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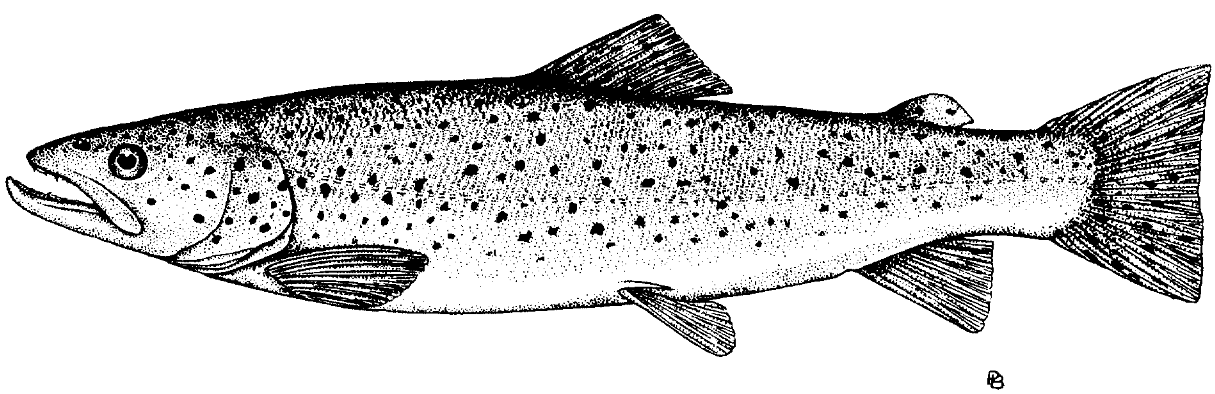
HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: BROWN TROUT



and Wildlife Service

Department of the Interior

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 ______________________

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HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: BROWN TROUT

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PREFACE

The revised model contains significant changes from the previous model (FWS/OBS-82/10.71). The major changes include addition and deletion of habitat variables, shapes of individual SI curves, and modification of the intermediate and final aggregation equations. The model user should carefully review this revised model for applicability and probably use it in place of the earlier version.

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. The models are hypotheses of species-habitat relationships, and model users should recognize that the degree of veracity of the HSI model, SI graphs, and assumptions may vary according to geographical area and the extent of the data base for individual variables. After clear study objectives have been set, the HSI model building techniques presented in U.S. Fish and Wildlife Service (1981) and the general guidelines for modifying HSI models and estimating model variables presented in Terrell et al. (1982) 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. Statistically-derived models that are an alternative to using Suitability Indices to calculate an HSI are referenced in the text.

A brief discussion of the appropriateness of using selected Suitability Index (SI) curves from HSI models as a component of the Instream Flow Incremental Methodology (IFIM) is provided. Additional SI curves, developed specifically for analysis of brown trout habitat with IFIM, also are presented.

Results of a model performance test in a limited geographical area are summarized, but model reliability is likely to vary in different geographical areas and situations. The U.S. Fish and Wildlife Service encourages model 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. Please send comments to:

Habitat Evaluation Procedures Group or
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National Ecology Center
U.S. Fish and Wildlife Service
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Fort Collins, CO 80526-2899

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FIGURES

ACKNOWLEDGMENTS

Dr. Robert Behnke, Colorado State University; Leo D. Lentsch, Yellowstone Fishery Investigations, U.S. Fish and Wildlife Service; Dr. Harold W. Lorz, Oregon Department of Fish and Wildlife; Dr. Neil H. Ringler, State University of New York; Dr. Thomas Wesche, Wyoming Water Research Center; and Dr. Ray J. White, Montana State University, all provided useful and valuable critiques of this manuscript. However, the reader should not construe this as an endorsement of the model contents. Charles Solomon reviewed the model, managed the contract and prepared the final manuscript for publication. Cathy Short and Jim Zuboy conducted the editorial review, and word processing was provided by Carolyn Gulzow and Dora Ibarra. The cover is from Freshwater Fishes of Canada, Bulletin 184, Fisheries Research Board of Canada, by W. B. Scott and E. J. Crossman.

BROWN TROUT (*Salmo trutta*)

INTRODUCTION

This publication contains habitat models constructed and information compiled for two distinctly different purposes. The Habitat Suitability Index (HSI) models by Raleigh and Zuckerman contain a synoptic overview of the life history and known habitat requirements (18 variables) of brown trout by life stage. The HSI models provide an objective, quantifiable method of assessing the existing habitat conditions for brown trout within a study area by measuring how well each habitat variable meets the habitat requirements of the species by life stage. The model, thus, provides an objective basis for predicting probable project impacts, documenting postproject impacts, and guiding habitat protection, mitigation, enhancement, and management decisions.

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

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

Instream flow SI graphs may be based on literature, professional judgement, lab studies, or field observations of the frequency with which certain values within a range of values for a habitat variable, such as gravel size, are used by individuals of a species (Bovee 1986). The premise with field data is that individuals of the species will select and occupy the best habitat conditions available to them. Optimal conditions for a variable are considered to be those under which most individuals are observed. Range limits for a variable are the conditions under which the fewest are observed.

The Physical Habitat Simulation System (PHABSIM) component of the IFIM utilizes four variables: flow velocity, depth, substrate composition, and cover. Wherever individuals of a species are observed in the stream, measurements are taken on the above four variables. In most cases to date SI curve data have not been tested for cross-correlations among variables, and only univariate curve functions have been developed. If multivariate SI functions are not available for use in IFIM, then each variable is treated independently of the others. SI curves assume that a full range of preferred and tolerated variable values were available for selection by individuals of the species at each study stream site. Otherwise, bias may occur in the frequency analysis method, unless habitat availability limitations are factored out (Bovee 1986).

Information for SI graph construction gleaned from field and laboratory studies have limitations. It is sometimes difficult to determine if the full range of usable values for the variable have been included in field studies. For example, the species may have been observed using spawning gravel ranging from 0.3 to 5 cm in size. Studies of the effects of siltation on embryo survival for the species may indicate that the lower limit of 0.3 cm appears acceptable. If different streams had been included in the studies, however, the upper gravel size limit may have exceeded 5 cm.

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

Biologists familiar with the ecology of brown trout have reviewed the data base and SI graphs of the brown trout HSI model. Suggested changes by the reviewers that are not at variance with accepted brown trout study results have been incorporated. The user is advised, however, to review each SI graph to see how well it represents known regional requirements for the species. Changes should be made if indicated, and the reasons for each change should be fully documented.

HABITAT USE INFORMATION

General

Although the HSI model section contains both riverine and lacustrine models to estimate brown trout standing crops, the primary use of HSI models is not intended to yield estimates of brown trout biomass. The HSI models are intended to produce a matrix of reasonably accurate suitability indices for the 18 brown trout model variables by life stage. Such an array can be used to evaluate brown trout habitat suitability before and after aquatic project developments, assist the user to better visualize probable project impacts, and to guide brown trout habitat-oriented management decisions.

Distribution

The brown trout (Salmo trutta) is native to the Eurasian mainland from Cape Kerin to the upper Amu Darya drainage of the Aral Sea in Afghanistan, North Africa, westward throughout Europe and into Iceland and the British Isles (MacCrimmon and Marshall 1968; Behnke 1979). Brown trout were first introduced into the United States in 1883 and are now found in all states with trout fishing (MacCrimmon and Marshall 1968; Needham 1969). Two subspecies, Salmo trutta trutta (German brown trout) and S. t. levenensis (Lochleven trout) were formerly recognized but are now considered ecotypes, similar to rainbow and steelhead trout (Salmo gairdneri) (Robert J. Behnke, Colorado State University, Fort Collins, Colorado; pers. comm.). These two ecotypes, although recognized for many years in the United States (Scott and Crossman 1973; Eddy and Underhill 1974), have become mixed in hatcheries and in the wild to the extent that they often are no longer distinguishable (Staley 1966). Anadromous, lacustrine, and riverine populations of brown trout are now firmly established in North America.

Age, Growth, and Food

Brown trout mature as early as the end of their first year (McFadden et al. 1965) and as late as their eighth year (Moyle 1976), but most mature in their third to fifth year (Alm 1951; Lorz 1974). Marshall and MacCrimmon (1970) observed ages to 13 years in freshwater Canadian brown trout populations. Anadromous brown trout up to age 18 have been reported from Great Britain (Nall 1930). The average size attained is usually 0.1 to 1.8 kg (0.25 to 4 pounds) in inland streams. The record brown trout from Scotland is 18 kg (40 pounds) (Needham 1969). Berg (1948) described a subspecies from the Caspian Sea with weights up to 51 kg; however, Behnke (1979) believes the 51 kg weight to be highly suspect. The average size of the 1916 spawning run into the Kara River was 15 kg (Behnke, pers. comm.). Weights up to 31 kg have been verified from the Wolfgangsee (Neresheimer 1937).

In rivers and streams, brown trout, up to 25.0 to 30.0 cm in length, are size-selective feeders, selecting primarily larger prey (Ringler 1979). They feed generally on terrestrial and aquatic insects (primarily Ephemeroptera, Trichoptera, and Plecoptera) but, as they exceed 25.0 cm, fish and crustaceans become more important in the diet (Metzelaer 1929; O'Donnell and Churchill 1943; McCormack 1962; Brynildson et al. 1963; Hannukula 1969). Mature brown trout are active night feeders (McClane and Rayner 1974). They are also occasionally active throughout the winter, feeding periodically even in frazil ice (Maciolek and Needham 1952). In lakes, brown trout may be more active in the day than at night, with most activity at dawn (Swift 1962, 1964). Small brown trout in lakes feed heavily on zooplankton, gradually switching first to bottom-dwelling insect larvae and amphipods and then, at lengths greater than 25.0 cm, to fish (Moyle 1976). Members of the genus Alosa (alewives) are a major forage fish for brown trout in the Great Lakes, as is Caspialosa in the Caspian Sea (Behnke 1979).

Reproduction

Brown trout are typically stream spawners. Homing of spawning brown trout to specific natal streams with a high degree of accuracy and a low incidence of straying has been confirmed (Stuart 1953; Tilzey 1977). They generally move upstream in the fall to spawn or, in the case of lakes and reservoirs, into tributary streams. Females build nests or redds in the spawning gravel and demersal eggs are deposited and covered with gravel. After the spawning period, nests are left unguarded (Greeley 1932; Breder and Rosen 1966). While brown trout usually spawn in running water, Borgeson (1966) reported successful spawning of brown trout over seepage areas of lakes. Adequate spawning habitat to support abundant trout populations appears to be ≈5% of the total trout habitat utilized in a river system, or an area equal to about 3% of the surface area of a lake.

Brown trout are fall spawners with apparent latitudinal differences in time of onset. Spawning migrations appear to be triggered by decreasing day length, increased late fall flows, or drops in water temperature to <9 °C (Stuart 1953, 1957; Frost and Brown 1967; Rieser and Wesche 1977), though these events are usually concurrent. In California, however, Staley (1966) reported that spawning often occurs when stream flows are low.

Anadromy

Anadromous brown trout breed in freshwater and, after a period of freshwater residence, the young return to the sea to grow and mature. The young fish spend one to two growing seasons at sea and then return to their natal rivers in the fall to spawn. Like steelhead trout, many brown trout adults survive to spawn again. There are records of individuals spawning up to 12 times (Mills 1971). Adult brown trout feed during the spawning run.

In anadromous populations of brown trout, smoltification results in changes in behavior and physiology. The smolts are not territorial, and tend to school. They move up from tactile contact with the substrate and drift downstream with the current. Nocturnal movements appear to be preferred by brown trout, as with other salmonid smolts.

The onset of smoltification is regulated by increasing day length and water temperature in the spring (Folmar and Dickhoff 1980), and by an endogenous factor manifested as a critical body size. The availability of environmental iodine has been noted as a possible aid to the necessary physiological changes. Smolting brown trout juveniles lose weight and have a lean, firm appearance. There is also a distinct preference for increasing salinities along a downstream gradient (Mills 1971).

Behnke (pers. comm.) believes that no true anadromous brown trout populations exist in North America. There are examples of estuarine feeding populations, but no true sea-run populations as are typical in Europe.

Habitat Characteristics

Optimal brown trout riverine habitat is characterized by clear, cool to cold water; a relatively silt-free rocky substrate in riffle-run areas; a 50% to 70% pool to 30% to 50% riffle-run habitat combination with areas of slow, deep water; well vegetated, stable stream banks; abundant instream cover; and relatively stable annual water flow and temperature regimes. Brown trout tend to occupy the lower reaches of low to moderate gradient areas (<1%) in suitable, high gradient river systems.

Optimal lacustrine brown trout habitat is characterized by clear, cool to cold, deep lakes that are typically oligotrophic, but may vary in size and chemical quality, particularly in reservoir habitats. Brown trout normally are stream spawners and require tributary streams with gravel substrate in riffle-run areas for optimal reproduction to occur.

High gradient, headwater trout streams are relatively unproductive. Most energy inputs to the stream are in the form of allochthonous materials, such as terrestrial vegetation and terrestrial insects (Idyll 1942; Chapman 1966; Hunt 1971). The gradient, water velocity, and substrate size tend to decrease downstream, whereas the pool to riffle ratio, temperature, productivity, and species diversity tend to increase.

Aquatic invertebrates are most abundant and diverse in riffle areas with a rubble substrate and on submerged aquatic vegetation (Hynes 1970). However, optimal substrate for maintenance of a diverse invertebrate community consists of a mosaic of mud, gravel, rubble, and boulders, with rubble dominant. The invertebrate fauna is much more abundant and diverse in riffles than in pools (Hynes 1970). In riffle areas, the presence of fines (>10%) reduces the production of invertebrate fauna (adapted from Cordone and Kelly 1961; Crouse et al. 1981). Binns (1979) found that late summer nitrate-nitrogen measurements in Wyoming, were correlated with habitat productivity and trout standing crops, with optimal levels 0.15 to 0.25 mg/l.

When different trout species occur in the same high gradient river systems, they tend to occupy the suitable trout habitat in a longitudinally stratified manner from headwater areas downstream. Typically, brook (Salvelinus fontinalis) or cutthroat trout (Salmo clarki) tend to occupy the colder, swifter, less fertile headwater region, rainbow trout the midregion of the river system with intermediate habitat conditions, and brown trout the deeper, lower velocity, warmer, more fertile downstream region.

Canopy cover (shade) is important in small brown trout streams. Riparian trees and bushes help keep water temperatures down during the hot summer months, provide habitat for potential terrestrial insect prey, and provide allochthanous materials for much of the primary production in a stream ecosystem. Shading becomes less important as stream size increases. The greater volume and depth of larger streams helps to compensate for the relative lack of shade. The Oregon/Washington Interagency Wildlife Committee (1979) recommended 60% to 100% shading for eastern Washington and Oregon trout streams. Too much shade, however, can restrict primary productivity in small, cold trout streams (Brocksen et al. 1968; Murphy and Hall 1981). In view of these findings, 50% to 75% midday shade was assumed to be optimal for most small brown trout streams Nationwide.

In addition, a well vegetated riparian area helps control watershed erosion. In moderate gradient areas of clearcut logging or overgrazed rangeland, a buffer strip about 30 m wide, 80% of which is either well vegetated or has stable, rocky stream banks, usually provides adequate erosion control and maintains the undercut stream banks characteristic of good trout habitat (adapted from Oregon/Washington Interagency Wildlife Committee 1979). The presence of fines (<3 mm) in riffle-run areas can adversely affect embryo survival, food production, and cover for juveniles.

The annual flow regime and the quality of salmonid riverine habitat are closely related. The critical period for brown trout is the time between egg deposition in late summer and fall, and fry emergence in the following spring. Although flows must be adequate to meet the needs of the developing embryos and yolk sac fry in the gravel, abnormally low or high flows can be destructive. Significant mortalities to salmonid embryos and yolk sac fry have been reported due to freezing of redds caused by insufficient flow in winter, and from redd destruction caused by gravel movement and displacement of newly emerged fry during abnormally high freshets (Sheridan and McNeil 1960; Andrew and Geen 1960). An annual base flow ≥50% of the average annual daily flow is considered excellent for salmonid production, a base flow of 25% to 50% is considered fair to good, and one of <25% is considered poor (adapted from Tennent 1976; Binns and Eiserman 1979; Wesche 1980). Nehring and Anderson (1982, 1983) consider a peak flow of about five times the magnitude of an excellent base flow, or about two times the average annual daily flow (Lister and Walker 1966) to be acceptable for good salmonid production. Peak flows approaching twice these limits are considered progressively more destructive. Peak and base flow volumes that are controlled in trout habitats in dam tailwaters can enhance production of juvenile chum, coho, and chinook salmon (Lister and Walker 1966) and trout (Nehring and Anderson 1982, 1983), or give a competitive edge to spring or fall spawning stocks, depending on timing and amplitude of flow releases.

Specific Habitat Requirements

The habitat requirements of brown trout are described on a life stage basis: adult, embryo, fry, and juvenile. For purposes of the model, the embryo stage includes the incubating eggs and developing fry up to time of emergence from the gravel. The fry stage extends from emergence from the gravel through the first year of life. The juvenile stage is the second year of life until the sexually mature adult stage.

Adult. Temperature is probably the single most important environmental variable determining the geographic distribution of suitable brown trout streams. The upper limiting, near lethal water temperature for brown trout (Needham 1969) is 27.2 °C, at which naturally reproducing, viable stream populations would not be maintained. Optimal temperature requirements for good growth and survival of brown trout are 12 to 19 °C (Frost and Brown 1967; Mills 1971; Brown 1973; Tebo 1975), with a temperature tolerance range of 0 to 27 °C (Maciolek and Needham 1952; Mills 1971).

