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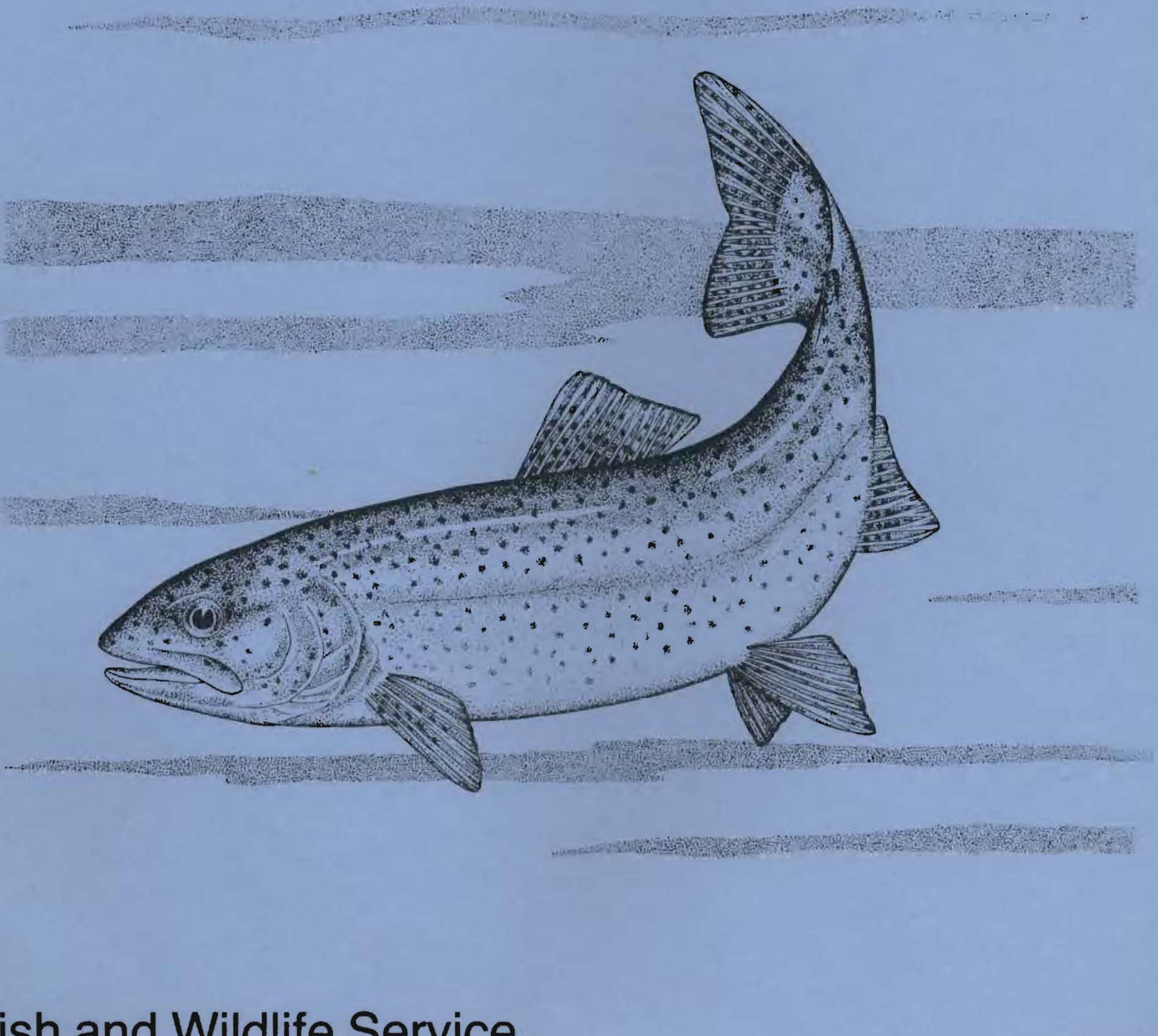
HABITAT SUITABILITY INFORMATION: RAINBOW TROUT



Fish and Wildlife Service

S. Department of the Interior

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January 1984

HABITAT SUITABILITY INFORMATION: RAINBOW TROUT

by

Robert F. Raleigh
P.O. Box 625
Council, ID 83612

Terry Hickman
Endangered Species Office
U.S. Fish and Wildlife Service
1311 Federal Building
125 S. State Street
Salt Lake City, UT 84138

R. Charles Solomon
Habitat Evaluation Procedures Group
Western Energy and Land Use Team
U.S. Fish and Wildlife Service
Drake Creekside Building One
2627 Redwing Road
Fort Collins, CO 80526-2899

and

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

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

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PREFACE

The Habitat Suitability Index (HSI) models presented in this publication aid in identifying important habitat variables. Facts, ideas, and concepts obtained from the research literature and expert reviews are synthesized and presented in a format that can be used for impact assessment. 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 will 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)[1] and the general guidelines for modifying HSI models and estimating model variables presented in Terrell et al. (1982)[2] 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.

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 rainbow trout habitat with IFIM, also are presented.

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

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

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

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RAINBOW TROUT (Salmo gairdneri)

HABITAT USE INFORMATION

General

Because of variations in their life history pattern and the habitat in which they spend the majority of their adult lives, rainbow trout (Salmo gairdneri) can be subdivided into three basic ecological forms: (1) anadromous steelhead trout; (2) resident stream rainbow trout; and (3) lake or reservoir dwelling rainbow trout. It is important to recognize that there is a genetic or hereditary basis for each ecological form. For example, a "lake or reservoir" rainbow may react very differently to environmental stimuli associated with survival, feeding, and growth if it belongs to a population that has been evolving and adapting to the particular lake for hundreds or thousands of years, when compared to hatchery rainbow trout that have just been released in the lake.

Nonanadromous rainbow trout are native to the Pacific Coast drainages inland as far as the Rockies and from the Rio del Presidio River in Mexico to the Kuskokwim River in Southwestern Alaska (Behnke 1979). They are also native to the Peace River drainage of British Columbia and the headwaters of the Athabaska River (of the McKenzie River basin) in Alberta (MacCrimmon 1971). Their present range extends from the Arctic Circle to 55° S latitude. They are perhaps the most widely introduced fish species; the only continent lacking rainbow trout is Antarctica (McAfee 1966; MacCrimmon 1971). Rainbow trout occur from 0 to 4,500 m above sea level (MacCrimmon 1971).

Anadromous steelhead trout are distributed along the Pacific coast from the Santa Ynez Mountains, California, to the Alaska Peninsula (Jordan and Evermann 1902; Withler 1966). Large rainbow trout on and north of the Alaska Peninsula appear to be nonanadromous.

Age, Growth, and Food

Female rainbow trout typically become sexually mature during their third year; males become sexually mature during their second or third year (Holton 1953; Lagler 1956; McAfee 1966). Life expectancy averages 3 to 5 years in most southern lake populations, but life expectancy of steelhead and northern lake populations appears to be 4 to 8 years. Maximum size also varies with population, area, and habitat. Steelhead may grow to 122 cm long and weigh 16 kg. The average angler's catch is 3.6 to 4 kg. Great Lakes rainbow grow to 244 cm, but seldom exceed 9 kg (Scott and Crossman 1973). Size in wild rainbow trout appears to be a function of longevity, delayed age at maturity, and length of ocean residence for steelhead.

Adult and juvenile rainbow trout are basically opportunistic feeders and consume a wide variety of foods. Availability of different foods depends on many factors, including water type, season, and size of the trout (McAfee 1966). The diet of rainbow trout consists mainly of aquatic insects (Allen 1969; Carlander 1969; Baxter and Simon 1970; Scott and Crossman 1973), although foods, such as zooplankton (McAfee 1966), terrestrial insects, and fish (Carlander 1969), are locally or seasonally important. The relative importance of aquatic and terrestrial insects to resident stream rainbow trout varies greatly among different environments, seasonally and dielly, and with the age of the trout (Bisson 1978). Forty to fifty percent or more of the summer food of trout in headwater streams may be composed of terrestrial insects (Hunt 1971). Adult stream rainbow trout occasionally consume significant quantities of vegetation, mostly algae (McAfee 1966). Stream trout have no mechanism to break down cell walls in vegetation and cannot obtain nutrients from it, therefore, vegetation is thought to be consumed because of the invertebrates attached to it (Behnke pers. comm.). Bottom fauna may comprise 83 to 94% of the winter diet of adult and juvenile lake rainbow trout (Crossman and Larkin 1959). Lake trout usually reach 30 cm in length before they actively prey on other fish species (Crossman 1959; Crossman and Larkin 1959; Johannes and Larkin 1961).

Reproduction

Rainbow trout spawn almost exclusively in streams. Some rainbow and rainbow-cutthroat trout hybrids have successfully reproduced in lakes without tributary streams (Behnke, pers. comm.). Spawning in certain river systems may occur in intermittent tributary streams (Everest 1973; Price and Geary 1979). In one case, up to 47% of the stream rainbow trout population spawned in intermittent tributaries that dried up in midsummer and fall (Erman and Leidy 1975; Erman and Hawthorne 1976). Spawning normally occurs from January to July, depending on location. Hatchery selection has resulted in fall spawning strains, and spawning of hatchery fish may occur in almost any month of the year, depending on the strain (Behnke 1979). A few populations outside of the native range have modified their spawning times to avoid adverse environmental conditions (Van Velson 1974; Kaya 1977). Viable eggs have resulted from December and January spawning at water temperatures of 0.3 to 2.0° C in a tributary of Lake Huron (Dodge and MacCrimmon 1970). However, eggs exposed to long periods of 0 to 4° C temperatures suffered high mortality and abnormalities.

The female generally selects a redd site in gravel substrate at the head of a riffle or downstream edge of a pool (Greeley 1932; Orcutt et al. 1968). The redd pit, constructed primarily by the female, is typically longer than the female and deeper than her greatest body depth (Greeley 1932). Average depth of egg deposition is 15 cm (Hooper 1973).

Rainbow trout residing in lakes and reservoirs have a similar life history pattern to the steelhead trout, but generally lack a physiological smolt stage. Juveniles migrate from natal streams to a freshwater lake rearing area, instead of to the ocean. Lake rainbow trout most commonly spend two summers in a stream and two summers in a lake before maturing (Greeley 1933). Spawning takes place during the growing season in an inlet or an outlet stream, with more than 90% of the trout returning to the stream of natal origin (Greeley 1933; Lindsey et al. 1959). Lakes with no inlet or outlet streams generally do not possess a reproducing population of rainbow trout. Whether spawning adults enter through an inlet or an outlet, they and their progeny will return to the lake (Lindsey et al. 1959). These movements from natal sites to lake rearing areas appear to be directed by genetic/environmental interactions (Raleigh 1971).

Spawning usually begins one month earlier in the outlet than in the inlet (Lindsey et al. 1959; Hartman et al. 1962); the difference in time is apparently related to temperature differences (Lindsey et al. 1959). In Bothwell Creek, a tributary of Lake Huron, 65% of the spawning run were repeat spawners (Dodge and MacCrimmon 1970). The typical survival rate of repeat spawners is 10-30%, with extremes from 1% to more than 65%.

Average fecundity of rainbow trout is related to length, but is highly variable, ranging from 500 to 3,161 eggs per stream resident female (Carlander 1969). Fecundity of lake resident females ranges from 935 to 4,578 eggs per female, with an average of 2,028 eggs per female (Mann 1969).

Anadromy

Anadromous steelhead spawn in freshwater streams. Steelhead smolt and migrate in late spring (Wagner 1968; Chrisp and Bjornn 1978). Photoperiod appears to be the dominant triggering mechanism for parr-smolt transformation, with temperature affecting the rate of transformation (Wagner 1974). Smolts that have not migrated by approximately the summer solstice revert to parr and attempt to migrate the following season (Zaugg and Wagner 1973). Juveniles reside in freshwater for 1 to 4 years before migrating to the sea as smolts. They mature after 1 to 4 years of ocean residence and return to freshwater rivers to spawn (Chapman 1958; Withler 1966). A large number of the steelhead adults die after spawning, but some (3 to 53%) return to the ocean and spawn again (Bjornn 1960; Withler 1966; Fulton 1970). Steelhead spawners tend to be larger and older in the northern portion of their range (Withler 1966).

There are both winter and summer-run steelhead. Summer-run adults enter freshwater rivers in the spring and early summer. Winter-run steelhead enter freshwater rivers in the fall and winter. As many as 98.8% of the trout return to their natal stream (McAfee 1966). Both groups typically spawn in the spring and early summer months, March through early July (Withler 1966; Orcutt et al. 1968), although spawning at other times of the year has been reported. Summer-run and winter-run steelhead are distinguished by differences in behavior prior to spawning and, to a limited extent, by appearance (Withler 1966).

When fish migrate from freshwater to saltwater, they are moving from a hypotonic medium to a hypertonic medium. Gill Na-K ATPase activity appears to be related to saltwater tolerance and smolting (Conte and Wagner 1965; Zaugg and Wagner 1973; Adams et al. 1975). Water temperature affects Na-K-related ATPase activity. Juvenile steelhead kept in water warmer than 13° C from March to June experienced reduced levels of smoltification and very low levels of ATPase activity (Zaugg and McLain 1972; Zaugg and Wagner 1973; Wagner 1974). Water temperatures of 10.5 to 13° C resulted in a moderate ATPase response, and temperatures of 6.5 to 10° C resulted in the highest activity levels for the longest period of time (Adams et al. 1975). The effect of temperature on ATPase activity is reversible within a season (Zaugg and McLain 1972).

Coefficient of condition is another indicator of parr-smolt transformation. Juvenile steelhead not undergoing a smolt transformation do not lose weight; whereas, steelhead undergoing transformation lose enough weight to result in a greatly reduced coefficient of condition (Adams et al. 1973; Wagner 1974).

A fork length (i.e., anterior most extremity to the notch in the tail fin of fork-tailed fish or to the center of the tail fin when the tail is not forked) of 160 mm is the average length juvenile parr must reach before they undergo the physiological and morphological changes of smolting (Fessler and Wagner 1969; Chrisp and Bjornn 1978). Hatchery-reared steelhead typically reach critical size in one growing season, but native stream steelhead usually require two or more growing seasons (Chrisp and Bjornn 1978). Migrating smolts at the lower end of the minimum length requirement stay in the ocean longer than smolts that are larger in size when they migrate (Chapman 1958).

The freshwater habitat requirements of adult and juvenile steelhead are assumed to be essentially the same as those for other rainbow trout. Exceptions for steelhead are: (1) low temperature (< 13° C) requirements during the spring months for smoltification of juveniles; and (2) the presence of moderate temperatures (preferably ≤ 20° C) and freshets (periodic high flows) during the upstream migration of adults.

Specific Habitat Requirements

Optimal rainbow trout riverine habitat is characterized by clear, cold water; a silt-free rocky substrate in riffle-run areas; an approximately 1:1 pool-to-riffle ratio, with areas of slow, deep water; well-vegetated stream banks; abundant instream cover; and relatively stable water flow, temperature regimes, and stream banks (Raleigh and Duff 1980).

