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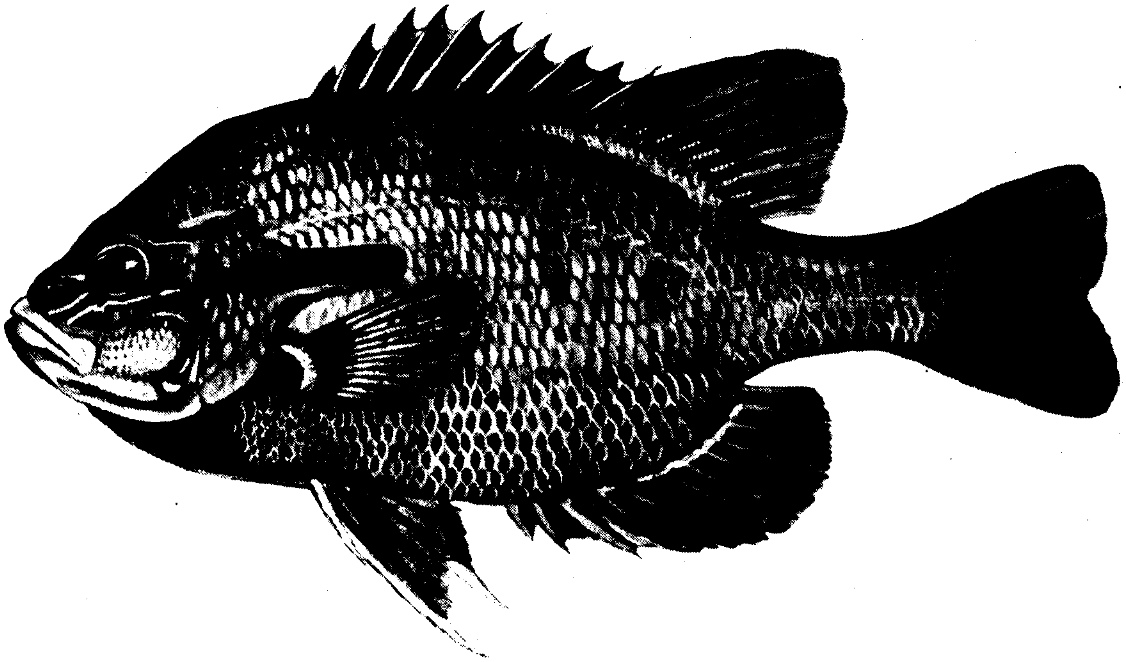

Fish and Wildlife Service

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HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: REDBREAST SUNFISH

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PREFACE

The Habitat Suitability Index (HSI) models and Suitability Index (SI) curves presented in this publication are intended to be an aid in identifying variables that determine the quality of redbreast sunfish habitat. Facts, concepts, field data, and opinions obtained from both published and unpublished reports are documented and presented in a format that can be used for habitat assessment and development of management alternatives.

This report contains two major parts: (1) a Habitat Use Information section, which provides a general summary of the habitats used throughout the life cycle of the redbreast sunfish, and (2) a Habitat Suitability Index Models section, which presents hypothesized relationships between various environmental variables and the concept of habitat quality for redbreast sunfish.

Proper use of the models or individual SI curves with the Habitat Evaluation Procedures (HEP) requires project scoping and the setting of clear study objectives. If HEP is to be used, HSI model building techniques presented by the U.S. Fish and Wildlife Service (1981) and the general guidelines for modifying HSI models presented by Terrell et al. (1982) may be useful for applying the HSI models and any additional habitat requirement data to specific habitat assessment problems. Hamilton and Bergersen (1984) summarize variable measurement techniques that should be useful when attempting site specific habitat evaluations.