Needham (1969) pointed out that both absolute temperature and thermal constancy determine habitat suitability. Streams with much shade or many cool springs have relatively constant temperatures and high rates of growth by trout. In the winter, both water temperature and available food are interrelated and limiting (Wingfield 1940). High winter mortality of brown trout is indirectly due to temperature (Maciolek and Needham 1952; Needham and Jones 1959). At temperatures below 0 °C, subsurface ice forms, and much winter mortality can be accounted for by ice scoured redds and dammed and dewatered pools (Maciolek and Needham 1952). Suffocation under snowbanks also can be a mortality factor (Needham and Jones 1959).

Dissolved oxygen requirements vary with species, age, prior acclimation temperature, water velocity, activity level, and concentration of substances in the water (McKee and Wolf 1963). As temperature increases, the dissolved oxygen saturation level in the water decreases, while the dissolved oxygen requirements for the fish increase. As a result, an increase in temperature can be detrimental to fish. Optimal oxygen levels for brown trout are not well documented, but appear to be ≥9 mg/l at temperatures ≤10 °C and ≥12 mg/l at temperatures >10 °C. Doudoroff and Shumway (1970) demonstrated that swimming speed and growth rates for salmonids declined with decreasing dissolved oxygen levels. In the summer (≥10 °C), trout generally avoid water with dissolved oxygen levels of less than 5 mg/l (May 1973).

The incipient lethal level of dissolved oxygen for adult and juvenile brown trout is approximately 3 mg/l or less, depending on environmental conditions, usually temperature (Burdick et al. 1954; Doudoroff and Shumway 1970). Although fish may survive at concentrations just above this level, they must make various physiological adaptations to accommodate survival, which may jeopardize their health (Randall and Smith 1967). Low levels of dissolved oxygen can cause reduced fecundity and prevent spawning. Large fluctuations in dissolved oxygen result in a loss of appetite and impaired growth (Doudoroff and Shumway 1970). In unpolluted trout streams, dissolved oxygen seldom falls below 5 mg/l. Insufficient dissolved oxygen is only a problem in streams with a slow current, excessive temperature, and a high biological oxygen demand or, occasionally, in streams with high groundwater seepage (Hansen 1975).

Oxygen depletion occurs in some lakes, possibly resulting in "winterkill" of trout. These lakes are usually shallow, snow covered, and contain a high volume of organic materials. Dissolved oxygen levels may become limiting with high dissolved carbon dioxide concentrations, high biochemical oxygen demand, and a low rate of primary production due to low light penetration through ice and snow cover (Needham 1969).

Brown trout occur within a pH range of 5.0 to 9.5 (Marshall and MacCrimmon 1970; Mills 1971; Heacox 1974). Optimal growth occurs at a pH of 6.8 to 7.8 (Heacox 1974). Wingfield (1940) reported faster growth and greater longevity for brown trout in alkaline water than in acidic water. The pH also may affect aquatic food resources. Food was abundant in coastal streams with a pH of 7.2 to 8.6, but limiting in high elevation Sierra streams with a pH of 5.8 to 7.1 (Needham 1969). Horton et al. (1968) substantiated the generalization that low pH (5.9 to 6.7) is correlated with slow trout growth and lack of bottom fauna, when compared to streams with a higher pH (7.4 to 8.8). Jacobsen (1977), in a controlled experiment with brown trout, found that moderate reductions in pH did not directly affect their growth rates.

A water depth ≥15 cm and a focal point velocity of <15 cm/s are recommended for optimal adult brown trout resting and feeding habitat (Wesche 1980).

Cover is recognized as one of the essential components of trout streams. Adult brown trout seek cover more than any other trout species. Boussu (1954) was able to increase the number and weight of brown trout in stream sections by adding artificial brush cover. Numbers and weight, particularly of adult trout, were decreased when brush cover and undercut banks were eliminated. Lewis (1969) reported that the amount of cover was important in determining the number of trout in sections of a Montana stream. Cover for adult brown trout consists of areas of obscured stream bottom where the velocity is low and depths are at least 15 cm. Wesche (1980) reported that, in larger streams, the abundance of brown trout ≥15 cm in length increased with depth; most were at depths ≥15 cm. In the Au Sable River, Michigan, adult brown trout preferred cover at lower water column depth to cover nearer the surface, cover with tactile stimulus, and cover with less light (DeVore and White 1978).

Escape cover is provided by overhanging and submerged vegetation; undercut banks; instream objects, such as debris piles, logs, and large rocks; and pool depth or surface turbulence. A cover area of ≥35% of the total stream area provides adequate cover for adult brown trout. The main use of summer cover is probably for predator avoidance and resting.

In winter, salmonids occupy different habitat areas than in the summer (Hartman 1963). Brown trout, along with other salmonids, show a strong hiding or cover response during winter (Hartman 1963). Winter hiding behavior in salmonids is triggered by low (4 to 8 °C) temperatures (Everest 1969). Adult brown trout tend to move into deep, low-velocity water. Bjornn (1971) reported that downstream movement of cutthroat trout during or preceding winter does not occur if sufficient winter cover is locally available. Trout move to winter cover to avoid predation, downstream displacement, physical damage from ice (Hartman 1963), and to conserve energy (Everest 1969).

Adult brown trout, except during the spawning season, occupy the same stations with very little movement to other stream sections from day to day or year to year (Schuck 1943; Allen 1951; Solomon and Templeton 1976).

Fall spawning migrations begin at water temperatures of 6 to 7 °C (Frost and Brown 1967; Mills 1971) or 6 to 12.8 °C (Hooper 1973); spawning occurs at 7 to 9 °C (Mansell 1966). In northern temperate areas, cold, well oxygenated, groundwater seepage may be important to successful spawning and incubation of brown trout, because it ensures uniform water temperatures from year to year (Benson 1953; McFadden et al. 1965). Potential spawning sites are characterized by upwelling of water through the gravel or by the presence of water currents flowing downward into the gravel (Benson 1953). Brown trout avoid areas of increased stream temperature or decreased dissolved oxygen content (Hansen 1975). Females become aware of these conditions during their movement upstream and select preferred areas for spawning (Mills 1971). Spawning sites are often located at the head of riffle areas or the tail of pools where gravel slopes gently upward (Mills 1971; Hooper 1973; Reiser and Wesche 1977), and sedimentation has less effect (Cordone and Kelly 1961).

Brown trout construct well-defined redds. Allen (1951) reported brown trout redds varying in width from <30 cm to >107 cm. Reiser and Wesche (1977) reported the deepest construction was 16 cm below the water substrate interface, whereas Frost and Brown (1967) reported that 7.62 cm (3 inches) was the usual depth. McKay (1957) reported a maximum depth of 30.5 cm.

Brown trout prefer gravel with a diameter of about 1.0 to 7 cm for spawning substrate (Stuart 1953; Frost and Brown 1967; Hooper 1973; Berg 1977; Reiser and Wesche 1977), but utilize gravel from 0.3 to 10 cm. The maximum usable gravel size is dependent on the size of the spawning female.

Water depths at redd sites ranged from 28.3 to 60.3 cm for the Yellowstone River and some of its tributaries (Berg 1977). Water depths of 45.7 cm (O'Donnell and Churchill 1943), 6.4 to 18.3 cm (Reiser and Wesche 1977), and 42.6 cm (Smith 1973) have been reported. Waters (1976) set the optimal water depth for brown trout redd construction at 24.4 to 45.7 cm, with a suitable range of 12.2 to 91.4 cm, whereas Shirvell and Dungey (1983) reported that 31.7 cm was the preferred spawning depth for brown trout. Riverine studies on maximum spawning depth selection are necessarily limited by the range of depths available with acceptable spawning gravel sizes and water velocities. Studies of other salmonid species (rainbow trout and chinook, coho, and pink salmon) indicate that depth per se beyond some minimal depth (about 15 cm for brown trout, Reiser and Wesche 1977) does not significantly affect the selection of redd sites or the survival of embryos (Chambers 1956; Andrew and Geen 1960).

Water velocities over redd sites ranged from 48.2 to 75.9 cm/s in the Yellowstone River (Berg 1977). Hooper (1973) reported a mean velocity of 46.6 cm/s, with a range of 30.5 to 76.2 cm/s, with most redds located in water velocities of 39.6 to 51.8 cm/s. Smith (1973) reported a mean velocity of 44.5 cm/s for Oregon populations of brown trout, with a range of 20.4 to 68.3 cm/s. Waters (1976) recommended 53.3 to 68.6 cm/s as the optimal water velocity range, with 15.2 to 91.4 cm/s having some suitability for spawning brown trout. Shirvell and Dungey (1983) stated that 39.4 cm/s was the mean preferred velocity for brown trout and that velocity was more important than depth as a selection criterion. Reiser and Wesche (1977) listed a velocity range of 13.7 to 45.7 cm/s for spawning brown trout. A velocity tolerance range of 15 to 90 cm/s, with an optimal range of 40 to 70 cm/s, was assumed for this model.

Embryo. The optimal temperature range for egg development, hatching success, and fry emergence was reported as 7 to 12 °C by Frost and Brown (1967), 6.6 to 12.8 °C by Markus (1962), and 5 to 13 °C for the embryo stage by Frost and Brown (1967). Embody (1934) reported 148 days from fertilization to hatching at 1.9° C and 34 days at 11.2 °C. At 13.9 °C, it took between 30 and 33 days for egg incubation (Needham 1969). Behnke (pers. comm.) reported that brown trout embryos in many areas incubate for many weeks at 1 to 2 °C. In the Firehole River, most eggs were dead or infertile in the redds with geothermally heated waters (13.3 °C) (Kaya 1977), but this may have been due to inviable milt from a too high water temperature at fertilization. Brown trout embryos overwinter in gravel that sometimes has anchor ice, with fry emergence in early spring. Therefore, optimal incubation temperatures are assumed to be 2 to 13 °C, with a tolerance range of 0 to 15 °C.

The suitability of the gravel environment for hatching and survival of salmonid embryos and fry depends on both water velocity and dissolved oxygen concentration. The embryo optima for velocity and oxygen are assumed to be the same as those described for redd site selection by spawning adults. Sedimentation alters gravel permeability, reduces intergravel water flows, and decreases the dissolved oxygen supply to the embryos (Ringler and Hall 1975; Tebo 1975). Koski (1966) reported entombment of preemergent salmonids by ≥15% fines on the stream substrate. Wickett (1962) and McNeil (1966) found that high survival of pink salmon fry was correlated with high gravel permeability, e.g., redds with medium sized gravel and ≤5% fines. Survival was low as fines approached and exceeded 15%. In a 30% sand to 70% gravel mixture, only 28% of implanted steelhead embryos hatched; of the 28% that hatched, only 74% emerged (Bjornn 1969). Optimal spawning gravel conditions for brown trout are assumed to be ≤5% fines; ≥30% fines are assumed to result in low survival of embryos and emerging fry. Embody (1934) stated that brown trout egg development ceased at dissolved carbon dioxide concentrations >22 ppm and dissolved oxgyen levels <4.5 ppm.

Fry. Dispersal of fry takes place immediately after emergence (Mortensen 1977b). Within a week, fry are distributed in suitable habitat. Brown trout fry are aggressive from the first day of emergence, and territories are the rule in running waters (Kalleberg 1958; Mills 1971). Mortality is very high for the first few months after fry emergence (Allen 1951), due to density-dependent factors of intraspecific territorial behavior (Mortensen 1977b). Survival from fry to yearling stages has been estimated at 2.7% (Mills 1971).

The optimal temperature range for free-feeding brown trout fry was reported as 7 to 12 °C by Frost and Brown (1967), with a temperature optimum for the onset of feeding of 10 to 12 °C. The reported overall temperature optimum was later adjusted to 7 to 15 °C by Brown (1973). Once feeding started, growth was best at 12.8 °C (Markus 1962). Heavy fry mortality occurred at temperatures of less than 4.5 °C after emergence from the gravel. An optimal temperature range of 6.7 to 12.8 °C was proposed by Markus (1962). The mean upper lethal temperature for fry has been reported as 25.46 °C (Spaas 1960). Fry asphyxiated quickly at 10.8 °C with 2.3 ppm dissolved oxygen and 14 ppm dissolved carbon dioxide (Burdick et al. 1954). The optimal temperature range of 7 to 15 °C (reported by Brown 1973) is assumed to be a reasonable estimate for brown trout fry, with an overall temperature tolerance of 5 to 25.5 °C.

Dissolved oxygen requirements for brown trout fry and juveniles are not well documented. We recommend using the data for adults for these life stages; i.e., a minimal to optimal range of >3 to ≥7 ppm at temperatures ≤15 °C and a minimal to optimal range of >5 to ≥9 ppm at temperatures >15 °C.

Bohlin (1977) found brown trout fry in areas without older trout. These areas often were shallow, with a smooth bottom and banks. Fry prefer pools and rocky substrates, but often are excluded from these areas by older and larger juvenile trout, which also prefer these areas. Jones (1975) consistently found brown trout fry at the edge of riffles. Lindroth (1955) found brown trout fry at the margins of a river, in sections with water depths of 20 to 30 cm. Fry were rarely found in still muddy backwaters or in areas with a small gravel substrate.

Cover is essential to brown trout fry survival. The clearing out of weeds, branches, twigs, and larger stones from a streambed resulted in high fry mortality (Mortensen 1977a). The physically more complex streambed provided greater cover, permitting a higher fry density. Brown trout fry prefer a rocky substrate. During the winter months, brown trout fry bury themselves in the stony substrate of the stream (Hartman 1963). Everest (1969) found rainbow trout fry 15 to 30 cm deep in the gravel during the winter. A substrate particle size of 10 to 40 cm offers excellent escape and winter cover for trout fry and smaller juveniles (Hartman 1965; Everest 1969).

Juvenile. Tebo (1975) set 19 °C for maximum growth during the summer for juvenile brown trout. Good growth occurred between 7 and 19 °C, with optimal growth at 12 °C (Frost and Brown 1967; Brown 1973). Juveniles showed a preference for 17.6 °C in a laboratory experiment (Coutant 1977). The mean upper short term lethal temperature for stream-resident brown trout juveniles was given as 29 °C (Spaas 1960). The temperature optima for brown trout juveniles is assumed to be 7 to 19 °C, with a range of 0 to 27 °C, similar to that of adults.

Doudoroff and Shumway (1970) reported that deaths of juveniles first occurred at dissolved oxygen concentrations of 1.6 to 2.8 ppm with temperatures of 9 to 21 °C. Half were dead at 1.5 to 2.5 ppm, and 100% were dead at 1.3 to 2.3 ppm dissolved oxygen. Juvenile brown trout were asphyxiated in 1.5 minutes at 19.1 °C, 1.94 ppm dissolved oxygen, and 39 ppm dissolved carbon dioxide. Burdick et al. (1954) stated that mean lethal dissolved oxygen levels ranged from 1.42 ppm at 9.4 °C to 2.53 ppm at 20.5 °C. Dissolved oxygen levels of ≥3.0 ppm in winter and ≥5.0 ppm in summer, with a summer optimum of ≥7.0 ppm at temperatures <15 °C and ≥9.0 ppm at temperatures ≥15.0 °C, are assumed to be optimal.

Juvenile brown trout occur at shallower depths and lower velocities than adults. Both fry and juvenile brown trout prefer velocities of <15 cm/s (Wesche 1980). As growth progresses, depths ≥15 cm are preferred (Wesche 1980). The highest densities of juveniles were in sections containing both pools and riffles (Jones 1975; Bohlin 1978).

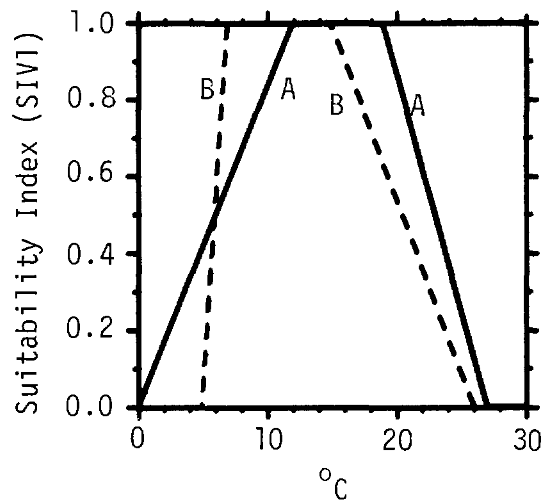
The pH range for juvenile brown trout is assumed to be similar to that for adults (5.0 to 9.5, with an optimal range of 6.7 to 7.8).

