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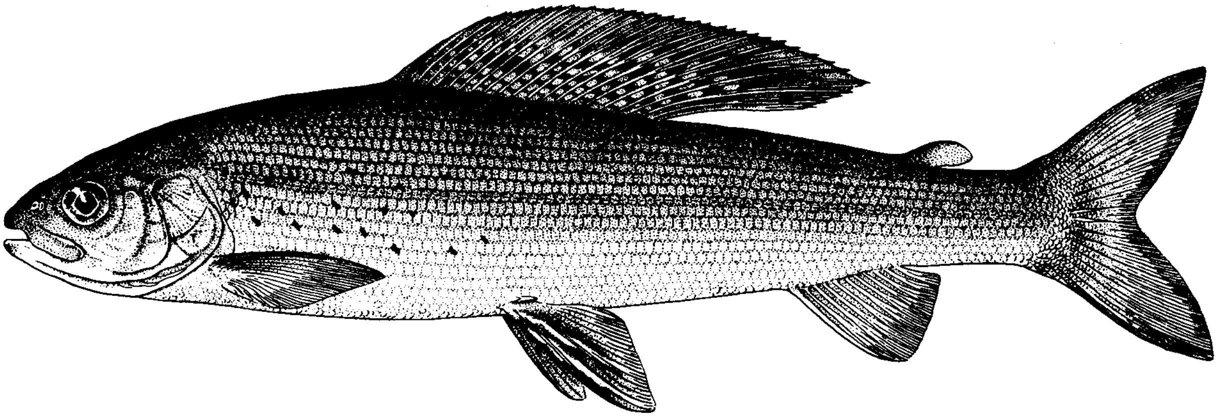

Fish and Wildlife Service

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HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: ARCTIC GRAYLING RIVERINE POPULATIONS

by

Wayne A. Hubert
Wyoming Cooperative Fishery and Wildlife Research Unit
University of Wyoming
Laramie, WY 82071

Rhonda S. Helzner
University of Wyoming
Laramie, WY 82071

Lawrence A. Lee
Colorado State University
Fort Collins, CO 80523

and

Patrick C. Nelson
Instream Flow and Aquatic Systems Group
Western Energy and Land Use Team
U.S. Fish and Wildlife Service
Drake Creekside Building One
2627 Redwing Road
Fort Collins, CO 80526-2899

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

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PREFACE

The Habitat Suitability Index (HSI) models presented in this publication aid in identifying important habitat variables. Facts, ideas, and concepts obtained from the research literature and expert reviews are synthesized and presented in a format that can be used for impact assessment. Users should recognize that the models are hypotheses of species-habitat relationships, and that the applicability of the HSI model, SI graphs, and assumptions will vary according to geographical area and the extent of the data base for individual variables. The HSI model building techniques published by the U.S. Fish and Wildlife Service (1981), and the general guidelines for modifying HSI models (Terrell et al. 1982) and estimating model variables (Hamilton and Bergersen 1984) may be useful for simplifying and applying the models to specific impact assessment problems. Simplified models should be tested with independent data sets, if possible.

Model reliability is likely to vary in different geographical areas and situations. The U.S. Fish and Wildlife Service encourages users to provide comments, suggestions, and test results that may help us increase the utility and effectiveness of this habitat-based approach to impact assessment.

The INSTREAM FLOW INCREMENTAL METHODOLOGY section of the report was written by P. Nelson. The remainder of the report was written by W. Hubert, R. Helzner, and L. Lee.

Additional information on Arctic grayling habitat requirements is currently being gathered by the Alaska Cooperative Fishery Research Unit, University of Alaska, Fairbanks, Alaska. Such data should lead to a refined Arctic grayling model in the near future with specific reference to Alaskan streams.

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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ARCTIC GRAYLING (Thymallus arcticus)

HABITAT USE INFORMATION

Distribution

The Arctic grayling (Thymallus arcticus) is a holarctic species that extends in North America across northern Manitoba, Saskatchewan, Alberta, British Columbia, the Northwest Territories, the Yukon, and most of Alaska (Kruger 1981). Relict populations occurred in Michigan and Montana, but they have been extirpated in Michigan (Holton 1971; Scott and Crossman 1973). The Arctic grayling has been introduced into Vermont, Colorado, Wyoming, Idaho, Utah and California (Nelson 1953; Baxter and Simon 1970; Scott and Crossman 1973; Rieber 1983).

The North American grayling was at one time separated into at least three species represented by isolated distribution patterns. They were Thymallus signifer in Alaska and northern Canada, T. montanus Milner in the Upper Missouri River drainage, and T. tricolor (Cope) in the Upper Great Lakes tributaries in Michigan. T. tricolor is now extinct (Creaser and Creaser 1935). T. signifer and T. montanus are now considered to be synonymous with T. arcticus.

Grayling inhabit clear water streams, rivers and lakes. They are also found in bog-fed streams in Alaska (Kreuger 1981, Armstrong 1982). Riverine populations depend on large streams, deep pools of small streams or spring-fed reaches that are not completely frozen in winter for overwinter survival (Nelson and Wojcik 1953; Craig and Poulin 1975). Populations not associated with lakes are found in Alaska and Montana.

Age and Growth

Arctic grayling fry reach 45 to 70 mm total length (TL) their first summer in Alaskan waters (Craig and Poulin 1975; Netsch 1975) and grow approximately 40 mm per year through age VI. As a general rule, northern populations grow slower, live longer, and reach smaller sizes than southern populations (Kruse 1959; Craig and McCart 1974a). Grayling in Montana and Wyoming have been found to reach 185 to 250 mm TL in 2 years and 285 to 375 mm in 4 years where overcrowded conditions do not occur (Brown 1938 and 1943; Nelson 1953; Peterman 1972; Curtis 1977; Likenes 1981). A growth rate of 40 mm/yr to age VII was found in a small Alaskan stream (Craig and Poulin 1975).

The life span of arctic grayling varies. Fish from Montana and Wyoming appear to have a maximum life span of 7 to 11 years (Brown 1938; Nelson 1954; Curtis 1977), while fish from Alaska have been observed to attain 15 to 22 years (de Bruyn and McCart 1974; Armstrong 1982).

Age at sexual maturity also varies, depending on latitude and crowding. Arctic grayling in Wyoming have been observed to mature at 2 to 3 years, but take as long as 4 to 6 years under overpopulated conditions (Curtis 1977). Observations of sexual maturity at age II or III also have been made in Michigan (Creaser and Creaser 1935) and Montana (Kruse 1959) streams. In Alaska, grayling seldom reach maturity before age VI when a total length of greater than 295 mm is attained (Reed 1964; Bishop 1971). Observations of sexual maturity between age IV and IX have been made in several Alaskan waters (Wojcik 1955; Alt 1976 and 1978; McCart et al. 1972; deBruyn and McCart 1974; Craig and Poulin 1975).

The largest grayling recorded in Alaska was 546 mm TL (2.13 kg). In Canada a 533 mm (2.71 kg) fish holds the record (Kreuger 1981).

Diet

Arctic grayling are sight feeders, which consume a wide array of food items primarily in drift (Kreuger 1981). They begin to take food at four days after hatching (Brown and Buck 1939). Young-of-year, stream-dwelling fish consume primarily small immature aquatic insects, including dipteran larvae and pupae, mayfly larvae, and caddis fly larvae (Reed 1964; Vascotto and Morrow 1973; Elliott 1980). As juveniles and adults they depend heavily on benthic and terrestrial insects in the stream drift (Rawson 1950; Vascotto 1970), but they have been observed to feed opportunistically on fish eggs, small fish and small mammals (Kruse 1959; Reed 1964; Schallock 1966; Bishop 1971). Arctic grayling apparently feed through the winter (Alt and Furniss 1976; Bendock 1979), but poor visibility under deep snow and ice probably limits efficiency.

Reproduction

Arctic grayling are believed to be annual stream spawners (Craig and Poulin 1975). At least some fish are believed to home to individual streams to spawn (Warner 1955; Craig and Poulin 1975; Tack 1980).