The HSI models and SI curves are hypotheses of species-habitat relationships, and users should recognize that the degree of veracity of the models, curves, and assumptions will likely vary according to geographical area and to the extent of the data base for each of the individual variables. The models and curves have not been tested against field data. Therefore, the U.S. Fish and Wildlife Service encourages users of the models or curves to send comments, suggestions, and field results that may help increase the utility and effectiveness of this habitat-based approach to impact assessment. Please send comments to:

Habitat Evaluation Procedures Group or
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REDBREAST SUNFISH *(Lepomis auritus)*

HABITAT USE INFORMATION

General

The redbreast sunfish (*Lepomis auritus*) is a widely distributed centrarchid in the eastern United States (Atlantic slope) (Scott and Dahlberg 1971; Scott and Crossman 1973; Carlander 1977). Its native range extends from New Brunswick, Canada, south to Florida, and east of the Appalachian Mountains. Populations in Texas and Oklahoma are thought to originate from introductions. The redbreast sunfish is considered by many investigators to be predominantly a stream-dwelling species, but it can successfully establish populations in lacustrine and palustrine (river-swamp) environments. Redbreast sunfish exploit a variety of ecological conditions and habitats from sea level to at least 1,345 meters elevation including headwater streams, coastal plain rivers, and lakes of various sizes (Shannon 1966). Among congeneric species of centrarchids, redbreast sunfish hybridize with warmouth (*Lepomis gulosus*), bluegill (*L. macrochirus*), green sunfish (*L. cyanellus*), and pumpkinseed (*L. gibbosus*) (Scott and Crossman 1973).

Despite the popularity and value of the redbreast sunfish as a game fish, particularly in southeastern waters, relatively little information is available on its life history and habitat preferences. Recently, reductions in the abundance of redbreast sunfish have been reported from several different watersheds in the Southeast. The reasons for these observed declines are unknown, but pesticide contamination of the water, loss of suitable habitat, and overexploitation are suspected (Davis 1972; Michaels et al. 1981; Sandow et al. 1974).

Age, Growth, and Food

Growth rates of redbreast sunfish are variable both within and between populations (Carlander 1977), but all exhibit patterns of indeterminant growth. There is a general tendency for growth rates to be greatest in the more southerly populations; however, some northern populations have comparable growth rates. In these northern locations, the increased growth rates are presumably due to changes in the density of redbreast sunfish and/or in prey availability. Despite the variability in size at a given age for different populations, sexually mature individuals have been first observed at age II; most individuals older than age III are reproductively active (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974; Carlander 1977). Maximum age for the species is reported as 8 years, but the average life span appears to be between 4 to 5 years.

Redbreast sunfish adults and juveniles are considered to be generalist invertivores; they use both benthic and drift-oriented foraging modes to feed on the nymphal stages of aquatic insects, particularly dipterans, ephemeropterans, and trichopterans, as well as terrestrial insects (Bass and Hitt 1974; Sandow et al. 1974; Coomer et al. 1977; Benke et al. 1979; Henry 1979). Cooner and Bayne (1982) reported a higher percentage of terrestrial insects in the stomachs of redbreast sunfish ≥ 101 mm total length than in the stomachs of individuals ≤ 100 mm. Redbreast sunfish also ingest significant amounts of decapod crustaceans and fish. As opportunistic feeders, diet varies according to prey availability and size. Their foraging behavior is, therefore, similar to that of several other species of sunfish as described by Keast and Webb (1966), Werner (1974), and Werner and Hall (1974). Plant material is occasionally observed in stomach contents, but is probably associated with prey capture and not selectively consumed. The diet of the larval and fry stages has not been intensively studied, but they feed primarily upon zooplankton, exhibiting size selectivity due to gape limitations (Lemly and Dimmick 1982). It is not known if larvae are opportunistic or species-selective in their prey preference.

Reproduction

Redbreast sunfish have an annual reproductive cycle (Hellier 1967; Davis 1972; Bass and Hitt 1974; Sandow et al. 1974; Siler 1975). Although females bearing ripe ova have been observed from April to October throughout the southeastern United States, peak spawning occurs between May and August, with a north-south cline in the timing of reproduction. In contrast to other species of centrarchids where individuals are known to be multiple spawners (e.g., warmouth—Toole 1946 (cited in Larimore 1957); bluegill—Wrenn and Grannemann 1980), redbreast sunfish appear to spawn only once during the summer (J. Germann, Georgia Department of Natural Resources, Dearing; pers. comm.). Temperatures of 20-25 °C are associated with maximum spawning activity (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974).

