where intragravel salinities ranged from 0 to 24 ppt, depending on stage of the tide.

The presence of upwelling ground water can be an important factor in chum salmon egg to fry survival (Kogl 1965; Vining et al. 1985). Upwelling ground water prevents dewatering and freezing when surface flows are low, maintains a more constant intragravel temperature, and supplies dissolved oxygen. Other factors, such as pH, CO_2, alkalinity, ammonia, and H_2S, may affect survival to emergence in altered systems, but the tolerances of chum salmon eggs and alevins to these factors are largely unknown (see Hale 1981:43-44). The pH of intragravel water at chum salmon redds was 6.5 in the Chena (Kogl 1965) and Amur (Levanidov 1954) rivers and 6.3-6.5 in a Hokkaido stream (Kobayashi 1968). McNeil and Bailey (1975) suggested that pH levels of 6.0 to 8.0 are desirable for Pacific salmon.

Rearing and downstream migration. Habitat requirements of fry from the period of emergence from the gravel to entrance into the sea center on favorable temperatures, cover from predators, availability of food, and (eventually), availability of seawater. Smoltification in chum salmon has not been studied extensively, and it is not clear how environmental factors in freshwater affect this process and affect the survival of young chum salmon in estuaries and in the ocean. However, information on other anadromous salmonids summarized by Wedemeyer et al. (1980) indicated that this stage is particularly sensitive to environmental stresses. Inferences made here about the factors that may adversely affect smoltification in chum salmon fry were drawn primarily from the review of salmonid smoltification by Wedemeyer et al.

Temperature can affect the timing of downstream migration, as well as the growth, survival, and smoltification of chum salmon fry. The recommended temperature range for successful downstream migration is 6.7 to 13.3° C (Bell 1973). In Alaska, out-migration of chum salmon fry was observed at temperatures of 3.0 to 5.5° C in the Delta River (Raymond 1981), 0.1 to 14.5° C in the Susitna River (peak outmigration began at temperatures > 6.0° C; Roth et al. 1984), and 5.0 to 7.0° C in the Salcha River during the peak migration (Trasky 1974). In Hokkaido, Japan, downstream migration began at temperatures of 2.0 to 3.0° C and peaked in May when temperatures were 6.0 to 10.0° C (Sano 1966). Semko (1954) measured temperatures of 4.6 to 5.5° C during downstream migration of chum salmon fry in April and May in the Bolshaia River, USSR. Temperatures > 15° C, which chum salmon fry generally avoid (Brett 1952; Levanidov 1954), may cause premature downstream migration. Keenleyside and Hoar (1955) reported that chum fry changed from positive to negative rheotaxis when temperatures rose above 10° C; Mihara (1958) observed this effect at temperatures above 15° C. The lower and upper lethal temperatures for chum salmon fry are near 0° C (Brett 1952; Brett and Alderdice 1958) and 23.8° C (Brett 1952). McNeil and Bailey (1975) stated that Pacific salmon fry grow at temperatures of 4.4 to 15.7° C, but that the ideal range is 10.1 to 12.9° C. Growth is slow at temperatures below 10° C and problems with diseases and other stress factors develop at 15.7° C or higher; temperatures of 20 to 22° C are tolerated only for limited periods. Wedemeyer et al. (1980) reported that elevated water temperatures during incubation accelerate the onset of smoltification and shortens the smolting period, and thus seaward migration of salmonid smolts may occur at a time when conditions are unfavorable; they recommended that temperatures should not exceed 10° C in late winter (to prevent accelerated smolting) and should not exceed 12° C during emergence and seaward migration in the spring (to prevent alteration of the smoltification process and reduce the risk of disease).

The effects of low temperatures on chum salmon fry during rearing and downstream migration are not well documented. However, temperatures < 8° C from March through June may render a stream less suitable as potential rearing habitat. Levanidov (1955) found that feeding and growth of the fry were reduced at temperatures ≤ 8° C in the laboratory. Similarly, Kobayashi and Ishikawa (1964) found that chum salmon fry grew slowly in March-April, the period during which most of the fry migrated to the sea, but that growth was more rapid after April because feeding increased as water temperatures rose. Kaeriyama et al. (1978) found that chum fry in the Tokachi River of Japan increased in weight as much as 310% during April and May of 1976; however, there was no increase in weight during the same months of 1975, when the river was colder and more turbid. Average weight of stomach contents in 1976 was four times that of 1975.

Predation is sometimes a major source of mortality in chum salmon fry (Hunter 1959; Kirkwood 1962). Hunter (1959) estimated that predation losses accounted for 23 to 85% of the total numbers of fry emerging from the gravel in Hooknose Creek, British Columbia. Although cover requirements of the fry are not well understood, the fry are known to hide in interstitial spaces in the substrate during the day as they migrate downstream in small coastal streams (Neave 1955). Suchanek et al. (1984) did not find a strong preference by Susitna River chum salmon fry for cover, but substrate, debris, and undercut banks were more preferred than aquatic or emergent vegetation. Schooling (Hoar 1956) and turbidity (Suchanek et al. 1984) also provide protection from predators. However, chum salmon tend to avoid high turbidity during the rearing phase (Suchanek et al. 1984). Exposure to high levels of suspended sediments can lead to "tail rot", as well as reduced gas exchange across gills as a result of damage, coating, or accumulation of mucus (Smith 1978). Smith (1978) determined that the 96-hr LC_{50} for suspended sediment for juvenile chum salmon was 15.8 to 54.9 g/l.

In addition to providing cover from predators, rocky substrates are seemingly necessary to maintain orientation in fry that still have a yolk sac upon emergence (Emadi 1973; McNeil and Bailey 1975). Emadi (1973) found that 30% of the chum salmon alevins reared on a smooth substrate in the laboratory were malformed; there was no malformation of the alevins reared on gravel substrate consisting of particles 2 to 3 cm in diameter. McNeil and Bailey (1975) also stated that hatchery-reared Pacific salmon require a gravel substrate after emergence.

Terrestrial and aquatic invertebrates are the primary food of chum salmon that delay seaward migration and rear for a time in fresh and intertidal waters (Sparrow 1968; Bakkala 1970; Mason 1974). Production of these food items is high in streams having abundant streambank vegetation and a substrate with low embeddedness and a low proportion of fines (Mundie 1969; Reiser and Bjornn 1979).

Both osmoregulatory ability and preference for seawater increase as chum salmon fry increase in age (Baggerman 1960; Houston 1961; McInerney 1964). Chum salmon fry that have absorbed their yolk sac can tolerate full strength seawater (Kashiwagi and Sato 1969). Mason (1974) showed that fry feeding in intertidal areas are highly tolerant of daily salinity changes. Chum salmon fry appear to have a physiological requirement for seawater within 3 to 4 months after emergence for normal development (Houston 1961), but have been raised experimentally to the adult stage in freshwater--with careful handling (Hoar 1976).

Levanidov (1954) noted that DO levels ≤ 1.5 mg/l at 10° C are lethal to chum salmon fry, but he found no change in feeding, assimilation, or growth of fry over the DO range of 5 to 11 mg/l. Lukina (1973) reported 8 to 9 mg/l as the most favorable concentration at 8 to 10° C. DO levels ≥ 5 mg/l cause no impairment of swimming ability (Dahlberg et al. 1968) or avoidance (Whitmore et al. 1960) in salmonid fry in general. DO levels ≥ 6 mg/l are recommended for successful rearing of Pacific salmon fry in hatcheries (McNeil and Bailey 1975).

Water velocity requirements for chum salmon fry while in fresh or intertidal waters are not well known. Levanidov (1954) reported that optimum stream velocities to support the feeding of fry in the Amur River, Siberia, were < 20 cm/sec, and Mason (1974) observed fry feeding at a wide range of velocities < 40 cm/sec in intertidal areas. Similarly, most chum fry in rearing areas of the Susitna River are found in areas with water velocities < 35 cm/sec (Suchanek et al. 1984). Out-migration of chum fry is often related to the rate of river discharge (Brannon and Salo 1982). Chum salmon out-migration in the Susitna River is positively correlated with discharge level (Roth et al. 1984). McDonald (1960) also reported that fry out-migration increased markedly during high flow periods.

HABITAT SUITABILITY INDEX (HSI) MODEL

Model Applicability

Geographic area. This model was designed for use throughout the range of chum salmon. However, accuracy can be expected to vary greatly, depending on the watershed.

Season. This model was structured to account for seasonal changes in life stage requirements of chum salmon during the parts of the life cycle when they inhabit freshwater, which may include all months of the year, depending on the stream.