Males initiate spawning activity by establishing spawning territories in small streams, larger males occupying deeper areas (Bishop 1971). Spawning has been observed to occur at 2 to 10° C, with most activity at the upper end of the range (Tryon 1947; Wojcik 1954; Rawson 1950; Warner 1957; Kruse 1958; Reed 1964; Williams 1968; Bishop 1971; Netsch 1975; Wells 1976; Falk et al. 1982). The spawning period lasts 2 to 24 days (Kratt and Smith 1977). Male territories are 1 to 10 m^2 (Kruse 1959; Tack 1971). Spawning usually occurs over gravel substrate (Hinshall 1907; Rawson 1950; Nelson 1954; Bishop 1971) with transition areas between the lower end of a riffle and a pool favored (Bishop 1951; Nelson 1954). Current velocities at spawning sites range from 0.34 to 1.46 m/s (Kreuger 1981). Grayling have been observed to spawn over mud-bottomed pools with vegetation (Scott and Crossman 1973), above rapids

(Rawson 1950), and in shallow backwaters (Wojcik 1954) with no specific substrate selection (Tryon 1947; Reed 1964). However, Bishop (1971) and Nelson (1954) noted that spawning did not occur over pure mud, silt, or clay: only gravel, rubble, and boulder areas were used.

No redd is prepared by either the male or female grayling (Warner 1955; Scott and Crossman 1973), although a small depression may result from tail vibrations (Reed 1964). During the spawning act, sand and small gravel coats the adhesive eggs while settling to the stream bottom (Kruse 1959).

Migration

Netsch (1975) described the general, annual movement pattern for stream-dwelling arctic grayling in Alaska. In late winter and early spring the fish begin to move under the ice of large streams. When the ice melts, adult grayling move into small spawning streams followed later by juveniles. Adults return to the larger streams and rivers after spawning, while juveniles remain in the spawning streams most or all of the growing season. By late summer or fall, all fish have moved downstream to wintering areas.

Arctic grayling may migrate long distances to reach tributary spawning streams (Henshall 1907; Brown 1938; Nelson 1954; Reed 1964; Bishop 1971; Craig and Poulin 1975; Kratt and Smith 1977). Arctic grayling may migrate from 10 to over 150 km to find suitable spawning areas (Nelson 1954; Reed 1964). Migration occurs immediately prior to or during the breakup of ice on the rivers (Brown 1938; Nelson 1954; Warner 1955; Schallock 1966; Tack 1971; Bishop 1971; Tripp and McCart 1974; Craig and Poulin 1975; Falk et al. 1982).

Upstream migration by mature adults begins when the water temperature is 0 to 4° C and the streams become passable (Wojcik 1955; Reed 1964; Williams 1968; Kreuger 1981; Falk et al. 1982). Migration to the spawning areas peaks during maximum spring discharge (MacPhee and Watts 1976; Tack 1980). Migration has also been associated with increasing water temperature and decreasing discharge and turbidity in a small Alaskan stream (Craig and Poulin 1975).

Once spawning is completed, adult grayling move upstream or downstream, or leave the stream to enter another, in order to reach summer feeding areas, probably areas with greater food availability (McCart et al. 1971; Williams and Morgan 1974; Craig and Poulin 1975; Williams 1975 and 1976; Tack 1980). Mature grayling may remain in larger spawning streams longer than in smaller streams (Reed 1964; Tripp and McCart 1974; Craig and Poulin 1975). Emigration of young-of-year and juvenile fish may also occur during the summer (Kreuger 1981). Downstream migration to wintering areas occurs when water temperatures approach 0° C (Yoshihara 1972).

All ages of grayling move downstream to overwintering areas in large streams and rivers during late summer and fall (Yoshihara 1972; Kratt and Smith 1977; Tack 1980). Wintering areas include pools of intermittent and flowing streams, as well as spring-fed streams (Craig and Poulin 1975), which do not freeze to the bottom during the winter months (Kreuger 1981).

Barriers preventing upstream movement to spawning areas can be caused by beaver dams (Nelson 1954; Liknes 1981) manmade structures (Vascotto 1970; MacPhee and Watts 1976), or waterfalls (Kreuger 1981). Barriers to downstream movement may include low flows and ice buildup (Kreuger 1981). Heaton (1960) and Liknes (1981) concluded that reduced flows limited production in the Big Hole River drainage of Montana.

Habitat Characteristics

Optimal Arctic grayling riverine habitat is characterized by cold water with abundant pool habitat. Grayling are found almost exclusively in pools, seldom in riffles (Vascotto and Morrow 1973). Bishop (1971) reports use of riffles as feeding areas. Grayling inhabit spring-fed streams, rapid-runoff streams, and bog-fed streams in Alaska (Reed 1964). Spring-fed streams tend to be cold and clear, have a constant flow, pH is 7.0 to 7.8, and there is abundant clean gravel. Bog-fed streams generally have brown water with irregular flow, warm summer temperatures, pH of 6.4 to 7.4, and a streambed of mud and sand.

During winter Arctic grayling generally reside in large streams or deep holes in smaller streams (Nelson and Wojcik 1953). They also have been observed to overwinter in beaver ponds and small spring-fed streams (Ward 1951; Craig and Poulin 1975).

Current velocities in overwintering areas are low (less than 0.15 m/s) (Kreuger 1981). Pool habitat in wintering areas has a depth of more than 1.4 m in Alaskan streams (Alt and Furniss 1976; Kreuger 1981).

Dissolved oxygen of 0.6 to 4.8 mg/l have been observed in overwintering areas (Alt and Furniss 1976; Bendock 1980).

Specific Habitat Requirements

The habitat requirements of arctic grayling are described on a life stage basis: embryo; fry; juvenile; and adult. The embryo stage includes the incubating eggs and developing fry up to emergence from the substrate. The fry stage extends from emergence through the first year of life. The juvenile stage is the second year of life until sexual maturity.

Embryo. Water temperature governs the development of embryos. Eggs hatch in 8 to 27 days at water temperature of 2.0 to 16.1° C (Henshall 1907; Ward 1951; Nelson 1954; Walting and Brown 1955; Kruse 1959). Fertilized eggs required only eight days to hatch in 15.5° C water at an Alaskan hatchery (Kreuger 1981). Kratt and Smith (1977) computed that grayling eggs require 186.24 degree-days to hatch at a mean temperature of 5.8° C and 175.76 degree-days at a mean of 7.1° C. Additional incubation data are presented by Ward (1951), Reed (1964), and Bishop (1971).

Eggs are most abundant in rubble and gravel substrate, generally in the transition between a riffle and pool (Nelson 1953). Eggs are not generally found on mud, silt, sand, or clay substrates (Nelson 1954; Bishop 1971). Many eggs commonly drift downstream soon after being spawned (Warner 1955).

During a post-hatching, subgravel stage, embryos spend 3 to 4 days buried under 2 to 3 cm of gravel (Kratt and Smith 1977). This stage is necessary so the embryos can cope with water currents and wave action when they become swim-up fry (Brown 1938; Bishop 1971).

Mortality during the embryo stage is high. Kruse (1959) estimated mortality to be 96% during embryo development.

Fry. Fry emerge from the gravel and remain in the small spawning streams throughout the summer (Craig and Poulin 1975). Fry are found in quiet backwaters (Tack 1972) and protected areas along the streambank away from strong currents (Nelson 1954; McCart et al. 1972; Chislett and Stuart 1979; Cuccarease et al. 1980). Fry are known to use interstitial spaces and shadows of boulders for cover (Kreuger 1981). Such habitat is considered critical to age 0 fish (James B. Reynolds, Alaska Cooperative Fishery Research Unit, University of Alaska, Fairbanks, Alaska; pers. comm.).

The fry stage is the least sensitive to high temperatures with a median tolerance limit of 24.5° C (LaPerriere and Carlson 1973). Summer temperatures of 16.7° C are common in Alaskan waters where fry occur (Craig and Poulin 1975). When acclimated to 13° C they loose equilibrium at 28.7° C (Feldmuth and Eriksen 1978). Grayling show considerable low oxygen tolerance for salmonids (Eriksen 1975). Critical oxygen minima when acclimated to 13° C ranges from about 1.4 mg/l at 8° C to 1.8 mg/l at 20° C (Feldmuth and Eriksen 1978).

Elliott (1980) found that "early" young-of-year occupied a mean current velocity of 0.07 m/s, while "larger" young-of-year inhabited 0.16 m/s water in the Gulkana River, Alaska. By fall, young-of-year grayling occupy areas with velocities up to 0.8 m/s (Chislett and Stuart 1979).

Juveniles. Juveniles move into the spawning streams 2 to 3 weeks after the adult spawners have departed (Craig and Poulin 1975). The juveniles remain during the summer low-flow period and when warmest water temperatures occur. They depart for larger streams by fall. Bioassays have shown a survival of 100% at 22.5° C, but 0% at 24.5° C for juvenile fish (20 cm fork length) (LaPerriere and Carlson 1973).

The mean water column current velocity occupied by juvenile fish in two Alaskan streams was 0.18 and 0.21 m/s, respectively (Elliott 1980; Kreuger 1981). Juvenile grayling are generally associated with pool and slough habitat (Alt 1978; Kreuger 1981) but may feed in riffles (Kreuger 1981). Juveniles will commonly use logs, boulders and turbulence for instream cover (Kreuger 1981).