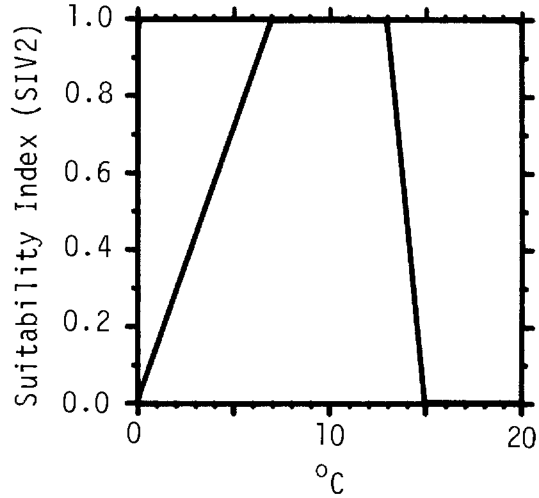
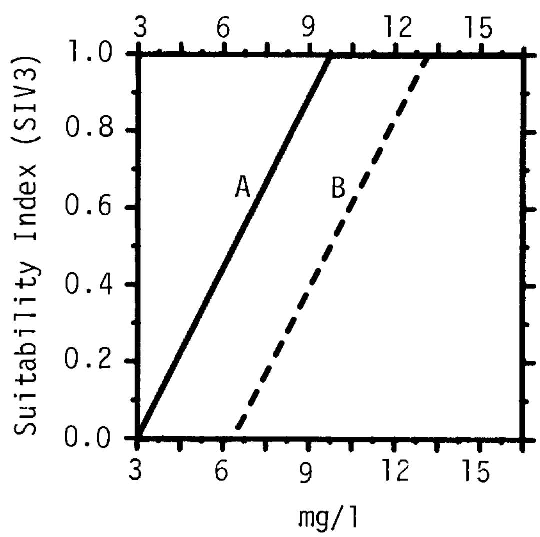
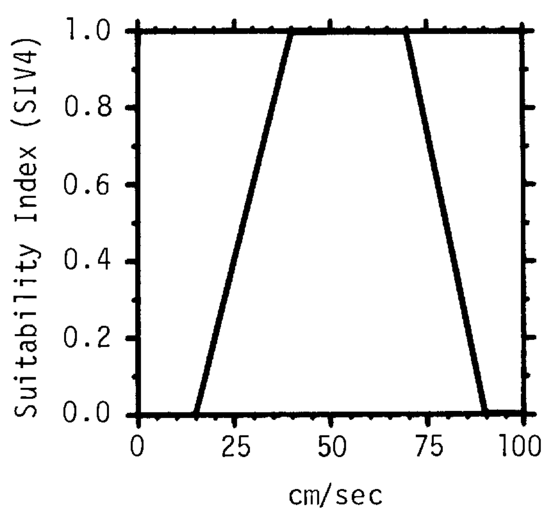
Because of their small size, an area ≥15% of the total stream area is assumed to provide adequate cover for brown trout fry and juveniles.

Suitability Index (SI) Graphs for Model Variables

This section contains suitability index graphs for 18 model variables. The graphs represent the authors' best estimate of suitability for the various levels of each variable based on data compiled from a comprehensive review of the literature. The graphs have been reviewed by biologists familiar with the ecology of the species, but responsibility for the accuracy of the graphs rests with the authors. The user is encouraged to modify the shape of the graphs when existing regional information indicates that the suitability relationship is different from that illustrated for any variable.

The habitat measurements and SI graph construction are based on the premise that extreme, rather than average, values of a variable most often limit the carrying capacity of a habitat. Thus, extreme conditions, such as maximum temperatures and minimum dissolved oxygen levels, often are used in the graphs to derive the SI's for the model. The letters R and L in the habitat column identify variables used to evaluate riverine (R) or lacustrine (L) habitats.

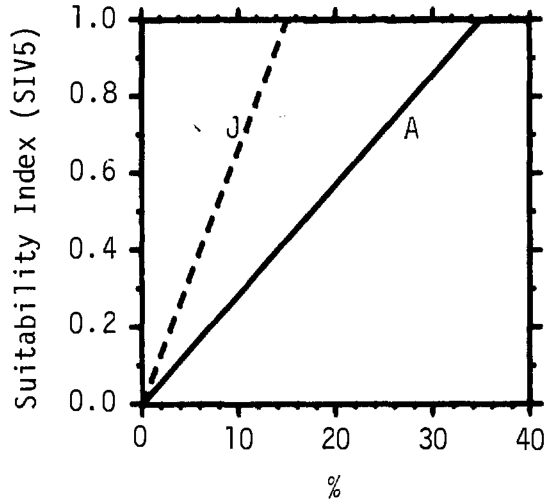
Habitat	Variable		Suitability graph
R,L	V_1	Maximum water temperature (°C) during the warmest period of the year (adult, juvenile, and fry). For lacustrine habitats, use the temperature strata nearest to optimum in dissolved oxygen zones >3 mg/l. A = adults and juveniles B = fry	

R	V_2	Maximum water temperature (°C) during embryo development.	
R,L	V_3	Minimum dissolved oxygen (mg/l) during the late growing season, low-water period and during embryo development (adult, juvenile, fry, and embryo). For lacustrine habitats, use the dissolved oxygen readings in temperature zones nearest to optimum where dissolved oxygen is >3 mg/l. A = ≤10 °C B = >10 °C	
R	V_4	Average velocity (cm/s) over spawning areas during spawning and embryo development.	

R V_5

Percent cover during the late growing season, low-water period at depths ≥15 cm and near bottom velocities <15 cm/s.

J = juveniles
A = adults



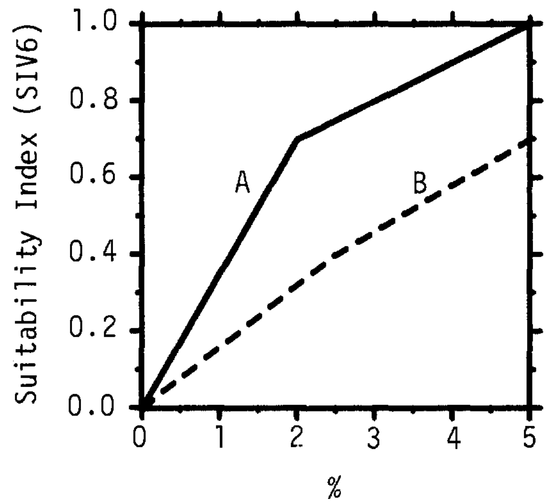
R V_6

Percent of total study area consisting of two spawning gravel size classes (A and B). Measure gravel sizes of 0.3 to 10 cm in areas ≥0.5 m^2 and at depths ≥15 cm only.

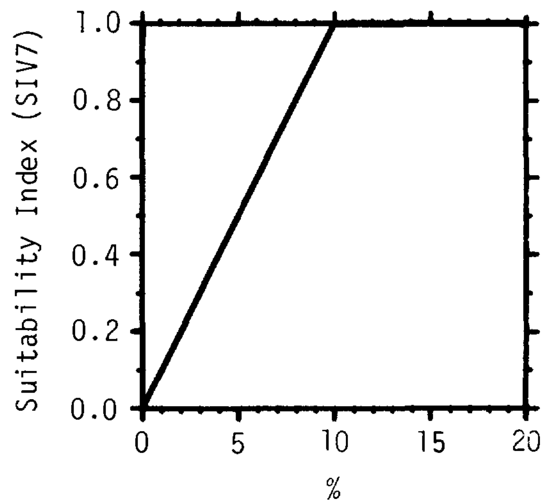
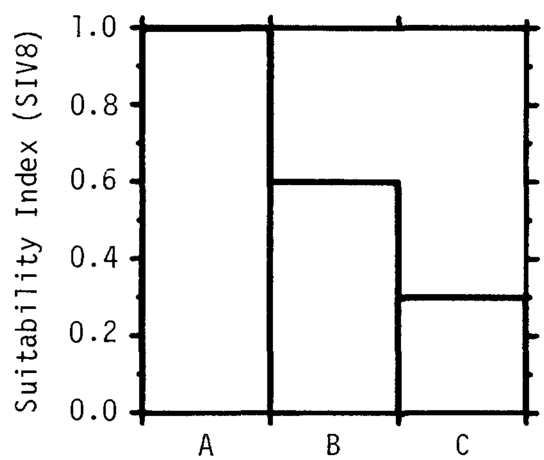
Class A = 1 to 7 cm
Class B = 0.3 to <1 and >7-10 cm

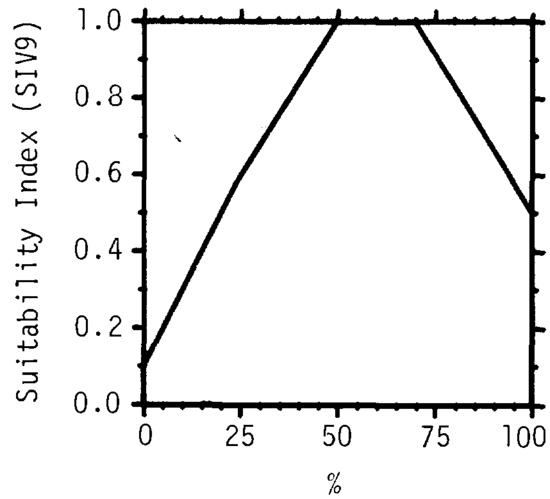
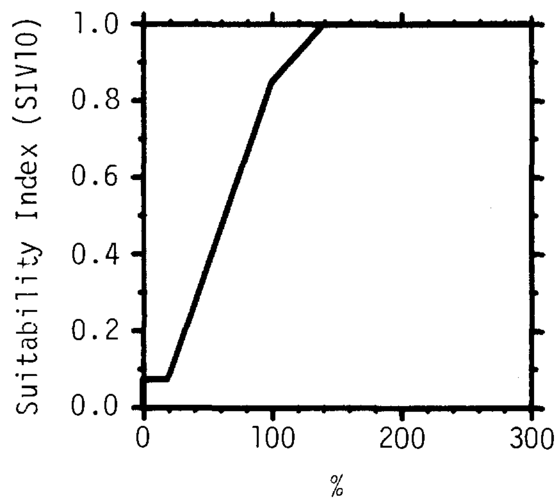
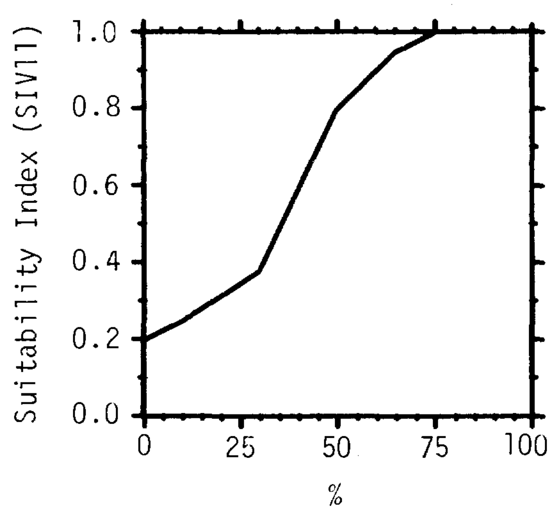
To obtain an SI score, use the percent of class A gravel % first. If class A area is ≥5%, then V_6 = class

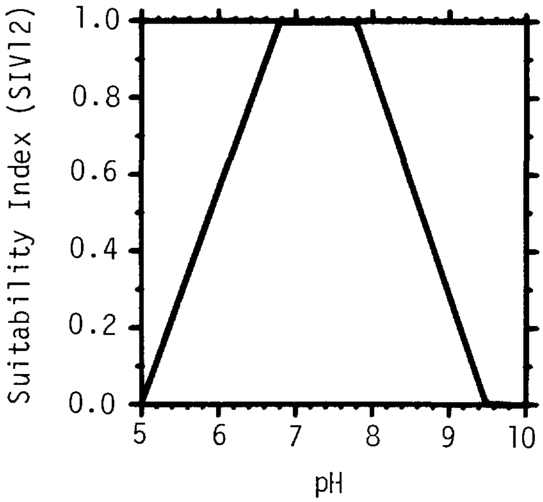
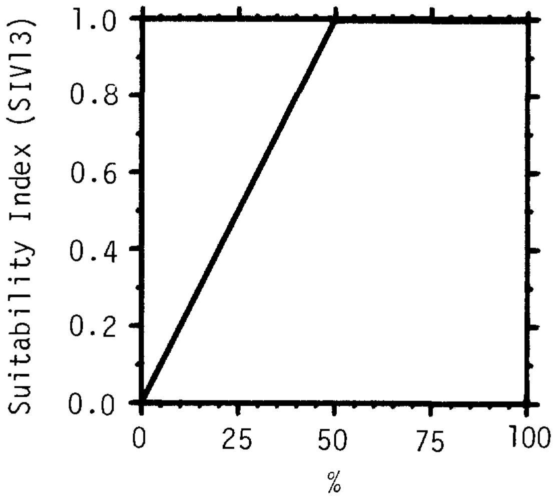
A SI. If class A is <5%, use class B to complete the sample or come as close to completing it as possible. If a combined sample (class A and B) is used, derive a weighted average SI score as follows:



$$V_6 \text{ SI} = \frac{\text{SIA } (\% \times 100) + \text{SIB } (\% \times 100)}{5}$$

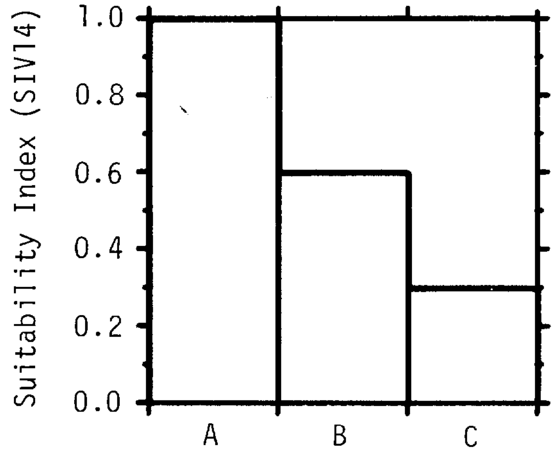
R	V_7	Percent of substrate as size class (10 to 40 cm) used for winter and escape cover by fry and small juveniles.	
R (Optional)	V_8	Dominant (≥50%) substrate type in riffle-run areas for food production. A) Rubble or small boulders, or aquatic vegetation in spring areas, dominant; limited amounts of gravel, large boulders, or bedrock. B) Rubble, gravel, boulders, and fines occur in approximately equal amounts or rubble-large gravel mixtures are dominant. Aquatic vegetation may or may not be present. C) Fines, bedrock, small gravel, or large boulders are dominant. Rubble and small boulders are insignificant (≥25%).	

R	V_9	Percent pools during the late growing season, low-water period.	
R (Optional)	V_{10}	Average percent vegetation (trees, shrubs, and grasses-forbs) along the streambank during the summer for allochthonous input. Vegetation Index = 2 (% shrubs) + 1.5 (% grasses) + (% trees) + 0 (% bare ground). (For unproductive streams ≤15 m wide)	
R (Optional)	V_{11}	Average percent rooted vegetation and stable rocky ground cover along the streambank during the summer (erosion control).	

R,L	V_{12}	Annual maximal or minimal pH. Use the measurement with the lowest SI. For lacustrine habitats, measure pH in the zone with the best combination of dissolved oxygen and temperature.	
R	V_{13}	Average annual base flow regime during the late summer or winter low-flow period as a percentage of the average annual daily flow (cfs). For embryo and fry habitat suitability, use the lowest flow that occurs during the intergravel occupation period, as a percentage of the average flow during spawning.	

R V₁₄ Pool class rating during the late growing season, low-flow period. The rating is based on the % of the area that contains pools of the three classes described below:

A) ≥30% of the area is composed of 1st-class pools.
B) ≥10% but <30% of the area is 1st-class pools or ≥50% is 2nd-class pools.
C) <10% of the area is 1st-class pools and <50% is 2nd-class pools.

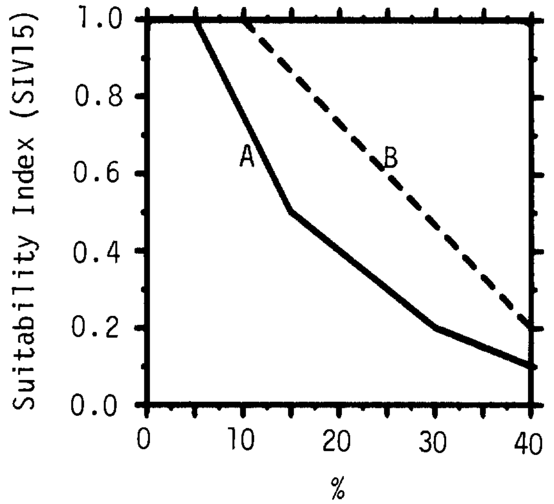
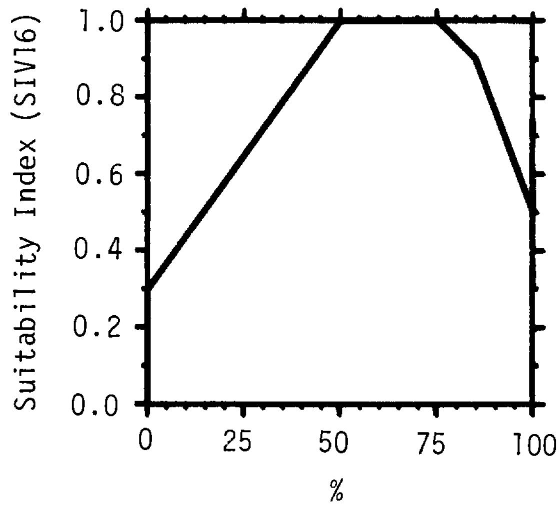
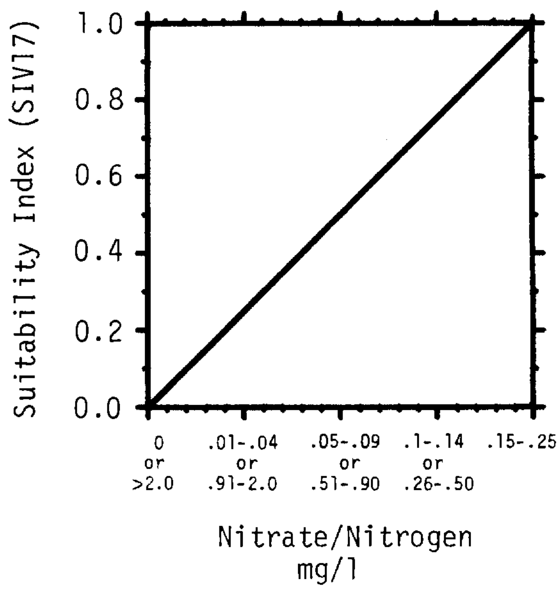


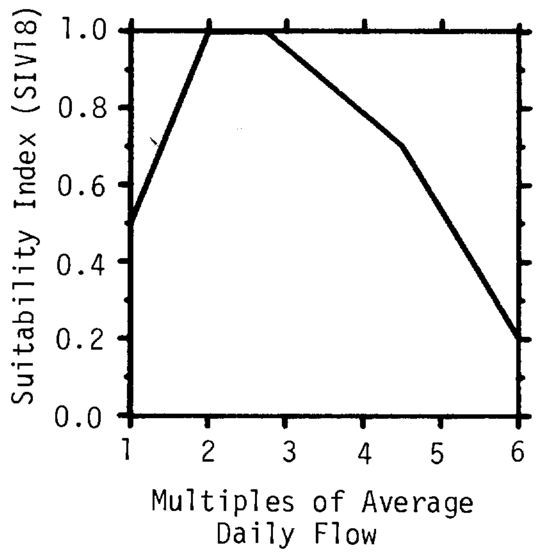
(See pool class descriptions below)

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

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

- Third-class pool: Small or shallow or both. Pool depth and size are sufficient to provide a low velocity resting area for adult trout. Cover, if present, is in the form of shade, surface turbulence, or very limited structures. Typical third-class pools are wide, shallow, reduced velocity areas of streams or small eddies behind boulders. Virtually the entire bottom area of the pool is discernible.