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

Trout production is typically greatest in streams with a pool-to-riffle ratio of approximately 1:1 (Fortune and Thompson 1969; Thompson and Fortune 1970). Pools are inhabited throughout the year by adult and juvenile stream rainbow trout. Pools are important to trout as a refuge from adverse conditions during the winter. Because pools differ in their ability to provide resting areas and cover, this model subdivides pools into three classes. Lewis (1969) found that streams with deep, low velocity pools containing extensive cover had the most stable trout populations.

Available trout literature does not often clearly distinguish between feeding stations, escape cover, and winter cover requirements. Prime requisites for optimal feeding stations appear to be low water velocity and access to a plentiful food supply; i.e., energy accretion at a low energy cost. Water depth is not clearly defined as a selection factor, and overhead cover is preferred but not essential. Escape cover, however, must be nearby. The feeding stations of dominant adult trout include overhead cover when available. The feeding stations of subdominant adults and juveniles, however, do not always include overhead cover. Antagonistic behavior occurs at feeding stations and hierarchies are established, but escape cover is often shared.

Cover is recognized as one of the essential components of trout streams. Boussu (1954) was able to increase the number and weight of trout in stream sections by adding artificial brush cover and to decrease numbers and weight of trout by removing brush cover and undercut banks. Lewis (1969) reported that the amount of cover was important in determining the number of trout in sections of a Montana stream. Stewart (1970) found that mean depth and underwater, overhanging bank cover were the most important variables in determining the density of brook and rainbow trout longer than 18 cm in a northcentral Colorado stream. Cover for adult trout consists of areas of obscured stream bottom in water ≥ 15 cm deep with a velocity of ≤ 15 cm/sec (Wesche 1980). Wesche (1980) reported that, in larger streams, the abundance of trout ≥ 15 cm in length increased with water depth; most trout were at depths of at least 15 cm. Cover is provided by overhanging vegetation; submerged vegetation; undercut banks; instream objects, such as debris piles, logs, and large rocks; pool depth; and surface turbulence (Giger 1973). A cover area of ≥ 25% of the total stream area provides adequate cover for adult trout; a cover area of ≥ 15% is adequate for juveniles. The main uses of summer cover are probably predator avoidance and resting.

In some streams, the major factor limiting salmonid densities may be the amount of adequate overwintering habitat, rather than the amount of summer rearing habitat (Bustard and Narver 1975a). Winter hiding behavior in salmonids is triggered by low temperatures (Chapman and Bjornn 1969; Everest 1969; Bustard and Narver 1975a,b). Cutthroat trout were found under boulders, log jams, upturned roots, and debris when temperatures neared 4 to 8° C, depending on the water velocity (Bustard and Narver 1975a). Everest (1969) found juvenile rainbow trout 15 to 30 cm deep in the substrate, which was often covered by 5 to 10 cm of anchor ice. Lewis (1969) reported that, during winter, adult rainbow trout tended to move into deeper water (first class pools). Bjornn (1971) indicated that downstream movement during or preceding winter did not occur if sufficient winter cover was available locally. Trout move to winter cover to avoid physical damage from ice scouring (Hartman 1965; Chapman and Bjornn 1969) and to conserve energy (Chapman and Bjornn 1969; Everest 1969).

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). Aquatic invertebrates are most abundant and diverse in riffle areas with rubble substrate and on submerged aquatic vegetation (Hynes 1970). However, optimal substrate for maintenance of a diverse invertebrate population consists of a mosaic of mud, gravel, rubble, and boulders, with rubble dominant. A pool-to-riffle ratio of about 1:1 (approximately a 40 to 60% pool area) appears to provide an optimal mix of food producing and rearing areas for trout (Needham 1940). In riffle areas, the presence of fines (> 10%) reduces the production of invertebrate fauna (based on Cordone and Kelly 1961; Crouse et al. 1981).

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

There is a definite relationship between the annual flow regime and the quality of trout habitat. The most critical period is typically during base flow (lowest flows of late summer to winter). A base flow ≥ 50% of the average annual daily flow is considered excellent for maintaining quality trout habitat, a base flow of 25 to 50% is considered fair, and a base flow of < 25% is considered poor (adapted from Binns and Eiserman 1979; Wesche 1980).

Adult. 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 requirement for the fish increases. As a result, an increase in temperature resulting in a decrease in dissolved oxygen can be detrimental to the fish. Optimal oxygen levels for rainbow trout are not well documented, but appear to be ≥ 7 mg/l at temperatures ≤ 15° C and ≥ 9 mg/l at temperatures > 15° 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), cutthroat trout generally avoid water with dissolved oxygen levels of less than 5 mg/l (Trojnar 1972; Sekulich 1974).

The incipient lethal level of dissolved oxygen for adult and juvenile rainbow trout is approximately 3 mg/l or less, depending on environmental conditions, especially temperature (Gutsell 1929; Burdick et al. 1954; Alabaster et al. 1957; Downing and Merken 1957; Doudoroff and Warren 1962). Although fish can survive at concentrations just above this level, they must make various physiological adaptations to low levels of dissolved oxygen that may jeopardize their health (Randall and Smith 1967; Kutty 1968; Hughes and Saunders 1970; Cameron 1971; Holeton 1971). For example, low levels of dissolved oxygen can result in reduced fecundity and even prevent spawning. Large fluctuations in dissolved oxygen may cause a reduction in food consumption and impaired growth (Doudoroff and Shumway 1970).

The upper and lower incipient lethal temperatures for adult rainbow are 25° and 0° C, respectively (Black 1953; Lagler 1956; McAfee 1966; Bidgood and Berst 1969; Hokanson et al. 1977). Zero growth rate occurred at 23° C for rainbow trout in the laboratory (Hokanson et al. 1977). Changes in the natural growth rate of rainbow trout are detrimental to their development and survival. Therefore, 25° C should be considered the upper limit suitable for rainbow trout and then only for short periods of time. Adult lake rainbow trout select waters with temperatures between 7 to 18° C (Fast 1973; May 1973) and avoid permanent residence where temperatures are above 18° C (May 1973). Adult stream rainbow trout select temperatures between 12.0 and 19.3° C (Garside and Tait 1958; Bell 1973; Cherry et al. 1977; McCauley et al. 1977). Dickson and Kramer (1971) reported that the greatest scope of rainbow trout activity occurred at 15 and 20° C when tested at 5° C temperature intervals. Stream rainbow trout select temperatures between 12 and 19° C; lake resident trout avoid temperatures > 18° C. Therefore, the optimal temperature range for rainbow trout is assumed to be 12 to 18° C.

The depth distribution of adult lake rainbow trout is usually a function of dissolved oxygen, temperature, and food. Adult lake rainbow trout remain at depths ≤ the 18° C isotherm and at dissolved oxygen levels > 3 mg/l (May 1973; Hess 1974).

Focal point velocities for adult cutthroat trout at territorial stations in Idaho streams were primarily between 10 and 14 cm/sec, with a maximum of 22 cm/sec (Griffith 1972). The focal point velocities for adult rainbow trout are assumed to be similar.

Precise pH tolerance and optimal ranges are not well documented for rainbow trout. Most trout populations can probably tolerate a pH range of 5.5 to 9.0, with an optimal range of 6.5 to 8.0 (Hartman and Gill 1968; Behnke and Zarn 1976).

Withler (1966) suggested that the correlation between the winter steelhead run and increased water volume indicates that a freshet condition is required to initiate upstream movement of spawners. Everest (1973) stated that speed of migration of summer-run steelhead in the Rogue River was inversely related to temperature and directly related to streamflows. Hanel (1971) observed that steelhead migration into the Iron Gate fish hatchery ceased when the water temperature dropped to 4° C and did not resume for several weeks until the temperature increased. This suggests that water temperatures should be $> 4°$ C but $\leq 18°$ C, and streamflow conditions should be above normal seasonal flows during upstream migrations of steelhead adults.

Embryo. Incubation time varies inversely with temperature. Eggs usually hatch within 28 to 40 days (Cope 1957), but may take as long as 49 days (Scott and Crossman 1973). The optimal temperature for embryo incubation is about 7 to 12° C. Calhoun (1966) reported increased mortalities of rainbow embryos at temperatures $< 7°$ C and normal development at temperatures ≥ 7 but $\leq 12°$ C. The optimal water velocity above rainbow trout redds is between 30 and 70 cm/sec. Velocities less than 10 cm/sec or greater than 90 cm/sec are unsuitable (Delisle and Eliason 1961; Thompson 1972; Hooper 1973).

The combined effects of temperature, dissolved oxygen, water velocity, and gravel permeability are important for successful incubation (Coble 1961). In a 30% sand and 70% gravel mixture, only 28% of implanted steelhead embryos hatched; of the 28% that hatched, only 74% emerged (Bjornn 1969; Phillips et al. 1975). Optimal spawning gravel conditions are assumed to include $\leq 5\%$ fines; $\geq 30\%$ fines are assumed to result in low survival of embryos and emerging yolk-sac fry. Suitable incubation substrate is gravel that is 0.3 to 10.0 cm in diameter (Delisle and Eliason 1961; Orcutt et al. 1968; Hooper 1973; Duff 1980). Optimal substrate size depends on the size of the spawners, but is assumed to average 1.5 to 6.0 cm in diameter for rainbows < 50 cm long and 1.5 to 10.0 cm in diameter for spawners ≥ 50 cm long (Orcutt et al. 1968). Doudoroff and Shumway (1970) reported that salmonids that incubated at low dissolved oxygen levels were weak and small with slower development and more abnormalities. Dissolved oxygen requirements for rainbow trout embryos are not well documented, but are assumed to be similar to the requirements for adults.

Fry. Rainbow trout remain in the gravel for about 2 weeks after hatching (Scott and Crossman 1973) and emerge 45 to 75 days after egg fertilization, depending on water temperature (Calhoun 1944; Lea 1968). When moving from natal gravels to rearing areas, rainbow trout fry exhibit what appears to be three distinct genetically controlled movement patterns: (1) movement downstream to a larger river, lake, or to the ocean; (2) movement upstream from an outlet river to a lake; or (3) local dispersion within a common spawning and rearing area to areas of low velocity and cover (Raleigh and Chapman 1971). Fry of lake resident fish may either move into the lake from natal streams during the first growing season or overwinter in the spawning stream and move into the lake during subsequent growing seasons.

Fry residing in streams prefer shallower water and slower velocities than do other life stages of stream trout (Miller 1957; Horner and Bjornn 1976). Fry utilize velocities less than 30 cm/sec, but velocities less than 8 cm/sec are preferred (Griffith 1972; Horner and Bjornn 1976). Fry survival decreases with increased velocity after the optimal velocity has been reached (Bulkley and Benson 1962; Drummond and McKinney 1965). A pool area of 40% to 60% of the total stream area is assumed to provide optimal fry habitat. Cover in the form of aquatic vegetation, debris piles, and the interstices between rocks is critical. Griffith (1972) states that younger trout live in shallower water and stay closer to escape cover than do older trout. Few fry are found more than 1 m from cover. As the young trout grow, they move to deeper, faster water. Everest (1969) suggested that one reason for this movement was the need for cover, which is provided by increased water depth, surface turbulence, and substrate that consists of large material.

Stream resident trout fry usually overwinter in shallow areas of low velocity near the stream margin, with rubble being the principal cover (Bustard and Narver 1975a). Optimal size of substrate used as winter cover by rainbow fry and small juveniles ranges from 10 to 40 cm in diameter (Hartman 1965; Everest 1969). An area of substrate of this size class that is ≥ 10% of the total habitat probably provides adequate cover for rainbow fry and small juveniles. The use of small diameter rocks (gravel) for winter cover may result in increased mortality due to greater shifting of the substrate (Bustard and Narver 1975a). The presence of fines (≥ 10%) in the riffle-run areas reduces the value of the area as cover for fry and small juveniles. Mantelman (1958) reported a preferred temperature range of 13 to 19° C for fry. Because fry occupy habitats contiguous with adults, their temperature and oxygen requirements are assumed to be similar to those of adults.

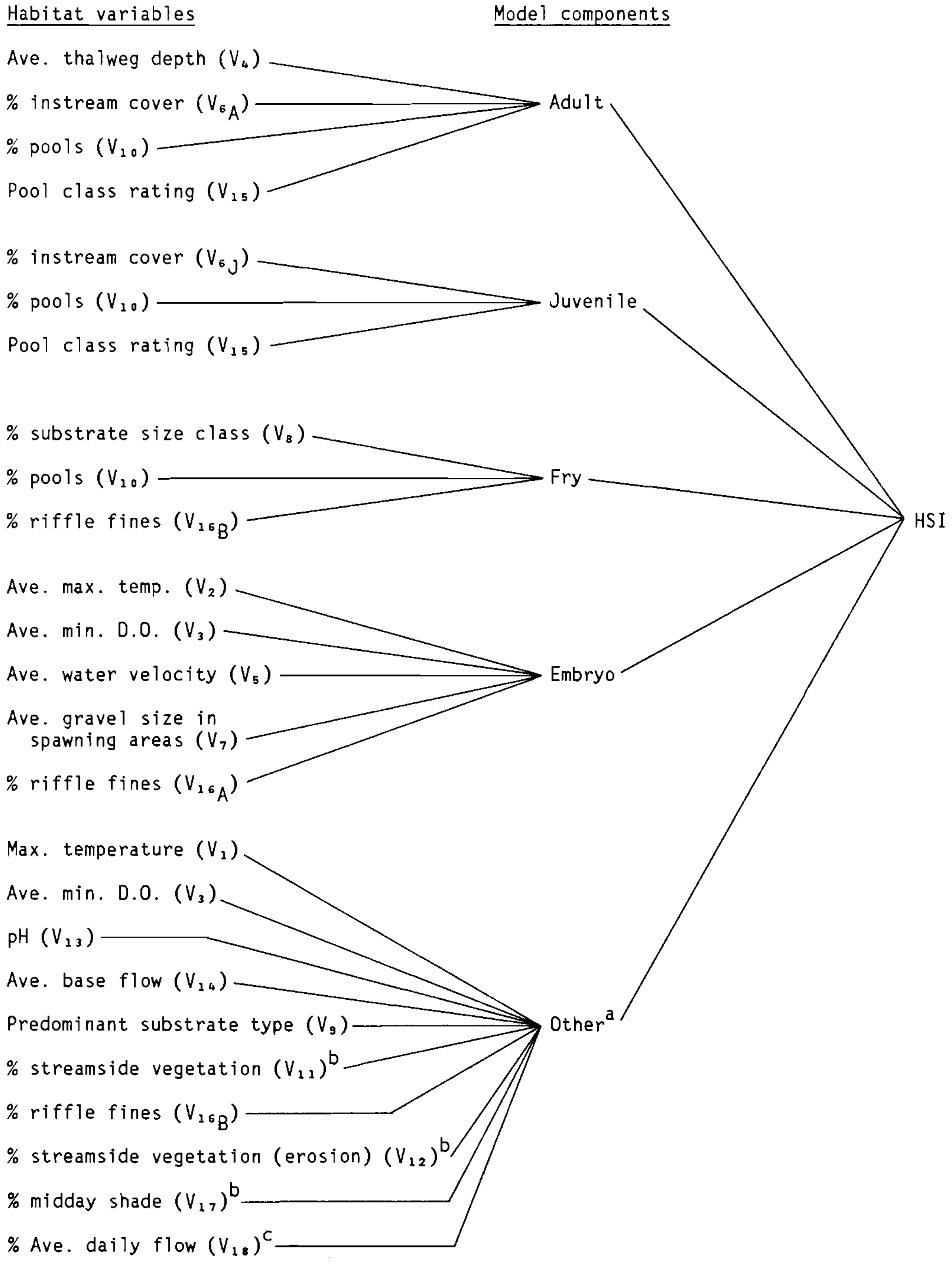
Juvenile. Griffith (1972) reported focal point velocities for juvenile cutthroat in Idaho of between 10 and 12 cm/sec, with a maximum velocity of 22 cm/sec. Metabolic rates are highest between 11 and 21° C, with an apparent optimal temperature of between 15 and 20° C (Dickson and Kramer 1971). In steelhead streams, temperatures should be < 13 but > 4° C (optimal 7 to 10° C) from March until June for normal smoltification to occur (Wagner 1974; Adams et al. 1975).