Adult. Although, they have been observed to be stressed at 16.5° C (Nelson and Wojcik 1953), adult grayling are tolerant of water temperatures in excess of 20° C (LaPerrier and Carlson 1973). When acclimated to 13° C they loose equilibrium at 26.9° C (Feldmuth and Eriksen 1979). Wojcik (1955) found grayling were stressed at 17.2° C and actively avoided 20° C water.

Observations of adult fish indicate they spend most of their time in a current of about 0.26 m/s (Kreuger 1981). Vincent (1962) defined Arctic grayling habitat as water with a velocity between 0.31 and 0.61 m/s; gradient 0.09 - 0.28% with a maximum of 0.38%. Liknes (1981) found grayling to be most abundant at 0.21 m/s, gradient - 0.29%.

Nelson (1954) observed grayling in water with 7.2 mg/l dissolved oxygen, 70% of saturation. Critical oxygen minima when acclimated to 13° C ranges from about 1.7 mg/l at 6° C to 2.2 mg/l at 19° C. Adult grayling consistently avoid turbid waters below placer mines, but they can survive under turbid conditions (Reynolds 1984). Grayling tend to associate with aquatic vegetation in both lakes (Eriksen 1975) and streams (Liknes 1981). In streams, such habitat is associated with pools and fine-sediment substrates (Vincent 1962; Liknes 1981).

HABITAT SUITABILITY INDEX (HSI) MODELS

Model Applicability

Habitat types. The models are applicable to freshwater riverine habitats.

Minimum habitat area. Minimum habitat area is the minimum area of continuous habitat that is required for Arctic grayling to survive and reproduce. Arctic grayling require suitable spawning, nursery and wintering areas. It may be possible to find such areas within less than 100 m of each other in a stream system.

Verification level. The present acceptable level of performance for these arctic grayling models is for them to produce an index between 0 and 1 that authors and biologists familiar with Arctic grayling ecology believe is positively correlated with the suitability of the habitat. Model verification consisted of checking the models' output from improvised data sites developed by the authors to simulate high, medium, and low quality arctic grayling habitat.

Model Description

The HSI model consists of two components: (1) spawning and embryo development; and (2) migratory and wintering habitat for juvenile and adult life stages.

Spawning and embryo development component. This component includes six habitat variables that are believed to govern spawning success and embryo survival of arctic grayling. Variables V_1 and V_2 describe water temperature and dissolved oxygen concentrations required, while variables V_3 and V_4 describe substrate requirements. Variable V_5 assesses current velocity and V_6 assesses pool availability.

Migratory and wintering component. This component uses four habitat variables that probably influence the quality of juvenile and adult habitat. Variables V_7 and V_8 describe water temperature and dissolved oxygen concentrations needed by these life stages. Variable V_9 describes the need for migratory routes between wintering areas and spawning streams, while V_{10} assesses overwinter habitat quality.

Suitability Index (SI) Graphs for Model Variables

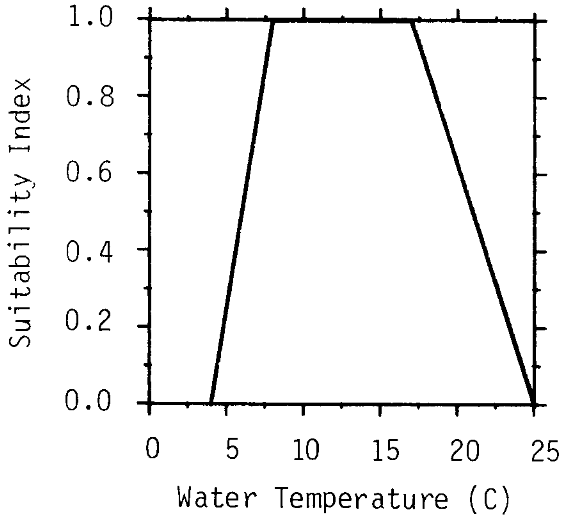
This section contains suitability index graphs for the 10 model variables. Equations and instructions for combining groups of variable SI's and component scores into an Artic grayling HSI are included. The habitat measurements and SI graphs construction are based on the premise that extreme, not average, variable values generally limit the carrying capacity of a habitat. Data sources and the assumptions used to construct the suitability index graphs for the Arctic grayling HSI model are presented in Table 1.

The graphs were constructed by quantifying information in the literature on the effect of each habitat variable on survival and abundance of Arctic grayling. The curves were built on the assumption that increments of survival and abundance plotted on the y-axis of the graph could be directly converted into an index of suitability from 0.0 to 1.0 for the species. The graphs represent the authors' best estimate of suitability for various levels of each variable. The graphs have been reviewed by biologists familiar with the ecology of the species, but the graphs have not been tested with field measurements. The user is cautioned to consider the graphs as hypotheses of species response and is encouraged to modify the shape of the graphs when existing regional information indicates that the variable relationship is different from that illustrated.

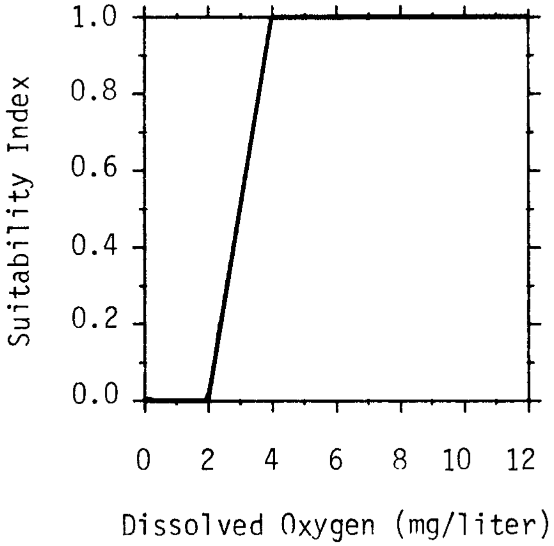
Variable

Suitability graphs

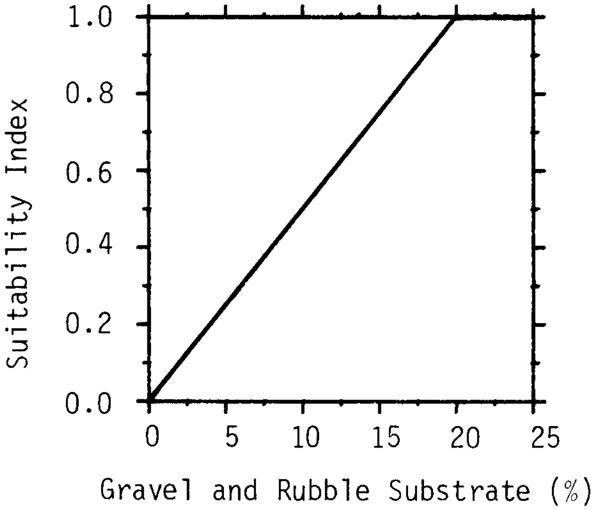
V_1 Average maximum water temperature (C) during the warmest period of the year in spawning streams.



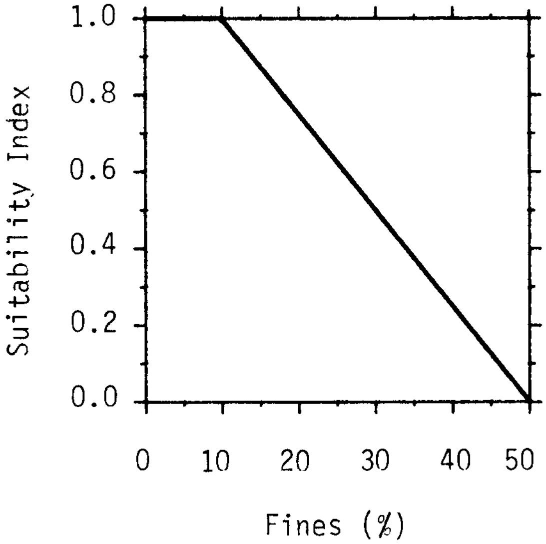
V_2 Average minimum dissolved oxygen (mg/l) during the late summer, low-flow period in spawning streams.