Eggs are deposited in nests built and guarded by males (Scott and Crossman 1973). Nest location is typically associated with natural physical obstructions in lotic systems (e.g., logs, stumps, boulders) (Davis 1972), but redds have been observed in the quiet backwaters of streams or congregated in open areas of lakes, ponds, and reservoirs. Davis (1972) reported an average nest diameter of 0.9 m and the depth of the nest depression to be 12-20 cm with all nests being located in water depths of 35-38 cm. Other studies have indicated considerably more variation in the depth placement of the nest (25-150 cm) but all have shown a preference for shallow water (Raney 1965; Bass and Hitt 1974; Sandow et al. 1974). Most redbreast sunfish nests are found on firm substrates. Sand and gravel (particle size 0.1-0.5 cm) are preferentially selected over other substrate types, particularly silt or detrital materials, for nest construction (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974). The redbreast sunfish appears to be a colonial spawner with internest distances ranging from 30-60 cm (Raney 1965).

Specific Habitat Requirements

Cover, current velocity, and variables correlated with velocity (e.g., gradient, riffle/pool ratios) appear to be major determinants of the distribution and abundance of redbreast sunfish in lotic systems. Both juvenile and adult redbreast sunfish are usually found in shallow water areas situated near cover, although they can be found in deep water, particularly during summer when surface water temperatures are high or during winter when large aggregations form in low velocity, pool habitats (Breder and Nigrelli 1935). Cover types used by the redbreast sunfish include hard structure, such as fallen trees, stumps, or root masses, and *in situ* vegetation (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974; Benke et al. 1979). Either type of cover provides a source of shelter, but the availability of hard structure is a major factor influencing spawning (i.e., nest site selection), foraging behavior, and invertebrate prey production. Where detailed observations have been made on nest placement, all nests have been located adjacent to hard structural objects (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974). Invertebrate production on these same types of hard structure has been shown to account for more than 60% of the food of *Lepomis* spp. (including the redbreast sunfish) in the Satilla River, Georgia (Benke et al. 1979; Henry 1979; Benke et al. 1985). It has been proposed, therefore, that invertebrate production is substrate limited (Benke et al. 1979; Henry 1979; Benke 1984; Benke et al. 1985) and its magnitude may strongly influence fish production. Using morphological characteristics of the fish to infer patterns of habitat utilization, Gatz (1981) identified redbreast sunfish as being maneuverable and visually-oriented predators that prefer areas of low water velocity. Thus, they are adapted for existence in structured environments.

Stream pools, protected margins, backwaters, and adjacent marshes are used by all life history stages of the redbreast sunfish. Redbreast sunfish are capable of establishing populations over a wide range of lotic conditions (Shannon 1966); however, they, and centrarchids in general, are more abundant in low (<2 m/km) rather than moderate to high gradient streams (Finnell et al. 1956; Funk 1957a; Moyle and Nichols 1973; Trautman 1981). Redbreast sunfish also prefer moderate-size streams (4-40 m average width) over small headwater streams. Fluctuations in river discharge can have a major effect on recruitment, growth, and survival. In the Satilla River, Georgia, for example, periods of low, stable flow have increased rates of recruitment to existing stocks (Michaels et al. 1981). If maintained for an extended period of time, however, low flows can decrease growth rates and survival of the older age classes due to a loss of habitat area and substrate for invertebrate production (Michaels et al. 1981). Variable discharge patterns between years, whether natural or due to periodic releases from impoundments, can cause significant fluctuations in year class strength (Horwitz 1978).