R	V_{15}	Percent fines (<3 mm) in riffle-run and spawning areas during average summer flows. A = spawning B = riffle-run	
R (Optional)	V_{16}	Percent of stream area shaded between 1000 and 1400 hr (for streams ≤50 m wide). Do not use for cold (<18 °C), unproductive streams.	
R (Optional)	V_{17}	Levels of late summer nitrate-nitrogen in mg/l.	

R	V_{18}	Average annual peak flow as a multiple of the average annual daily flow. For embryo and fry habitat suitability, use the average and highest flows that occur from time of egg deposition until two weeks after fry emergence.	

Data sources and the assumptions used to construct the suitability index graphs for the brown trout HSI models are presented in Table 1.

Table 1. Data sources for brown trout suitability indices.

Variable and source[a]		Assumption
V_1	Maciolek and Needham 1952 Spaas 1960 Frost and Brown 1967 Needham 1969 Mills 1971 Brown 1973	Average maximum daily water temperatures have a greater effect on trout growth and survival than minimum temperatures. The temperature that supports the greatest growth and survival is optimal.
V_2	Embody 1934 Markus 1962 Frost and Brown 1967 Needham 1969 Ringler and Hall 1975	The average maximum daily water temperature during the embryo development period that is related to the highest survival of embryos is optimal. Temperatures that reduce embryo survival are suboptimal.
V_3	Burdick et al. 1954 McKee and Wolf 1963 Doudoroff and Shumway 1970 May 1973 Ringler and Hall 1975	The average minimum daily dissolved oxygen level during embryo development and the late growing season that is related to the greatest growth and survival of brown trout embryos is optimal. Dissolved oxygen concentrations that reduce survival and growth are suboptimal.
V_4	Hooper 1973 Smith 1973 Waters 1976 Berg 1977 Reiser and Wesche 1977 Shirvell and Dungey 1983	The average velocities over spawning areas affect the suitability with which dissolved oxygen is carried to, and waste products are carried away from, the developing embryos. Average velocities that result in the highest survival of embryos are optimal. Velocities that result in reduced survival are suboptimal.

Table 1. (Continued)

Variable and source[a]		Assumption
V_5	Hartman 1963 Everest 1969 Lewis 1969 Bjornn 1971 Mortensen 1977 Wesche 1980	Trout standing crops are correlated with the amount of usable cover. Usable cover is associated with water ≥15 cm deep and velocities ≤15 cm/s. These conditions are associated more with pool than with riffle conditions. The best ratio of habitat conditions is approximately 60% pool area to 40% riffle area. Not all of the area of a pool provides usable cover. Thus, it is assumed that optimal cover conditions for trout streams require <50% of the total stream area.
V_6	Allen 1951 Stuart 1953 Frost and Brown 1967 Hooper 1973 Berg 1977 Reiser and Wesche 1977	The average size of spawning gravel that is correlated with the best water exchange rates, proper redd construction, and highest fry survival is assumed to be optimal. The percent total spawning area needed to support a good non-anadromous trout population was calculated from the following assumptions: 1. Excellent riverine trout habitat supports about 500 kg/ha. 2. Spawners compose about 80% of the weight of the population. 500 kg x 80% = 400 kg of spawners. 3. Brown trout adults each average about 0.2 kg. $\frac{400\ \text{kg}}{0.2\ \text{kg}}$ = 2,000 adult spawners/ha 4. There are two adults per redd. $\frac{2{,}000}{2}$ = 1,000 pairs

Table 1. (Continued)

Variable and source[a]		Assumption
		5. Each redd covers ≥0.5 m². $1,000 \times 0.5 = 500$ m²/ha 6. There are 10,000 m² per hectare. $\frac{500}{10,000} = 5\%$ of total area
V_7	Hartman 1965 Everest 1969	The substrate size range selected for escape and winter cover by trout fry and small juveniles is assumed to be optimal.
V_8	Hynes 1970	The dominant substrate type containing the greatest number of aquatic insects is assumed to be optimal for insect production.
V_9	Estimated by authors	The percent pools during late summer low flows that is associated with the greatest trout abundance is optimal.
V_{10}	Idyll 1942 Chapman 1966 Hunt 1971	The average percent vegetation along the streambank is related to the amount of allochthonous materials deposited annually in the stream. Shrubs are the best source of allochthanous materials, followed by grasses and forbs, and then trees. The vegetation index is a reasonable approximation of optimal and suboptimal conditions for most trout streamside vegetation cover conditions.
V_{11}	Oregon/Washington Interagency Wildlife Committee 1979	The average percent rooted vegetation and rocky ground cover that provides adequate erosion control to the stream is optimal.
V_{12}	Heacox 1974 Marshall and MacCrimmon 1970 Mills 1971	The average annual maximal or minimal pH levels related to high survival of trout are optimal.

Table 1. (Concluded)

Variable and source[a]		Assumption
V_{13}	Tennent 1976 Binns and Eiserman 1979 Wesche 1980	Flow variations affect the amount and quality of pools, instream cover, and water quality. Average annual base flows associated with the highest standing crops are optimal.
V_{14}	Lewis 1969	Pool classes associated with the highest standing crops of trout are optimal.
V_{15}	Cordone and Kelly 1961 Koski 1966 McNeil 1966 Bjornn 1969 Tebo 1975 Crouse et al. 1981	The percent fines associated with the highest standing crops of food organisms, embryos, and fry in each designated area are optimal.
V_{16}	Brocksen et al. 1968 Oregon/Washington Interagency Wildlife Committee 1979 Murphy et al. 1981	The percent of shaded stream area during midday that is associated with optimal water temperatures and photosynthesis rates is optimal.[b]
V_{17}	Binns 1979	The levels of late summer nitrate-nitrogen in the water correlated with the highest standing crops of trout are optimum.
V_{18}	Sheridan and McNeil 1960 Andrew and Geen 1960 Lister and Walker 1966 Nehring and Anderson 1982-83	Peak flows help cleanse the streams of silt and debris, but too-high flows cause bank cutting, siltation, scouring of periphyton and insects, and can cause loss of pool area, embryos, and intergravel fishes due to excessive substrate movement.

[a]References may include data from studies on related salmonid species. This information has been selectively used to supplement, verify, or fill data gaps on some little known habitat requirements of brown trout.

[b]Shading requirements vary from site to site. Low elevations and warmer climates require abundant shading to maintain cool waters. At higher elevations and cooler climates, the absence of shading may be beneficial because it results in higher photosynthetic rates and warming of water towards optimal temperatures.

HABITAT SUITABILITY INDEX (HSI) MODELS

Model Applicability

Geographic area. The following models are applicable over the entire North American range of brown trout.

Season. The model rates the freshwater habitat of brown trout for all seasons of the year. However, it is recommended that the model variables be measured at the appropriate times indicated for each life stage.

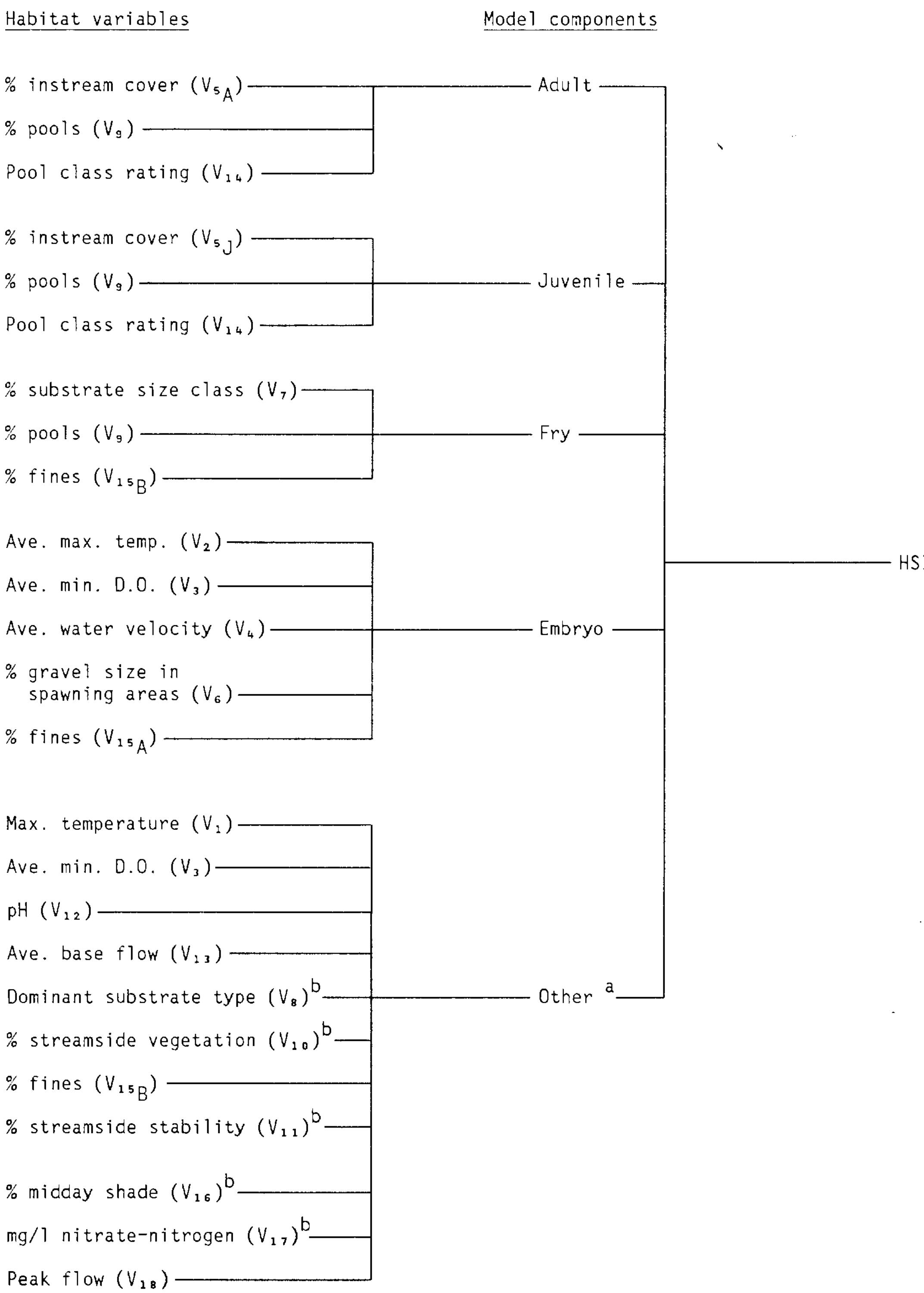
Cover types. The models are applicable to freshwater riverine or lacustrine habitats.

Minimum habitat area. Minimum habitat area is the minimum area of contiguous habitat that is required for a species to live and reproduce. Because trout may live their entire lives within a few meters of river, or may move considerable distances to spawn or locate suitable summer or winter rearing habitat, no attempt was made to define a minimum habitat size for the species except that a spawning redd requires an average gravel area ≥0.5 m^2.

Verification level. The present acceptable level of performance for this brown trout model is for it to produce an index between 0 and 1 for each variable that the authors and other biologists familiar with brown trout ecology believe is positively correlated with the suitability to brown trout production. Model verification consisted of checking the model outputs from improvised data sets developed by the authors and reviews by authorities on brown trout ecology.

Model Description

The HSI model consists of five components: Adult (C_A), Juvenile (C_J), Fry (C_F), Embryo (C_E), and Other (C_O). Each life stage component contains variables specifically related to that component. Component C_O contains variables related to water quality and food supply that affect all life stages of brown trout. Figure 1 depicts the theoretical relationships among model variables, components, and the HSI for the brown trout model.



[a]Variables that affect all life stages.

[b]Optional variables.

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

Adult component. Variable V_5, percent instream cover, is included because standing crops of adult trout are correlated with the amount of cover available. Percent pools (V_9) is included because pools provide cover and resting areas for adult trout. Variable V_9 also quantifies the amount of pool habitat that is needed. Variable V_{14}, pool class rating, is included because pools differ in the amount and quality of escape cover, winter cover, and resting area that they provide.

Juvenile component. Variables V_5, percent instream cover; V_9, percent pools; and V_{14}, pool class rating are included in the juvenile component for the same reasons listed above for the adult component. Juvenile brown trout use these essential stream features for escape cover, winter cover, and resting areas.

Fry component. Variable V_7, percent substrate size class, is included because trout fry utilize substrate as escape and winter cover. Variable V_9, percent pools, is included because fry use the shallower, slow water areas of pools and stream edges as resting and feeding stations. Variable V_{15}, percent riffle fines, is included because the percent fines affects the ability of the fry to utilize the rubble substrate for cover.

Embryo component. It is assumed that habitat suitability for trout embryos depends primarily on average maximum water temperature, V_2; average minimum dissolved oxygen, V_3; average water velocity, V_4; gravel size in spawning areas, V_6; and percent fines, V_{15}. Water velocity, V_4; gravel size, V_7; and percent fines, V_{15}, are interrelated factors that affect the transport of dissolved oxygen to the embryo and the removal of metabolic waste products from the embryo. In addition, the presence of too many fines in the redds blocks movement of the fry from the incubating gravels to the stream. Too-low base flows (V_{13}) and too-high peak flows (V_{18}) during embryo stage can result in high embryo mortality.

Other component. This component contains model variables for water quality and food supply that affect all life stages. The water quality component contains four variables: maximum temperature, V_1; average minimum dissolved oxygen, V_3; pH, V_{12}; average base flow, V_{13}; and peak flows, V_{18}. All five variables affect the growth and survival of all life stages except the embryo, whose water quality requirements are included with the embryo component. In addition, stream flows fluctuate on a seasonal cycle. A correlation exists between the average annual daily streamflow and the annual peak and base flow periods in maintaining desirable stream habitat features for all life stages. Variables V_{13} and V_{18} are included to quantify the relationship between annual water flow fluctuations and trout habitat suitability.

The food supply component contains five variables: dominant substrate type, V_8; percent streamside vegetation, V_{10}; percent riffle fines, V_{15}; nitrate-nitrogen, V_{17}; and peak flows, V_{18}. Dominant substrate type, V_8, is included because the abundance of aquatic insects, an important food item for brown trout, is correlated with substrate type. Variable V_{15}, percent fines in riffle areas, is included because the presence of excessive fines in riffle areas reduces the production of aquatic insects. Variable V_{17}, nitrate-nitrogen, is an important component of autotrophic production in aquatic habitats. Variable V_{18}, peak flows, can result in excessive loss of periphyton and invertebrate food items by scouring the substrate.

Variables V_8, V_{10}, V_{11}, V_{16}, and V_{17} are optional variables to be used only when needed and appropriate. These variables can be used selectively when stream food productivity, water quality, or riparian problems need to be evaluated.

Two HSI models are presented based on habitat variables data and SI scores by life stage (Table 2). The first model uses a simple limiting factor theory. The second model uses a partial compensatory limiting factor theory.

Model 1, Limiting Factor

The limiting factor model assumes that each variable in the model can significantly affect the ability of the habitat to produce brown trout; that high SI values in some variables cannot compensate for low SI values in other variables; and that, hence, the life stage or species HSI cannot exceed the lowest SI value for any pertinent variable. The limiting factor model method would yield a brown trout HSI of 0.6 for adults and juveniles, 0.7 for embryos and fry, and an HSI of 0.6 for the species using the data and SI values shown in Table 2.

Model 2, Compensatory Limiting Factor

This model also assumes that each variable can significantly affect the ability of the habitat to produce brown trout. The model also assumes, however, that low values of some dependent variables can be partially compensated by high values in other variables of the set. A variable SI ≤ 0.3, however, cannot be compensated.