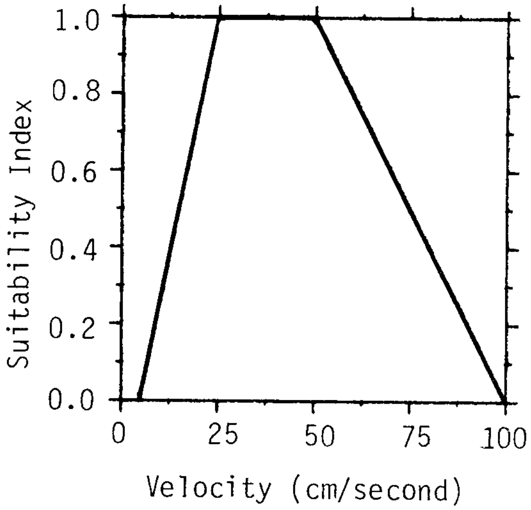
V_3 Percent of substrate in spawning areas composed predominantly of gravel and rubble (1.0 to 20.0 cm diameter).



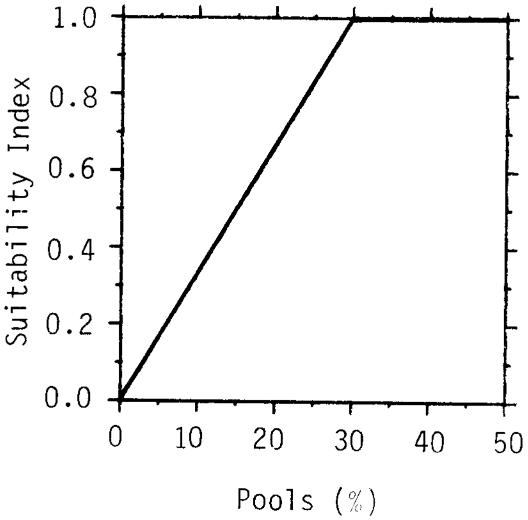
V_4 Percent fines (< 3 mm diameter) in spawning areas and downstream riffle areas during spawning and embryo development period.



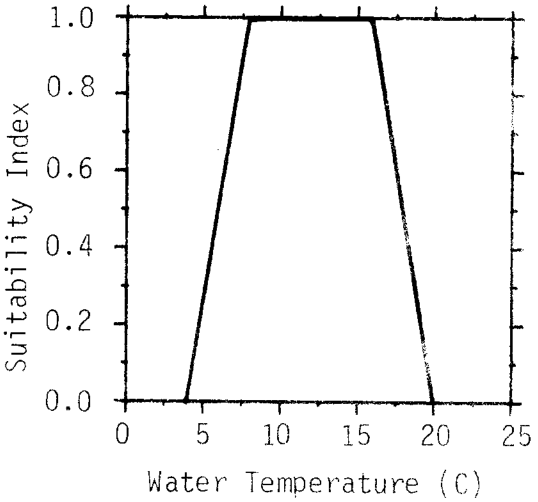
V_5 Average velocity (cm/s) at 0.6 the water depth over spawning areas during the spawning and embryo development period.



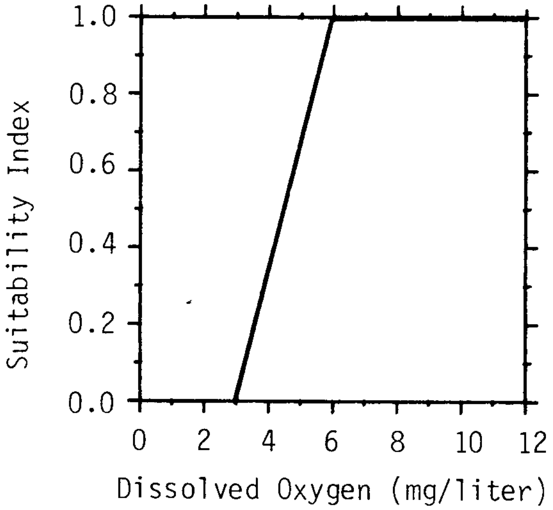
V_6 Percent of the spawning and nursery area downstream from the spawning areas, backwater and sidechannel areas with a current velocity less than 0.15 m/s (measured at a point 0.6 the water depth below the surface).



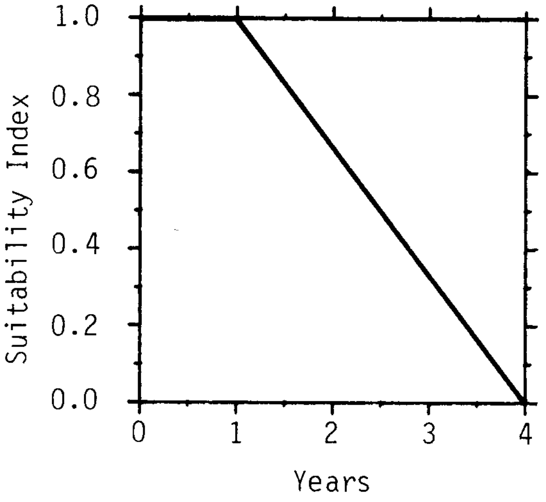
V_7 Average maximum water temperature (C) during the warmest period of the year in large streams and rivers inhabited by adults.



V_8 Average minimum dissolved oxygen (mg/l) during the late summer, low-flow period in large streams and rivers inhabited by adults.



V_9 Annual frequency of early spring access to tributary spawning streams within 150 km of wintering areas.



V_{10} Occurrence of winter habitat (deep pools with current velocities of less than 0.15 m/s and water depths greater than 1.2 m in large streams or springfed reaches of small streams that do not freeze solid in winter, having current velocities less than 0.15 m/s, and maintaining dissolved oxygen levels of more than 1.0 mg/l during winter).

SI = 1.0 if deep pools present.
SI = 0.0 if deep pools absent.

Table 1. Data sources and assumptions for Arctic grayling suitability indices.

Variable and source*		Assumptions
V_1	Henshall 1907 Ward 1951 Nelson 1954 Watling and Brown 1955 Kruse 1959 LaPerriere and Carlson 1973 Craig and Poulen 1975 Feldmuth and Eriksen 1978 Kreuger 1981 Kratt and Smith 1981	Average maximum daily water temperature has a greater effect on embryo growth and survival than minimum temperatures. The temperature that supports the greatest growth and survival is optimal.
V_2	Feldmuth and Eriksen 1978	The average minimum daily dissolved oxygen level during the late summer is related to growth and survival of Arctic grayling fry. Dissolved oxygen concentrations that reduce survival and growth are suboptimal.
V_3	Brown 1983 Nelson 1953 Nelson 1954 Bishop 1971 Kratt and Smith 1977 Kreuger 1981	Survival of embryos is correlated with the amount of interstitial cover. It is assumed that optimal cover conditions are achieved when greater than 20% of the bottom provides cover.
V_4	Brown 1983 Nelson 1953 Nelson 1954 Bishop 1971 Kratt and Smith 1977	High amounts of fines prevent embryos from entering interstiial spaces, prevent water flow to the embryos, and hinder emergence. Less than 50% fines in gravel and rubble areas is needed for optimum embryo survival.
V_5	Vincent 1962 Liknes 1981 Raleigh 1982	A measurable current velocity through embryo habitat is needed to prevent fines from settling; provide dissolved oxygen and carry away waste products. An optimal current velocity accomplishes these needs without flushing the embryos from the substrate.
V_6	Nelson 1954 Tack 1972 McCart et al. 1972 Craid and Poulin 1975 Chislett and Stuart 1979 Cuccarease et al. 1980 Elliott 1980 Kreuger 1981	Backwater and sidechannel areas with low current velocity are needed by fry. Fry survival is correlated with the amount of such habitat.

Table 1. (concluded)

Variable and source*		Assumptions
V_7	Nelson and Wojcik 1953 LaPerriere and Carlson 1973 Feldmuth and Eriksen 1978	Average maximum daily water temperature has a greater effect on adult growth and survival than minimum temperatures. The temperature that supports the greatest growth and survival is optimal.
V_8	Feldmuth and Eriksen 1978 Nelson 1954	The average minimum daily dissolved oxygen level during the late-summer is related to growth and survival of Arctic grayling adults. Dissolved oxygen concentrations that reduce survival and growth are suboptimal.
V_9	Henshall 1907 Brown 1938 Nelson 1954 Warner 1955 Wojcik 1955 Reed 1964 Williams 1968 Vascotto 1970 Bishop 1971 Kratt and Smith 1977 Tack 1980 Kreuger 1981 Liknes 1981 Falk et al. 1982	Arctic grayling are annual spawners with a relatively short life span on reaching sexual maturity. They are believed to home to spawning streams. Barriers that inhibit migration to spawning areas prevent successful spawning and impact particular spawning populations. Optimal access to spawning tributaries is annual.
V_{10}	Ward 1951 Nelson and Wojcik 1953 Yoshihara 1972 Craig and Poulin 1975 Alt and Furniss 1976 Kratt and Smith 1977 Tack 1980 Bendock 1980 Kreuger 1981	Suitable overwinter habitat within a stream system is mandatory for the survival of Arctic grayling populations.