Redbreast sunfish are commonly found in lacustrine and palustrine environments, but the populations are not as well studied as in riverine habitats. Fertile lakes, ponds, and reservoirs with an extensive littoral zone generally support large standing crops of several centrarchid species in southeastern waters (Lewis and English 1967; Clugston 1973; Jenkins 1976; Winter 1977; Ploskey and Jenkins 1982). While the redbreast sunfish was not a major component of the centrarchid assemblage in any of these studies, similar trends in abundance and biomass across lacustrine productivity gradients are anticipated in lakes and reservoirs containing significant numbers of this sunfish. The development of a large littoral zone, however, is not a requisite for the establishment and persistence of the redbreast sunfish, as some small populations have been found in lentic systems having virtually no aquatic macrophyte development or hard structure cover (Clugston 1973; Aho and Anderson, Savannah River Ecology Laboratory (SREL), pers. obs.). For example, in Pond C, a 67 ha reservoir receiving heated effluents from a nuclear production reactor on the Savannah River Plant in South Carolina, macrophyte establishment is limited to less than 5% of the shoreline, yet redbreast sunfish have persisted for >20 years consistently constituting ≤5% of the fish assemblage. The presence of deep water is important for overwintering and as a retreat from high surface water temperatures during the summer (Breder and Nigrelli 1935).

Water quality requirements for redbreast sunfish are not completely known. Redbreast sunfish are commonly found in both clear and tannin-stained water (Scott and Dahlberg 1971; Scott and Crossman 1973; Bass and Hitt 1974; Sandow et al. 1974). Moderate turbidity levels (25–100 Jackson Turbidity Unit's [JTU's]) are positively related to abundance of other centrarchids (Cross 1967; Moyle and Nichols 1973; Trautman 1981) and may have a similar relationship to the population size for redbreast sunfish. Values within this range should not impair foraging success, but when turbidity level exceeds 100 JTU's, the visual acuity and reactive distance of the fish is progressively reduced (O'Brien 1979). As demonstrated for largemouth bass (*Micropterus salmoides*) (Buck 1956; Bulkley 1975; Muncy et al. 1979), high turbidity levels also can affect reproductive success through an increase in larval mortality or by altering the relationship of body size to fecundity through a reduction in growth rate. Redbreast sunfish are tolerant of low pH, having been found in several locations where pH levels are near 4.0 (Shannon 1966; Scott and Crossman 1973; Sandow et al. 1974; Carlander 1977). Assuming redbreast sunfish respond to pH similar to bluegill, increased mortality would be expected at long-term exposure to pH values less than 4.0 and greater than 10.0 (Trama 1954; Calabrese 1969; Ultsch 1978). However, they are anticipated to exhibit an avoidance behavioral response to these extreme water quality conditions, similar to that reported for bluegill by Prete et al. (1981), if conditions are more favorable at other locations. In environments where low pH has been considered an important determinant of centrarchid species abundance and distribution patterns (e.g., *Lepomis* spp. and *Enneacanthus* spp. in the New Jersey coastal plain), no significant reductions in growth and survival could be demonstrated for species thought to be intolerant of these conditions (Graham and Hasting 1984). Instead, pH determines the trophic qualities of the system that control food availability (type and quantity) and thus, strongly influences population dynamics (Graham and Hastings 1984). The interaction of pH on lentic or lotic trophic status may, therefore, be influential in the observed patchy distribution and abundance of redbreast sunfish throughout the southeastern U.S. and the remainder of its range.