Common types of cover for juvenile trout are upturned roots, logs, debris piles, overhanging banks, riffles, and small boulders (Bustard and Narver 1975a). Young salmonids occupy different habitats in winter than in summer, with log jams and rubble important as winter cover. Wesche (1980) observed that larger cutthroat trout (> 15 cm long) and juveniles (≤ 15 cm) tended to use instream substrate cover more often than they used streamside cover (undercut banks and overhanging vegetation). However, juvenile brown trout preferred streamside cover. An area of cover ≥ 15% of the total habitat area appears to provide adequate cover for juvenile trout.

Because juvenile rainbow trout occupy habitats contiguous with adults, their temperature and oxygen requirements are assumed to be similar.

HABITAT SUITABILITY INDEX (HSI) MODELS

Figure 1 illustrates the assumed relationships among model variables, components, and the HSI for the rainbow trout model.



[a] Variables that affect all life stages.

[b] Optional variables.

[c] Steelhead variable.

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

Model Applicability

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

Season. The model rates the year-round freshwater habitat of rainbow trout.

Cover types. The model is applicable to freshwater riverine or lacustrine habitats.

Minimum habitat area. Minimum habitat area is the minimum area of continuous habitat that is required for a species to live and reproduce. Because trout can move considerable distances to spawn or locate suitable summer or winter rearing habitat, no attempt has been made to define a minimum amount of habitat for the species.

Verification level. An acceptable level of performance for this rainbow trout model is for it to produce an index between 0 and 1 that the authors and other biologists familiar with rainbow trout ecology believe is positively correlated with long term carrying capacity of the habitat. Model verification consisted of testing the model outputs from sample data sets developed by the authors to simulate rainbow trout habitat of high, medium, and low quality and model review by rainbow trout experts.

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. The component C_O contains variables related to water quality and food supply that affect all life stages of rainbow trout.

The model utilizes a modified limiting factor procedure. This procedure assumes that model variables and components with suitability indices in the average to good range, > 0.4 but < 1.0, can be compensated for by higher suitability indices of other related model variables and components. However, variables and components with suitabilities ≤ 0.4 cannot be compensated for and, thus, become limiting factors for the habitat suitability.

Adult component. Variable V_6, percent instream cover, is included because standing crops of adult trout are assumed to be related to the amount of cover available based on studies of brook and cutthroat trout. Percent pools (V_{10}) is included because pools provide cover and resting areas for adult trout. Variable V_{10} also quantifies the amount of pool habitat that is needed. Variable V_{15}, pool class rating, is included because pools differ in the amount and quality of escape cover, winter cover, and resting areas that they provide. Average thalweg depth (V_4) is included because average water depth affects the amount and quality of pools and instream cover available to adult trout and the migratory access to spawning and rearing areas.

Juvenile component. Variables V_6, percent instream cover; V_{10}, percent pools; and V_{15}, pool class rating are included in the juvenile component for the same reasons listed above for the adult component. Juvenile rainbow trout use these essential stream features for escape cover, winter cover, and resting areas.

Fry component. Variable V_8, percent substrate size class, is included because trout fry utilize substrate as escape cover and winter cover. Variable V_{10}, percent pools, is included because fry use the shallow, slow water areas of pools and backwaters as resting and feeding stations. Variable V_{16}, 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_5; gravel size in spawning areas, V_7; and percent riffle fines, V_{16}. Water velocity (V_5), gravel size (V_7), and percent fines (V_{16}) are interrelated factors that effect 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.

Other component. This component contains model variables for two subcomponents, water quality and food supply, that affect all life stages. The subcomponent water quality contains four variables: maximum temperature (V_1); average minimum dissolved oxygen (V_3); pH (V_{13}); and average base flow (V_{14}). The waterflow of all streams fluctuates on a seasonal cycle, and a correlation exists between the average annual daily streamflow and the annual low base flow period. Average base flow (V_{14}) is included to quantify the relationship between annual water flow fluctuations and trout habitat suitability. These four variables affect the growth and survival of all life stages except embryos, whose water quality requirements are included with the embryo component. The subcomponent food supply contains three variables: dominant substrate type (V_9); percent streamside vegetation (V_{11}); and percent riffle fines (V_{16}). Predominant substrate type (V_9) is included because the abundance of aquatic insects, an important food item for rainbow trout, is correlated with substrate type. Variable V_{16}, percent fines in riffle-run and spawning areas, is included because the presence of excessive fines in riffle-run areas reduces the production of aquatic insects. Variable V_{11} is included because allochthonous materials are an important source of nutrients in cold, unproductive trout streams.

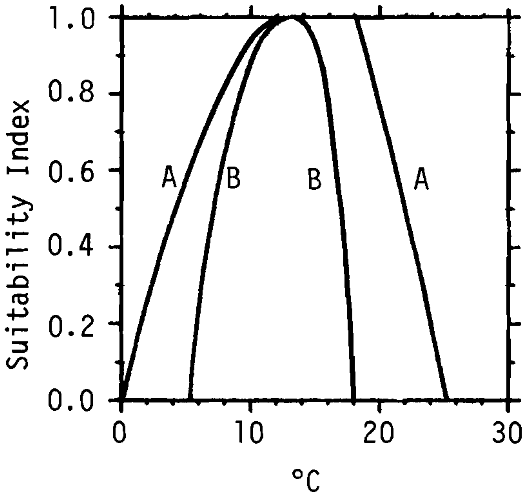
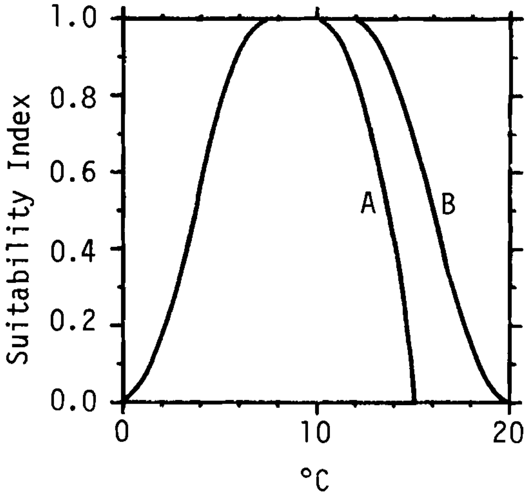
Variables V_{12}, V_{17}, and V_{18} are optional variables to be used only when needed and appropriate. Streamside vegetation, V_{12}, is an important means of controlling soil erosion, a major source of fines in streams, and for input of terrestrial insects. Variable V_{17}, percent midday shade, is included because the amount of shade can affect water temperature and photosynthesis in streams. Average daily flows, V_{18}, are associated with rapid upstream migration of steelhead adults. Variables V_{12} and V_{17} are used primarily for streams ≤ 50 m wide where temperature, photosynthesis, or erosion problems occur or when changes in the riparian vegetation are part of a potential project plan. Variable V_{18} is used only for habitat evaluation for spawning migration of steelhead trout.

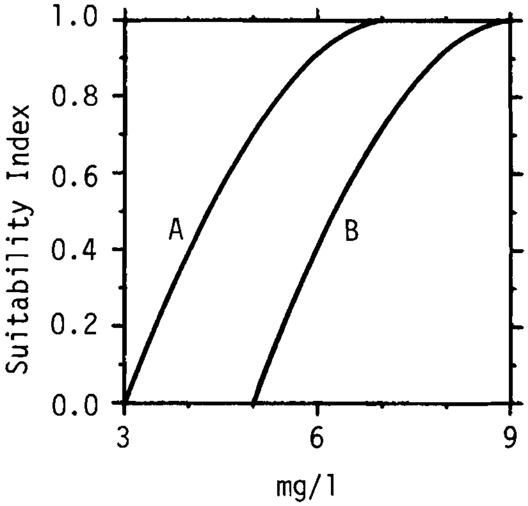
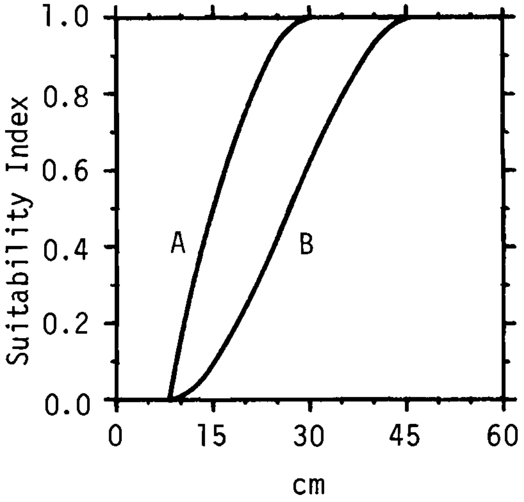
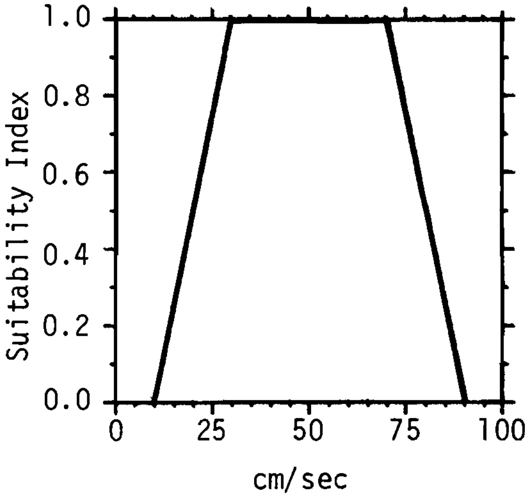
Suitability Index (SI) Graphs for Model Variables

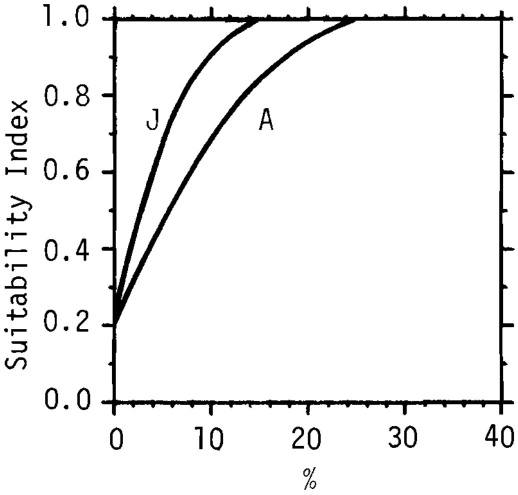
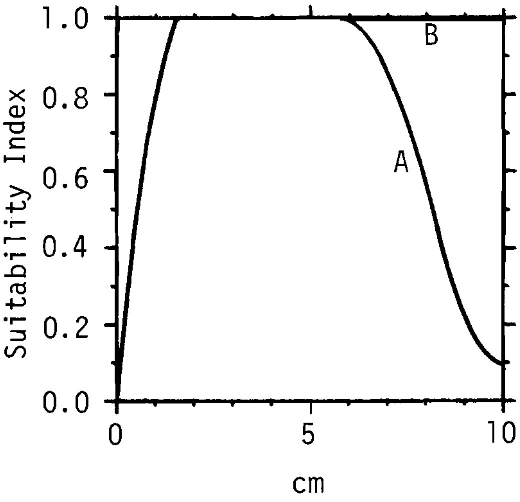
This section contains suitability index graphs for the 18 model variables. Equations and instructions for combining groups of variable SI scores into component scores and component scores into rainbow trout HSI scores are included.

The graphs were constructed by quantifying information on the effect of each habitat variable on the growth, survival, or biomass of rainbow trout. The curves were built on the assumption that increments of growth, survival, or biomass plotted on the y-axis of the graph could be directly converted into an index of suitability from 0.0 to 1.0 for the species, with 0.0 indicating unsuitable conditions and 1.0 indicating optimal conditions. Graph trend lines represent the authors' best estimate of suitability for the various levels of each variable. The graphs have been reviewed by biologists familiar with the ecology of the species, but some degree of SI variability exists. The user is encouraged to modify the shape of the graphs when existing regional information indicates that the variable suitability relationship is different from that illustrated.

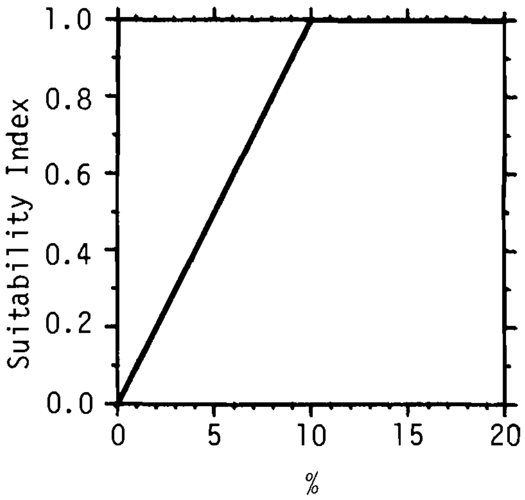
The habitat measurements and the SI graph construction are based on the premise that extreme, rather than average, values of a variable most often limit the carrying capacity of a habitat. Thus, extreme conditions, such as maximum temperatures and minimum dissolved oxygen levels, are often used in the graphs to derive the SI values 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	Average maximum water temperature (°C) during the warmest period of the year (adult, juvenile, and fry), and during upstream migrations of adult steelhead. For lacustrine habitats, use the temperature strata nearest to optimal in dissolved oxygen zones > 3 mg/l. A = resident rainbow trout B = migrating adult steelhead	
R	V_2	Average maximum water temperature (°C) during embryo development (all rainbows) and during the March to June smoltification period (steelhead juveniles). A = steelhead smolts B = embryos	

R,L	V_3	Average 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 optimal where dissolved oxygen is > 3 mg/l. A = ≤ 15° C B = > 15° C	
R	V_4	Average thalweg depth (cm) during the late growing season low water period (adult). A = ≤ 5 m stream width B = > 5 m stream width	
R	V_5	Average velocity (cm/sec) over spawning areas during embryo development.	