*References include data from studies on brook trout, another salmonid species. This information has been selectively used to supplement data gaps on the habitat requirements of Arctic grayling.

Model

The model is composed of two components: (1) spawning, embryo, and fry development habitat; and (2) adult and juvenile habitat.

Spawning, embryo, and fry (A_1). A_1 variables include V_1, V_2, V_3, V_4, V_5 and V_6.

$$A_1 = \text{Lowest value of } V_1, V_2, V_3, V_4, V_5, \text{ or } V_6$$

Adult and juvenile (A_2). A_2 variables include V_7, V_8, V_9 and V_{10}.

$$A_2 = \text{Lowest value of } V_7, V_8, V_9, \text{ or } V_{10}$$

HSI determination. An HSI can be derived for a single component, or for both components combined. If both components are used the HSI score is computed as:

$$\text{HSI} = A_1 \text{ or } A_2, \text{ whichever is lower}$$

Interpreting Model Outputs

The HSI model for Arctic grayling is not intended to predict standing crops of fish throughout North America. Standing crop limiting factors, such as interspecific competition, predation, and angler exploitation, are not included in the model. The model includes physical habitat variables believed important in maintaining viable populations of Arctic grayling. If the model is correctly structured, a high HSI for a habitat would indicate near optimal physical conditions for Arctic grayling and a low HSI would indicate poor habitat conditions. An HSI of 0 does not necessarily mean that the species is not present; it does indicate that the habitat is very poor and the species is likely to be scarce or absent.

Assumed data sets selected by the authors to represent various habitat conditions are included in Table 2, along with the SI's and HSI's generated by the Arctic grayling model. The performance of the HSI model reflects the authors assumption that carrying capacity trends are reflected by habitat variables incorporated in the model.

Table 2. Sample data sets applied to the Arctic grayling HSI model.

Variable		Data Set I		Data Set 2		Data Set 3	
		Data	SI	Data	SI	Data	SI
Max. temp. (°C)	V_1	15	1.0	20	0.6	10	1.0
Max. dissolved O_2 (mg/l)	V_2	8	1.0	5	0.5	9	1.0
% substrate (1.0 to 20.0 cm)	V_3	15	0.75	20	1.0	25	1.0
% fines	V_4	30	0.5	10	1.0	5	1.0
Ave. velocity (cm/s)	V_5	20	0.75	25	1.0	30	1.0
% pools	V_6	25	0.85	40	1.0	50	1.0
Max. temp (°C)	V_7	12	1.0	18	0.5	15	1.0
Max. dissolved O_2 (mg/l)	V_8	8	1.0	5	0.65	8	1.0
Annual access to spawning tributaries	V_9	1	1.0	1	1.0	3	0.33
Winter habitat	V_{10}	Present	1.0	Present	1.0	Present	1.0

Data set 1 (Table 3) represents a situation where water temperature and dissolved oxygen conditions are optimum in both spawning streams and adult summer habitat. In addition, wintering areas are present and access to spawning tributaries is annual. Conditions within the spawning stream are not optimal with a substrate composed of mostly fine material, relatively low current velocity and few pools. The A_1 component value of 0.5 indicates less than optimal conditions in the spawning streams.

Data set 2 represents a situation where all habitat parameters except temperature and dissolved oxygen are optimal in both spawning streams and adult stream habitat. Temperatures exceeding optimum occur with subsequent dissolved oxygen levels less than optimum. Both the A_1 and A_2 component values, 0.5 and 0.5, respectively, indicate less than optimal conditions.

Data set 3 describes a situation where all habitat variables are in the optimum range with the exception of access to spawning tributaries. Access occurs on an average of once every 3 years to reduce the A_2 component value and the overall HSI.

Users of this Arctic grayling model are reminded that the model is based only on a review of the literature. The SI curves are hypothetical representations of how the authors believe habitat quality is related to grayling abundance. The HSI values computed in Table 3 are based purely on manufactured data to illustrate how the model may respond to real data. The HSI model for Arctic grayling has not been tested with actual field data to determine its accuracy or reliability. Use of this Arctic grayling model in habitat evaluation must be done with the realization that the model is hypothetical and untested.

Table 3. Computed HSI values using sample data sets for Arctic grayling.

Component	Data Set 1	Data Set 2	Data Set 3
A_1	0.5	0.5	1.0
A_2	1.0	0.5	0.33
HSI	0.5	0.5	0.33

INSTREAM FLOW INCREMENTAL METHODOLOGY

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

1. Habitat Time Series: To determine a project's impact on the habitat needed by a species' life stage by overlaying the project's operation curves on the baseline flow time series and integrating the difference over time;

2. Effective Habitat Time Series: To calculate 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: To determine the 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 uses 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.

Availability of SI Curves for Use in IFIM

The SI curves available for IFIM analyses of Arctic grayling habitat are category one, based on professional judgement and information derived from the literature. No sources of field data were available for developing category two or three curves. Investigators are encouraged to review the curves carefully and verify them before use in IFIM analyses.

Spawning and egg incubation. Arctic grayling generally spawn some time between March and June, depending on locale, time of ice breakup, water temperatures, and streamflow (Carlander 1969; Craig and Poulin 1975; MacPhee and Watts 1976; Tack 1980). Duration of spawning is approximately one month (Carlander 1969; Kratt and Smith 1980). Egg incubation requires 2 to 3 weeks, depending on water temperatures (Carlander 1969). Therefore, investigators will have to determine those months of each year when spawning and egg incubation habitat will be required in their given study streams.

There are two approaches for determining the amount of spawning/egg incubation habitat for a stream reach. One approach treats spawning and egg incubation as separate life stages, each with its own set of habitat suitability criteria, and assumes that weighted useable area does not vary by more than 10% during the spawning and egg incubation periods. In this case, Arctic grayling spawning and egg incubation curves are combined (Fig. 1), assuming that no significant difference in physical microhabitat requirements exists between the two life stages (e.g., depths and velocities suitable for spawning are also suitable for egg incubation).

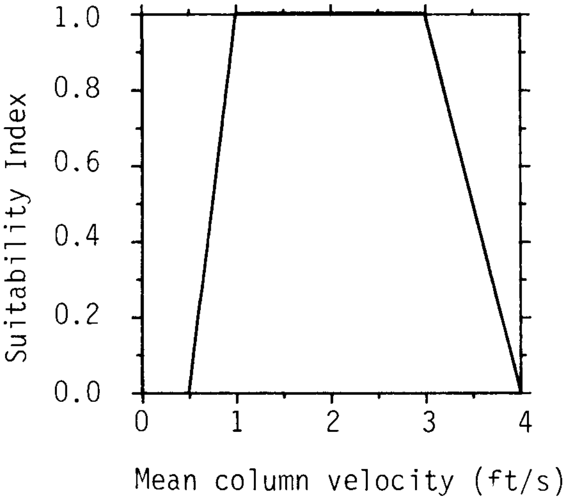
Tack (1971) found that the velocities of surface currents ranged from 1.1 to 4.8 ft/s (with a mean of 2.6 ft/s) in male grayling territories in the outlet of Mineral Lake, Alaska. Warner (1955) observed grayling spawning at surface velocities of approximately 3.9 ft/s in a Fielding Lake inlet stream. Reed (1964) observed spawning in low-velocity waters, and Wojcik (1954) reported grayling spawning in slow, shallow backwaters. The SI curve for spawning and egg incubation velocity (Fig. 1) was based on this information, and the assumptions that mean column velocities are approximately equal to 80% of surface velocities, and that intragravel velocities necessary for successful egg incubation are related to mean column velocities.

Arctic grayling have been reported to spawn in depths ranging from 0.5 to 3.0 ft (Warner 1955; Tack 1971; Cuccarease et al. 1980). The SI curve for spawning and egg incubation depth (Fig. 1) was based on the assumption that depths above a minimum are not limiting.

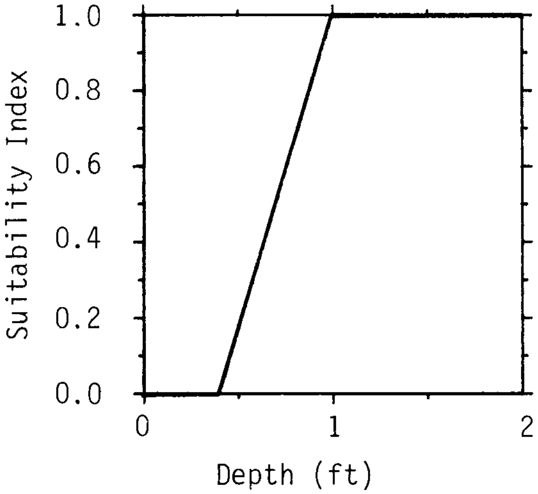
Grayling generally spawn in fine gravel of particle-size diameters ranging from 0.2 to 1.5 inches (Warner 1955; Kruse 1959; Tack 1971; Bendock 1979; Cuccarease et al. 1980; Elliott 1980). The SI curve for spawning and egg incubation substrate (Fig. 1) is based on the assumption that a minimal particle size diameter is necessary for successful egg incubation.