Verification level. The model represents our interpretation of how specific environmental variables combine to determine overall suitability of a habitat for chum salmon. As a first step in the model evaluation process (Farmer et al. 1982), we solicited comments from expert reviewers. Solicitation of review comments does not imply endorsement by the reviewers. The model has not been field tested.

Model Description

Overview. The HSI model presented here represents an attempt to synthesize information on freshwater habitat requirements of chum salmon into a set of habitat evaluation criteria. The model uses habitat variables based on parameters known to affect the growth, survival, distribution, abundance, or behavior of chum salmon. The model produces an index of the ability of a present or future habitat to meet the requirements of chum salmon during the three freshwater phases (designated as model components) of upstream migration, the spawning, embryo, and alevin stages, and rearing and downstream migration. The relation between habitat variables, model components, and HSI is illustrated in Figure 1.

The following sections document the reasons for choosing a particular set of habitat variables as a measure of habitat suitability for chum salmon during a particular phase of freshwater residence. The definition and justification of the suitability levels for each variable are described in a later section (Suitability Index Graphs).

Upstream migrant component. We included variable one (V_1, Fig. 1) in this component because temperature can alter timing of upstream migration of chum salmon (Hunter 1959) and affects the susceptibility of prespawning salmonids to disease (Wedemeyer 1970); V_2 was included because dissolved oxygen affects swimming ability (Davis et al. 1963; Dahlberg et al. 1968) and avoidance behavior in anadromous salmonids (Whitmore et al. 1960).

No specific variables were included in this component as measures of the accessibility of the spawning stream. Physical features encountered by chum salmon while migrating upstream should nevertheless be considered to determine if the habitat being rated is accessible. Passage criteria for successful upstream migration of chum salmon have been identified as depths > 0.18 m and velocities < 2.44 m/sec (Thompson 1972) and, for successful passage from the mainstem river into natural spawning areas, depths > 0.16 m (Blakely et al. 1985). Use of the Instream Flow Incremental Methodology (Bovee 1982) may be appropriate to determine if altered discharge regimes provide passage flows.

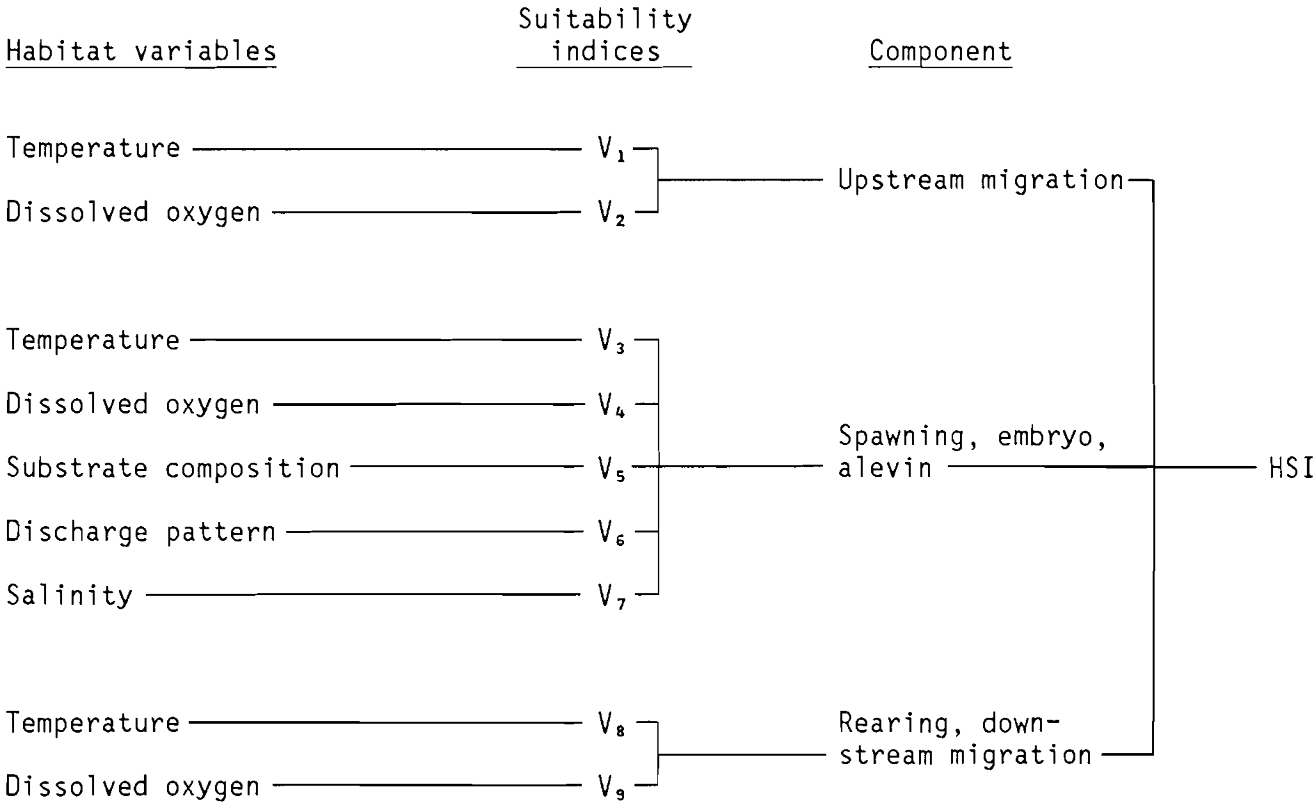


Figure 1. Diagram illustrating habitat variables and suitability indices for the chum salmon HSI model. HSI = the lowest of the suitability index ratings for variables V_1 through V_9.

Spawning, embryos, and alevins component. We included V_3 in this component because temperature affects time and duration of spawning (Hunter 1959; Schroder 1973), survival of embryos (Schroder 1973; Koski 1975), and timing of emergence and survival of chum salmon fry (Koski 1975). We included V_4 because DO levels affect embryo survival, incidence of developmental abnormalities, and timing of emergence of chum salmon fry (Wickett 1954, 1958; Alderdice et al. 1958; Koski 1975).

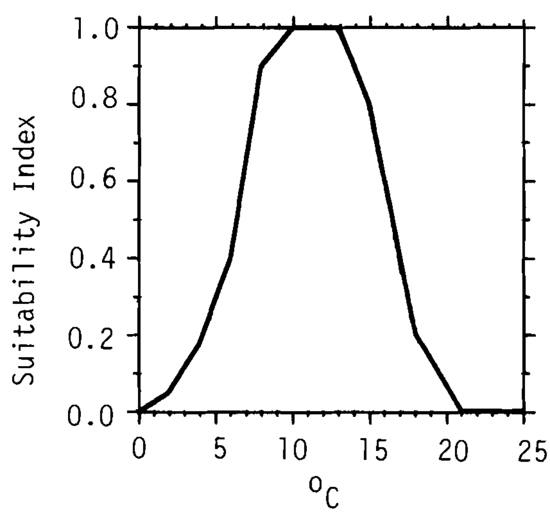
The index V_5 was included because spawning will occur only in a limited range of substrates and because embryo survival, emergence, and production of fry have been related to substrate composition of spawning redds of chum salmon (Wickett 1958; McNeil 1966; Rukhlov 1969; Dill and Northcote 1970; Koski 1975). V_6 was included because spawning does not occur where the velocity is too great and because discharge has been related to survival and production of eggs and alevins (Wickett 1958; Hunter 1959; McNeil 1966;

Cederholm and Koski 1977). V_7 was included because salinity affects embryo survival (Rockwell 1956; Kashiwagi and Sato 1969). Water depth and the presence or absence of upwelling ground water should also be considered as factors influencing spawning and incubation.