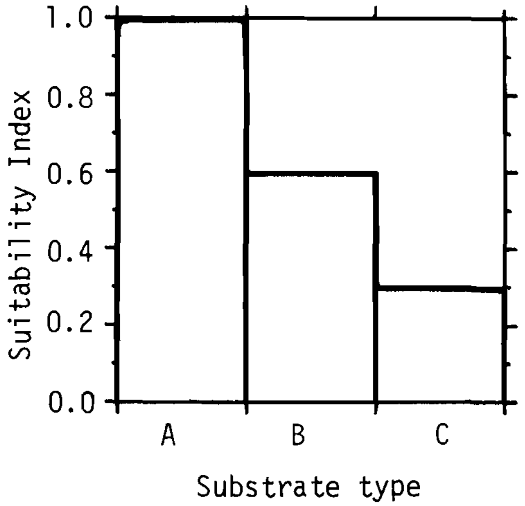
R	V_6	Percent instream cover during the late growing season low water period at depths ≥ 15 cm and velocities < 15 cm/sec. J = juveniles A = adults	
R	V_7	Average size of substrate (cm) in spawning areas, preferably during the spawning period. A = average size of spawner < 50 cm B = average size of spawner ≥ 50 cm To derive an average value for use with graph V_7, include areas containing the best spawning substrate sampled until all potential spawning sites are included or until the sample contains an area equal to 5% of the total rainbow habitat being evaluated.	

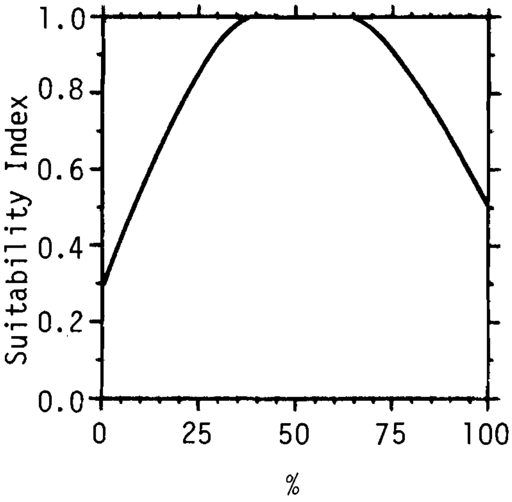
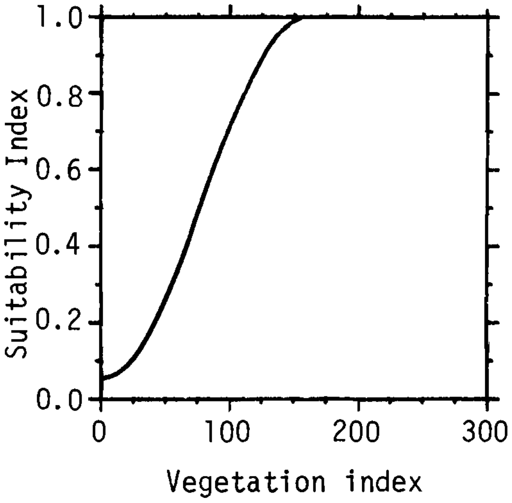
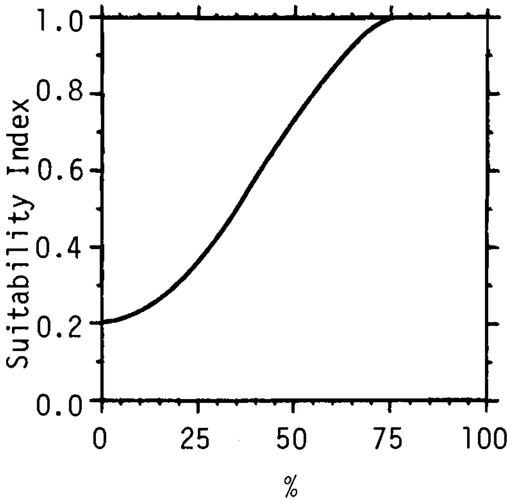
R V_8 Percent substrate size class (10 to 40 cm) used for winter and escape cover by fry and small juveniles.



R V_9 Predominant (≥ 50%) substrate type in riffle-run areas for food production.

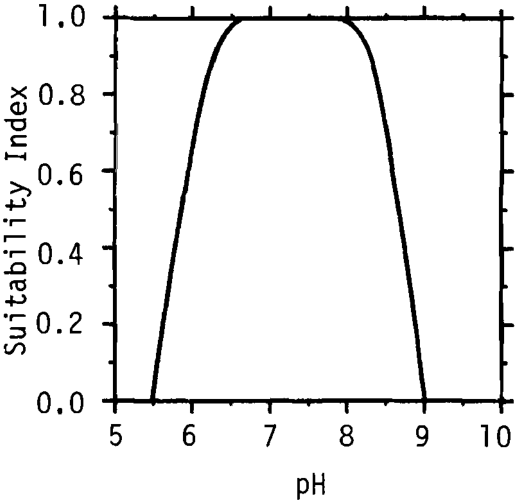
A) Rubble or small boulders (or aquatic vegetation in spring areas) predominant; limited amounts of gravel, large boulders, or bedrock.
B) Rubble, gravel, boulders, and fines occur in approximately equal amounts, or gravel is predominant. Aquatic vegetation may or may not be present.
C) Fines, bedrock, or large boulders are predominant. Rubble and gravel are insignificant (≤ 25%).



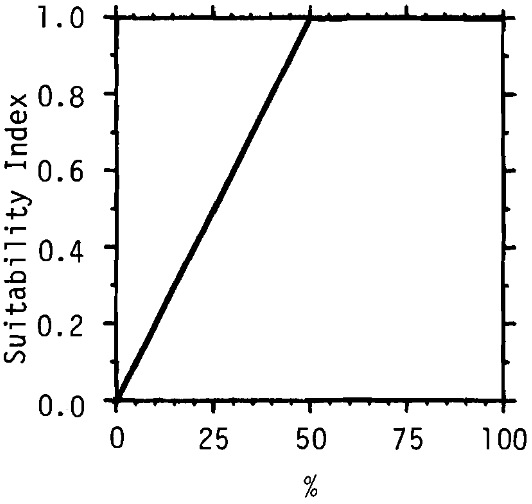
R	V_{10}	Percent pools during the late growing season low water period.	
R	V_{11}	Average percent vegetational ground cover and canopy closure (trees, shrubs, and grasses-forbs) along the streambank during the summer for allochthonous input. Vegetation Index = 2(% shrubs) + 1.5(% grasses) + (% trees). (For streams ≤ 50 m wide)	
R	V_{12} (Optional)	Average percent rooted vegetation and stable rocky ground cover along stream bank.	

R,L V_{13} Annual maximal or minimal pH. Use the measurement with the lowest SI value.

For lacustrine habitats, measure pH in the zone with the best combination of dissolved oxygen and temperature.



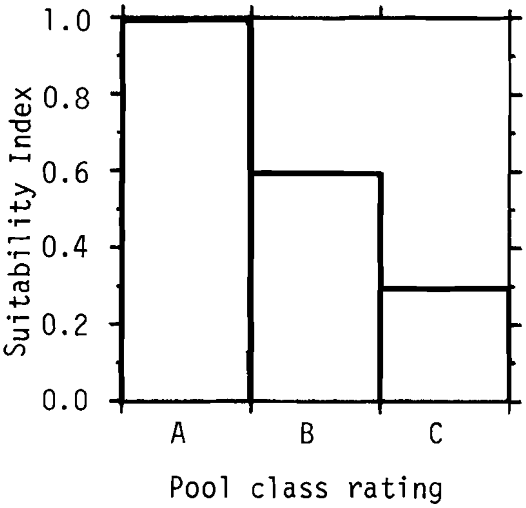
R V_{14} Average annual base flow regime during the late summer or winter low flow period as a percentage of the average annual daily flow.



R V_{15} 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 comprised 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.

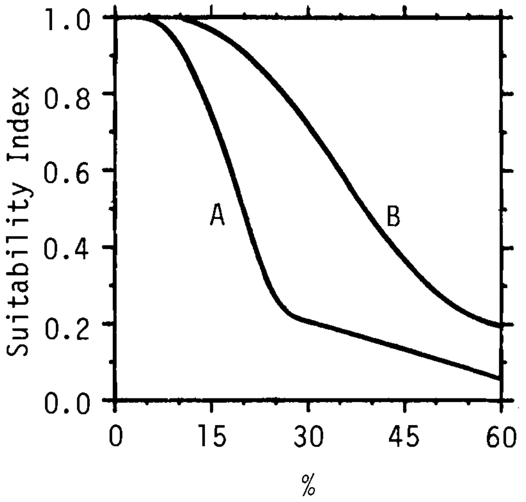
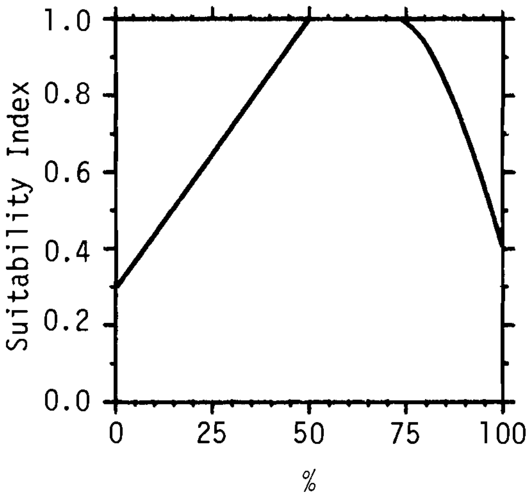
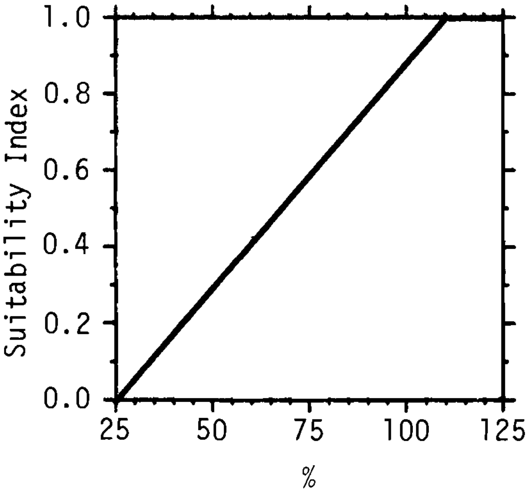
(See pool class descriptions below)



- First-class pool: Large and deep. Pool depth and size are sufficient to provide a low velocity resting area for several 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 a few 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 one to a very few adult trout. Cover, if present, is in the form of shade, surface turbulence, or very limited structures. Typical third-class pools are wide, shallow pool areas of streams or small eddies behind boulders. The entire bottom area of the pool is visible.

R	V_{16}	Percent fines (< 3 mm) in riffle-run and spawning areas during average summer flows. A = spawning B = riffle-run	
R	V_{17} (Optional)	Percent of stream area shaded between 1000 and 1400 hrs (for streams ≤ 50 m wide). Do not use for cold (< 18° C max. temp.), unproductive streams.	
R	V_{18} (Optional)	Percent average daily flow during the season of upstream migration of adult steelhead.	

An HSI based on the concept of a limiting factor can be obtained for a particular life stage of rainbow trout, or all life stages combined, by selecting the lowest suitability index (SI) for the appropriate listed habitat variables as is done in Table 1.

Alternate models and mathematical methods of aggregating SI's into life stage and species HSI's are presented in the following pages.

Table 1. Matrix table for displaying suitability indices (SI's) for rainbow trout habitat variables.

	SI's				
Variables	Adult	Embryo	Fry	Juvenile	Other
V_1 Maximum temperature					X
V_2 Maximum temperature (embryo)		X			
V_3 Minimum dissolved O_2		X			X
V_2 Average thalweg depth	X				
V_5 Average velocity (spawning)		X			
V_6 % cover	X			X	
V_7 Substrate size (spawning)		X			
V_8 % substrate class			X		
V_9 Substrate type (food)					X
V_{10} % pools	X		X	X	
V_{11} % riparian vegetation					X
V_{12} % ground cover (erosion)[a]					
V_{13} Maximum-minimum pH					X
V_{14} Average annual base flow					X
V_{15} Pool class	X			X	
V_{16} % fines		X	X		X
V_{17} % shade[a]					
V_{18} % average daily flow[a]					

[a] Optional variables.

Data sources and the assumptions used to construct the suitability index graphs for rainbow trout HSI models are presented in Table 2.

Riverine Model

This model uses a life stage approach with five components: adult; juvenile; fry; embryo; and other.

Adult (C_A). C_A variables: V_4; V_5; V_{10}; V_{15}; V_{1B}; and V_{18}

Case 1: Where V_6 is > $(V_{10} \times V_{15})^{1/2}$,

$$C_A = [V_4 \times V_6 \ (V_{10} \times V_{15})^{1/2}]^{1/3}$$

Case 2: Where V_6 is ≤ $(V_{10} \times V_{15})^{1/2}$,

$$C_A = [V_4 \ (V_{10} \times V_{15})^{1/2}]^{1/2}$$

Case 3: Steelhead (C_{AS})

$$C_{AS} = (C_A \times V_{1B} \times V_{18})^{1/3}$$

If V_4 or $(V_{10} \times V_{15})^{1/2}$ is ≤ 0.4 in either equation, then C_A = the lowest factor score.

Juvenile (C_J). C_J variables: V_6; V_{10}; V_{15}; and V_{2A}

Case 1:

$$C_J = \frac{V_6 + V_{10} + V_{15}}{3}$$

Or, if any variable is ≤ 0.4, C_J = the lowest variable score.

Table 2. Literature sources and assumptions for rainbow trout suitability indices.