Adult. Temperature is an important characteristic of a fish's habitat, an axis of its multidimensional niche (Magnuson et al. 1979). Temperature preference and critical thermal maxima of the redbreast sunfish are not well known for any life history stage. Mathur et al. (1981) used regression methods to describe the relationship of acute temperature preference (temperature selected by fish within a few hours after they are placed in a thermal gradient) to acclimation temperature. They concluded that the redbreast sunfish and four other centrarchids (including largemouth bass and bluegill) have similar acute preferenda. Redbreast sunfish have been observed at temperatures as high as 33–35 °C, based on collections made in thermally impacted reservoirs on the Savannah River Plant, South Carolina (Aho and Anderson, Savannah River Ecology Lab (SREL), pers. obs.; Clugston 1973; Siler 1975). The seasonal distribution patterns of the redbreast sunfish, however, parallel those of the largemouth bass in thermally impacted cooling reservoirs (Clugston 1973; Siler 1975; Aho and Anderson, pers. obs.). Therefore, the actual mean thermal preferenda of the redbreast sunfish probably more closely approximates the values determined for the largemouth bass (27–29 °C) (Coutant 1975a,b; Reynolds et al. 1976; Reynolds and Casterlin 1976; Block et al. 1984) or green sunfish (28 °C) (Beitinger et al. 1975) than for bluegill (29–31 °C) (Cherry et al. 1975; Beitinger 1976; Beitinger and Magnuson 1976; Peterson and Schutsky 1976; Reynolds and Casterlin 1976; Beitinger 1977; Block et al. 1984). The critical thermal maxima is also anticipated to be closer to the approximate value of 36 °C reported for largemouth bass (Brett 1956; Holland et al. 1974; Smith and Scott 1975; Cvancara et al. 1976; Reynolds and Casterlin 1979) for the aforementioned reasons. Exact temperature selection also may be modified by intra- or interspecific interactions as has been observed for largemouth bass and bluegill in these thermal environments (Block et al. 1984). Mean thermal preferenda and optimal growth temperatures are closely correlated (Beitinger and Fitzpatrick 1979; McCauley and Casselman 1981; Kellogg and Gift 1983); therefore, temperatures of 25–30 °C should result in maximum growth, survival, and reproduction. Reduced growth and survival are expected to occur at temperatures less than 15 °C or greater than 33 °C.

Dissolved oxygen (DO) concentration requirements also are incompletely known, but presumably are similar to those of the bluegill. No adverse effects on growth, survival, or distribution patterns of bluegill have been detected when values have exceeded 5.0 mg/l (Stewart et al. 1967; Petit 1973). Prolonged exposure to levels below 1.0 mg/l is considered lethal (Moore 1942).

Spawning and embryo. Nests are constructed in shallow water (<1.5 m) (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974); thus, rapid reductions in water level of more than 1 m during the spawning period may adversely affect embryo development and survival. Nest site water velocities range from 3.4 to 56.1 cm/s with a mean of 17.9 cm/sec (Davis 1972). The larvae, upon hatching, will utilize both hard structural cover and vegetated areas for shelter and feeding sites. Temperatures corresponding to a high level of spawning activity in the redbreast sunfish (21.0–25.0 °C) (Davis 1972), and that are optimum for incubation of largemouth bass embryos (21–27 °C) (Kelly 1968; Coutant 1975a, 1977), are assumed to provide excellent conditions for embryo growth and survival. Fluctuations in water temperature have been reported to significantly reduce spawning activity, embryo survival, and growth for many species of centrarchids (Larimore 1957; Wrenn and Grannemann 1980).

The dissolved oxygen requirements of redbreast sunfish embryos are not well documented. For largemouth and smallmouth bass (*Micropterus dolomieui*), no adverse effects on embryonic growth, development, and survival were observed when DO concentrations exceeded 5 mg/l. DO levels less than 2.0 mg/l are lethal to bass embryos (Siefert et al. 1974; Eipper 1975).

Fry. Fry are found in shallow water and are usually associated with either hard structure or vegetation cover types. A reduction in the amount of available structural space for the fry will probably limit growth and survival, because cover provides both shelter and a source of food. However, the relationship between the percent of a water body with suitable fry cover types and adult recruitment is unknown. We assumed that areas of low current velocity (less than 10 cm/s) are required in order for fry to maintain their stream position for feeding (Kallemyn and Novotny 1977). Temperature and DO concentrations corresponding to maximal rates of growth and survival are assumed to approximate those for the adult and embryo stages.

Juvenile. The habitat requirements of juvenile redbreast sunfish are not known. We assumed that they are similar to adult requirements or other juvenile lepomids, except juveniles seem to prefer slightly faster current velocities and are more abundant in smaller size (<4 m average width) streams (Aho and Anderson, pers. obs.).