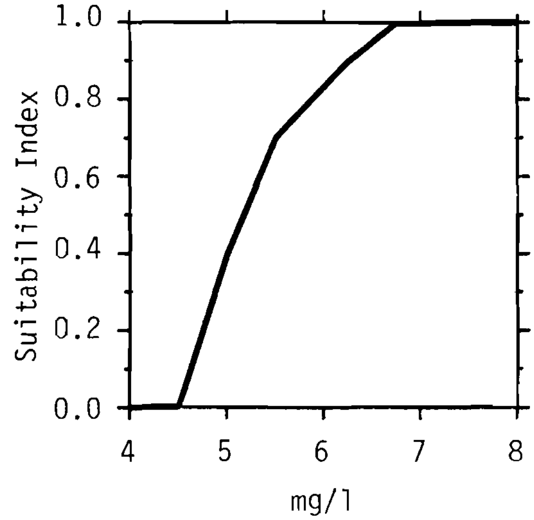
Rearing and downstream migration component. We included V_8 in this component because temperature affects the mortality of chum salmon fry (Brett 1952) and, in general, can alter the timing of seaward migration, smoltification, and the susceptibility of salmonid smolts to disease (Wedemeyer et al. 1980). The index V_9 was included because DO concentration could potentially affect downstream migration by decreasing swimming speed (Dahlberg et al. 1968), eliciting avoidance (Whitmore et al. 1960), or causing direct mortalities of smolts. Model users may also want to consider discharge pattern. Out-migration of chum fry in the Susitna River is correlated with discharge level (Roth et al. 1984). Fish appear to reach a point where they are physiologically ready to migrate downstream and then an increase in discharge provides the environmental cue to begin migrating. There may also be some physical flushing of fish as the heads of rearing sloughs are inundated by rising water. Food availability should also be considered.

Suitability Index (SI) Graphs for Model Variables

Table 1 lists the sources of information and rationale used in constructing each SI graph. Graphs were constructed by converting available information on the habitat requirements of chum salmon into an index of suitability ranging from 0.0 (unsuitable) to 1.0 (optimum or most preferred level). These graphs should not be construed as graphical presentations of real data, but rather as hypothetical models of the relation between levels of a particular environmental variable and its corresponding suitability as habitat for chum salmon. All variables pertain to riverine (R) habitat.

Habitat	Variable		Suitability graphs
R	V_1	Maximum temperature during upstream migration.	

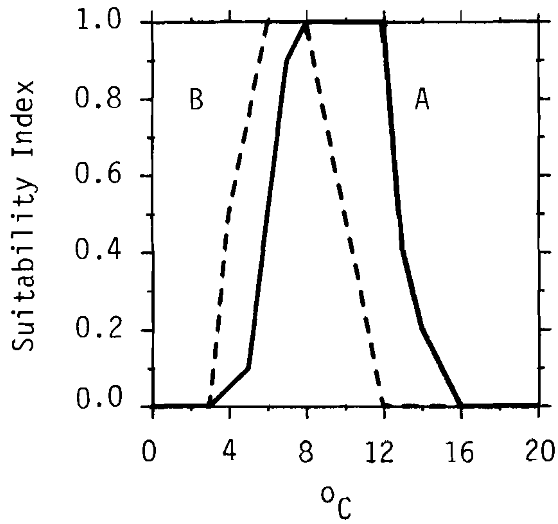
R V_2 Minimum dissolved oxygen (DO) concentration during upstream migration.



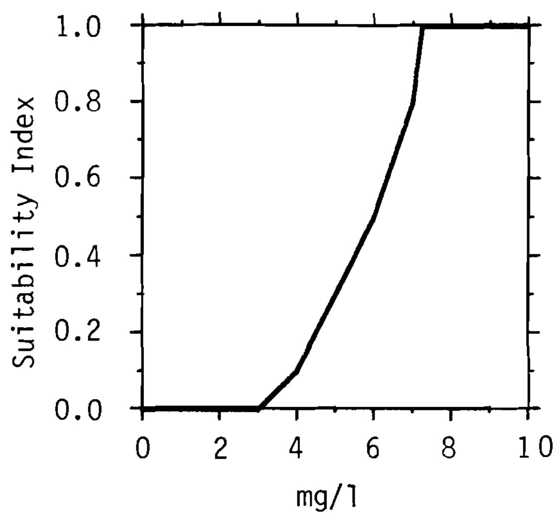
R V_3 Extreme intragravel temperatures from spawning to emergence of fry.

A. Maximum
B. Minimum

SI for V_3 = SI for A or B, whichever is lower

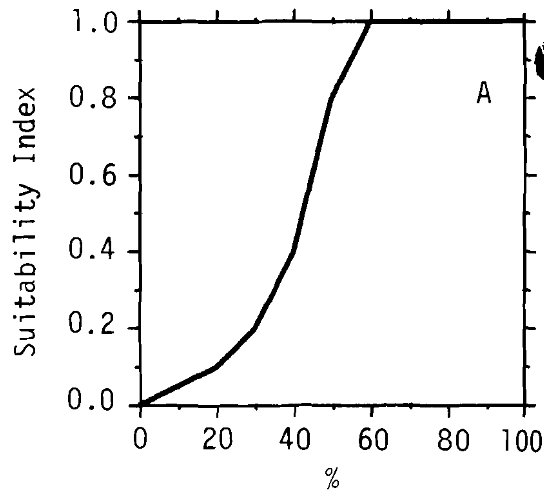


R V_4 Minimum DO concentration from spawning to emergence of fry.

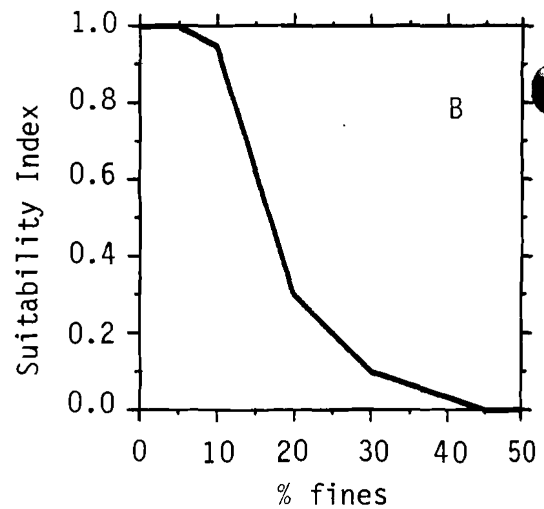


R V_5 Substrate composition within riffle and run areas.

A. Percent of gravel substrate 10-100 mm in diameter.



B. Percent fines (< 6 mm) or $\frac{\text{(Percent embeddedness of substrate)}}{2}$



$$\text{SI for } V_5 = \frac{\text{SI for A + SI for B}}{2}$$

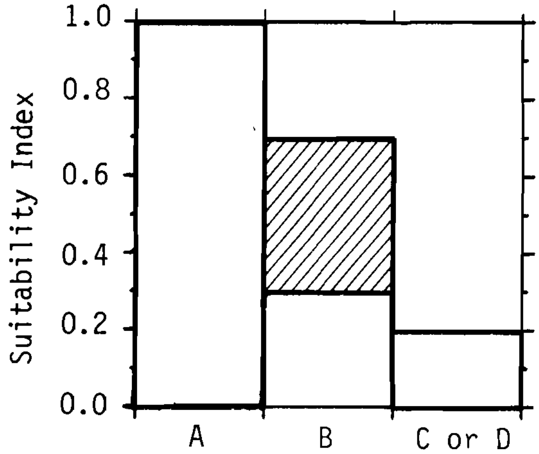
R V$_6$ Stream discharge pattern from egg deposition to downstream migration of fry.

A. Streamflow stable, < 100-fold difference between extreme average daily stream discharges; stream channel stable, with little shifting.

B. Moderate potential for flooding: 100 to 500-fold difference between extreme average daily stream discharges. (Hatch marks indicate suggested range of SI's for discharge range, 100-fold equals 0.7, 500-fold equals 0.3).

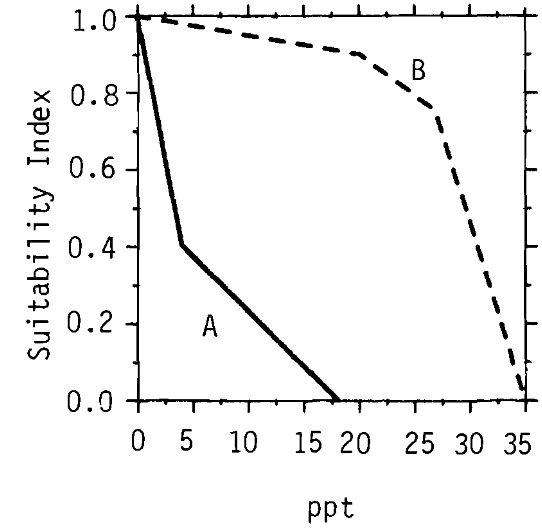
C. High potential for substrate scouring: > 500-fold difference between extreme average daily stream discharges during this period; stream channel easily altered during freshets; substrate unstable and easily displaced during freshets.

D. High potential for low winter flow or dewatering, resulting in exposure or freezing of redds.



R V_7 Mean intragravel salinity.