Examples:

1. Adult and juvenile components. It is assumed that the variables percent pools (V_9) and pool class (V_{14}) are compensatory in their effect on brown trout habitat suitability.

Table 2. Habitat variable measurement data, SI scores, and model component HSI scores by life stage for brown trout.[a]

Variables		Adult Data	Adult SI	Embryo Data	Embryo SI	Fry Data	Fry SI	Juvenile Data	Juvenile SI
V_1	Max. temperature	15	1.0			15	1.0	15	1.0
V_2	Max. temperature (embryo)			12	1.0				
V_3	Min. D.O.	8	0.7	12	1.0	8	0.7	8	0.7
V_4	Av. vel. (embryo)			45	1.0				
V_5	% cover	29	0.8			29	1.0	29	1.0
V_6	% sp. gravel			A+B	0.7				
V_7	% sub. size					15	1.0		
V_8	Dom. sub.[b]	19	1.0			A	1.0	A	1.0
V_9	% pools	50	1.0			50	1.0	50	1.0
V_{10}	Veg. index[b]	200	1.0			200	1.0	200	1.0
V_{11}	% stability[b]	50	0.8			50	0.8	50	0.8
V_{12}	Max-min pH	7	1.0			7	1.0	7	1.0
V_{13}	Base flow	28	0.8	28	0.8	28	0.8	28	0.8
V_{14}	Pool class	B	0.6					B	0.6
V_{15}	% fines	8	1.0	10	0.7	8	1.0	8	1.0
V_{16}	% shade	50	1.0	50	1.0	50	1.0	50	1.0
V_{17}	Nitrate-nit.[b]	0.1	0.7			0.1	0.7	0.1	0.7
V_{18}	Peak flows	4	0.8	2	1.0	4	0.8	4	0.8
Component HSI			0.6		0.7		0.7		0.6
Species HSI			0.6						

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

[b]Optional brown trout variables to be used when deemed necessary by the user.

$$\text{Lowest SI} = \frac{0.6(V_{14}) + 1.0(V_9)}{2} = 0.80$$

The pool class variable (V_9) SI for both adults and juveniles would increase from 0.6 to 0.8. The adult and juvenile component SI scores would now be dissolved oxygen (V_3) limited so that adult and juvenile component SI scores would now be 0.7.

2. Embryo component. It is assumed that the variables average water column velocity (V_4), percent gravel size (V_6), and percent fines (V_{15}) are dependent, compensatory variables.

$$\text{Lowest SI} = \frac{1.0(V_4) + 0.7(V_6) + 0.7(V_{15})}{3} = 0.8$$

The SI for variables V_6 and V_{15} would increase from 0.7 to 0.8 and the embryo component SI would now be base flow (V_{13}) limited. The embryo component SI would now be 0.8.

The species HSI would increase from 0.6 to 0.7, the lowest SI score for any model component after compensation.

Model Use and Interpretation

The primary purposes of the aquatic HSI model are to provide:

(1) reliable information on the known habitat requirements of a species by life stage;

(2) an extensive list of specific habitat variables for a species along with brief instructions on when and where to measure them;

(3) an objective method of estimating how well specific habitat variables meet the habitat requirements of a species by life stage; and

(4) an objective, measurable basis for predicting or documenting project impacts, guiding habitat management decisions, and habitat improvement procedures.

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

In practice, the habitat variables are measured in the selected study area. The data collected for each variable are compiled and analyzed, SI scores derived by use of the SI graphs provided, and the information arranged in a matrix similar to Table 1. This will provide quantified information on the relative condition of the habitat from which habitat management decisions can be made. For project impact analysis purposes, habitat variable measurements should be done prior to project initiation to document existing habitat conditions, and as a basis for projecting probable project impacts. Such information is extremely valuable in negotiating project design features and conditions and timing of construction phases. The habitat variables are measured again after construction is completed to document specific changes in suitability and to guide postproject mitigation and habitat enhancement efforts.

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

We believe that the data base and SI graphs are reasonably accurate. We have done a thorough job of reviewing the available data and the model has received excellent peer review. The individual variable SI scores can be reasonably relied on to indicate the relative suitability of each variable in meeting the habitat requirements of the species if the habitat measurements were correctly taken.

We recognize the theoretical correlation between habitat condition and stock density, but past attempts to produce HSI model equations that yielded life stage or species HSI scores correlated with stock density have not been successful. We lack sufficient understanding of the interactions among the various habitat variables to accurately weigh these variables in model equations. Tests of the cutthroat trout model HSI against cutthroat trout stocks in Yellowstone Park streams yielded a correlation coefficient of 0.37. Goertler et al. (1985) tested an early brown trout HSI model score against brown trout stocks in 10 Wyoming streams. They found that using all of the brown trout variables in model equations only accounted for 10 percent of the variation in brown trout population size in the test streams. They produced a three variable model that accounted for 63 percent of the variation in brown trout standing stocks in the Wyoming test streams. Models that estimate standing stocks of fishes are useful management tools. We have included some of these in the brown trout model section. Such models typically use a minimum number of variables identified by regression analysis that account for significant percentages of variability in stock size. Models with a limited number of variables have limited usefulness in evaluating a variety of possible project impacts. If the user wishes to estimate standing stocks of brown trout, use the models included for that purpose.

However, the brown trout HSI scores are not useful in predicting standing stock size. They are models that offer the user a maximum number of habitat variables for a species, and are useful in providing an objective method of assessing a wide variety of project impacts, and in guiding management decisions. We advise the use of the individual variable SI scores rather than life stage or species HSI scores as the most reliable guides in protecting, managing, and enhancing brown trout habitat.

ADDITIONAL HABITAT STOCK DENSITY MODELS

To obtain HSI scores from these models divide the model output by regional optimal values as follows:

$$HSI = \frac{\text{Model output density/ha}}{\text{Regional optimal density/ha}}$$

Model 1

A low effort system for predicting habitat suitability of planned cool-water and cold-water reservoirs for individual fish species developed by McConnell et al. (1982) is available.

Model 2

Baxter et al. (1985) submitted a completion report to the Wyoming Game and Fish Department that estimates trout density per hectare in small to medium sized reservoirs (50-890 ha). The model uses total dissolved solids (TDS) and maximum depth (Max. Depth) as variables.

$$\text{Log}_e \text{ Density} = 4.002 + 0.004 \text{ (TDS)} - 0.024 \text{ (Max. Depth)}$$

Model 3

A riverine trout habitat model developed by Binns and Eiserman (1979) and Binns (1979, 1982) is available.

$$HSI = \frac{\text{model output of kg/ha}}{\text{regional optimal kg/ha}}$$

Model 4

Goertler et al. (1985) developed a three-variable model to predict brown trout population size. The model uses:

$$\text{Brown trout (kg/ha)} = -104.7 + 65.1\ \text{TCRL} + 29.6\ \text{RCSVEL} + 186.8V_{14}$$

where

TCRL = trout cover rating

RCSVEL = rated cross-sectional velocity

V_{14} = base flow

INSTREAM FLOW INCREMENTAL METHODOLOGY (IFIM)

The Instream Flow Incremental Methodology (IFIM) is 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; to evaluate habitat improvement projects, mitigation proposals, and fish stocking programs; and to assist in negotiating releases from existing water storage projects. The IFIM has a modular design, which 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 (SI curves) entered into the model. The output can be used for several IFIM habitat display and interpretation techniques, including the following three:

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).

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

Suitability Index (SI) curves used in PHABSIM describe the instream suitability of the habitat variables most closely related to stream hydraulics and channel structure (e.g., velocity, depth, substrate, and cover) for each major activity or 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 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 from which the environmental bias has been 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 the quality or accuracy of curves differ among the four categories.

Availability of Graphs for Use in IFIM

All curves recommended for an IFIM analysis of brown trout habitat are category one curves (Table 3) and supersede curves for brown trout in Bovee (1978). Investigators are asked to review the curves (Figures 2 to 5) and modify them, if necessary, before use.

Description of Data and Information Sources Used to Develop SI Curves for IFIM

SI curves for brown trout fry and adult velocity, depth, and substrate utilization were derived from data collected by Gosse et al. (1977) and Gosse (1981). During the summer of 1977, Gosse et al. (1977), using SCUBA, observed brown trout in the Logan River system of northern Utah. At each location where a fish was observed, the mean column velocity (at 0.6 depth), fish nose velocity (at the location of the fish), water column depth, and substrate type (<0.3 cm = silt, 0.3 to 8.0 cm = gravel, 8.0 to 30.0 cm = rubble, >30.0 cm = rock) were measured. Young-of-year were defined as individuals less than 5.7 inches in length, juveniles as ranging from 5.7 to 9.3 inches, and adults as longer than 9.3 inches. No description of the study site was available. Velocities available to the fish ranged from 0 to 5 ft/s, depths ranged from 0 to 13 ft, and substrate types ranged from silt to boulder.

From August 1977 through March 1978 and from June 1978 through February 1979, Gosse (1981) used SCUBA to observe brown trout in the canyons of the Logan and Provo River systems of northern Utah. The same information collected during the previous study was recorded at each fish location, but this time the data were grouped according to fish activity as follows: resting (fish stationary, no swimming motion, fish usually lying on the bottom), feeding (fish observed consuming particles), stationary swimming (fish stationary, actively swimming against a current), and random swimming (fish not swimming against a current, no net change in fish location). SI curves were developed only for those sets of data where the sample size was greater than 190. Gosse did not delineate size classes, but grouped fish into age classes of age 0, juvenile, and adult. Little information was available about the study site. The Logan River discharge was reported as averaging 275 cfs, elevations ranged

Table 3. Availability of SI curves for IFIM analyses of brown trout habitat.

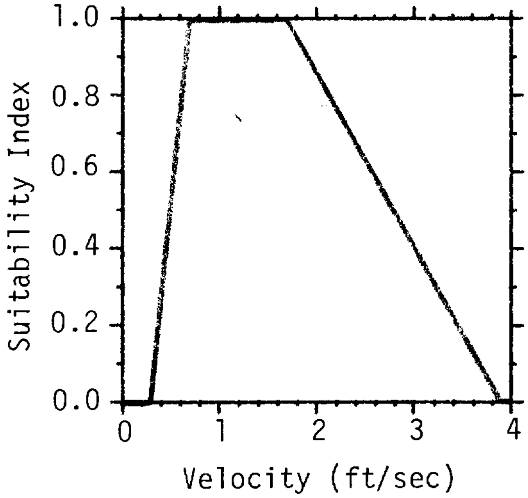
	Velocity	Depth	Substrate	Temperature	Cover
Spawning	Use SI curve, Fig. 2.	Use SI curve, Fig. 2.	Use SI curve, Fig. 2.	Use SI curve, Fig. 2.	No curve necessary.
Egg incubation	Use SI curve, Fig. 2.	Use SI curve, Fig. 2.	Use SI curve, Fig. 2.	Use SI curve, Fig. 2.	No curve necessary.
Fry	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.[a]	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.
Juvenile	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.[a]	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.
Adult	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.[a]	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.

[a]The following categories can be used for IFIM analyses (see Bovee 1982):

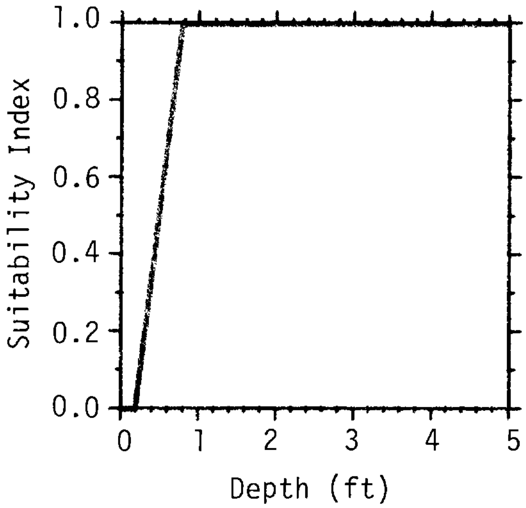
1 = plant detritus/organic material
2 = mud/soft clay
3 = silt (particle size F 0.062 mm)
4 = sand (particle size 0.062-2.000 mm)
5 = gravel (particle size 2.0-64.0 mm)
6 = cobble/rubble (particle size 64.0-250.0 mm)
7 = boulder (particle size 250.0-4000.0 mm)
8 = bedrock (solid rock)

Coordinates

x	y
0.00	0.00
0.30	0.00
0.70	1.00
1.70	1.00
3.90	0.00
100.00	0.00



x	y
0.0	0.0
0.2	0.0
0.8	1.0
100.0	1.0



x	y
0.00	0.00
0.10	0.00
0.25	1.00
3.00	1.00
3.40	0.00
100.00	0.00

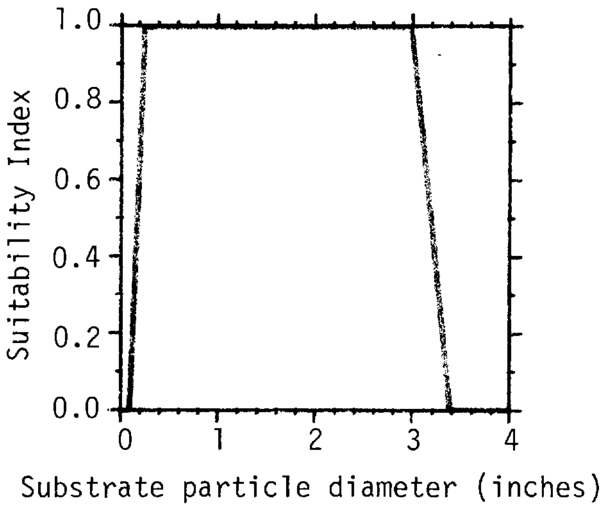


Figure 2. Category one SI curves for brown trout spawning and egg incubation velocity, depth, substrate, and temperature suitability.

Coordinates

x	y
0.0	0.0
32.0	0.0
43.0	1.0
48.0	1.0
55.0	0.0
100.00	0.0

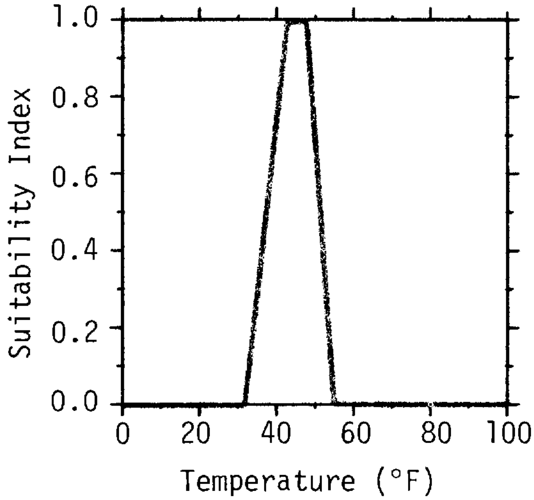
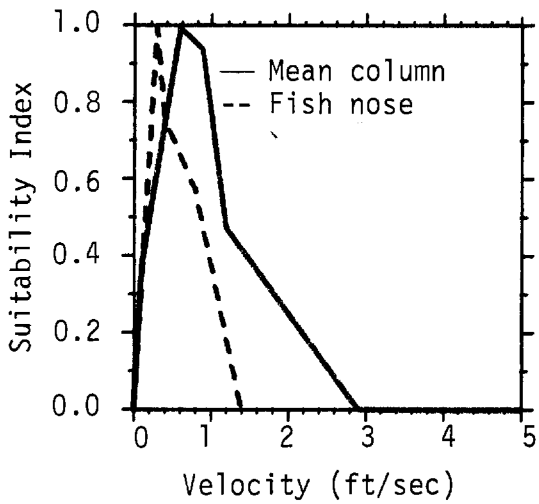


Figure 2. (concluded).