HABITAT SUITABILITY INDEX (HSI) MODELS

Model Applicability

Geographic area. The models were developed to quantify changes in wetland habitats on the Savannah River Plant (SRP) located near Aiken, South Carolina, concomitant with the restart of one of five on-site nuclear production reactors (L-Reactor). Alterations in redbreast sunfish habitat are anticipated as a result of changes in channel morphology due to greatly increased water discharge rates and the elevation of water temperatures with the downstream release of thermal effluents. The standard of comparison for each of the individual suitability indices is the optimal value of individual or population responses (e.g., growth, survival) reported for the species. Model variables should be applicable throughout the native and introduced ranges of redbreast sunfish in North America. However, a suitability index of 1.0 (optimum) may never occur in water bodies in the North for temperature related variables that do not reach the optimal values found in the southern portion of the species range. The model is designed for use primarily in the southeastern coastal plain, where streams are low gradient (<2 m/km) with few riffle/pool sequences. The relationship of abundance to either gradient or the amount of pool habitat is not considered. Gradient and amount of pool habitat may be more important in other areas where redbreast sunfish are found. For most centrarchids, reductions in population size occur as gradient increases. Greater quantities of pool habitat result in increased populations (Larimore 1957; Minckley 1963; Trautman 1981).

Season. The model provides an index of the ability of an area to support a self-perpetuating population of redbreast sunfish throughout the year. Conditions believed to preclude reproduction or cause all individuals to leave an area result in an HSI of 0.

Cover types. The models are applicable to riverine, lacustrine, and palustrine habitats as classified by Cowardin et al. (1979). For the SRP and all other thermally impacted aquatic environments, it is assumed that some cool-water refuge areas will be present if portions of the water body have water temperatures exceeding lethal levels. These refuges are necessary to ensure the survival of the animal populations in a water body and provide a source pool for future recolonization and recovery once the environmental stress (e.g., thermal effluent) is either reduced or eliminated.

Minimum habitat area. Minimum habitat area is defined as the minimum area of contiguous suitable habitat that is required for a species to live and reproduce. Although information is available determining mobility and home range size of several species of centrarchids (e.g., largemouth bass—Lewis and Flickinger 1967; Warden and Lorio 1975; Quinn et al. 1978; Winter 1977; Fish and Savitz 1983; bluegill—Gunning and Shoop 1963; Fish and Savitz 1983; longear sunfish—Gunning and Shoop 1963; Berra and Gunning 1972), only limited information is available on the redbreast sunfish. While no studies have determined home range size, the redbreast sunfish has been found to be a semimobile species (*sensu* Funk 1956) with <50% of the individuals remaining within 0.16 km of the original point of capture and some individuals moving in excess of 8 km (Hudson and Hester 1975). Other studies have found centrarchids to be more restrictive in their movement patterns (see above citations). Thus, the relationship of home range size to minimum habitat area is currently unknown, so no attempt has been made to specify the minimum habitat area for the redbreast sunfish.

Verification level. The suitability indices and HSI models are conceptual models that are open to modification. As preliminary attempts to quantify habitat requirements, they should be interpreted with caution. The models were synthesized from information available in the literature, personal observations, and relationships for other congeneric species. They have not been tested against habitats of known quality to determine their validity. However, as a first step in the model verification and validation process (Farmer et al. 1982), fish biologists and ecologists familiar with this species, or other centrarchids, were consulted. Many reviewer comments and criticisms regarding our description of the habitat requirements of the redbreast sunfish were incorporated into the final model documentation. However, we were not able to follow reviewer suggestions that the relationship of model-generated HSI's to observed population levels be field tested before the model is used to justify decisions. Reviewers did not necessarily agree that the SI curves or modeling approach were valid. Future refinements through field testing and modifications of structure (c.f. Layher and Maughan 1985) should lead to greater model applicability. The useability (but not the accuracy) of the model was evaluated in the field by one of the reviewers (Brownell).