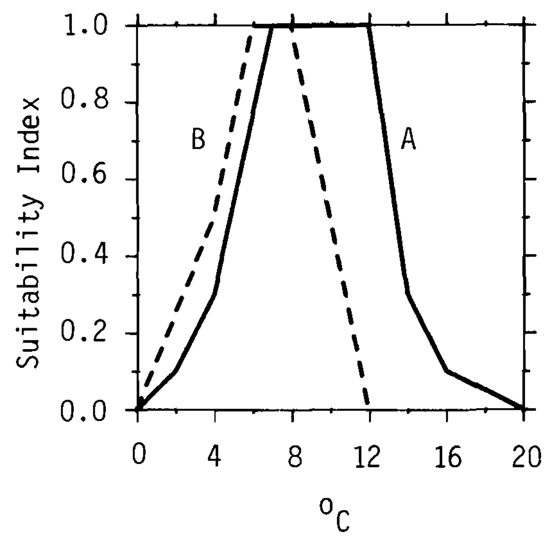
A. For eyed embryos.
B. For alevins.



R V_8 Temperature extremes during rearing and downstream migration of fry.

A. Maximum
B. Minimum

SI for V_8 = SI for A or B, whichever SI is lower.



R V_9 Minimum DO concentration during rearing and downstream migration of fry.

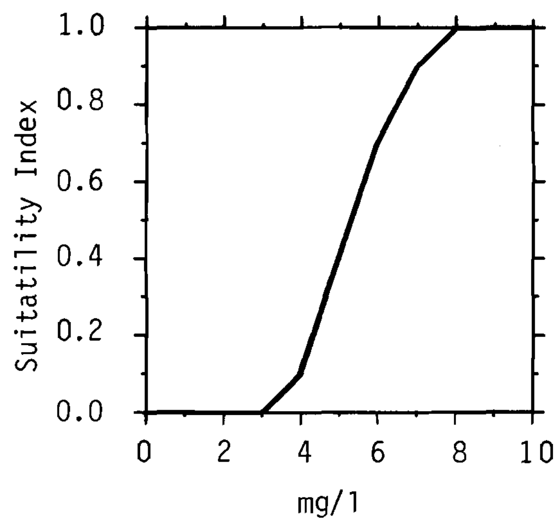


Table 1. Sources of information and rationale used in constructing suitability index graphs. Habitat for chum salmon is classified as "excellent" at 0.8 to 1.0, "good" at 0.5 to 0.7, "fair" at 0.2 to 0.4, and "poor" at 0.0 to 0.1.

Variable	Sources and rationale
V_1	Inasmuch as upstream migration of salmon is closely tied to the temperature regime characteristic of each spawning stream (Sheridan 1962), we assumed that any deviations from the normal seasonal temperature cycle during upstream migration would be suboptimum. Chum salmon migrate upstream primarily at 8 to 14° C (Hunter 1959; Sano 1966). However, temperatures of 8 to 12° C were considered excellent, because disease rates for anadromous salmonids increase markedly at temperatures above 12.7° C (Fryer and Pilcher 1974; Holt et al. 1975; Groberg et al. 1978). Temperatures ≥ 20° C were deemed poor because: (1) temperatures ≥ 25.5° C are lethal to anadromous salmonids (Bell 1973); (2) sublethal temperatures > 20° C are associated with high disease-induced mortality (Wedemeyer 1970); and (3) upstream migrations of Pacific salmon are delayed by temperatures > 20° C (Bell 1973). Temperatures of 15 to 20° C were deemed only fair because little upstream migration has been observed within this temperature range (see text).
V_2	Dissolved oxygen concentrations that enable undiminished swimming abilities (> 6.5 mg/l; Davis et al. 1963) and that are recommended for successful upstream migration of anadromous salmon (> 6.3 mg/l; Davis 1975) were considered excellent. We considered as poor the levels at which coho salmon swimming speed is greatly reduced (Davis et al. 1963) or avoidance is high (< 4.5 mg/l; Whitmore et al. 1960), or that are associated with high mortality of ripe pink salmon in southeast Alaska streams (≤ 4 mg/l; Edgington 1981 pers. comm. in Krueger 1981).
V_3	Unusually low or high temperatures result in emergence of salmonid fry at times inappropriate for their survival in the estuary (Sheridan 1962). Delayed chum salmon fry emergence due to reduced temperatures has been documented by Koski (1975) and Wangaard and Burger (1983). Temperatures of 7.2 to 12.8° C were considered excellent because they were related to high survival (Bailey and Evans 1971) and normal timing of emergence of pink salmon fry (Godin 1980). Temperatures that adversely affect survival and development of chum salmon eggs (< 4.4° C; Schroder 1973; Koski 1975; Raymond 1981; Wangaard and Burger 1983) or that inhibit chum salmon spawning (< 2.5° C; Schroder 1973) were considered poor, as were temperatures above the upper threshold for successful incubation of pink salmon embryos (≥ 15° C; Kwain 1982).

Table 1. (continued)

Variable		Sources and rationale
		McNeil and Bailey (1975) suggested that, like pink salmon embryos (Bailey and Evans 1971), chum salmon embryos tolerate temperatures near freezing, provided temperatures exceed 4.4° C for at least 30 days after fertilization.
V_4		Low DO levels increase mortality, decrease fitness, and alter timing of emergence of chum salmon embryos and fry (Wickett 1954, 1958; Alderdice et al. 1958; Koski 1975). Levels corresponding to high survival, unaltered timing of emergence, and highest fitness of chum salmon embryos and fry (> 6 mg/l; Alderdice et al. 1958; Lukina 1973; Koski 1975) were considered good to excellent. Concentrations corresponding to poor or no survival (< 3 mg/l; Wickett 1954; Mattson et al. 1964; Koski 1975), or delayed timing of emergence (< 3 mg/l; Alderdice et al. 1958; Koski 1975), were deemed poor.
V_5	A.	Hunter (1959) reported that chum salmon spawn in gravel 13 to 130 mm in diameter. Sano (1959) reported that chum salmon redds consisted of > 30% gravel (> 31 mm in diameter). Burner (1951) reported that chum salmon redds in tributaries of the Columbia River were composed of 81% gravel (< 152 mm). Dill and Northcote (1970) found survival of chum salmon eggs to be 100% in gravel 50 to 102 mm diameter but only 38% in gravel of 10 to 38 mm. On the basis of this information, we assumed that a substrate composition of ≥ 60% gravel 10 to 100 mm in diameter (and < 10% fines) is excellent.
	B.	Sedimentation during incubation is a major source of chum salmon egg mortality (Neave 1953; Wickett 1954; McNeil 1966; Rukhlov 1969; Scrivener and Brownlee 1982, in prep.). Koski (1975) observed an inverse relationship between percent fines (< 3.3 mm but > 0.1 mm) and percent survival to emergence of chum salmon. Higher percentages of fines led to premature emergence of fry, lower yolk conversion efficiency, smaller size at hatching, and slower growth. Thorsteinson (1965) reported that redds with > 13% fines (< 0.833 mm diameter) were poor producers of chum salmon fry because intragravel permeability was reduced. Scrivener and Brownlee (1982) found reduced chum egg-to-fry survival with increased sedimentation. Thus, levels of fines associated with high production and survival of chum eggs and fry (< 13%, Thorsteinson 1965; < 14%, Rukhlov 1969) and high survival and emergence of salmonid fry in general (< 10%, Hall and Lantz 1969; Phillips et al. 1975) were considered excellent. Levels of fines (> 15%) corresponding to lower survival and emergence of fry were considered fair to poor. We assumed that, if necessary, percent fines could be estimated by dividing the percent embeddedness by 2.