Variable	and source[a]	Assumptions
V_1	Black 1953 Garside and Tait 1958 Dickson and Kramer 1971 Hanel 1971 May 1973 Cherry et al. 1977	Average maximal daily water temperatures have a greater effect on trout growth and survival than minimal temperatures. The temperature that supports the greatest scope of activity is optimal. In addition, the temperature range associated with rapid migration rates for adult steelhead is optimal.
V_2	Snyder and Tanner 1960 Calhoun 1966 Zaugg and McLain 1972 Zaugg and Wagner 1973 Wagner 1974	The average maximal daily water temperature during the embryo and smoltification development periods that is related to the highest survival of embryos and normal development of smolts is optimal. Temperatures that reduce survival or development of smolts are suboptimal.
V_3	Randall and Smith 1967 Doudoroff and Shumway 1970 Trojnar 1972 Sekulich 1974	The average minimal daily dissolved oxygen level during embryo development and the late growing season that is related to the greatest growth and survival of rainbow trout and trout embryos is optimal. Dissolved oxygen concentrations that reduce survival and growth are suboptimal.
V_4	Delisle and Eliason 1961 Estimated by authors.	Average thalweg depths that provide the best combination of pools, instream cover, and instream movement of adult trout are optimal.
V_5	Delisle and Eliason 1961 Thompson 1972 Hooper 1973 Silver et al. 1963	The average velocities over spawning areas affect habitat suitability because 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 2. (continued)

	Variable and source[a]	Assumptions
V_6	Boussu 1954 Elser 1968 Lewis 1969 Wesche 1980	Trout standing crops are correlated with the amount of usable cover. Usable cover is associated with water $\geq$ 15 cm deep and velocities $\leq$ 15 cm/sec. These conditions are associated more with pool than with riffle conditions. The best ratio of habitat conditions is approximately 50% pool area to 50% riffle area. Not all of the area of a pool provides usable cover. Thus, it is assumed that optimal conditions exist when usable cover comprises < 50% of the total stream area.
V_7	Orcutt et al. 1968 Bjornn 1969 Phillips et al. 1975 Duff 1980	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 comprise about 80% of the weight of the population. 500 kg x 80% = 400 kg of spawners. 3. Rainbow adults average about 0.2 kg each. $\frac{400\text{ kg}}{0.2\text{ kg}} = 2{,}000$ adult spawners per hectare 4. There are two adults per redd. $\frac{2{,}000}{2} = 1{,}000$ pairs

Table 2. (continued)

Variable and source[a]	Assumptions
	5. Each redd covers $\geq 0.5\ m^2$. $1{,}000 \times 0.5 \geq 500\ m^2/ha$ 6. There are 10,000 m^2 per hectare. $\frac{500}{10{,}000} = 5\%$ of total area
V_8 Hartman 1965 Everest 1969 Bustard and Narver 1975a	The substrate size range selected for escape and winter cover by trout fry and small juveniles is assumed to be optimal.
V_9 Pennak and Van Gerpen 1947 Hynes 1970 Binns and Eiserman 1979	The predominant substrate type containing the greatest numbers of aquatic insects is assumed to be optimal for insect production.
V_{10} Elser 1968 Fortune and Thompson 1969 Hunt 1971	The percent pools during late summer low flows that is associated with the greatest trout abundance is optimal.
V_{11} Idyll 1942 Delisle and Eliason 1961 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 allochthonous materials, followed by grasses and forbs, and then trees. The vegetational index is a reasonable approximation of optimal and suboptimal conditions for most trout stream habitats.
V_{12} Oregon/Washington Interagency Wildlife Conference 1979 Raleigh and Duff 1980	The average percent rooted vegetation and rocky ground cover that provides adequate erosion control to the stream is optimal.
V_{13} Hartman and Gill 1968 Behnke and Zarn 1976	The average annual maximal or minimal pH levels related to high survival of trout are optimal.

Table 2. (concluded)

	Variable and source[a]	Assumptions
V_{14}	Duff and Cooper 1976 Binns 1979	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_{15}	Lewis 1969	Pool classes associated with the highest standing crops of trout are optimal.
V_{16}	Cordone and Kelly 1961 Bjornn 1969 Phillips et al. 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_{17}	Sabean 1976, 1977 Anonymous 1979	The percent of shaded stream area during midday that is associated with optimal water temperatures and photosynthesis rates is optimal.[b]
V_{18}	Withler 1966 Everest 1973	The above average daily flows (freshets) associated with rapid upstream migrations of steelhead adults are optimal. Low flows associated with migration delays are suboptimal.

[a] The above references include data from studies on related salmonid species. This information has been selectively used to supplement, verify, or fill data gaps on the habitat requirements of rainbow trout.

[b] Shading is highly variable from site to site. Low elevations with warmer climates require abundant shading to maintain cool waters. At higher elevations with cooler climates, the absence of shading is beneficial because it results in higher photosynthetic rates and warming of water to a more optimal temperature.

Case 2: Steelhead (C_{JS})

$$C_{JS} = (C_J \times V_{2A})^{1/2}$$

Fry (C_F). C_F variables: V_8; V_{10}; and V_{16}

$$C_F = [V_{10} (V_8 \times V_{16})^{1/2}]^{1/2}$$

Or, if V_{10} or $(V_8 \times V_{16})^{1/2}$ is ≤ 0.4, C_F = the lowest factor score.

Embryo (C_E). C_E variables: V_2; V_3; V_5; V_7; and V_{16}

Steps in calculating C_E:

A. A potential spawning site is a ≥ 0.5 m^2 area of gravel, with an average diameter of 0.3 to 8.0 cm, covered by flowing water ≥ 15 cm deep. For steelhead, increase the spawning site area from 0.5 to 2.0 m and the gravel size to 0.3 to 10.0 cm. At each spawning site sampled, record:

   1. The average water velocity over the site;
   2. The average size of all gravel 0.3 to 8.0 cm;
   3. The percentage of fines < 0.3 cm in the gravel; and
   4. The total area.

B. Derive a spawning site suitability index (V_s) for each site by combining V_5, V_7, and V_{16} values for each site as follows.

$$V_s = (V_5 \times V_7 \times V_{16})^{1/3}$$

C. Derive a weighted average ($\bar{V}_s$) for all sites included in the sample.

Select the best V_s scores until all sites are included or until a total spawning area equal to, but not exceeding, 5% of the total trout habitat has been included, whichever comes first.

$$\bar{V}_s = \frac{\sum_{i=1}^{n} A_i \, V_{si}}{\text{total habitat area}} / 0.05 \text{ (output cannot exceed 1.0)}$$

where A_i = the area of each spawning site in m^2, but ΣA_i cannot exceed 5% of the total habitat

V_{si} = the individual SI's from the best spawning areas until all spawning sites have been included or until the SI's from an area equal to 5% of the total habitat being evaluated have been included, whichever occurs first.

Disregard area restrictions for steelhead. Because advanced juvenile and adult steelhead mature in the ocean, they can theoretically utilize a much greater spawning area than nonanadromous rainbows.

D. Derive C_E

C_E = the lowest score of V_2, V_3, or $\bar{V}_s$

Other (C_O). C_O variables: V_1; V_3; V_9; V_{11}; V_{12}; V_{13}; V_{14}; V_{16}; and V_{17}

$$C_O = \left[\frac{(V_9 \times V_{16})^{1/2} + V_{11}}{2} \times (V_1 \times V_3 \times V_{12} \times V_{13} \times V_{14} \times V_{17})^{1/N}\right]^{1/2}$$

where N = the number of variables within the brackets. Note that variables V_{12} and V_{17} are optional and, therefore, can be omitted (see page 13).

HSI determination. HSI scores can be derived for a single life stage, a combination of two or more life stages, or all life stages combined. In all cases, except for the embryo component (C_E), an HSI is obtained by combining one or more life stage component scores with the C_O component score.

1. Equal Component Value Method. The equal component value method assumes that each component exerts equal influence in determining the HSI. This method should be used to determine the HSI unless information exists that suggests that individual components should be weighted differently. Components: C_A; C_J; C_F; C_E; and C_O

$$HSI = (C_A \times C_J \times C_F \times C_E \times C_O)^{1/N}$$

where N = the number of components in the equation

Or, if any component is ≤ 0.4, the HSI = the lowest component value.

Solve the equation for the number of components included in the evaluation. There will be a minimum of two; one or more life stage components and the component (C_O), unless only the embryo life stage (C_E) is being evaluated, in which case, the HSI = C_E.

2. Unequal Component Value Method. This method also uses a life stage approach with five components: adult (C_A); juvenile (C_J); fry (C_F); embryo (C_E); and other (C_O). However, the C_O component is divided into two subcomponents, food (C_{OF}) and water quality (C_{OQ}). It is assumed that the C_{OF} subcomponent can either increase or decrease the suitability of the habitat by its effect on growth at each life stage, except embryo. The C_{OQ} subcomponent is assumed to exert an influence equal to the combined influence of all other model components in determining habitat suitability. This method also assumes that water quality is excellent; i.e., $C_{OQ} = 1$. When C_{OQ} is < 1, the HSI is decreased. In addition, when a basis for weighting the individual components exists, model component and subcomponent weights can be increased by multiplying each index value by multiples > 1. Model weighting procedures must be documented.

   Components and subcomponents: C_A; C_J; C_F; C_E; C_{OF}; and C_{OQ}

   Steps:

   A. Calculate the subcomponents C_{OF} and C_{OQ} of C_O

$$C_{OF} = \frac{(V_9 \times V_{16})^{1/2} + V_{11}}{2}$$

$$C_{OQ} = (V_1 \times V_3 \times V_{13} \times V_{14})^{1/4}$$

   Or, if any variable is ≤ 0.4, C_{OQ} = the value of the lowest variable.

B. Calculate the HSI by either the noncompensatory or the compensatory option.

Noncompensatory option. This option assumes that degraded water quality conditions cannot be compensated for by good physical habitat conditions. This assumption is most likely to be true for small streams (≤ 5 m wide) and for persistently degraded water quality conditions.

$$HSI = (C_A \times C_J \times C_F \times C_E \times C_{OF})^{1/N} \times C_{OQ}$$

Or, if any component is ≤ 0.4, the HSI = the lowest component value.

where N = the number of components and subcomponents inside the parentheses or, if the model components or subcomponents are weighted, N = the summation of weights selected

For steelhead, substitute C_{AS} and C_{JS} for C_A and C_J.

If only the embryo component is being evaluated, then HSI = $C_E \times C_{OQ}$.

Compensatory option. This method assumes that moderately degraded water quality conditions can be partially compensated for by good physical habitat conditions. This assumption is most useful for large rivers (≥ 50 m wide) and for temporary poor water quality conditions.

1) $HSI' = (C_A \times C_J \times C_F \times C_E \times C_{OF})^{1/N}$

Or, if any component is ≤ 0.4, the HSI' = the lowest component value.

where N = the number of components and subcomponents in the equation or, if the model components or subcomponents are weighted, N = the summation of the weights selected

For steelhead, substitute C_{AS} and C_{JS} for C_A and C_J.

2) If C_{OQ} is < HSI' , then $HSI = HSI' \times [1 - (HSI' - C_{OQ})]$;
if C_{OQ} is ≥ HSI, then HSI = HSI'.

3) If only the embryo component is being evaluated, substitute C_E for HSI' and follow the procedure in Step 2.

Lacustrine Models

The following models are designed to evaluate rainbow trout lacustrine habitat. The lacustrine model contains two components, water quality (C_{WQ}) and reproduction (C_R).

Water Quality (C_{WQ}). C_{WQ} variables: V_1; V_3; and V_{13}

$$C_{WQ} = (V_1 \times V_3 \times V_{13})^{1/3}$$

Or, if the SI scores for V_1 or V_3 are ≤ 0.4, C_{WQ} = the lowest SI score for V_1 or V_3.

Note: Lacustrine rainbows require a tributary stream for spawning and embryo development. If the embryo life stage habitat is included in the evaluation, use the embryo component steps and equations in the riverine model above, except that the area of spawning gravel needed is only about 1% of the total surface area of the lacustrine habitat.

Embryo (C_E). C_E variables: V_2; V_3; V_5; V_7; and V_{16}

$$\bar{V}_s = \frac{\sum_{i=1}^{n} A_i \; V_{si}}{\text{total habitat area}} / 0.01 \text{ (output cannot be > 1.0)}$$

$$HSI = (C_{WQ} \times C_E)^{1/2}$$

If only the lacustrine habitat is evaluated, the HSI = C_{WQ}.

Interpreting Model Outputs

Model HSI scores for individual life stages, composite life stages, or for the species as a whole are a relative indicator of habitat suitability. The HSI models, in their present form, are not intended to predict standing crops of fishes throughout the United States. Standing crop limiting factors, such as interspecific competition, predation, disease, water nutrient levels, and length of growing season, are not included in the aquatic HSI models. The models contain physical habitat variables important in maintaining viable populations of rainbow trout. If the model is correctly structured, a high HSI score for a habitat would indicate near optimal regional conditions for rainbow trout for those factors included in the model, intermediate HSI scores would indicate average habitat conditions, and low HSI scores would indicate poor habitat conditions. An HSI of 0 does not necessarily mean that the species is not present; it does mean that the habitat is very poor and that the species is likely to be scarce or absent.

Rainbow trout tend to occupy riverine habitats where few other fish species are present. Thus, factors such as disease, interspecific competition, and predation may have little affect on the model. When the rainbow trout model is applied to rainbow trout streams containing few other species and similar water quality and length of growing season conditions, it should be possible to calibrate the model output to reflect the size of standing crops within some reasonable confidence limits. This possibility, however, has not been tested with the present model.

Sample data sets selected by the authors to represent high, intermediate, and low habitat suitabilities are in Table 3, along with the SI's and HSI's generated by the rainbow trout nonanadromous riverine model. The model outputs calculated from the sample data sets (Tables 4 and 5) reflect what the authors believe carrying capacity trends would be in riverine habitats with the listed characteristics; thus, the model meets the specified acceptance level.

ADDITIONAL HABITAT MODELS

Model 1

Optimal riverine rainbow trout habitat is characterized by:

1. Clear, cold water with an average maximum summer temperature of < 22° C;

2. Approximately a 1:1 pool-to-riffle ratio;

3. Well vegetated, stable stream banks;

4. Cover ≥ 25% of the stream area;

5. Relatively stable water flow regime with < 50% of the annual fluctuation from the average annual daily flow;

Table 3. Sample data sets using the nonanadromous riverine rainbow trout HSI model.

		Data set 1		Data set 2		Data set 3	
Variable		Data	SI	Data	SI	Data	SI
Max. temperature (°C)	V_1	14	1.0	15	1.0	16	1.0
Max. temperature (°C)	V_2	12	1.0	15	0.66	17	0.4
Min. dissolved O_2 (mg/l)	V_3	9	1.0	7	0.73	6	0.42
Ave. depth (cm)	V_4	25	0.9	18	0.6	18	0.6
Ave. velocity (cm/s)	V_5	30	1.0	25	0.7	20	0.57
% cover	V_6	20	A 0.95 J 1.0	10	A 0.65 J 0.92	10	A 0.65 J 0.92
Ave. gravel size (cm)	V_7	4	1.0	3	1.0	2.5	1.0
Predom. substrate size (cm)	V_8	15	1.0	7	0.7	7	0.7
Predom. substrate type	V_9	Class A	1.0	Class B	0.6	Class B	0.6
% pools	V_{10}	55	1.0	15	0.65	10	0.46
% streamside vegetation	V_{11}	225	1.0	175	1.0	200	1.0
% bank vegetation	V_{12}	95	1.0	40	0.6	35	0.5
Max. pH	V_{13}	7.1	1.0	7.2	1.0	7.2	1.0
% average base flow	V_{14}	37	0.8	30	0.6	25	0.5
Pool class rating	V_{15}	Class A	1.0	Class B	0.6	Class C	0.3
% fines (A)	V_{16}	5	1.0	20	0.5	20	0.5
% fines (B)	V_{16}	20	0.9	30	0.6	30	0.6
% midday shade	V_{17}	60	1.0	60	1.0	60	1.0

Table 4. Average value method.