Coordinates

x	y
0.0	0.0
0.5	0.0
1.0	1.0
3.0	1.0
4.0	0.0
100.0	0.0



x	y
0.0	0.0
0.4	0.0
1.0	1.0
100.0	1.0



x	y
0.00	0.0
0.18	0.0
0.20	1.0
1.50	1.0
3.00	0.0
100.00	0.0

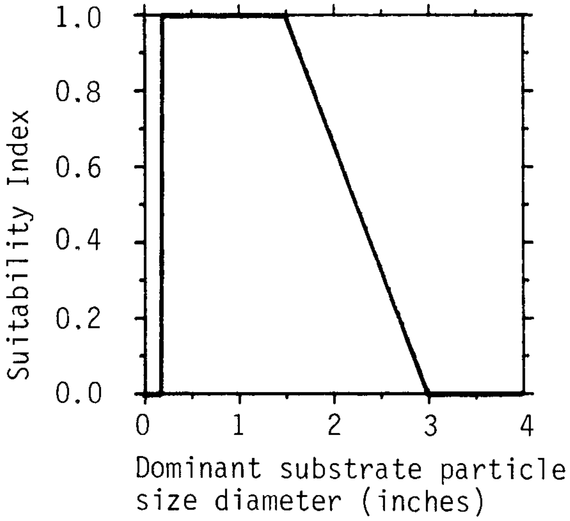


Figure 1. Category one SI curves for Arctic grayling spawning and egg incubation velocity, depth, substrate, and temperature suitability.

Coordinates

x	y (spawning; solid line)	y (egg incubation; broken line)
0.0	0.0	0.0
39.0	0.0	0.0
40.0	1.0	--
46.0	--	1.0
52.0	1.0	--
55.0	0.0	--
63.0	--	1.0
77.0	0.0	0.0
100.0	0.0	0.0

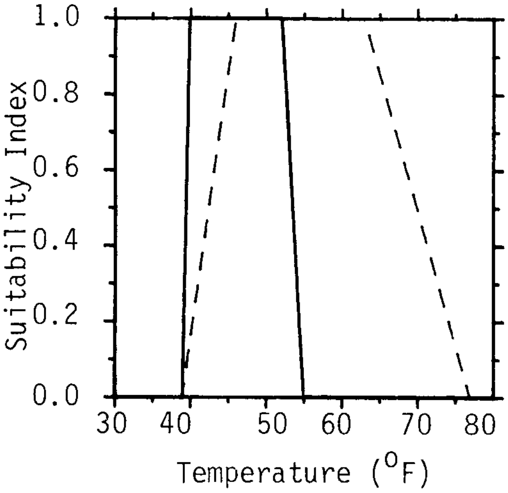


Figure 1. (concluded)

No information was found in the literature suggesting that grayling require cover during spawning. Unless future information indicates otherwise, the author assumes that a cover curve is unnecessary for IFIM analyses of spawning habitat, and that the SI curve for substrate will satisfy the cover requirements of incubating embryos.

Most of the literature indicated that grayling spawning occurs at water temperatures ranging from 40 to 52° F (Brown 1938; Wojcik 1954; Kruse 1959; Bishop 1971; McCart et al. 1972; Tack 1972; Cuccarease et al. 1980). Tack (1972) reported that spawning ceased when water temperatures dropped below 40° F, and resumed as temperatures rose above 40° F. No spawning activity was reported above 52° F. The SI curve for spawning (Fig. 1) was based on this information, while the curve for egg incubation was taken from the HSI model section of this report (V_1; Fig. 1).

The other approach, which determines spawning and egg incubation habitat, measures effective spawning habitat (Milhous 1982) and is recommended when weighted useable area varies by more than 10% during the spawning and egg incubation period, as a result of streamflow variation. 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 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. 2) can be determined by:

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

where Vc = 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

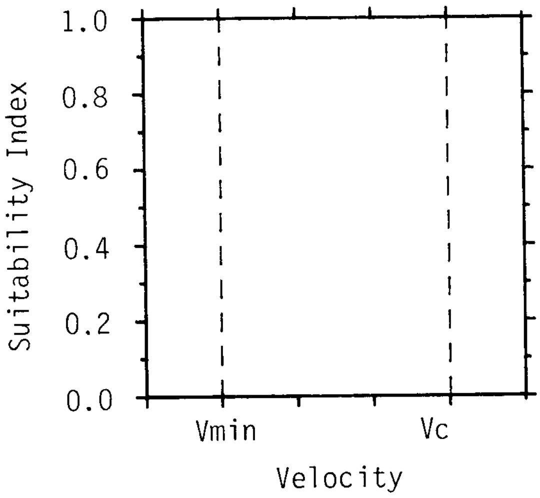
K_s = 0.080, a constant pertaining to the general movement of the surface particles

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

Coordinates

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

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



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

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

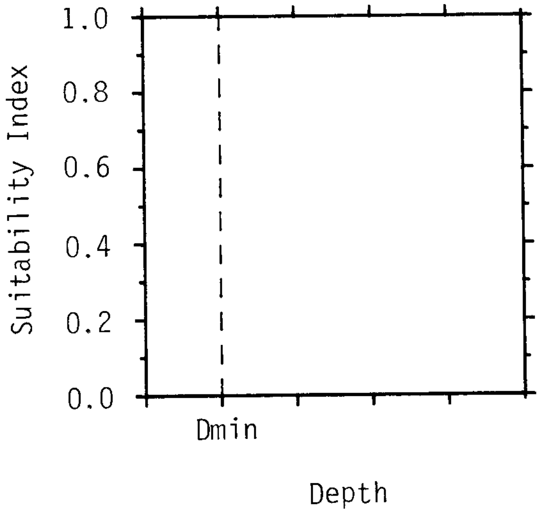


Figure 2. SI curves for spawning/egg incubation velocity and depth, for effective spawning habitat analyses.

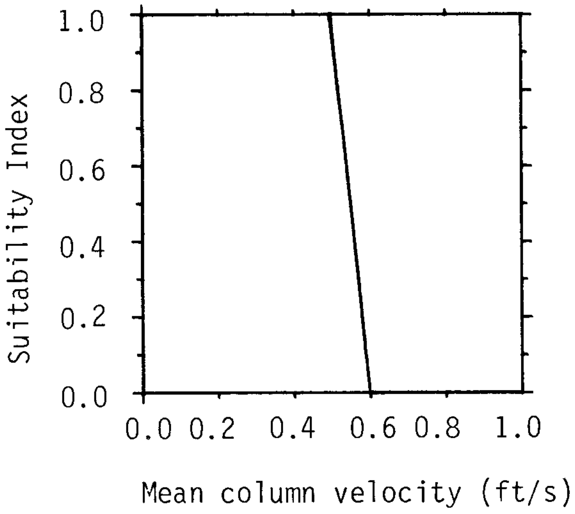
Factors to consider when determining habitat reduction from siltation include suspended sediment concentrations, minimum velocities necessary to prevent siltation (Fig. 2), and dissolved oxygen concentrations among the embryos. More detailed information about the analysis of effective spawning habitat is presented in Milhous (1982).

Fry. Arctic grayling fry are considered to be individuals less than 2.0 inches in length. Fry habitat is required for the time period from 2 weeks after the beginning of spawning to approximately 4 months after the end of spawning, depending on locale. Newly hatched fry remain in the gravel for 1 to 2 weeks during yolk sac absorption (Nelson 1954; Kratt and Smith 1977), and their habitat requirements are assumed to be the same as for egg incubation (Fig. 1). After fry emerge from the gravel, they occupy quiet backwaters or migrate downstream to lakes (Kruse 1959; McCart et al. 1972). Mean column velocities selected by grayling fry ranged 0.0 to 0.5 ft/s (Fig. 3) and depths ranged 0.3 to 2.8 ft (Elliot 1980). The upper limit of the SI curve for depth (Fig. 3) is based on the assumption that grayling fry are more susceptible to predation in deeper waters (unless cover is available). Evidence of substrate preferences of fry were not found in the literature, although Kreuger (1981) stated that fry will use substrate as a form of cover when they are disturbed. The SI curve for fry substrate suitability (Fig. 3) is based on the assumption that all substrate types are suitable, but cobble and boulder are optimal. No curve was developed for cover, although the substrate curve may be used to satisfy cover requirements of fry. Other cover types (such as submerged or emergent vegetation) may be equally suitable, but optimal amounts could not be determined. The SI curve for fry temperature (Fig. 3) was taken from the HSI model section of this report (V_7) assuming that temperatures suitable for adult grayling are also suitable for fry.