Table 1. (continued)

Variable	Sources and rationale
V_6	Survival of chum salmon embryos and alevins is high in more stable flow regimes (McNeil 1966, 1969), whereas it is poor in streams with shifting stream channels and extreme fluctuations in discharge that result in scouring of redds (Neave 1953; Wickett 1958; McNeil 1966, 1969). Poor survival of chum salmon eggs and alevins has also been observed during periods of low winter flows (Hunter 1959; McNeil 1966, 1969). On the basis of the findings of McNeil (1966, 1969), Cederholm and Koski (1977), and Lister and Walker (1966), we classified as excellent the streams with a low probability of redd scouring, i.e., those with stable flow regimes (< 100-fold difference between extreme average daily stream discharges) and stable stream channels. Considered poor were streams with a high probability of redd scouring (> 500-fold difference between extreme average daily stream discharges during winter) or redd freezing or desiccation, i.e., streams with unstable stream channels and streambeds and high potential for flooding, or high probability of very low flows during the incubation period. Streams with characteristics intermediate between these extremes were assumed to be good to fair.
V_7	Rockwell (1956) reported that survival of chum salmon embryos was highest in constant salinities < 6 ppt (corresponding to upper and middle reaches of the study area); mortality increased to 67% at 6.0 to 11.6 ppt, and 100% at > 12 ppt. Kashiwagi and Sato (1969) found that percent mortality of chum salmon eggs to hatching was 0 at ≤ 9 ppt, 25 at 18 ppt, 50 at 27 ppt, and 75 at 35 ppt. However, nearly all alevins hatched from eggs exposed to salinities > 9 ppt died within a few days. Helle (pers. comm.) found no survival of eggs deposited by chum and pink salmon in a saline (4 to 8 ppt) stream. On the basis of these somewhat conflicting results, we assumed < 4 ppt to be excellent, 4 to 9 ppt to be good to fair, and > 9 ppt to be poor. It should be noted that Hartman (pers. comm.) has observed that chum eggs can survive tidal inundation by water of up to 24 ppt salinity if there is periodic (daily) flushing of redds by freshwater. The laboratory observation by Rockwell (1956) that chum salmon eggs and alevins can survive in seawater up to 30 ppt for several days at low temperatures provides corroborating support for this suggestion. We therefore assumed that short term high salinities caused by tidal inundation would be a less appropriate measure of habitat suitability than some measure of average salinity conditions.

Table 1. (concluded)

Variable	Sources and rationale
V_8	To insure optimum conditions for smoltification, timing of seaward migration, and survival of chum salmon smolts, temperature should follow a natural seasonal cycle as closely as possible (Wedemeyer et al. 1980). Temperatures of 7 to 12° C were considered excellent because temperatures ≤ 12° C were recommended by Wedemeyer et al. (1980) for seaward migration of salmonid smolts to prevent altered timing of migration and smoltification, and because Bell (1973) listed 6.7 to 13.3° C as the temperature range suitable for downstream migration of chum salmon. Slightly warmer temperatures (about 8 to 13° C) would be optimum for growth (Brett 1952; Levanidov 1954; McNeil and Bailey 1975). Temperatures of 14 to 20° C were considered only fair because the risk of disease is probably higher (Fryer and Pilcher 1974; Holt et al. 1975). Temperatures > 20° C were considered poor because growth of the fry of chum salmon (Kepshire 1976) and other salmonids (Reiser and Bjornn 1979) ceases in this range and because mortality occurs at 23.8° C (Brett 1952).
V_9	We considered as excellent the DO levels corresponding to high feeding and growth rates in chum salmon fry (> 5 to 11 mg/l; Levanidov 1954) and the lack of impairment in swimming (> 5 mg/l; Dahlberg et al. 1968) and lack of avoidance (> 5 mg/l; Whitmore et al. 1960). Levels causing high avoidance and reduced swimming ability in salmonid fry in general, or mortality in chum salmon fry (1.5 mg/l; Levanidov 1954), were deemed poor.

Descriptors for each habitat variable were chosen to emphasize limiting conditions for each variable. This choice reflects our assumption that extreme, rather than average, values of a variable most often limit the carrying capacity of a habitat.

Use of the Model

HSI determination. It was assumed that the most limiting factor (i.e., the lowest SI score) defines habitat suitability for chum salmon in freshwater; thus,

$$\text{HSI} = \text{minimum value among suitability indices } V_1 \text{ to } V_9.$$

Field application of the model. General guidelines for measuring aquatic habitat variables are provided by Hamilton and Bergersen (1984). Detailed sampling of habitat variables over time would provide the most reliable and replicable HSI values. The method used to calculate SI values should be carefully documented to insure that decision makers understand the quality of the data used in determining the HSI for a particular chum salmon habitat.

Model Interpretation and Limitations

The model described here is a general description of the freshwater habitat requirements for chum salmon and should not be expected to discriminate among different habitats with a high resolution. A positive relation between HSI's generated from this model to measurable indices of population abundance (e.g., standing crop) should not be assumed, unless it has been demonstrated by testing in habitats similar to those where the model will be applied. The major reason no relation is assumed is that although the model variables may be necessary in determining the suitability of habitat for chum salmon, they may not be sufficient. Other factors not included in this model, including differences in a watershed or in a run or stock, may determine abundance to a greater degree than the variables included in this model. Data describing measurable population responses of chum salmon to additional factors, however, are insufficient at this time to use in a chum salmon habitat model. The user should consult Hale (1981) for detailed discussion of the further research needed to overcome the deficiencies in the existing knowledge of freshwater habitat requirements of chum salmon.

The proper interpretation of the HSI is one of comparison. If two areas have different HSI's, the one with the higher HSI should have the potential to support more chum salmon than the one with a lower HSI. Outputs of the model should be interpreted as indicators (or predictors) of the quality of habitat for chum salmon: excellent (HSI 0.8 to 1.0); good (0.5 to 0.7); fair (0.2 to 0.4), or poor (0.0 to 0.1). Proper use of this model should follow the admonition by Banks (1969:131) that "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."

ADDITIONAL HABITAT MODELS

No other freshwater habitat models for chum salmon were found in the literature. Habitat suitability index models for the estuarine phase of the chum salmon life cycle are given by Sheperd and Washington (1982). The user is referred to Terrell et al. (1982) and U.S. Fish and Wildlife Service (1981) for general guidance in modifying habitat models to meet specific needs.

INSTREAM FLOW INCREMENTAL METHODOLOGY

Instream Flow Incremental Methodology (IFIM) is a process of stepwise analysis used to assess instream flow problems (Bovee 1982). The Physical Habitat Simulation System (PHABSIM) model (Milhous et al. 1984), a component of IFIM, is used to compute the amount of available instream habitat for life stages of a species as a function of streamflow.

The output generated by the PHABSIM component of IFIM 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, cover, and temperature) for each major life stage of a given fish species (e.g., spawning, egg incubation, larval, juvenile, and adult). The Western Energy and Land Use Team 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.

IFIM analyses may utilize any or all categories of curves, but category three and four curves should yield the most precise results. Category two curves yield accurate results if they are transferable to the stream segment under investigation. If category two curves are not transferable for a particular application, category one curves may be a better choice.

For an IFIM analysis of riverine habitat, an investigator may utilize the curves available in this publication. If an investigator believes that spawning habitat utilization in the study stream is different from that represented by the SI curves, he or she may want to modify the existing SI curves or collect data to generate new curves. Once the curves to be used have been defined, the curve coordinates are used to build a computer file (FISHFIL), which becomes a necessary component of PHABSIM analyses (Milhous et al. 1984).

Modeling of chum salmon habitat by use of PHABSIM has been done for the spawning (Vincent-Lang et al. 1984) and the rearing (Hale et al. 1984) life stages.

Availability of SI Curves for Use in IFIM

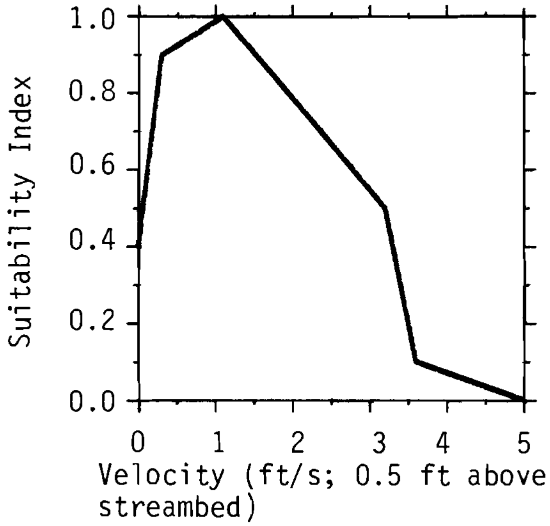
The IFIM is used for riverine environments, and since chum salmon utilize streams only for spawning migration, spawning, egg incubation, rearing and fry outmigration, no SI curves are necessary for the sea life juvenile and adult stages. All of the SI curves for IFIM analyses of chum salmon habitat presented in Figures 2-4 are category one (except for spawning velocity), and were developed from data and information found in the literature. Because IFIM uses English units, all of the SI curves are given in English units. Investigators are encouraged to review the curves carefully, compare them with curves derived from field data when possible, and modify them if appropriate. Vincent-Lang et al. (1984) present category 2 and 3 curves for chum salmon spawning depth, velocity, substrate, and upwelling. Suchanek et al. (1984) describe category 2 and 3 curves for depth, velocity, and cover during the fry life stage of chum salmon.