Variable	Suitability index Data set 1	 Data set 2	 Data set 3
Component			
C_A	0.95	0.62	0.37
C_J	1.00	0.72	0.30
C_F	1.00	0.65	0.55
C_E	1.00	0.66	0.40
C_O	0.96	0.79	0.73
Species HSI	0.98	0.68	0.30

Table 5. Average value, probability method.

Variable	Suitability index Data set 1	 Data set 2	 Data set 3
Component			
C_A	0.95	0.62	0.37
C_J	1.00	0.72	0.30
C_F	1.00	0.65	0.55
C_E	1.00	0.66	0.40
C_{OF}	0.97	0.80	0.80
C_{OQ}	0.95	0.81	0.68
Species HSI			
Noncompensatory	0.94	0.56	0.30
Compensatory	0.95	0.70	0.30

6. Relatively stable summer temperature regime, averaging about 13° C ± 4° C; and

7. A relatively silt free rocky substrate in riffle-run areas.

$$HSI = \frac{\text{number of attributes present}}{7}$$

Model 2

A riverine trout habitat model has been developed by Binns and Eiserman (1979) and Binns (1979). Transpose the model output of pounds per acre to an index as follows:

$$HSI = \frac{\text{model output of pounds per acre}}{\text{regional maximum pounds per acre}}$$

Model 3

Optimal lacustrine rainbow trout habitat is characterized by:

1. Clear, cold water with an average summer midepilimnion temperature of $< 22°$ C;

2. Dissolved oxygen content of epilimnion of ≥ 8 mg/l;

3. Access to riverine spawning tributaries;

4. A midepilimnion pH of 6.5-8.0; and

5. Abundance of aquatic invertebrates.

$$HSI = \frac{\text{number of attributes present}}{5}$$

However, a high elevation lake with optimal habitat will have only a fraction of the trout production of a more eutrophic lake at a lower elevation, if no other fish species are present in either lake.

Model 4

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

INSTREAM FLOW INCREMENTAL METHODOLOGY (IFIM)

The U.S. Fish and Wildlife Service's Instream Flow Incremental Methodology (IFIM), as outlined by Bovee 1982, is a set of ideas used to assess instream flow problems. The Physical Habitat Simulation System (PHABSIM), described by Milhous et al. 1981, is one component of IFIM that can be used by investigators interested in determining the amount of available instream habitat for a fish species as a function of streamflow. The output generated by PHABSIM can be used for several IFIM habitat display and interpretation techniques, including:

1. Optimization. Determination of monthly flows that minimize habitat reductions for species and life stages of interest;

2. Habitat Time Series. Determination of the impact of a project on habitat by imposing project operation curves over historical flow records and integrating the difference between the curves; and

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

Suitability Index Graphs as Used in IFIM

PHABSIM utilizes Suitability Index graphs (SI curves) that describe the instream suitability of the habitat variables most closely related to stream hydraulics and channel structure (velocity, depth, substrate, temperature, and cover) for each major life stage of a given fish species (spawning, egg incubation, fry, juvenile, and adult). The specific curves required for a PHABSIM analysis represent the hydraulic-related parameters for which a species or life stage demonstrates a strong preference (i.e., a pelagic species that only shows preferences for velocity and temperature will have very broad curves for depth, substrate, and cover). Instream Flow Information Papers 11 (Milhous et al. 1981) and 12 (Bovee 1982) should be reviewed carefully before using any curves for a PHABSIM analysis. SI curves used with the IFIM are quite similar to the SI curves developed in many HSI models. These two types of SI curves may be interchangeable after conversion to the same units of measurement (English, metric, or codes). SI curve validity is dependent on the quality and quantity of information used to generate the curve. The curves used need to accurately reflect the conditions and assumptions inherent to the model(s) used to aggregate the curve-generated SI values into a measure of habitat suitability. If the necessary curves are unavailable or if available curves are inadequate (i.e., built on different assumptions), a new set of curves should be generated.

There are several ways to develop SI curves. The method selected depends on the habitat model that will be used and the available database for the species. The transferability of the curve is not obvious and, therefore, the method by which the curve is generated and the extent of the database are very important. Care also must be taken to choose the habitat model most appropriate for the specific study or evaluation; the choice of models will determine the type of SI curves that will be used.

A system with standard terminology has been developed for classifying SI curve sets and describing the database used to construct the curves in IFIM applications. There are four categories in the classification. A category one curve has a generalized description or summary of habitat preferences as its database. This type of curve is based on information concerning the upper and lower limits of a variable for a species (e.g., juveniles are usually found at water depths of 0.3 to 1.0 m). Expert opinion can also be used to define the optimal or preferred condition within the limits of tolerance (e.g., juveniles are found at water depths of 0.3 to 1.0 m, but are most common at depths from 0.4 to 0.6 m).

Utilization curves (category two) are based on frequency analyses of fish observations in the stream environment with the habitat variables measured at each sighting [see Instream Flow Information Paper 3 (Bovee and Cochnauer 1977) and Instream Flow Information Paper 12 (Bovee 1982:173-196)]. These curves are designated as utilization curves because they depict the habitat conditions a fish has been observed to use within a specific range of available conditions. If the data are correctly collected for utilization curves, the resulting function represents the probability of occurrence of a particular environmental condition, given the presence of a fish of a particular species, $P(E|F)$. However, due to sampling problems, a utilization curve cannot be assumed to reflect fish preference or optimal conditions. Also, utilization curves may not be transferable to streams that differ substantially in size or complexity from the streams where the data were obtained.

A preference curve (category three) is a utilization curve that has been corrected for environmental bias. For example, if 50% of the fish are found in pools over 1.0 m deep, but only 10% of the stream has such pools, the fish are actively selecting that type of habitat. Preference curves approximate the function of the probability of occurrence of a fish in a given set of environmental conditions:

$$P(F|E) \approx \frac{P(E|F)}{P(E)}$$

Only a limited number of experimental data sets have been compiled into IFIM preference curves. The development of these curves should be the goal of all new curve development efforts for use in IFIM.

An additional set of curves is still largely conceptual. One type of curve under consideration is a cover-conditioned, or season-conditioned, preference curve set. Such a curve set would consist of different depth-velocity preference curves as a function or condition of the type of cover present or the time of year. No fourth category curves have been developed at this time.

The advantage of these last two sets of curves is the significant improvement in precision and confidence in the curves when applied to streams similar to the streams where the original data were obtained. The degree of increased accuracy and transferability obtainable when applying these curves to dissimilar streams is unknown. In theory, the curves should be widely transferable to any stream in which the range of environmental conditions is within the range of conditions found in the streams from which the curves were developed.

Availability of Graphs for Use in IFIM

Numerous curves are available for the IFIM analysis of rainbow trout habitat (Table 6). Investigators are asked to review the curves (Figs. 2-5) and modify them, if necessary, before using them.

Spawning. For IFIM analyses of rainbow trout spawning habitat, use curves for the time period during which spawning occurs (which is dependent on locale). Spawning curves are broad and, if more accuracy is desired, investigators are encouraged to develop their own curves which will specifically reflect habitat utilization at the selected site.

Spawning velocity. Hartman and Galbraith (1970) measured water velocities 0.66 feet above 550 redds during April through June, 1966 and 1967, in the Lardeau River, British Columbia, and found few redds constructed in areas where velocities were less than 1.0 feet per second (fps); most redds were associated with velocities ranging 1.6 to 3.0 fps (velocities from zero to greater than 4.0 fps were available). Smith (1973) determined that 95% of the redds (n = 51) observed in the Deschutes River, Oregon, were in velocities ranging from 1.6 to 3.0 fps; Hooper (1973) measured velocities over redds (n = 10) which ranged from 1.4 to 2.7 fps in the South Fork of the Feather River, California; and Orcutt et al. (1968) found that average velocities 0.4 feet above redds (n = 54 to 68) ranged from 2.3 to 2.5 fps in Idaho streams. The SI curve for spawning velocity (Fig. 2) assumes that velocities less than 1.0 or greater than 3.0 fps are unsuitable for rainbow trout spawning.

Table 6. Availability of curves for IFIM analysis of rainbow trout habitat.

	Velocity[a]	Depth[a]	Substrate[a,b]	Temperature[a]	Cover[a]
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 for V_{7B}.	Use SI curve for V_{2B}.	No curve necessary.
Fry	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	No curve available.
Juvenile	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve for V_6.
Adult	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Use SI curve for V_6.

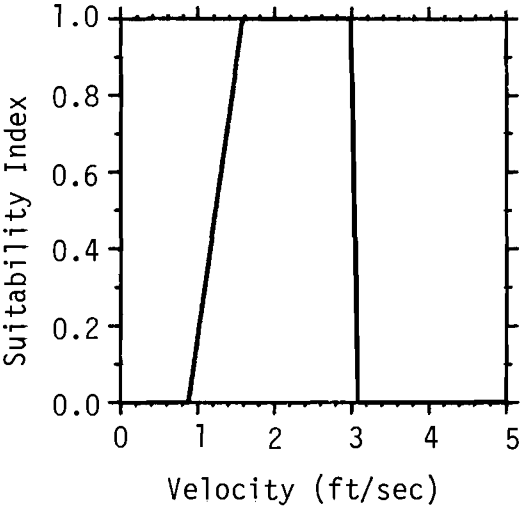
[a] When use of SI curves is prescribed, refer to the appropriate curve in the HSI or IFIM section.

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

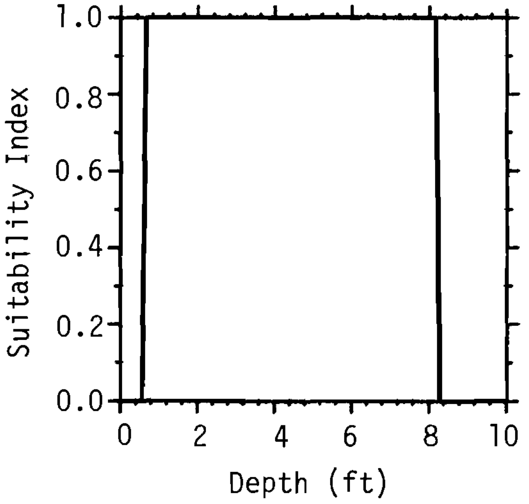
1 = plant detritus/organic material
2 = mud/soft clay
3 = silt (particle size < 0.062 mm)
4 = sand (particle size 0.062-2.000 mm)
5 = gravel (particle size 2.0-64.0 mm)
6 = cobble/rubble (particle size 64.0-250.0 mm)
7 = boulder (particle size 250.0-4000.0 mm)
8 = bedrock (solid rock)

Coordinates

x	y
0.0	0.0
0.9	0.0
1.6	1.0
3.0	1.0
3.1	0.0
100.0	0.0



x	y
0.0	0.0
0.6	0.0
0.7	1.0
8.2	1.0
8.3	0.0
100.0	0.0



x	y
0.0000	0.0
0.0005	0.0
0.0010	1.0
4.0000	1.0
4.1000	0.0
100.0000	0.0

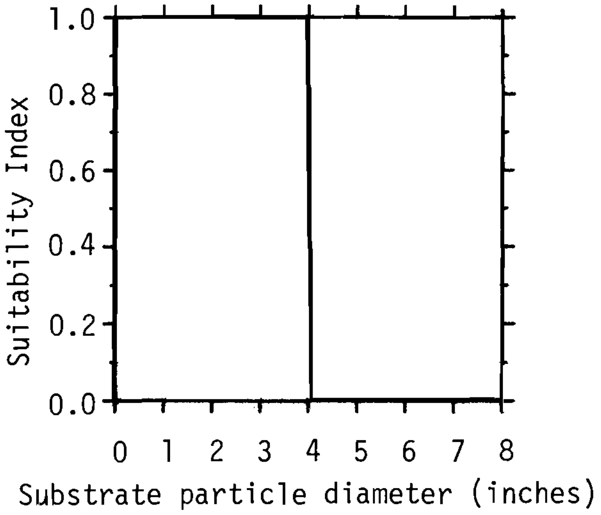


Figure 2. SI curves for rainbow trout spawning velocity, depth, substrate, and temperature.

Coordinates

x	y
0.0	0.0
35.0	0.0
36.0	1.0
60.0	1.0
61.0	0.0
100.0	0.0

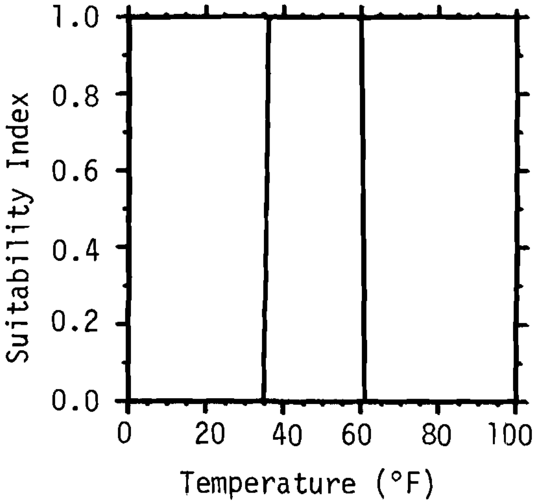


Figure 2. (concluded)

Spawning Depth. Smith (1973) found 95% of rainbow trout redds in depths greater than 0.6 feet; Hooper (1973) found depths of redds ranged from 0.7 to 1.1 feet; Orcutt et al. found redds in depths from 0.7 to greater than 5.0 feet; Hartman and Galbraith (1970) found the majority of redds (n = 550) in depths ranging from 1.6 to 8.2 feet, and the most intensive nest digging occurred in depths of 5.7 to 6.6 feet (maximum depths available ranged from 13 to 16 feet). Therefore, depths less than 0.6 and greater than 8.2 feet are assumed to be unsuitable for spawning (although 8.2 feet may not be the upper limit; Fig. 2).

Spawning substrate. Hartman and Galbraith (1970) found that gravel composed of particle sizes ranging from 0.04 to 4.0 inches in diameter were utilized for spawning, two-thirds of which were from 0.5 to 3.0 inches in diameter (particle sizes to 18 inches in diameter were available). Hooper (1973) found that preferred spawning substrate consisted of particles from 0.5 to 1.5 inches in diameter, although particles from 0.25 to 3.0 inches were utilized; Orcutt et al. (1968) found that steelhead favored gravels from 0.5 to 4.0 inches in diameter; Coble (1961) stated that salmonids dug redds in substrates ranging from silt to 3-inch diameter cobble (particles up to 4 inches in diameter were available) in Lincoln County, Oregon. Therefore, substrates consisting of particle sizes ranging from silt (< 0.002 inches) to cobble (4.0 inches) are considered suitable for spawning (though not necessarily suitable for egg incubation; Fig. 2). The particle size range of spawning substrate selected may be dependent on the size of the spawner.

Spawning cover. No information was found in the literature concerning cover requirements for rainbow trout spawning. The author assumes that cover is not important, and it may be omitted from the FISHFIL (Milhous et al. 1981).