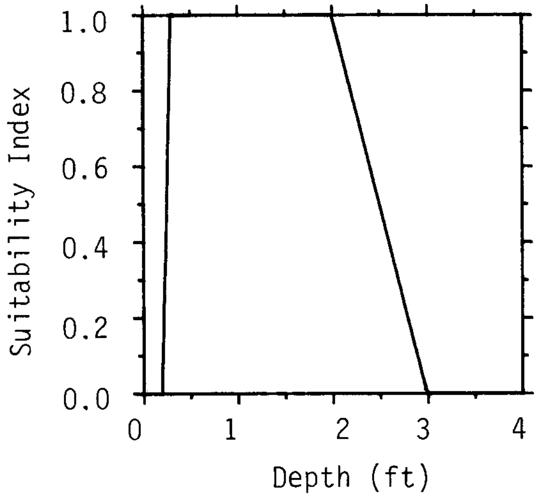
Juveniles and adults. Most grayling mature at age III at total lengths ranging from 8 to 15 inches (Carlander 1969). Therefore, juveniles are considered to be individuals between 2 and 10 inches in length, and adults are considered to be individuals greater than 10 inches in length. Both juvenile and adult habitat is required year-round. SI curves for juvenile and adult habitat requirements have been combined (Fig. 4). Elliot (1980) found that the average mean velocity occupied by juvenile grayling was 0.7 ft/s, and by adults was 0.9 ft/s. Velocities less than these are considered equally suitable because grayling are often found in lakes. There is evidence which suggests that velocities used by grayling are a function of fish size, season (summer vs. winter), and activity (feeding vs. resting) (Zakharchenko 1973; Kreuger 1981). Therefore, judgement should be used before using the SI curve for velocity (Fig. 4). Depths used by juveniles and adults have been reported to range from 0.7 to 3.8 ft (Kreuger 1981), and the SI curve is based on the assumption that all depths greater than 0.7 ft are suitable. For overwintering, pool depths greater than 4.5 ft are recommended (Bendock 1980; Kreuger 1981), especially where ice buildup is a problem. No evidence was found to suggest that substrate is important to grayling adults or juveniles, and a curve may not be required for IFIM analyses. Grayling will use various cover types, however, not enough information was available for development of cover curves. The SI curve for temperature was taken from the HSI model section of this report (V_7), assuming that temperature requirements of juveniles are similar to those of adults.

Coordinates

x	y
0.0	1.0
0.5	1.0
0.6	0.0
100.0	0.0



x	y
0.0	0.0
0.2	0.0
0.3	1.0
2.0	1.0
3.0	0.0
100.0	0.0



x (Code)	Particle size	y (SI)
1	Plant detritus/ organic material	0.5
2	Mud/soft clay	0.5
3	Silt (< 0.062 mm)	0.5
4	Sand (0.062-2.0 mm)	0.5
5	Gravel (2.0-64.0 mm)	0.5
6	Cobble (64-250 mm)	1.0
7	Boulder (250-4,000 mm)	1.0
8	Bedrock (solid rock)	0.5

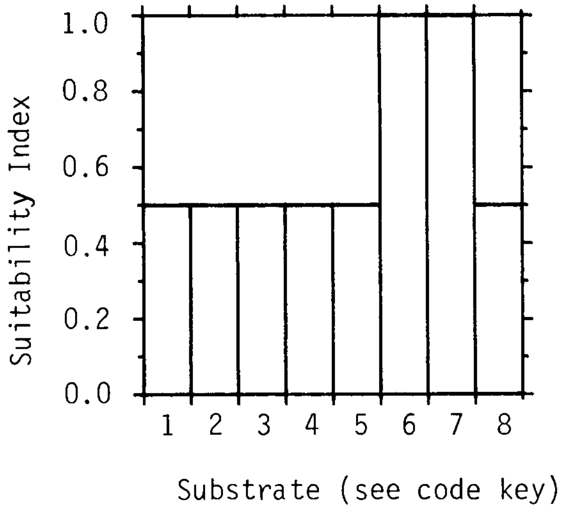


Figure 3. Category one SI curves for Arctic grayling fry velocity, depth, substrate, and temperature suitability.

Coordinates

x	y
0.0	0.0
39.0	0.0
46.0	1.0
61.0	1.0
68.0	0.0
100.0	0.0

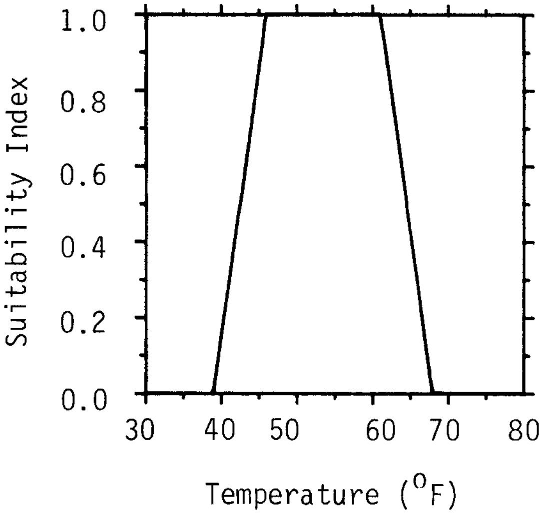
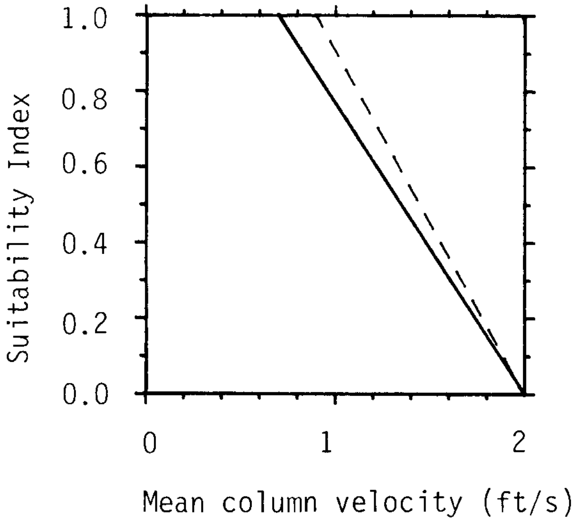
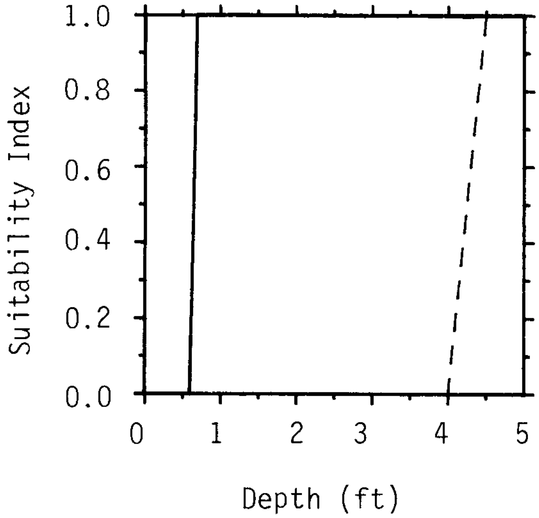


Figure 3. (concluded)

x	y (juvenile; solid line)	y (adult; broken line)
0.0	1.0	1.0
0.7	1.0	--
0.9	--	1.0
2.0	0.0	0.0
100.0	0.0	0.0



x	y (summer; solid line)	y (winter; broken line)
0.0	0.0	0.0
0.6	0.0	--
0.7	1.0	--
4.0	--	0.0
4.5	--	1.0
100.0	1.0	1.0



x	y
0.0	0.0
39.0	0.0
46.0	1.0
61.0	1.0
68.0	0.0
100.0	0.0

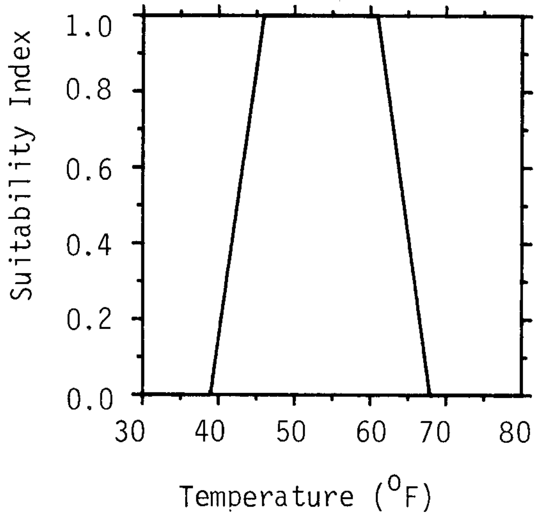


Figure 4. Category one SI curves for Arctic grayling juvenile and adult velocity, depth, and temperature suitability.