Model Description—General

The use of the Habitat Suitability Index (HSI) for displaying habitat quality in the Habitat Evaluation Procedures (HEP) (U.S. Fish and Wildlife Service 1981) is based on the precept that the HSI is a linear index of the concept of "carrying capacity." We have tried to adhere to that precept, but have not tested the model as an index of carrying capacity, and therefore do not have evidence of our success or failure in following the precept. In developing the individual suitability index (SI) graphs (which are used together to provide a single HSI that represents the concept of carrying capacity for an entire year), relationships of physical, chemical, and biological parameters to population performance measures should be formulated. The first step in the development of these graphs is to define the independent variables (e.g., amount of cover, depth of water overlying the sediments, current velocity, dissolved oxygen concentration) believed to influence the carrying capacity of the habitat. Each model variable must be capable of being measured in the field and should account for spatial and temporal variation of the habitat variable, to be useful for the generation of a meaningful Habitat Suitability Index. The model variable definitions are subjective. Many of the habitat variables from which the model variables are defined vary both temporally and spatially, and specific levels will be either selected for, or avoided by, the fish. The model variable definitions are interpretive rules for transforming habitat variable data into model variable values. Alternative rules are certainly possible, and users are encouraged to modify model variable definitions to reflect their knowledge of how the species reacts to temporal and spatial variation in habitat variables.

Many of the variables selected for use in the development of suitability index graphs are likely to interact; however, we did not have enough data to examine variable interrelationships. Instead, we used the concept of maximum performance (Li et al. 1984) to define an individual suitability index. Under this concept, an individual or population response (e.g., standing crop) is used as the measure of performance (dependent variable) and the suitability index represents the highest proportion of the maximum known performance that has been measured in conjunction with each independent variable value. For example, using standing crop as the measure of performance, the highest standing crop possible with an SI of 0.8 should be 0.8 times the highest known standing crop. Variable values with an SI equal to 1.0 are assumed to be necessary for the occurrence of maximal species performance. Variable values having an SI <1.0 are assumed to be sufficient to preclude the occurrence of a performance level higher than that obtained as the product of the SI and the maximum performance level known to occur. Standing crops (or other measures of performance) associated with, for example, an SI equal to 0.8 could be below 0.8 times the maximal value of performance, because interactive factors other than the variable for which the SI was calculated determine actual standing crop.

Estimates of the standing crop of redbreast sunfish from a variety of habitat types are not readily available in the literature. Where measurements have been made, biomass varies substantially both within and between years. For example, in the Satilla River, Georgia, standing crop values have been found to range from 1.9 to 27.5 kg/ha in October rotenone samples for the years 1970, 1972–74, and 1977–79, and from 0.9 to 9.2 kg/ha within a month (September-October 1973) from either the same or closely associated sites (R. Gilbert, University of Georgia, Athens; letter dated August 16, 1985). Other sites in the State of Georgia have redbreast sunfish standing crop estimates of 0.4-30.3 kg/ha. This wide range of variability, together with a lack of associated habitat data, precluded the development of empirically derived SI graphs or the derivation of statistical models based on fish standing crop as a measure of population performance. Instead, we used information detailing the distribution, abundance, growth rate, survivorship, and reproductive capabilities of the redbreast sunfish and its congeners, as described in the literature, to formulate judgements (i.e., the SI curves) on how different levels of the model variables we defined might limit standing crop. The accuracy of the SI curves in depicting these limiting relationships is uncertain. However, Layher (1983) found good agreement between some SI curves developed in a similar manner for other centrarchids, and SI curves he developed empirically from plots of average population sizes associated with different variable values.

How suboptimum variable values might actually limit populations is not addressed in the SI curves or HSI models. We have identified potential pathways through food, water quality, reproduction, and cover components (Figures 1, 2, and 3). However, the proper classification of a variable into a specific component is not critical for model usage because the model gives equal weight to all variables.