Spawning temperature. Scott and Crossman (1973) stated that rainbow trout usually spawn at 50 to 60° F; Carlander (1969) stated that peak spawning near Finger Lakes, New York, occurred at 42 to 55° F; Hooper (1973) stated that temperatures ranging from 37 to 55° F are desirable for spawning; and Orcutt et al. (1981) found that spawning occurred at 36 to 47° F in Idaho streams. The author assumes that temperatures ranging from 36 to 60° F are suitable for spawning (Fig. 2), depending on locale.

Egg incubation. For IFIM analyses of rainbow trout egg incubation habitat, curves should be used for the time period from the beginning of spawning to 30 to 100 days beyond the end of spawning, depending on locale and water temperatures (Carlander 1969). The recommended analysis of incubation with IFIM is the effective spawning program, which computes suitability of each stream cell based on both spawning and incubation criteria over a range of flows. This program is explained in a working paper available from IFG (Milhous 1982).

Egg incubation velocity. Evidence suggests that water velocity may not be important for embryo hatching success if dissolved oxygen concentrations around embryos are greater than 2.6 ppm (Coble 1961; Silver et al. 1963; Reiser and White 1981, 1983). At low concentrations of dissolved oxygen, however, apparent velocities must be sufficient to deliver oxygen to embryos, remove metabolic waste products, and keep the substrate free from silt. Silver et al. (1963) found that rates of development and lengths of fry upon hatching were greater at higher velocities and dissolved oxygen concentrations. Therefore, given suitable spawning velocities (Fig. 2), it may be assumed that egg incubation velocities above redds which range from 1.0 to 3.0 fps (at adequate levels of dissolved oxygen and suitable substrate) will yield suitable apparent velocities among embryos. Another type of incubation velocity criteria is based on the shear velocities needed to prevent sediment of various sizes from settling out on the redds. This approach is documented in the effective spawning working paper mentioned above.

Egg incubation depth. Depth may not be an important variable for egg incubation in many cases (Reiser and White 1981, 1983) as long as eggs are kept moist during incubation and redds are submerged when fry begin to hatch and emerge. Therefore, the author assumes that the SI curve for spawning depth (Fig. 2) may also be used for egg incubation depth.

Egg incubation substrate. Although rainbow trout utilize a wide range of substrate types for spawning (Coble 1961), the author assumes that particles must be at least 0.5 inches in diameter to permit adequate percolation for successful embryonic development, and the SI curve for V_{7B} (page 16) may be used.

Egg incubation cover. The author assumes that cover is not important, and cover may, therefore, be omitted from FISHFIL. The egg incubation substrate curve should satisfy embryo cover requirements.

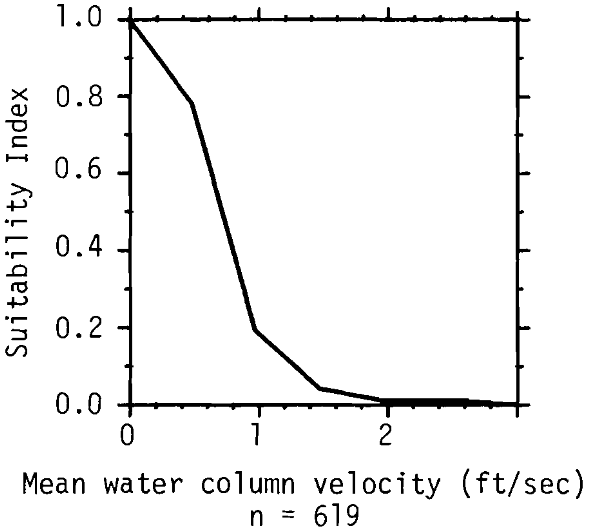
Egg incubation temperature. Kwain (1975) found the highest survival rate for rainbow trout embryos at temperatues of 45 and 50° F; low survival (15 to 40%) at 59° F; and moderate survival at 37 and 41° F. According to Hooper (1973), the desirable temperature range for egg incubation of trout is 42 to 54° F, and the extremes are 35 and 61° F. Therefore, the SI curve for V_{2B} (page 14) may be used.

Fry. Rainbow trout fry lose their yolk sacs at lengths of 1.4 to 1.6 inches, approximately 3-4 months after hatching (Carlander 1969). The author assumes that fry habitat is required from the end of the spawning period to 4 months beyond the end of the egg incubation period (from the time that fry emerge from the spawning gravel to when they become juveniles).

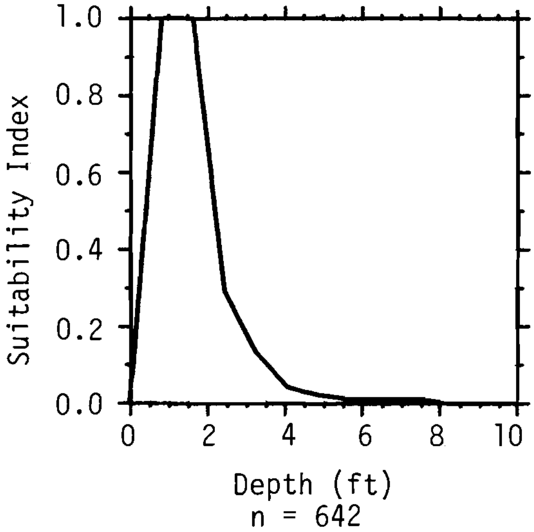
Fry velocity. Moyle et al. (1983) observed fry ($\leq$ 2 inches in length) in Cherry and Eleanor Creeks (n=404), Putah Creek (n=134), and Deer Creek (n=81), California. Maximum velocities available were 2 fps in Putah Creek and > 3.44 fps in Cherry, Eleanor, and Deer Creeks. Weighted mean frequencies were calculated for each velocity and then normalized, with the highest frequency being set to SI = 1.0 (Fig. 3).

Coordinates

x	y
0.00	1.00
0.49	0.78
0.98	0.19
1.48	0.04
1.97	0.01
2.46	0.01
2.95	0.00
100.00	0.00



x	y
0.00	0.00
0.10	0.11
0.82	1.00
1.64	1.00
2.46	0.29
3.28	0.13
4.10	0.04
4.92	0.02
5.74	0.01
7.38	0.01
8.20	0.00
100.00	0.00



x	y
0.0	0.00
1.0	0.00
2.0	0.02
3.0	0.01
4.0	0.17
5.0	0.13
6.0	1.00
7.0	1.00
8.0	0.18
8.1	0.00
100.0	0.00

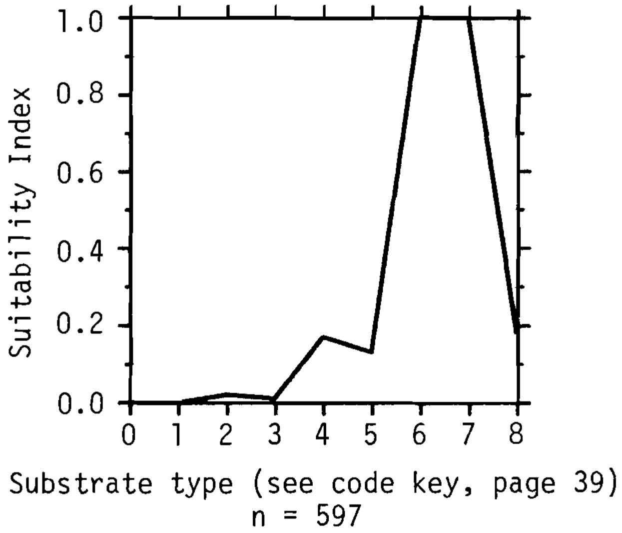


Figure 3. SI curves for rainbow trout fry velocity, depth, substrate, and temperature.

Coordinates

x	y
0.0	0.00
32.0	0.00
37.4	0.08
50.0	0.80
56.8	1.00
66.2	1.00
69.8	0.80
77.0	0.00
100.0	0.00

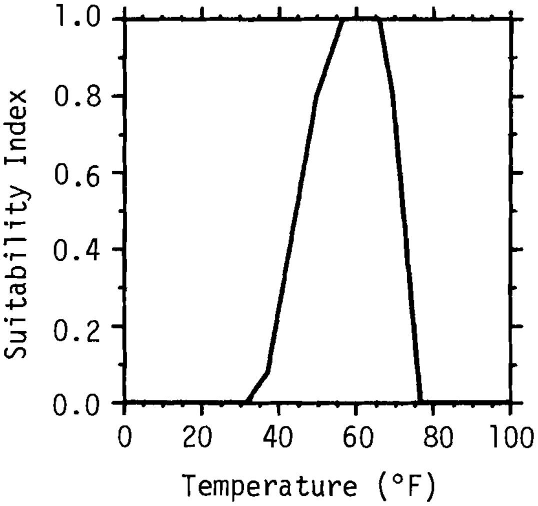


Figure 3. (concluded)

Fry depth. The SI curve for fry depth was developed in the same manner as the velocity curve, using data from Deer Creek (n=103), Cherry and Eleanor Creeks (n=404), and Putah Creek (n=135) (Moyle et al. 1983). Depths to 1.7 ft were available in Putah Creek; to 6.6 ft in Deer Creek; and to greater than 9.0 ft in Cherry and Eleanor Creeks. The final curve (Fig. 3) was modified based on the assumption that SI = 1.0 at depths ranging from 0.82 ft (as in Putah and Deer Creeks) to 1.64 ft (as in Cherry and Eleanor Creeks); and that SI = 0.0 at a depth of 0.0 ft and SI = 0.11 at a depth of 0.1 ft. For depths greater than 1.7 ft, Putah Creek was excluded, and for depths greater than 6.6 ft, Deer Creek was excluded from the analysis.

Fry substrate. The SI curve for fry substrate was generated in the same way as the curves for depth and velocity. Substrate available in Putah Creek (n=123) ranged from mud to bedrock; and in Deer Creek (n=70), Cherry Creek, and Eleanor Creek (n=404) it ranged from silt to bedrock. The curve (Fig. 3) was modified based on the assumption that SI = 1.0 for cobbles (as in Deer and Putah Creeks) and for boulders (as in Cherry and Eleanor Creeks). Bustard and Narver (1975) also found that age 0 steelhead associated with substrate consisting primarily of particles from 4 to 10 inches in diameter (cobble) in Carnation Creek, British Columbia, during the winter.

Fry cover. Cover requirements of rainbow trout fry are unknown by IFASG at this time. The author assumes that substrate is used for cover, and thus cover may be omitted from FISHFIL; or a cover curve may be developed by the investigator.

Fry temperature. Peterson et al. (1979), in lab experiments, found that temperatures preferred by rainbow trout fry (between 1.1 and 1.8 inches in length) ranged from 56.8 to 58.6° F (n=30). Kwain and McCauley (1978) found that age was a factor in temperatures preferred (selected) by rainbow trout, and fry at 1 month selected 66.2° F; at 2 months, 65.3° F; at 3 months, 64.4° F; and at 5 months, 59.7 to 63.7° F. Kwain (1975) found that the growth rate of fry at 50 F was ten times greater than at 37.4° F. Based on the information available for fry up to 1.8 inches in length and up to 4 months after hatching, the SI curve for temperature (Fig. 3) is assumed to be reasonably accurate. It will be modified as new information becomes available.

Juvenile. Juvenile rainbow trout range in length from approximately 1.8 to 7.9 inches, or from 4 months of age to sexual maturity (usually age II or III; Carlander 1969). Juveniles are probably the most difficult life stage for which to develop criteria, because of the variability in size.

Juvenile velocity. Factors which may affect velocity preferences of rainbow trout include water temperature, size and activity of the individual trout, stream flow, season, habitat availability, species interactions, and stream location (Logan 1963; Chapman and Bjornn 1969; Bjornn 1971; Everest and Chapman 1972; Bustard and Narver 1975; Moyle et al. 1983). Moyle et al. (1983) observed juvenile rainbow trout (from 2.0 to 4.7 inches in length) in Putah Creek (n=35), Deer Creek (n=108), Martis Creek (n=58), Cherry Creek, and Eleanor Creek (n=300), and in the Tuolumne River (n=45). The maximum velocity available in Putah Creek was 2.0 fps; in the Tuolumne River it was 2.5 fps; in Martis Creek it was 4.2 fps; and in Deer, Cherry, and Eleanor Creeks it was greater than 3.4 fps. Data from all streams were used to generate the velocity curve (Fig. 4). Weighted means were calculated for each velocity and then normalized, with the highest SI being set to 1.0. The final curve is very similar to the results of Bustard and Narver (1975) who collected Age 0 (n=78) and Age I+ (n=122) juvenile steelhead trout in Carnation Creek, British Columbia, during the winter. They found that juveniles preferred velocities less than 0.5 fps, and almost no individuals were found in velocities greater than 1 fps at 45° F. Gosse (1982), however, found that velocities preferred by juvenile rainbow trout (< 9 inches in length) were partially dependent upon activity (random or stationary swimming), season, and flow. Gosse found that the average mean column velocities occupied by juveniles in low to high flows during random swimming ranged from 0.40 to 0.56 fps in the winter and from 0.43 to 0.75 fps in the summer. During stationary swimming, velocities ranged from 0.66 to 1.18 fps in the winter and from 1.05 to 2.00 fps in the summer. Differences may be due in part to differences in the sizes of the juveniles observed (Chapman and Bjornn 1969).

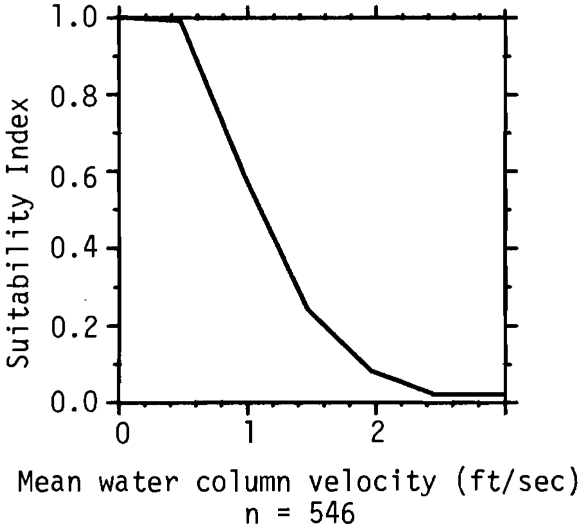
Juvenile depth. Factors which may affect depth preferences of juvenile rainbow trout are the same as those which affect velocity preferences. Observations of Moyle et al. (1983) in Putah Creek (n=36, maximum depths of 1.7 ft), Martis Creek (n=58, depths to 4 ft), Deer Creek (n=126, depths to 6.6 ft), Tuloumne River (n=44, depths to greater than 9 ft), and Cherry and Eleanor Creeks (n=301, depths to greater than 9 ft), of juveniles (2.0 to 4.7 inches in length) indicated substantial variability in depth preferences from stream to stream, with most fish located in depths of 1 to 4 ft. Bustard and Narver (1975), however, found that Age 0 steelhead in Carnation Creek, British Columbia, preferred depths to 1.5 ft, while Age I+ steelhead preferred depths greater than 3 ft. Also, Gosse (1982) found that the average water depths occupied by juvenile rainbow trout (< 9 to 10 inches in length) in the Green River below Flaming Gorge Dam, Colorado, ranged between 10 and 14 ft in the summer and between 18 and 20 ft in the winter (n=111 to 291). Therefore, it is easy to see that juvenile rainbow trout may occupy a wide variety of depths, and it is recommended that investigators develop their own depth curves, or assume that SI = 1.0 for all depths ≥ 2.0 feet (Fig. 4).