Migration. Spring migration to spawning grounds and summer feeding areas generally occurs at or near ice breakup (Nelson 1954; Netsch 1975). Distance of migration depends on the distance between overwintering areas and summer spawning/feeding areas, which may be as much as 53 mi (Craig and Poulin 1975). Upstream migration generally begins when water temperatures reach 33 to 39° F, and migration ceases at temperatures greater than 54 to 60° F (Warner 1955; Craig and Poulin 1974) (Fig. 5). Successful migration depends on absence of blockage caused by waterfalls, ice jams, beaver dams, or man-made dams (Nelson 1954; Kreuger 1981), and the minimal water depth considered suitable for migration is 0.4 ft (Fig. 5). Velocity preferences and tolerances for migration are unknown, and may be a function of fish size. No information was found to indicate that substrate or cover is a requirement for grayling migration.

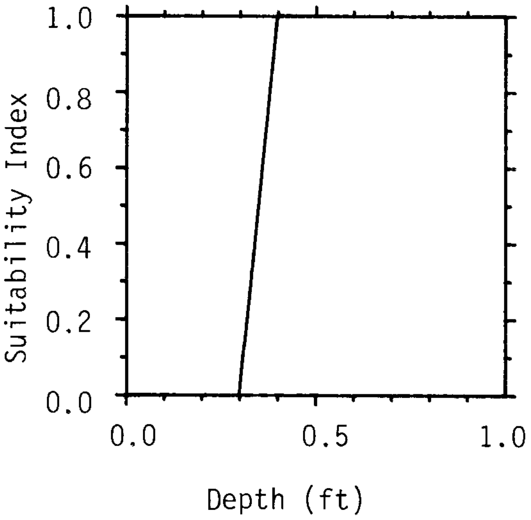
Timing of downstream migration to overwintering areas is variable, and may occur at any time from the end of spawning to the onset of ice formation, depending on locale. Migration generally occurs before streams become impassable due to low flows or ice buildup, possibly in response to declining water temperatures or declining flows (Kreuger 1981). Adults and juveniles may migrate at the same time, or adults may migrate before juveniles by several days or weeks.

Before attempting IFIM analyses it is important to develop a species periodicity chart for the study area of interest, to determine when and where habitat is required by each life stage (Fig. 6). The literature suggests that grayling exhibit complex migration patterns, so a basin-wide management approach may be required.

All SI curves for IFIM analyses of Arctic grayling habitat should be reviewed carefully before use. If any of the curves are believed not to represent local situations, then they will require modification. We recommend field verification if time and money are available.

Coordinates

x	y
0.0	0.0
0.3	0.0
0.4	1.0
100.0	1.0



x	y (spring; solid line)	y (fall; broken line)
31.0	0.0	0.0
32.0	0.5	1.0
34.0	1.0	--
39.0	--	1.0
40.0	--	0.0
53.0	1.0	--
54.0	0.5	--
60.0	0.0	--
100.0	0.0	0.0

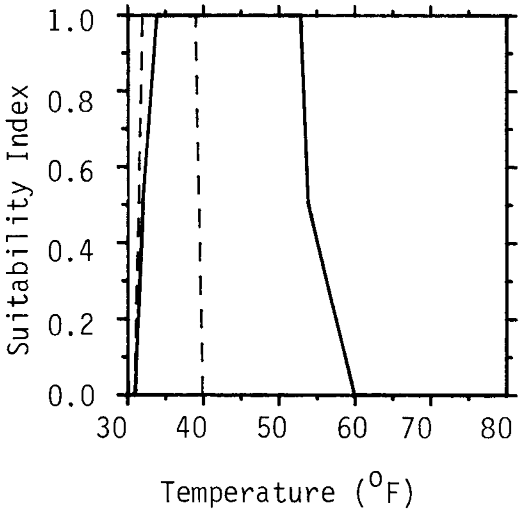


Figure 5. Category one SI curves for Arctic grayling migration depth and temperature suitability.

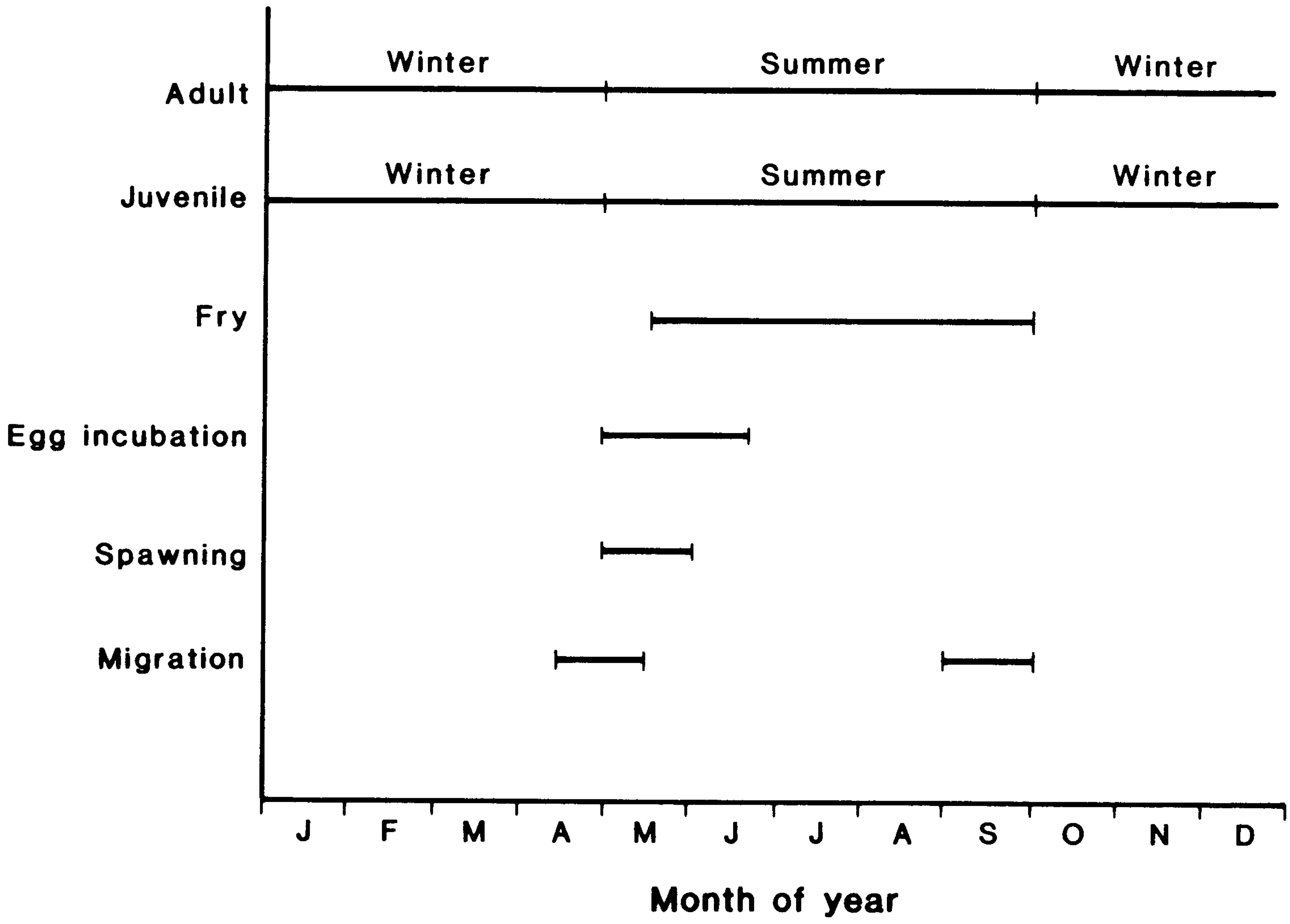


Figure 6. Example species periodicity chart for arctic grayling in an example river basin.

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A review and synthesis of existing information were used to develop a Habitat Suitability Index (HSI) model and instream flow suitability curves for Arctic grayling (Thymallus arcticus) riverine populations. 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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