Spawning migration. No curves are presented here for spawning migration requirements, although variables which may limit migration should be identified before proceeding with an investigation. Length of migration may vary from less than one mile to over 1,500 miles and, therefore, critical stream reaches should be identified which may impede passage to spawning areas. Out-migration of spawners is not of concern because chum salmon adults die after spawning. Other variables which may be limiting to migration include water temperature and dissolved oxygen concentrations. Curves for these variables are in the HSI model section of this report (V_1 and V_2, sources and assumptions in Table 1).

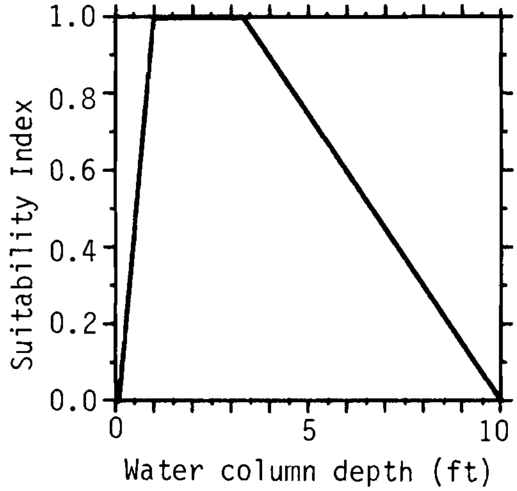
Spawning and egg incubation. There are two approaches for determining the amount of spawning and egg incubation habitat for a stream reach. One approach, which treats spawning and egg incubation as separate life stages (each with its own set of habitat suitability criteria), may be used when weighted useable area (WUA) does not vary by more than 10% during the spawning/egg incubation period. If WUA is found to vary by more than 10% (as a result of streamflow variation), then the determination of effective spawning habitat (Milhous 1982) is the recommended approach (to be discussed later).

Coordinates

x	y
0.0	0.4
0.3	0.9
1.1	1.0
3.2	0.5
3.6	0.1
5.0	0.0
20.0	0.0



x	y
0.0	0.0
0.1	0.0
1.0	1.0
3.3	1.0
10.0	0.0
100.0	0.0



x	y
30.0	0.0
34.0	0.0
43.0	1.0
55.0	1.0
62.0	0.0
100.0	0.0

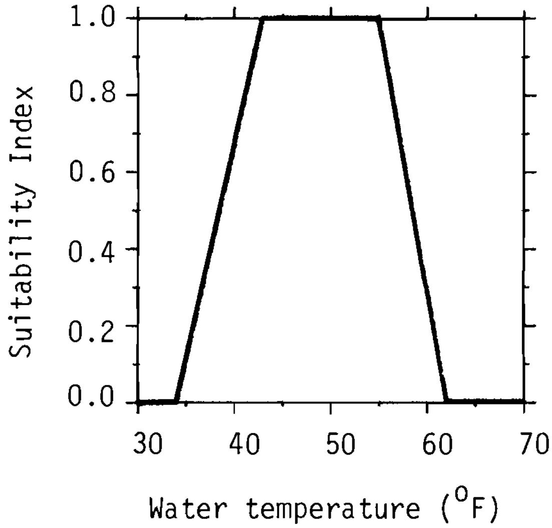
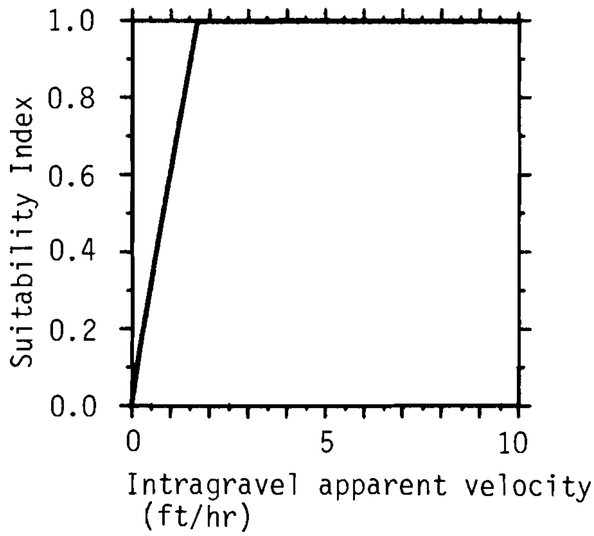


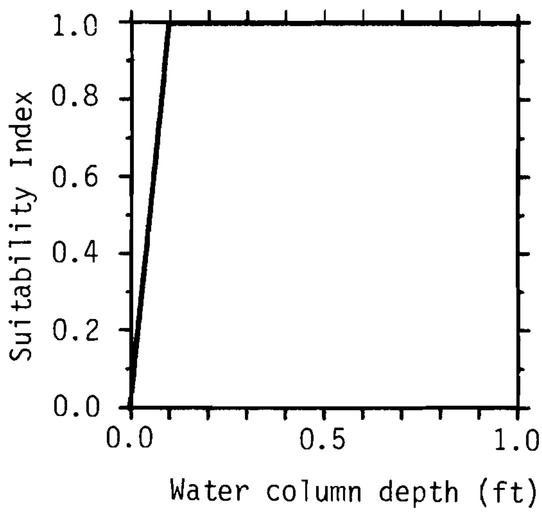
Figure 2. SI curves for chum salmon spawning velocity, depth, and temperature.

Coordinates

x	y
0.0	0.0
0.3	0.2
1.7	1.0
10.0	1.0
100.0	1.0



x	y
0.0	0.0
0.1	1.0
100.0	1.0



x	y
0.0	0.0
0.4	0.3
1.5	0.3
2.0	1.0
4.0	1.0
8.0	0.0
100.0	0.0

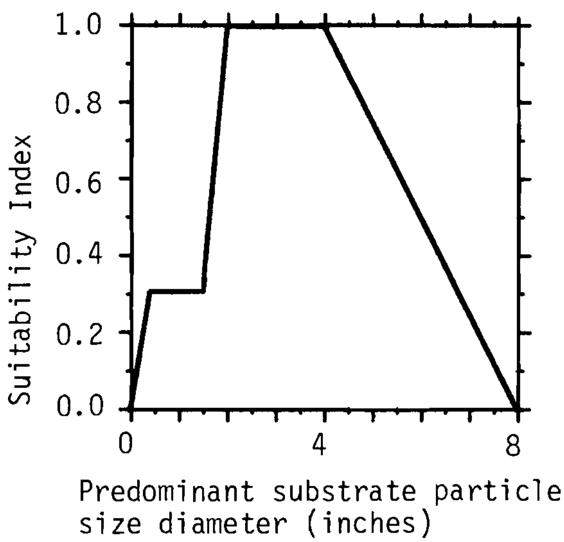


Figure 3. SI curves for chum salmon egg incubation velocity, depth, substrate, and temperature.

Coordinates

x	y
32.0	0.0
35.0	0.2
36.0	0.6
38.0	0.8
40.0	1.0
56.0	1.0
59.0	0.5
61.0	0.0
100.0	0.0

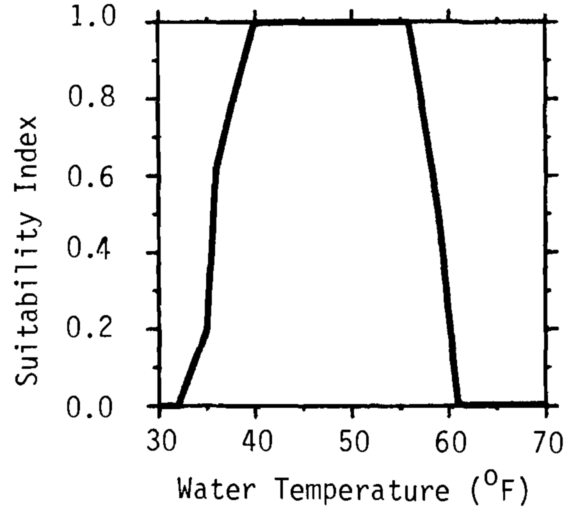
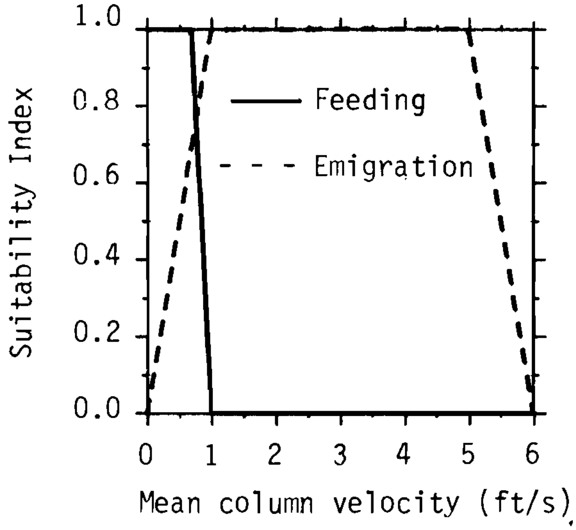