Juvenile substrate. Moyle et al. (1983) found most juvenile rainbow trout (2.0 to 4.7 inches in length) over gravel and cobble in Martis Creek (n=53), over cobble and boulders in Deer Creek (n=103), and over boulders in Cherry and Eleanor Creeks (n=301). The composite weighted substrate curve (Fig. 4) shows a preference for boulder substrate. In the Green River, Gosse (1982) found most juveniles (< 9 to 10 inches in length) over cobble and boulders during stationary swimming, but over silt and sand during random swimming. Bjornn (1971) found a correlation between the movement (out migration) of juvenile trout and the lack of large cobble substrate in Idaho streams. Therefore, it may be assumed that cobble and boulders are suitable juvenile substrate, or curves may be developed that are specific to the area of interest.

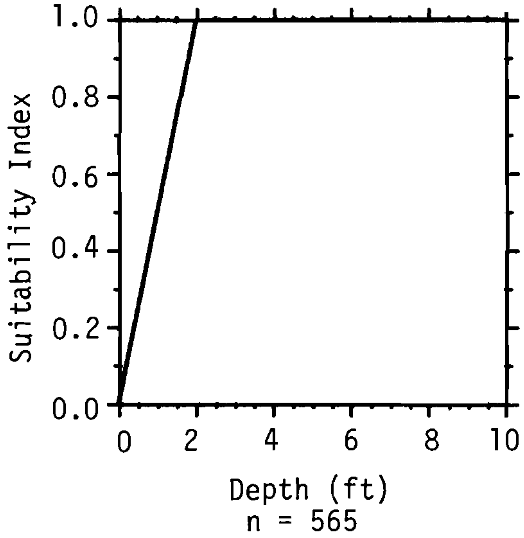
Juvenile cover. Cover requirements or preferences of juveniles are unknown. It may be assumed that substrate curve reflects cover requirements; cover curves may be developed by the investigator; cover may be omitted from FISHFIL; or, the curve for V_6 may be used to represent juvenile rainbow trout cover requirements (page 16).

Coordinates

x	y
0.00	1.00
0.49	0.99
0.98	0.59
1.48	0.24
1.97	0.08
2.46	0.02
3.44	0.02
3.50	0.00
100.00	0.00



x	y
0.0	0.0
2.0	1.0
100.0	1.0



x	y
0.0	0.00
2.0	0.00
3.0	0.02
4.0	0.11
5.0	0.21
6.0	0.77
7.0	1.00
8.0	0.47
8.1	0.00
100.0	0.00

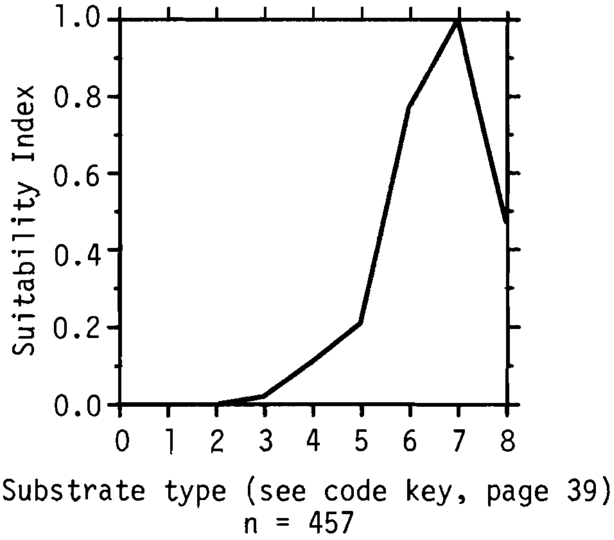


Figure 4. SI curves for rainbow trout juvenile velocity, depth, substrate, and temperature.

Coordinates	
x	y
0.0	0.0
32.0	0.0
50.0	1.0
72.0	1.0
84.0	0.0
100.0	0.0

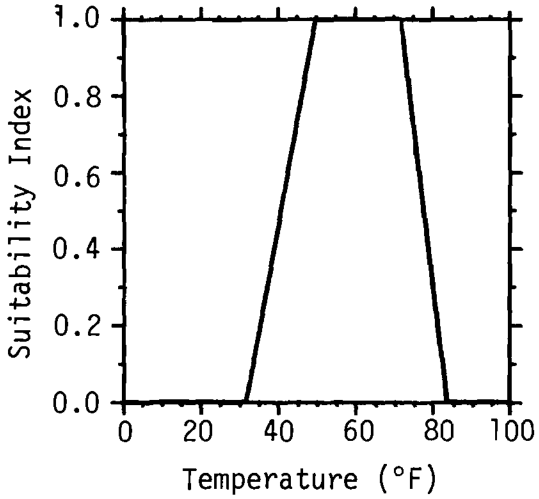


Figure 4. (concluded)

Juvenile temperature. There has been a great deal of variability among results of studies undertaken to determine temperature preferences of juvenile rainbow trout. Cherry et al. (1975) found that temperatures selected and avoided were a function of acclimation temperature; that rainbow juveniles selected temperatures ranging from 53 to 72° F when acclimated to 43 to 58° F; and that the lowest avoidance temperature was 41° F and the highest avoidance temperature was 77° F at the given acclimation temperatures. Coutant (1977) listed preferred temperatures of 64 to 66° F and 72° F, and avoidance temperatures of 57 and 72° F. Lee and Rinne (1980) found the critical thermal maxima for juveniles to be 84° F. McCauley et al. (1977) stated that acclimation temperatures had no significant effect upon preferred temperatures of juveniles, which ranged from 50 to 55° F. Kwain and McCauley (1978) found that temperature preferences were a function of age, and that juvenile rainbow trout 12 months after hatching preferred a temperature of 55° F. No studies were found which addressed maximum growth rate/low mortality temperatures. A final curve was drawn based on the limited information available and professional judgment (Fig. 4).

Adult. For the purposes of this model, rainbow trout are considered to be adult when they are greater than 7.9 inches in length at age II or III, and sexually mature (Carlander 1969).

Adult velocity. Moyle et al. (1983) collected rainbow trout adults (which they defined to be > 4.7 inches in length) from Deer Creek (n=104; maximum velocity > 3.4 fps), Cherry and Eleanor Creeks (n=360; maximum velocity > 3.4 fps), and the Tuolumne River (n=93; maximum velocity = 2.4 fps). The resulting weighted normalized curve suggests that preferred mean column velocities are near 0.5 fps. Lewis (1969), however, found a positive correlation between rainbow trout density and water velocity of 1.65 fps. Gosse (1982) found that rainbow trout generally tended to reposition themselves in the water column as streamflow changed, and that fish nose velocity varied less than mean column velocity with changes in streamflow. Average fish nose velocities for stationary swimming during the winter ranged from 0.7 to 1.0 fps (n=640); during the summer they ranged from 0.9 to 1.1 fps (n=224); for random swimming during the winter they ranged from 0.5 to 0.7 fps (n=308); and during the summer they ranged from 0.4 to 0.6 fps. Average mean column velocities for stationary swimming during the winter ranged from 1.1 to 1.7 fps (n=606); during the summer they ranged from 1.5 to 2.0 fps (n=219); for random swimming during the winter they ranged from 0.6 to 0.8 fps (n=308); and during the summer they ranged from 0.6 to 0.7 fps (n=171). Therefore, the final curve (Fig. 5) reflects the range of mean water column velocities preferred by adult (> 5 to 9 inch lengths) rainbow trout, although preferred fish nose velocities ranged from 0.5 to 1.1 fps. An investigator may choose to develop new curves specific to the area of interest.

Coordinates

x	y
0.00	0.81
0.50	1.00
2.00	1.00
2.46	0.02
2.95	0.02
3.44	0.01
3.50	0.00
100.00	0.00

x	y
0.0	0.0
1.5	1.0
10.0	1.0
100.0	1.0

x	y
0.0	0.00
1.0	0.01
2.0	0.01
3.0	0.75
5.0	0.75
6.0	1.00
7.0	1.00
8.0	0.20
8.1	0.00
100.0	0.00

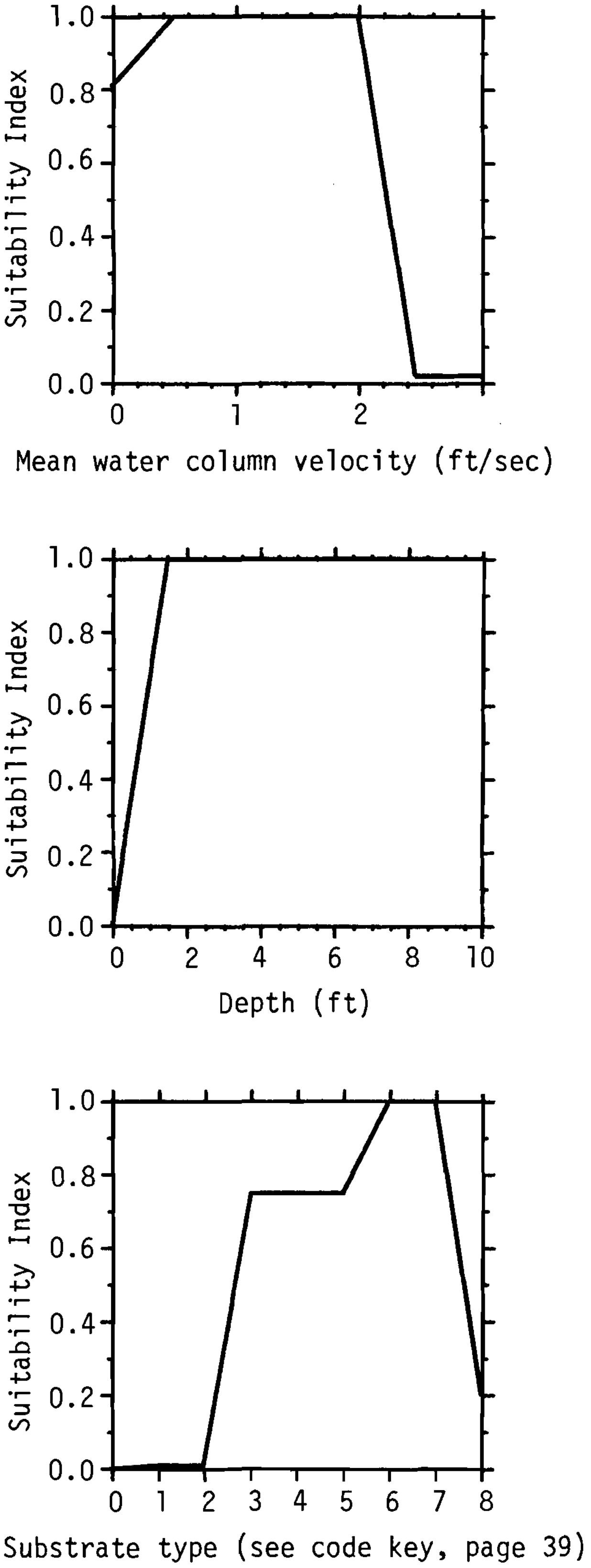


Figure 5. SI curves for rainbow trout adult velocity, depth, substrate, and temperature.

Coordinates

x	y
0.0	0.0
32.0	0.0
55.4	1.0
70.0	1.0
84.2	0.0
100.0	0.0

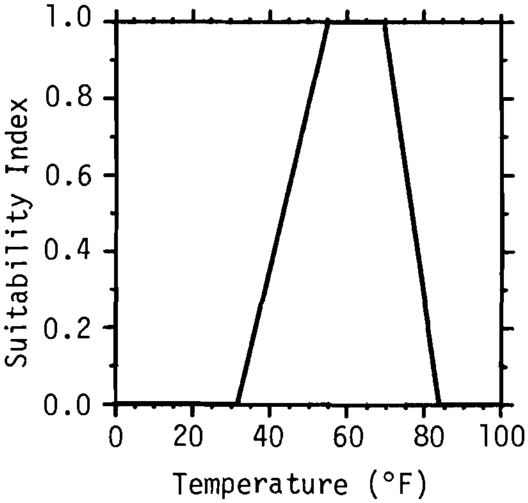


Figure 5. (concluded)

Adult depth. Depths most utilized (n=361) in Cherry and Eleanor Creeks ranged between 1.5 and 2.5 ft, whereas depths most utilized in the Tuolumne River ranged between 2.5 and 4.1 ft (Moyle et al. 1983). Adults in the Green River, however, primarily utilized depths ranging from 12 to 17 ft (Gosse 1982). Therefore, it may be assumed that the SI = 1.0 for all depths greater than 1.5 ft (Fig. 5), or curves may be developed that are specific to the area of investigation.

Adult substrate. Adults (> 4.7 inches) in Deer Creek (n=96) primarily utilized cobble; in Cherry Creek and Eleanor Creek, and the Tuolumne River (n=448) they primarily utilized boulders (Moyle et al. 1983). In the Green River, adults (> 9 to 10 inches in length) utilized cobble and boulders during stationary swimming; and silt, sand, and boulders during random swimming (Gosse 1982). The final curve (Fig. 5) is based on professional estimation.

Adult cover. Sufficient information was not located for the development of a curve for adult trout cover requirements. Lewis (1969) found a positive correlation between the amount of cover and adult density. Butler and Hawthorne (1968) found that rainbow trout had less affinity for cover than brook or brown trout. The investigator has several options when considering cover. Cover may be omitted as a model variable; cover curves may be developed independently; it may be assumed that cover is adequately addressed by substrate and depth; or the curve for V_6 (page 16) may be used to represent adult cover requirements.

Adult temperature. Preferred temperatures of rainbow trout adults have been found to be 55.4, 59.0, 61.7, 64.4, and 66.0 to 70.0° F (Coutant 1977; Spigarelli and Thommes 1979). Temperature selection may be a function of acclimation temperature, size of fish, and time of year. Lee and Rinne (1980) determined the critical thermal maxima at 84.2° F. The final curve (Fig. 5) is based on this information.

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A review and synthesis of existing information was used to develop riverine and lacustrine habitat models for rainbow trout (Salmo gairdneri) a freshwater species. The models are scaled to produce indices of habitat suitability between 0 (unsuitable habitat) and 1 (optimally suitable habitat) for freshwater areas of the continental United States. Other habitat suitability models found in the literature are also included. Habitat suitability indices (HSI's) are designed for use with Habitat Evaluation Procedures previously developed by the U.S. Fish and Wildlife Service.

Also included are discussions of Suitability Index (SI) curves as used in the Instream Flow Incremental Methodology (IFIM) and SI curves available for an IFIM analysis of rainbow trout habitat.

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