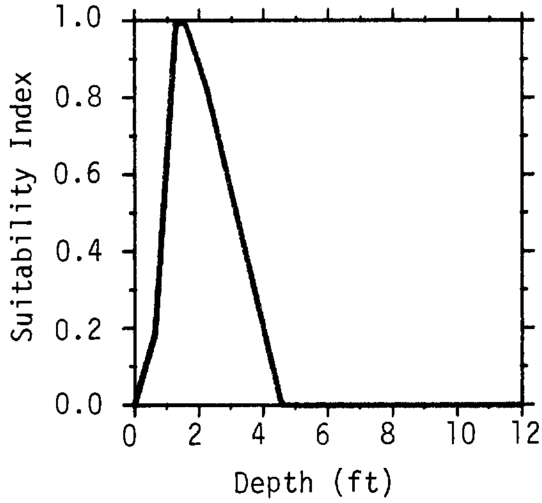
Coordinates

x	y Mean column	y Fish nose
0.0	0.00	0.00
0.1	0.38	-
0.3	-	1.00
0.4	-	0.76
0.6	1.00	-
0.8	-	0.57
0.9	0.94	-
1.2	0.47	-
1.4	-	0.00
2.9	0.00	-
100.0	0.00	0.00



Coordinates

x	y
0.00	0.00
0.66	0.19
1.31	1.00
1.61	1.00
2.30	0.82
4.60	0.00
100.00	0.00



x	y
1.0	0.76
2.0	0.76
3.0	0.76
4.0	0.76
5.0	1.00
6.0	0.35
7.0	0.04
8.0	0.04

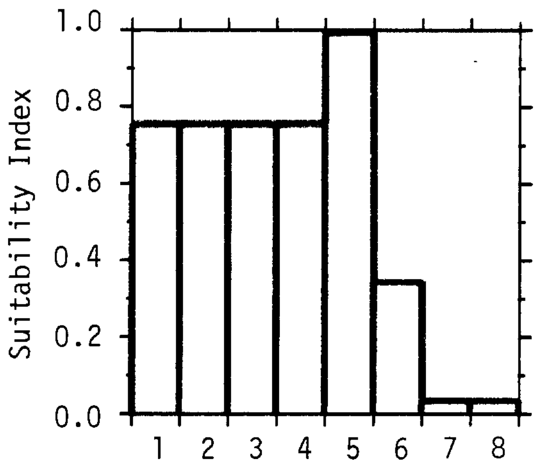
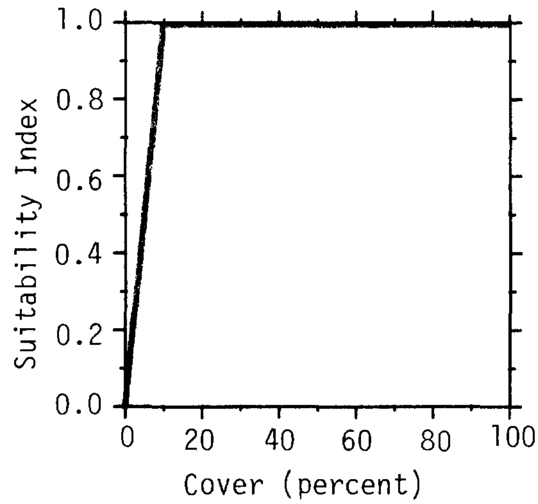


Figure 3. SI curves for brown trout fry velocity, depth, substrate, cover, and temperature suitability.

Coordinates

x	y
0.0	0.0
10.0	1.0
100.00	1.0



x	y
0.0	0.0
39.0	0.0
43.0	1.0
59.0	1.0
72.0	0.0
100.00	0.0

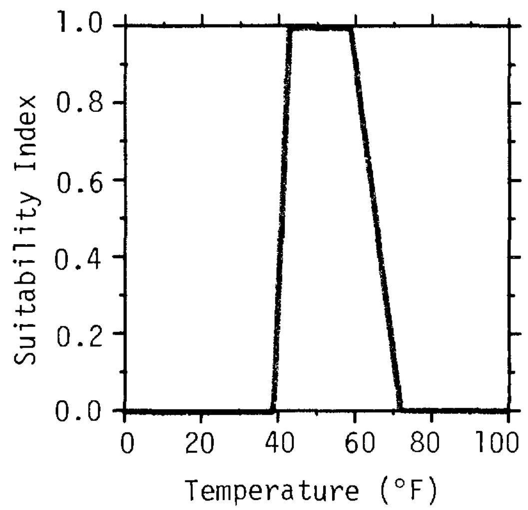
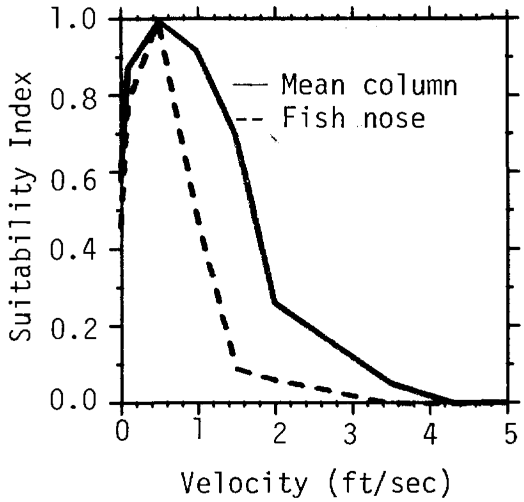


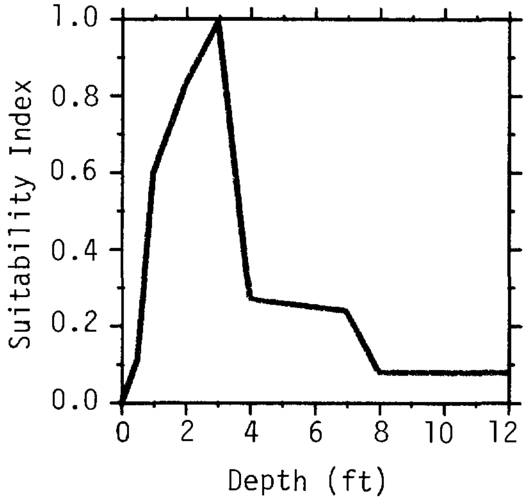
Figure 3. (concluded).

Coordinates

x	y Mean column	y Fish nose
0.0	0.58	0.46
0.1	0.88	0.78
0.5	1.00	1.00
1.0	0.92	0.48
1.5	0.70	0.09
2.0	0.26	0.06
3.5	0.05	0.00
4.3	0.00	-
100.0	0.00	0.00



x	y
0.0	0.00
0.5	0.12
1.0	0.61
2.0	0.84
3.0	1.00
4.0	0.27
7.0	0.24
8.0	0.08
100.0	0.08



x	y
1.0	0.66
2.0	0.66
3.0	0.66
4.0	0.66
5.0	1.00
6.0	0.97
7.0	0.12
8.0	0.12

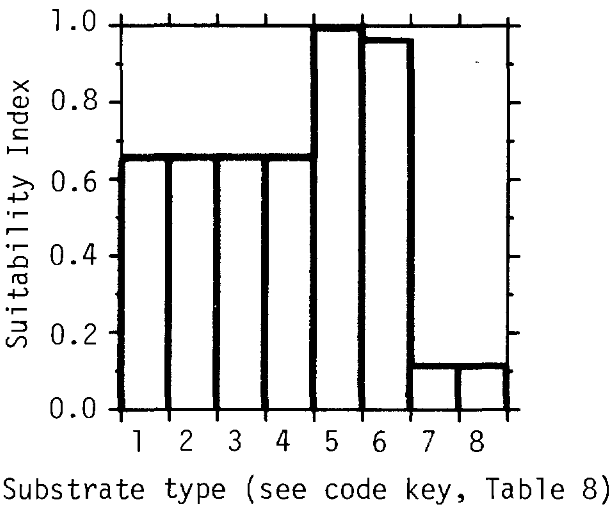
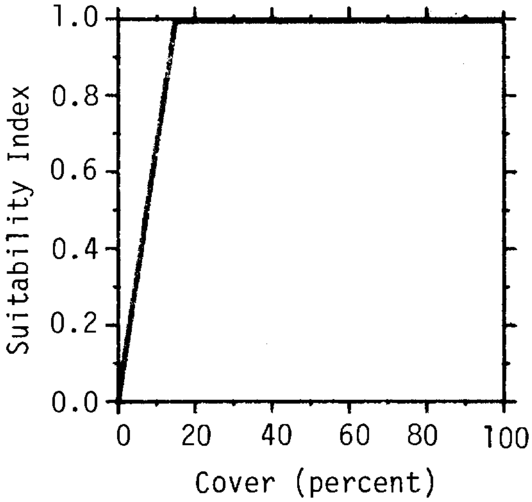


Figure 4. Category one SI curves for brown trout juvenile velocity, depth, substrate, cover, and temperature suitability.

Coordinates

x	y
0.0	0.0
15.0	1.0
100.00	1.0



x	y
0.0	0.0
32.0	0.0
43.0	1.0
75.0	1.0
79.0	0.0
100.00	0.0

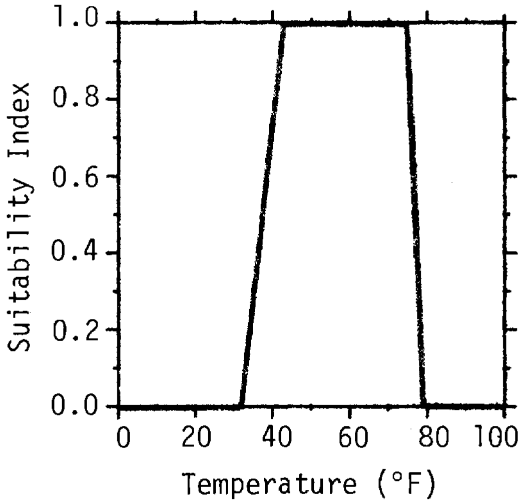


Figure 4. (concluded).

Coordinates

x	y Mean column	y Fish nose
0.0	0.21	0.54
0.1	0.70	0.92
0.5	1.00	1.00
1.0	0.69	0.34
1.5	0.50	0.11
2.4	0.20	0.00
3.1	0.03	-
5.0	0.03	-
6.0	0.00	-
100.0	0.00	0.00

x	y
0.0	0.00
1.6	0.87
2.0	0.95
2.6	1.00
3.6	0.84
4.0	0.45
5.0	0.30
7.0	0.21
100.0	0.21

x	y
1.0	1.00
2.0	1.00
3.0	1.00
4.0	1.00
5.0	0.54
6.0	0.86
7.0	0.12
8.0	0.12

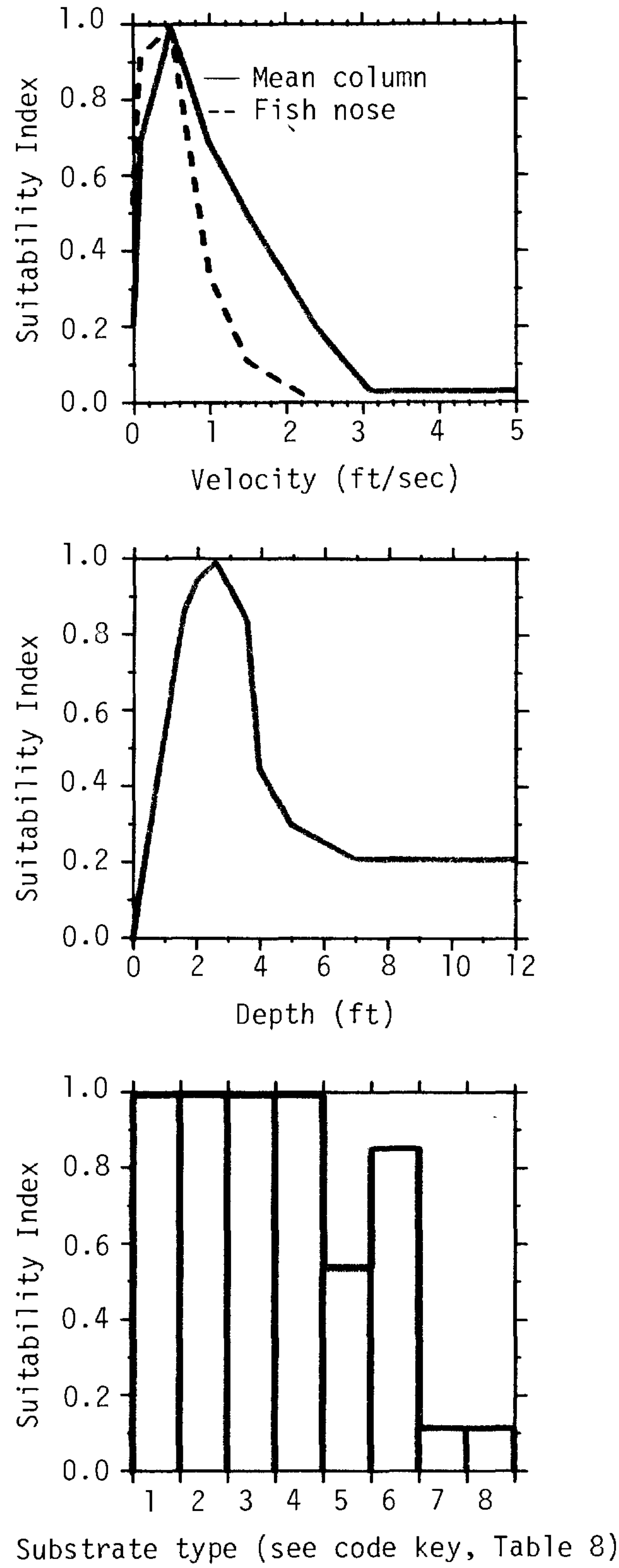
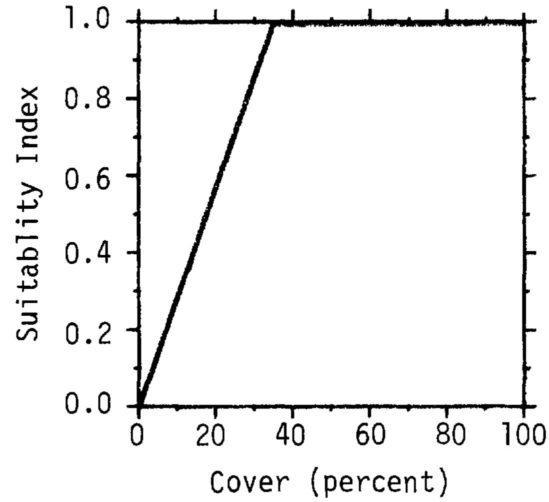


Figure 5. Category one SI curves for brown trout adult velocity, depth, substrate, cover, and temperature suitability.

Coordinates

x	y
0.0	0.0
35.0	1.0
100.00	1.0



x	y
0.0	0.0
32.0	0.0
43.0	0.5
54.0	1.0
72.0	1.0
75.0	0.0
100.00	0.0

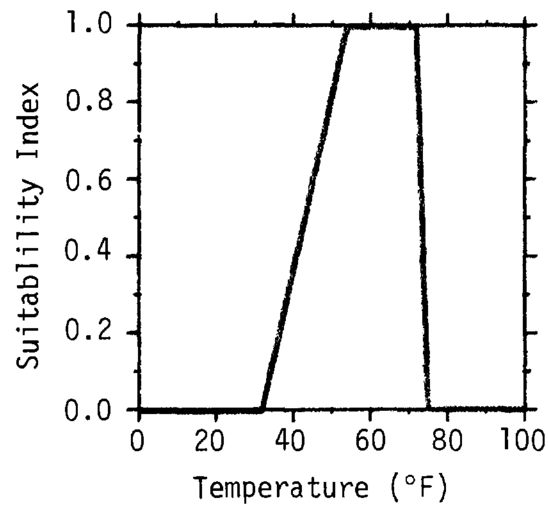


Figure 5. (concluded).

from 4,680 to 5,240 ft; and associated fish species included mountain whitefish, cutthroat trout, mottled sculpin, and rainbow trout. The Blacksmith Fork River discharge averaged 127 cfs, elevations ranged from 4,700 to 5,500 ft and associated fish species were the same as in the Logan River. The velocities available to the fish ranged from 0 to 5 ft/s, depths ranged from 0 to 12 ft, and substrate types ranged from silt to boulder.

The SI curves for juvenile brown trout velocity, depth, and substrate utilization were derived from data collected by Gosse et al. (1977), Gosse (1981), and Moyle et al. (1983). In the Moyle et al. study, brown trout were shocked in Martis Creek, a small tributary of the Truckee River on the east side of the Sierras, in Placer County, California. The variables measured at each fish location included mean column velocity, fish nose velocity, water column depth, and substrate type (see code key, Table 3). Juveniles were defined as individuals ranging in length from 2.0 to 4.7 inches. Little information was available about the study site. Velocities available to the fish ranged from 0 to 4.3 ft/s, depths ranged from 0 to 4 ft, and substrate types ranged from plant detritus to boulders.

The habitat utilization data from Gosse and Moyle were generally in the form of frequency (or percent frequency) distributions. In order to generate category two curves, the habitat variable value or interval with the highest frequency was assigned an SI of 1.0, and all other frequencies were normalized to 1.0. This generally resulted in a jagged curve, probably as a result of the small sample size. The jagged curve was smoothed by connecting the high points, based on the assumption that it makes no sense for fish to utilize, velocities of 0.6 and 0.9 ft/s for example, while avoiding velocities of 0.7 and 0.8 ft/s, or utilize depths of 1.0 and 2.0 ft while avoiding depths from 1.1 to 1.9 ft.

After developing category two curves for brown trout fry, juvenile, and adult velocity, depth, and substrate utilization, category one curves were developed for the same life stages and variables by combining the category two curves. The X,Y curve coordinates for each category two curve were weighted according to sample size, combined, and normalized to 1.0, after assigning an SI of 1.0 to the coordinate pair with the highest y-value. The category one curves may be more useful to an investigator than the category two curves because so little information was available concerning study site conditions, making curve transportability for use in other areas impossible without curve verification studies.

The SI curves for spawning/egg incubation and for cover and temperature for all life stages are category one curves, based on information from the literature and professional judgement. All curves can be updated or modified periodically as new information becomes available.

Spawning and egg incubation. Brown trout generally spawn some time between October and February, depending on locale, and egg incubation may require 33 to 165 days, depending on temperature (Carlander 1969). Therefore, SI curves should be used for the time period during which spawning and egg incubation occur in a given area.

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, brown trout spawning and egg incubation curves are combined (Figure 2), 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).

The category one curves for spawning and egg incubation velocity and depth utilization were based on several studies. The lowest spawning velocity identified was 0.35 ft/s (Witzel and MacCrimmon 1983); the highest was 3.8 ft/s (Hunter 1973); the mean was often 1.5 ft/s (Hooper 1973; Smith 1973; Witzel 1980; Gosse 1981; Witzel and MacCrimmon 1983). "Preferred" velocities (not defined by authors) generally fell within the 0.7 to 1.7 ft/s range (Johnson et al. 1966; Hooper 1973; Hunter 1973; Reiser and Wesche 1977; Gosse 1981; Shirvell and Dungey 1983). Minimum spawning depths ranged from 0.2 to 0.8 ft (Johnson et al. 1966; Hunter 1973; Smith 1973; Reiser and Wesche 1977; Witzel 1980; Shirvell and Dungey 1983; Witzel and MacCrimmon 1983). Information on maximum depths was not found in the literature and a maximum suitable depth was assumed not to exist.