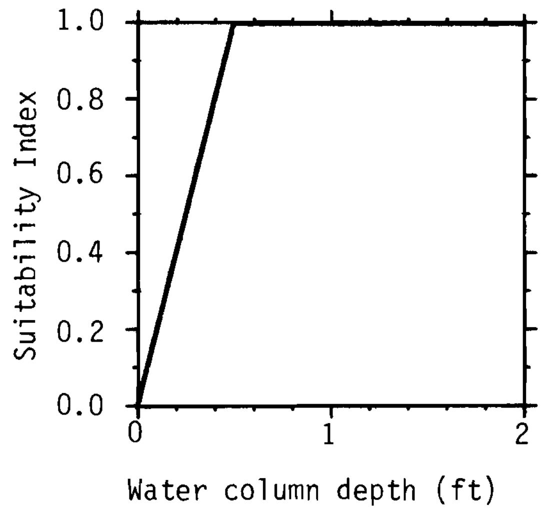
Figure 3. (concluded).

Coordinates

x	y (feeding)	y (emigration)
0.0	1.0	0.0
0.7	1.0	-
1.0	0.0	1.0
5.0	-	1.0
6.0	-	0.0
20.0	0.0	0.0



x	y
0.0	0.0
0.5	1.0
100.0	1.0



x	y
0.0	0.0
0.5	0.0
1.0	1.0
10.0	1.0
20.0	0.0
100.0	0.0

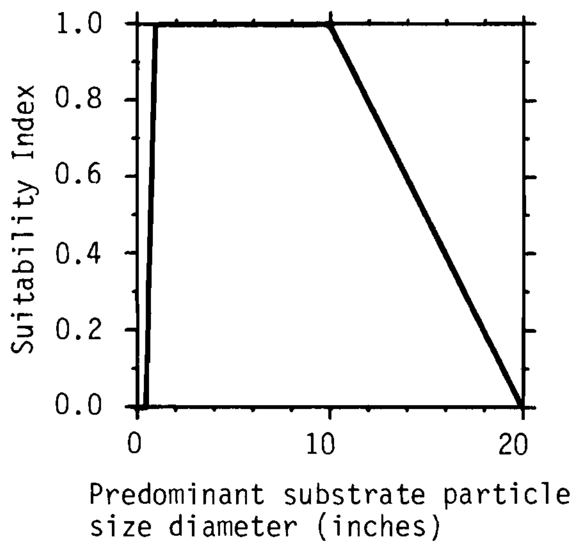


Figure 4. SI curves for chum salmon fry velocity, depth, substrate, and temperature.

x	y (feeding)	y (emigration)
31.0	0.0	0.0
39.0	0.1	-
41.0	0.9	-
46.0	1.0	1.0
54.0	1.0	1.0
57.0	0.8	0.8
61.0	0.2	0.2
100.0	0.0	0.0

A. Feeding and growth
B. Emergence and emigration

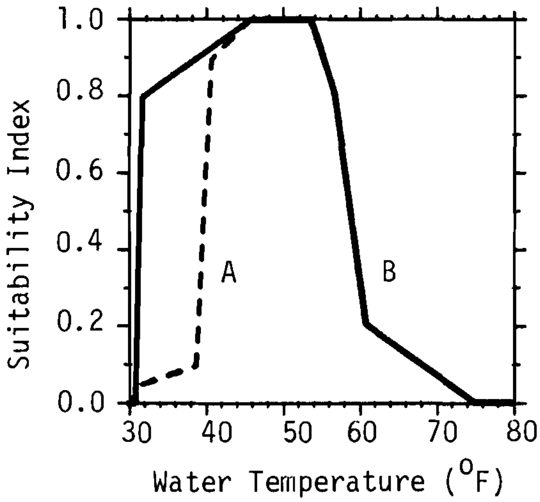


Figure 4. (concluded).

The SI curve for chum salmon spawning velocity utilization (Fig. 2) is category two, based on frequency analyses of data collected from the Skagit River near Marblemount, Washington, during December 1976 (Kurko 1977). Spawners were observed by boat, and velocity measurements (0.5 ft above the stream bottom) were taken at the upstream edge of each redd (n = 227). The resultant velocity curve is similar to that developed by Wilson et al. (1981), which was based on a combination of literature review, professional opinion, and field data. The range of velocities selected by spawning chum salmon in Kurko's study also encompasses spawning site velocity ranges reported by Smith (1973). The relative suitability of velocities greater than 1.0 ft/s, however, should be field-verified before using the curve in IFIM studies. Chum salmon tend to key on areas of upwelling ground water, which influences their selection of surface water velocities (Kogl 1965; Sano 1967; Vincent-Lang et al. 1984).

Chum salmon spawning has been reported to occur in depths ranging from 2 inches to 6.3 ft (see HABITAT USE INFORMATION). "Preferred" or recommended depths have generally been reported to be within the 1.0 to 3.3 ft range (Smith 1973; Hale 1981). There is general agreement on the suitability of depths to 3.0 ft (Hale 1981; Wilson et al. 1981), but the relative suitability of deeper waters is rather uncertain, possibly because of difficulties involved in sampling. The spawning depth utilization in any given stream may be a narrow subset of the literature-based curve presented here, and field verification is recommended.

No SI curve was developed for chum salmon spawning substrate suitability. Therefore, when evaluating spawning WUA as a function of streamflow, use of the egg incubation substrate SI curve is recommended.

No evidence was found to suggest that cover is a requirement for chum salmon spawning. Therefore, a cover SI curve is unnecessary for IFIM analyses.

The temperature ranges within which chum salmon spawning occurs may vary with locale and season. Among the spawning temperature ranges reported (see HABITAT USE INFORMATION), temperatures overlapped primarily within the 43 to 55° F range, and minimum and maximum temperatures reported were 35 and 61° F.

The water velocities required for successful egg incubation may be dependent upon several interrelated variables. A surface water velocity of 0.0 ft/s may be suitable if there is adequate groundwater upwelling, if dissolved oxygen concentrations (V_4) remain adequate, and if siltation, freezing, dessication, and metabolite buildup are not problems. The maximum velocities tolerable will depend on the "scourability" of the substrate, which is partly a function of substrate particle sizes. The SI curve for egg incubation velocity (Fig. 3) is based on information reviewed by Hale (1981), and represents relative suitability of velocities through the gravel.

The SI curve for water depth during the egg incubation period is based on the assumptions that (in most situations) eggs must remain submerged for the duration of the incubation period; that high water temperatures, low dissolved oxygen concentrations, and freezing are not problems at low flows (see Fig. 3 and V_4); and that embryos are at least 3 inches deep within the substrate. If any of these conditions cannot be met, then the depth curve may have to be modified to ensure embryo survival.

The SI curve for egg incubation substrate suitability is based, in part, on an experiment by Dill and Northcote (1970) who found 100% survival of embryos to emergence in substrate material 2 to 4 inches in diameter, and 31% survival in 0.4 to 1.5 inches. The curve is meant to represent relatively homogeneous substrate with less than 20% sand and silt content.

No SI curve is necessary for egg incubation cover because eggs are buried in the substrate. The substrate curve is assumed to take care of embryo cover requirements.

The SI curve for egg incubation temperature is based on information reviewed by Hale (1981). Investigators have reported that temperatures from 40 to 56° F are suitable for egg incubation, and that percent survival of embryos increases as temperatures increase from 32 to 40° F. No investigators reported finding eggs in water with temperatures greater than 52° F.

Effective spawning habitat. The other approach for determining spawning and egg incubation habitat measures effective spawning habitat (Milhous 1982) and is recommended when the spawning/egg incubation period is greater than 2 months and WUA varies by more than 10% during the spawning/egg incubation period. Effective spawning habitat is habitat that remains suitable throughout the spawning and egg incubation period. In a given stream 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 or otherwise determined to be unsuitable during egg incubation. Factors to consider when determining habitat reduction because of dewatering include the depth of the eggs 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 (Fig. 5) 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

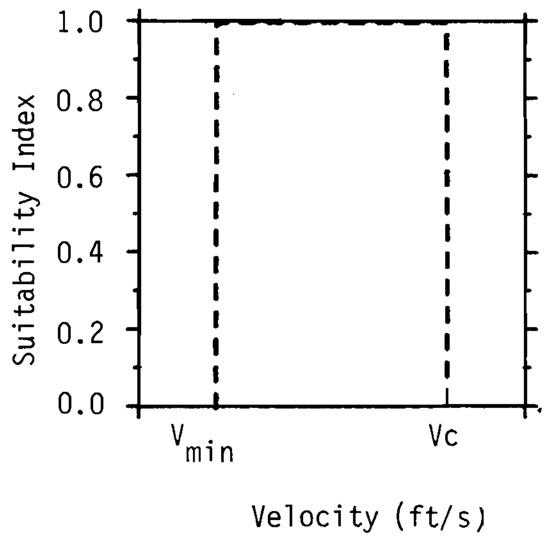
D65 = substrate particle size diameter (ft) not exceeded by 65% of the particles

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

Coordinates	
x	y
0	0
V_{min} - 0.001	0
V_{min}	1
V_c - 0.001	1
V_c	0
20	0

V_{min} is the minimum velocity necessary to prevent siltation of spawning sites; V_c is the critical velocity, above which scouring of spawning sites will occur.



x	y
0	0
D_{min} - 0.001	0
D_{min}	1
100	1

D_{min} is either the minimum depth required for egg incubation (≥ 0.0) or ice depth (when ice is present during egg incubation).

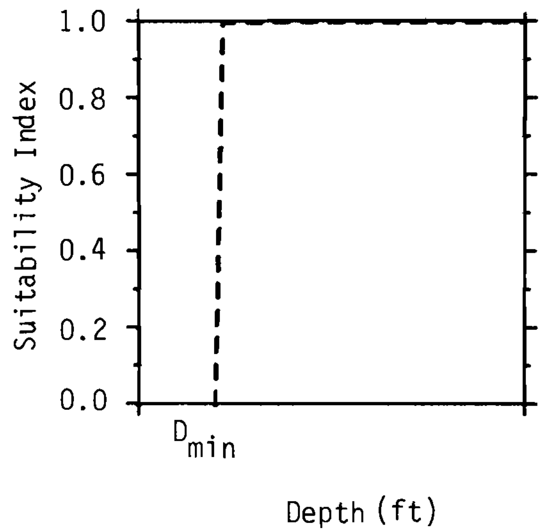


Figure 5. SI curves for spawning/egg incubation velocity and depth, for effective spawning habitat analyses (Milhous 1982).

Factors to consider when determining habitat reduction from siltation include suspended sediment concentrations, minimum velocities necessary to prevent siltation (Fig. 5), and dissolved oxygen concentrations among the embryos. More detailed information about the analysis of effective spawning habitat is presented in Milhous (1982).

Fry. Habitat for fry may be required for up to 120 days or more after the onset of hatching, depending on the time of hatching, the duration of fresh water rearing, and on the distance from the spawning site to the estuary. After egg hatching, alevins remain in the gravel for 1 to 3 months. While alevins are in the gravel, we have assumed that SI curves for egg incubation habitat are also suitable for fry requirements. Fry generally emerge from the gravel sometime between March and May, and may not begin downstream migration for a month or two. Out-migration may take another 2 months to complete. Therefore, habitat for free-swimming fry is required for the time period between emergence and completion of out-migration to estuaries, the duration of which is largely dependent on locale. If fry reach the estuary soon after emergence (as when chum salmon spawn in intertidal areas), then SI curves for fry are not required.

According to Levanidov (1954), velocities less than 0.66 ft/s are optimal for feeding by fry. Availability of higher velocities, however, may be important for assisting out-migration of fry. The SI curve for fry velocity is based on this information and the assumption that higher velocities will not injure fry during displacement.

The SI curve for fry depth was based on the assumption that all depths greater than a minimum are suitable, as long as cover is available, and that velocities and temperatures are within the range of suitability. Fry of many salmonid species have generally been found in depths ranging from 1 to 2 ft. Chum salmon fry in the Susitna River have been observed as deep as 3.5 ft, but most were found at depths < 1.6 ft (Suchanek et al. 1984). Fry may tend to select shallower water to avoid predation or to avoid higher water velocities.

The SI curve for fry substrate is based on the fact that chum salmon fry often use substrate for cover (Neave 1955) and the assumption that fry from 1.2 to 3.0 inches in length would require particles ranging from large gravel to small boulders (with less than 40% embeddedness and low percent fines) to provide adequate interstitial spaces. No curve was developed for fry cover. Requirements for cover may be partially represented by the fry substrate curve. Suchanek et al. (1984) did not find a strong preference by Susitna River chum salmon fry for object cover. Cover requirements of chum fry are often met by schooling behavior (Hoar 1956) and by turbidity (Suchanek et al. 1984).

The SI curve for fry temperature suitability was taken from Hale (1981). The curve suggests that minimum temperatures required for feeding and growth are higher than those required for out-migration.

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16. Abstract (Limit: 200 words)

A review and synthesis of existing information were used to develop a Habitat Suitability Index (HSI) model and instream flow suitability curves for the chum salmon (*Oncorhynchus keta*). 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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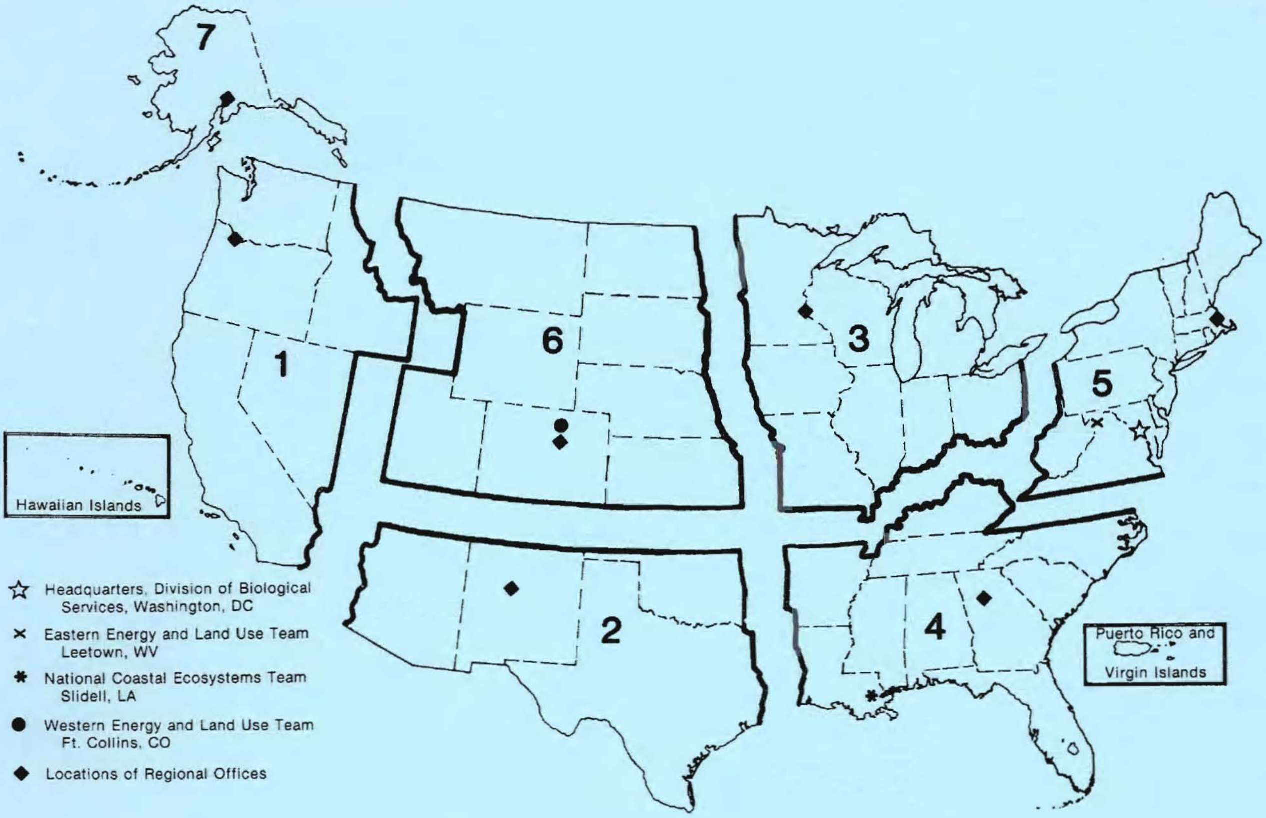

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