The category one SI curves for spawning and egg incubation substrate utilization and temperature suitability were taken from the HSI model section of this report (V_6 and V_2; information sources and assumptions in Table 1). The substrate curve generally agrees with information in Hunter (1973), Witzel (1980), Gosse (1981), Shirvell and Dungey (1983), and Witzel and MacCrimmon (1983). The temperature curve generally agrees with information in Hooper (1973), Hunter (1973), and Witzel (1980).

No SI curve was developed for spawning and egg incubation cover. There was no evidence in the literature to suggest that cover is a requirement for spawning, although there was some indication that brown trout utilize cover in some cases. Therefore, the assumption was that no cover is necessary for spawning and egg incubation.

The other approach for determining 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 (Figure 6) 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, ranges from 2.65 to 2.80

Factors to consider when determining habitat reduction from siltation include suspended sediment concentrations, minimum velocities necessary to prevent siltation (Figure 6), and dissolved oxygen concentrations among the embryos. More detailed information about the analysis of effective spawning habitat is presented in Milhous (1982).

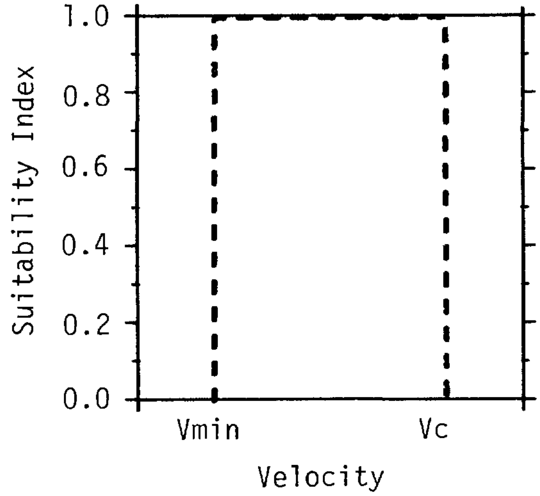
Fry. The size classes used to represent life stages of fishes often are very subjective. For purposes of IFIM analyses, the fry stage of a species is considered to be the period that begins with egg hatching and ends when larval fishes take on the appearance of the adults, which occurs at lengths ranging from 1.0 to 2.0 inches for many species. Brown trout are assumed to be fry up to a length of 2.0 inches. For IFIM analyses, assume that fry habitat is required from the end of the spawning period until 4 months after the end of the egg incubation period.

Very little habitat information was found in the literature for brown trout fry less than 2.0 inches in length. Gosse et al. (1977) collected data for young-of-year (age 0) brown trout, defined as less than 5.5 inches in length, and the category two SI curves for young-of-year velocity, depth, and substrate utilization (Figure 7) were derived from his data. The velocity curves graphically depict differences between utilization of mean column velocity and fish nose velocity, probably a result of fish positioning themselves in the water column at points below where mean column velocities were measured. The PHABSIM model can predict cell velocities (as a function of streamflow) at any preselected distance above the streambed (Milhous et al. 1984). For example, if a given species generally occurs 0.5 ft above the

Coordinates

x	y
0	0
V_{min} -.001	0
V_{min}	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
D_{min} -.001	0
D_{min}	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).

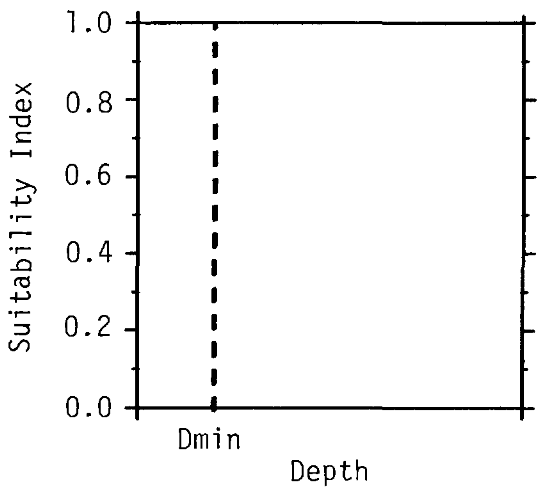


Figure 6. SI curves for spawning/egg incubation velocity and depth, for effective spawning habitat analyses.

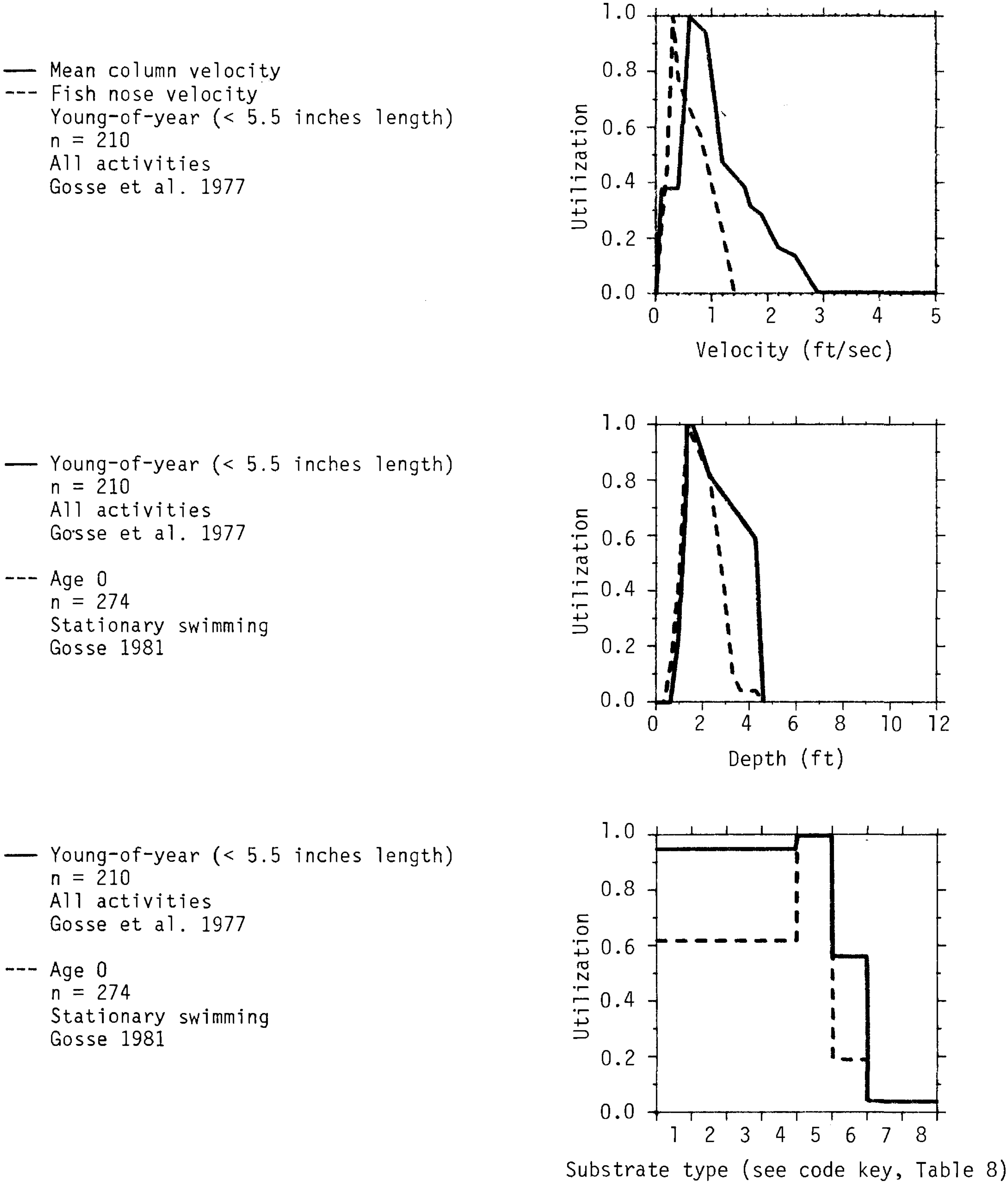


Figure 7. Category two SI curves for brown trout young-of-year velocity, depth, and substrate utilization.

streambed, the model can predict weighted useable area based on suitability of water velocities at that distance above the substrate at any given streamflow. Investigators may elect to use fish nose velocity curves in place of mean water column velocity curves, because they may more accurately represent velocities "selected" by fish.

The category two curves for depth and substrate utilization were derived from two sets of habitat utilization data (Gosse et al. 1977; Gosse 1981). One depth curve represents utilization for all activities combined (stationary swimming, random swimming, feeding, and resting), while the other curve represents utilization only during stationary swimming. The curves are similar, although it appears that slightly shallower waters are utilized during stationary swimming. The substrate curves also are similar to one another, but less so than the depth curves. Substrate types utilized by brown trout may be more a function of velocity preferences than of actual substrate type preferences.

The category one curves for velocity, depth, and substrate suitability (Figure 3) were derived by combining the category two curves (Figure 7) and represent habitat suitability for young-of-year brown trout. Until more information becomes available, fry are assumed to have the same habitat requirements as young-of-year.

The category one SI curves for fry cover and temperature suitability (Figure 3) were taken from the HSI model section (V_7 and V_{1B}, sources and assumptions in Table 1). The temperature curve agrees with information in Wingfield (1940), who determined that 43 °F was the lower limit for growth, and New York State (1976) which reported 72 to 73 °F as the upper lethal limit.

Juvenile. Brown trout juveniles were considered to range in length from 2.0 to 12.0 inches, the approximate length at sexual maturity. Most brown trout males mature at age IV and females at age V, at lengths generally ranging from 12 to 19 inches, although mature individuals have been reported as small as 5 or 6 inches (Carlander 1969). The exact length at sexual maturity is probably not important, assuming that physical microhabitat requirements are the same for all juveniles within the defined size range. If they are not, the juvenile life stage may need to be split into smaller size-interval groupings.

Three sets of data were analyzed to develop category two curves for brown trout juvenile velocity, depth, and substrate utilization (Figures 8 to 10) (Gosse et al. 1977; Gosse 1981; Moyle et al. 1983). As with young-of-year brown trout, juveniles tend to utilize velocities that are lower than mean column velocities. The fish nose velocity utilization curves (Figure 8) are quite similar, suggesting that juveniles select a specific range of velocities regardless of conditions in other parts of the water column. The depth curves (Figure 9) are somewhat similar. Juveniles observed by Moyle et al. (1983) utilized shallower water than those observed by Gosse et al. (1977) and Gosse (1981), possibly because juveniles, as defined by Moyle, were much smaller than juveniles as defined by Gosse. The differences also may have been related to differences in available depths in the two studies, i.e., depths to only 4 ft were available in Martis Creek (Moyle et al. 1983), whereas depths to 13 ft

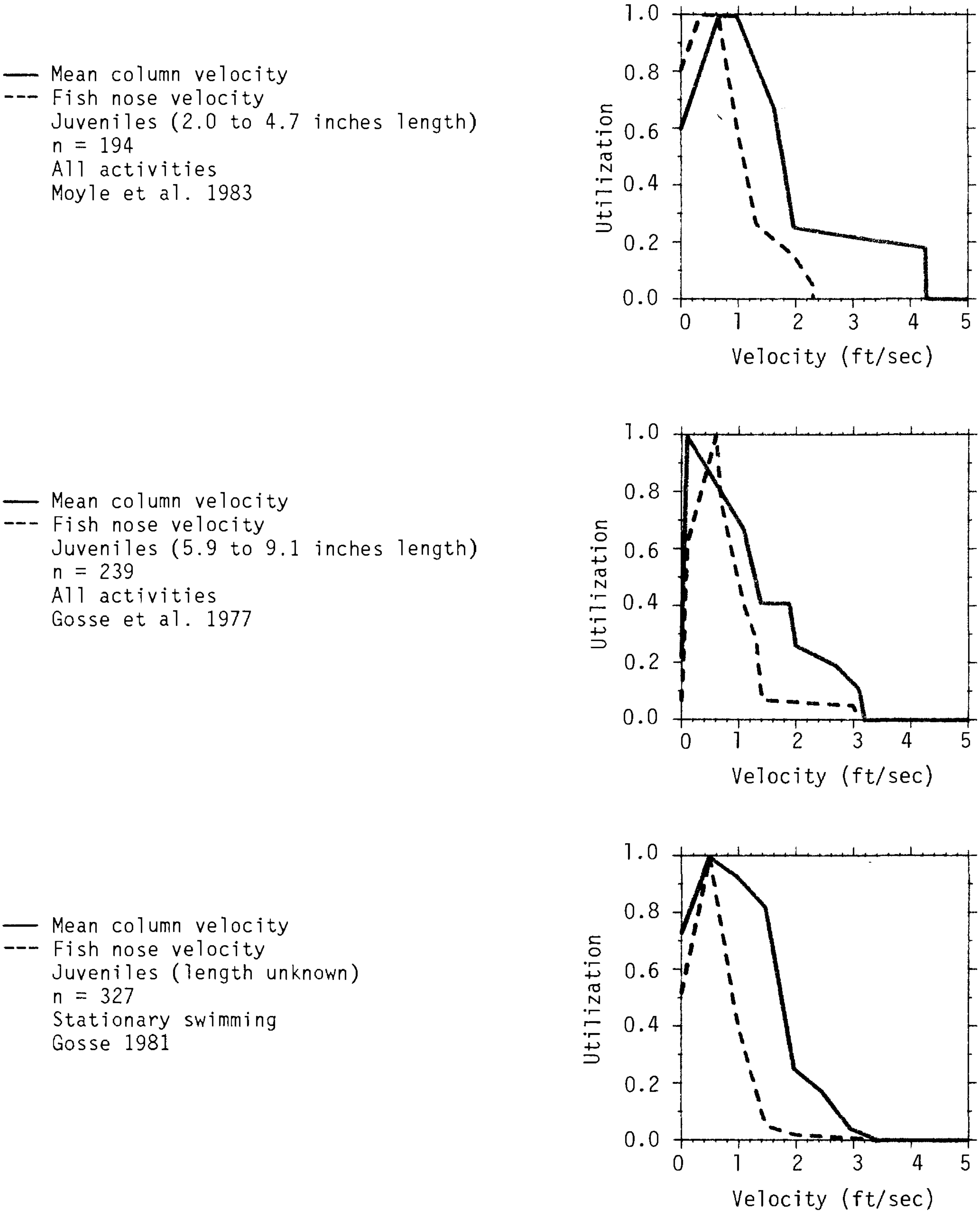
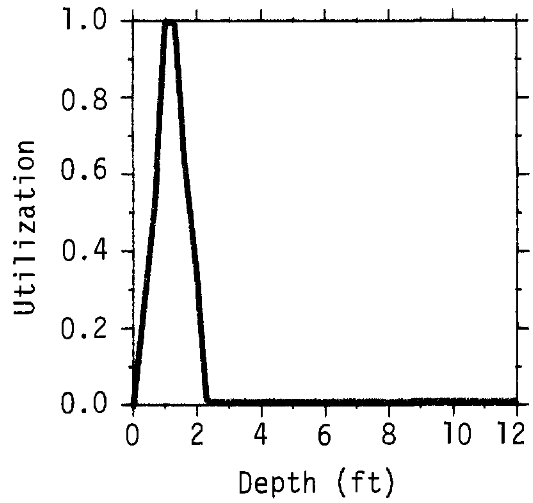
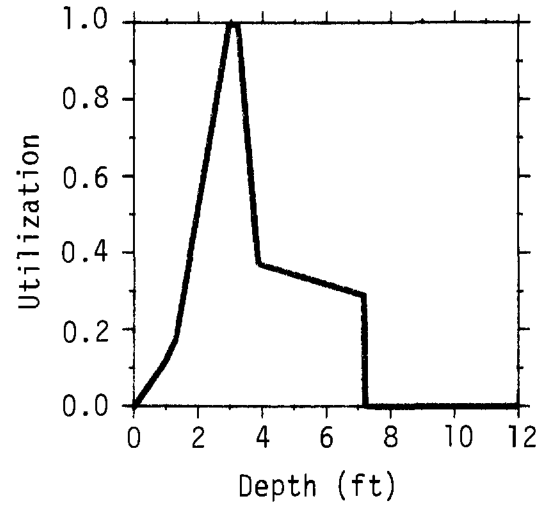


Figure 8. Category two SI curves for brown trout juvenile mean column velocity and fish nose velocity utilization.

Juveniles (2.0 to 4.7 inches length)
n = 194
All activities
Moyle et al. 1983



Juveniles (5.9 to 9.1 inches length)
n = 239
All activities
Gosse et al. 1977



Juveniles (length unknown)
n = 327
Stationary swimming
Gosse 1981

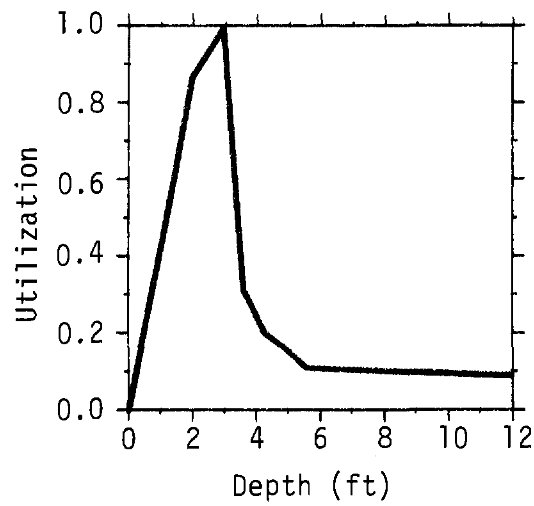
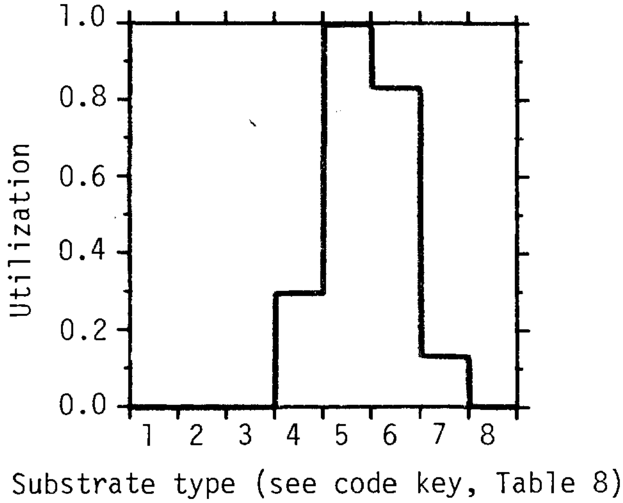
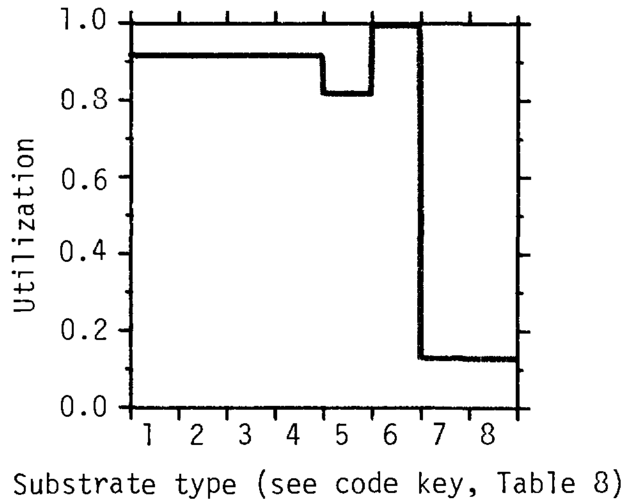


Figure 9. Category two SI curves for brown trout juvenile depth utilization.

Juveniles (2.0 to 4.7 inches length)
n = 194
All activities
Moyle et al. 1983



Juveniles (5.9 to 9.1 inches length)
n = 239
All activities
Gosse et al. 1977



Juveniles (length unknown)
n = 327
Stationary swimming
Gosse 1981

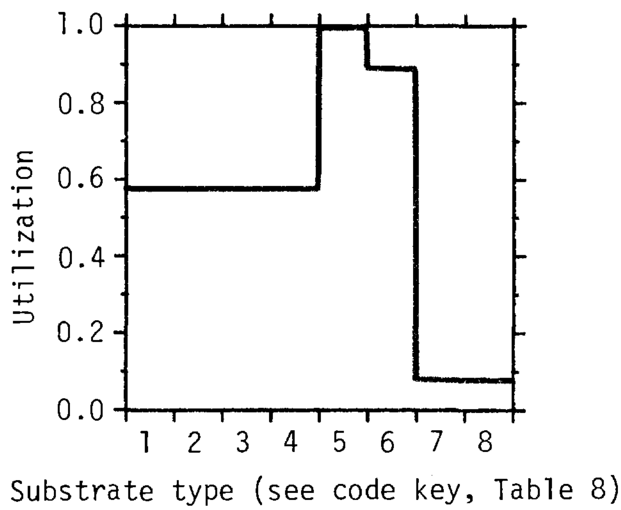


Figure 10. Category two SI curves for brown trout juvenile substrate utilization.

were available in the Logan River system (Gosse et al. 1977; Gosse 1981). The substrate curves (Figure 10) are similar in terms of high utilization of gravel and cobble and low utilization of boulders. Utilization of fine particle material appears quite variable. Substrate types utilized by brown trout juveniles may be more a function of water velocity, food availability, and fish activity than of actual substrate type selection.

The category one SI curves for brown trout juvenile velocity, depth, and substrate suitability (Figure 4) were derived from the category two curves (Figures 8 to 10). All curves are subject to modification as new information becomes available.

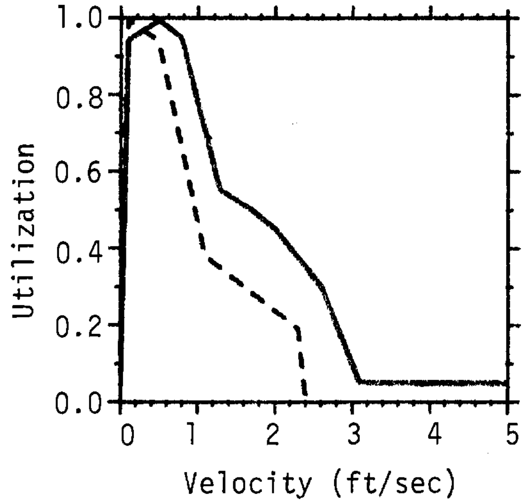
The category one curves for cover and temperature suitability (Figure 4) were taken from the HSI model section (V_5 and V_{1A}; sources and assumptions in Table 1). Wingfield (1940) reported that 43 °F was the lower limit for growth. Hunter (1973) reported that growth occurred from 65 to 75 °F and that 81 °F was the maximum temperature tolerated. New York State (1976) reported upper lethal temperatures of 79 to 84 °F.

Adult. Adult brown trout are considered to be sexually mature individuals at lengths greater than 12.0 inches (although there is a great degree of variability in age and length at sexual maturity within the range of the species). Gosse et al. (1977) defined adults as fish longer than 9.4 inches. Differences in habitat requirements between fishes 9.4 inches and fish 12 inches are assumed to be insignificant.

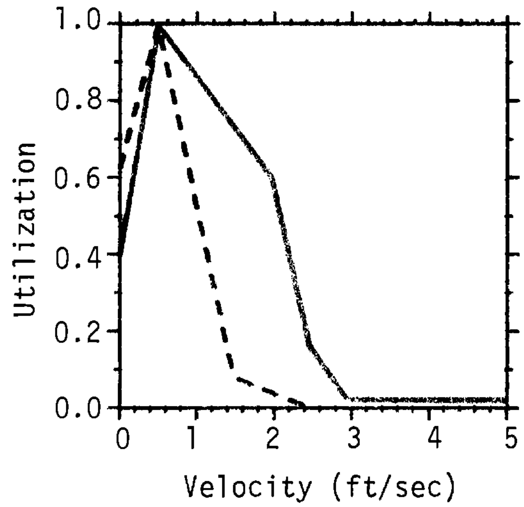
The category two SI curves for adult velocity, depth, and substrate utilization (Figures 11 to 13) were derived from Gosse's data (Gosse et al. 1977; Gosse 1981). The fish nose velocity curves (Figure 11) are quite similar, especially with regard to range and optimum. Velocities utilized by adults during resting are somewhat lower than those utilized during stationary swimming, as expected. Depth utilization curves (Figure 12) are similar up to depths of 2 to 3 ft, after which utilization becomes more variable, possibly due to differences in velocity distribution. Substrate utilization curves (Figure 13) reflect major differences between resting and stationary swimming activities, which may have resulted from differences in velocities selected or food availability.

The category one SI curves for brown trout adult velocity, depth, and substrate suitability (Figure 5) were derived from the category two curves (Figures 11 to 13). Velocity preferences of adult brown trout in other studies have ranged from 0 to 0.7 ft/s for resting and 0.5 to 1.5 ft/s for feeding (Baldes 1968; Hunter 1973; Wichers 1978; Helm 1982; Shirvell and Dungey 1983). Depths utilized generally have ranged from 0.2 to 5.5 ft (Baldes 1968; Helm 1982; Shirvell and Dungey 1983). The substrate most commonly utilized in a study by Wichers (1978) was rubble and gravel during pre-ice and ice conditions. Therefore, the category one curves generally agree with information in the literature. Any differences may be due, at least in part, to habitat availability, fish activity, or time of year during sampling.

—— Mean column velocity
--- Fish nose velocity
Adults (> 9.4 inches length)
n = 352
All activities
Gosse et al. 1977



—— Mean column velocity
--- Fish nose velocity
Adults (length unknown
n = 225
Stationary swimming
Gosse 1981



—— Mean column velocity
--- Fish nose velocity
Adults (length unknown)
n = 222
Resting
Gosse 1981

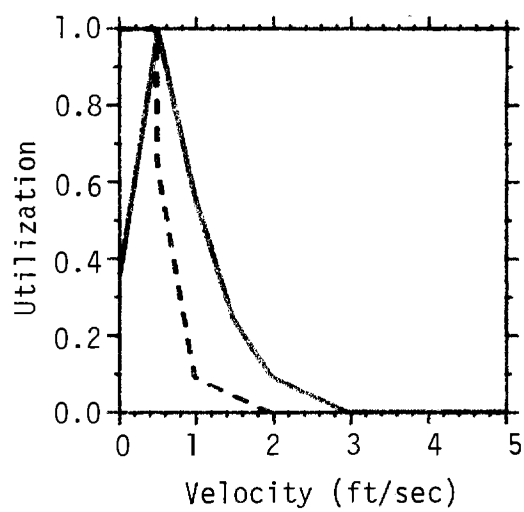
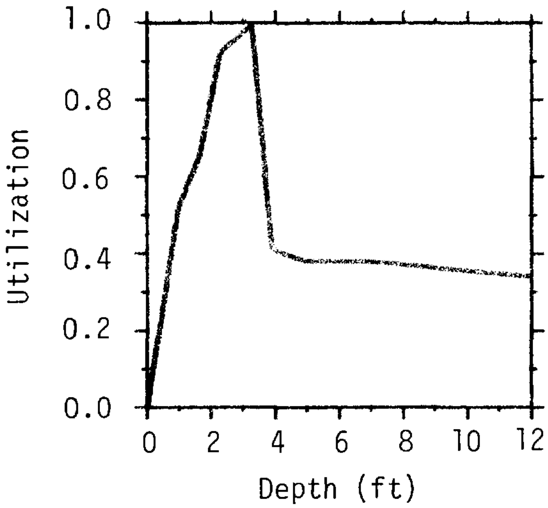
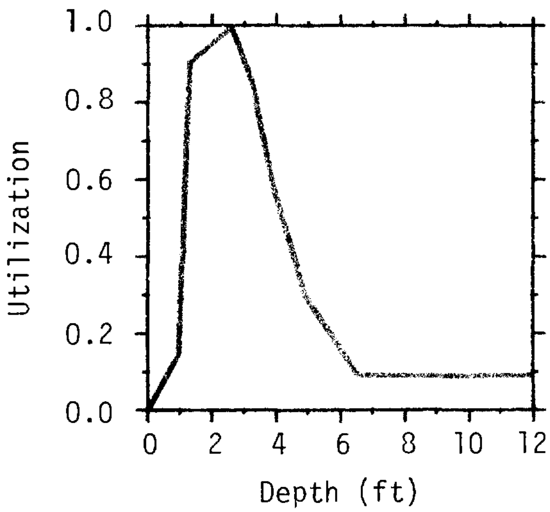


Figure 11. Category two SI curves for brown trout adult velocity utilization.

Adults (> 9.4 inches length)
n = 352
All activities
Gosse et al. 1977



Adults (length unknown)
n = 222
Stationary swimming
Gosse 1981



Adults (length unknown)
n = 216
Resting
Gosse 1981

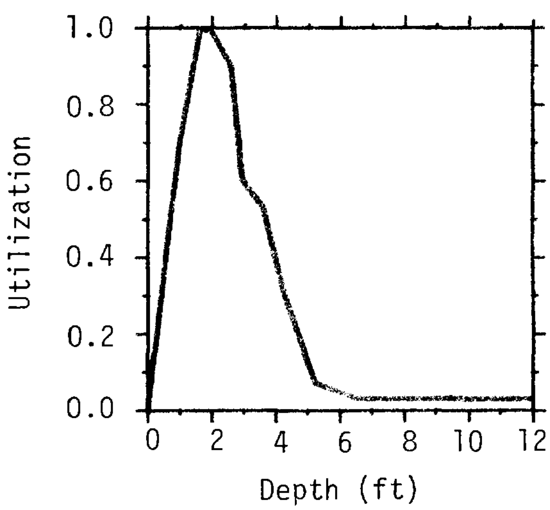
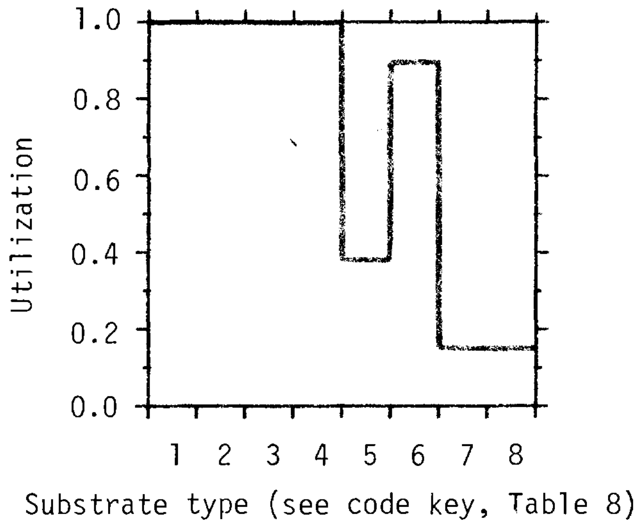
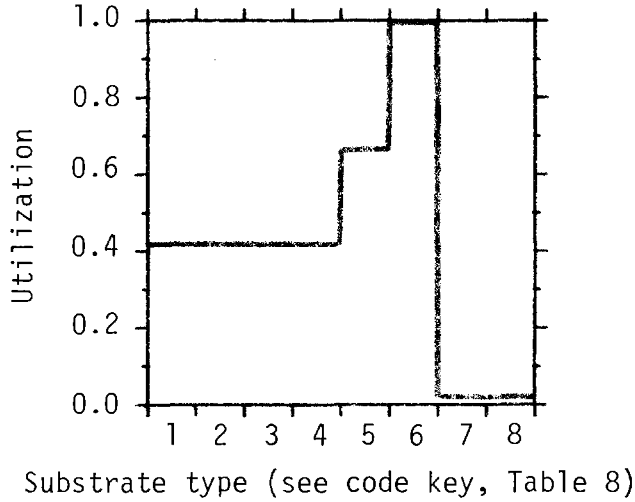


Figure 12. Category two SI curves for brown trout adult depth utilization.

Adults (> 9.4 inches length)
n = 352
All activities
Gosse et al. 1977



Adults (length unknown)
n = 225
Stationary swimming
Gosse 1981



Adults (length unknown)
n = 222
Resting
Gosse 1981

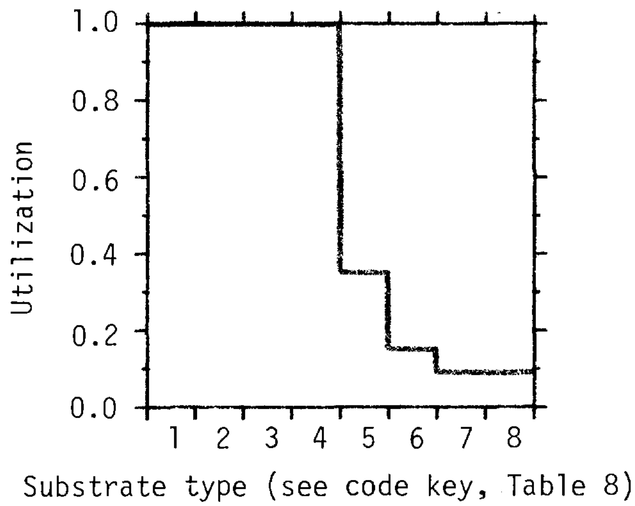


Figure 13. Category two SI curves for brown trout adult substrate type utilization.

The category one SI curves for cover and temperature suitability (Figure 5) were taken from the HSI model section (V_5 and V_{1A}; sources and assumptions in Table 1). The temperature curve is in close agreement with information in Wingfield (1940), Hunter (1973), New York State (1976), and Coutant (1977).

Summary. Varying amounts of information exist concerning the habitat requirements of brown trout. There was a certain amount of overlap ("consensus") in the available information for some variables, but not for others. Professional judgement was used throughout the process of defining relative suitabilities of a variable for each life stage. All curves are subject to refinement as new information becomes available. The category one SI curves for brown trout habitat suitability are assumed to be as accurate as possible based on present knowledge. Investigators who feel that the SI curves do not accurately reflect habitat utilization at their study site are encouraged to gather information specific to their area and modify the curves or develop new curves as needed.

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The Habitat Suitability Index (HSI) models presented in this publication aid in identifying important habitat variables for brown trout (*Salmo trutto* Linneas). 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.

A brief discussion of the appropriateness of using selected Suitability Index (SI) curves from HSI models as a component of the Instream Flow Incremental Methodology (IFIM) is provided. Additional SI curves, developed specifically for analysis of brown trout habitat with IFIM, also are presented.

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