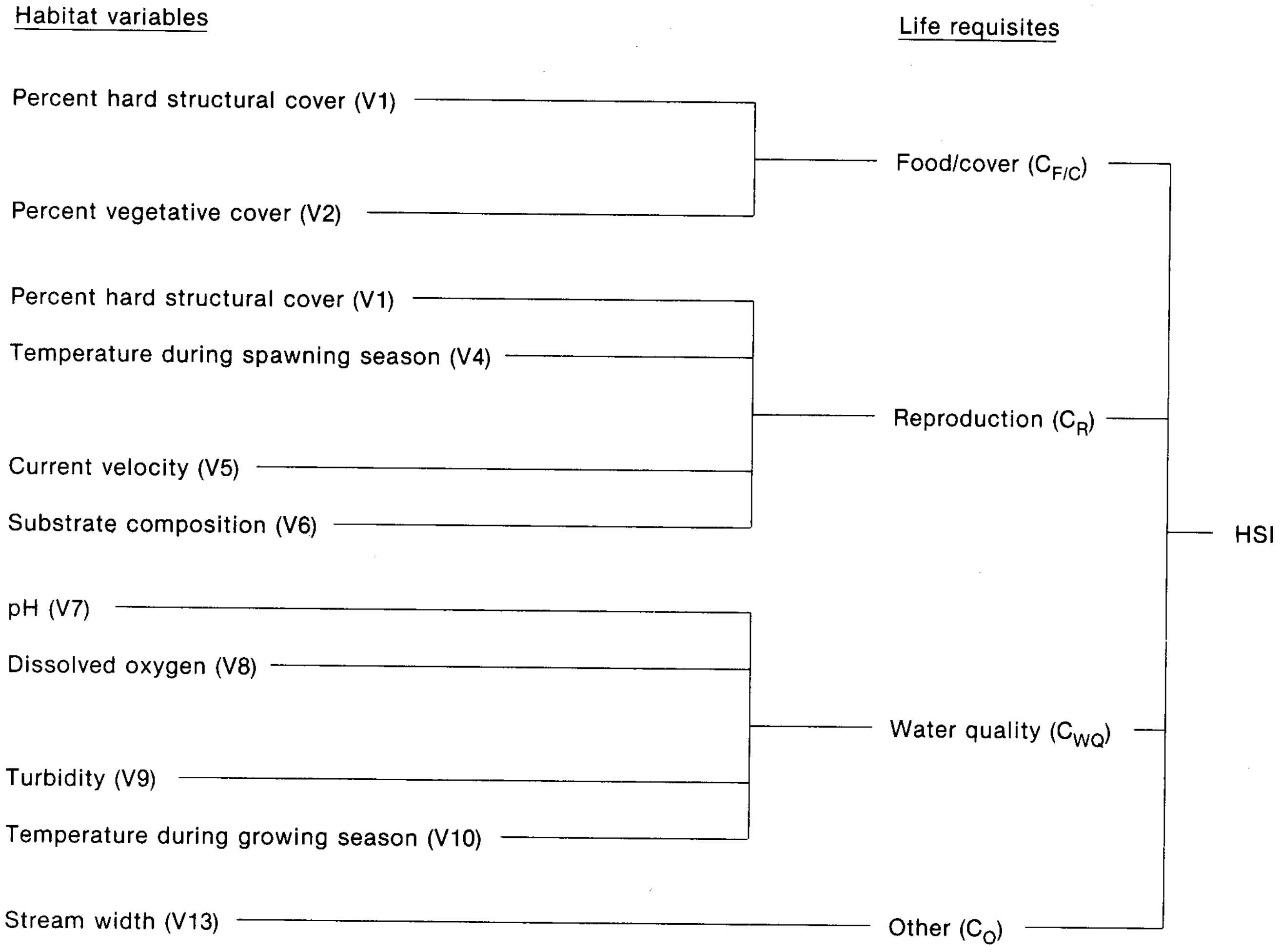


Figure 1. Habitat variables and life requisites in the riverine HSI model for the redbreast sunfish. HSI is equal to the lowest suitability index rating for a habitat variable.

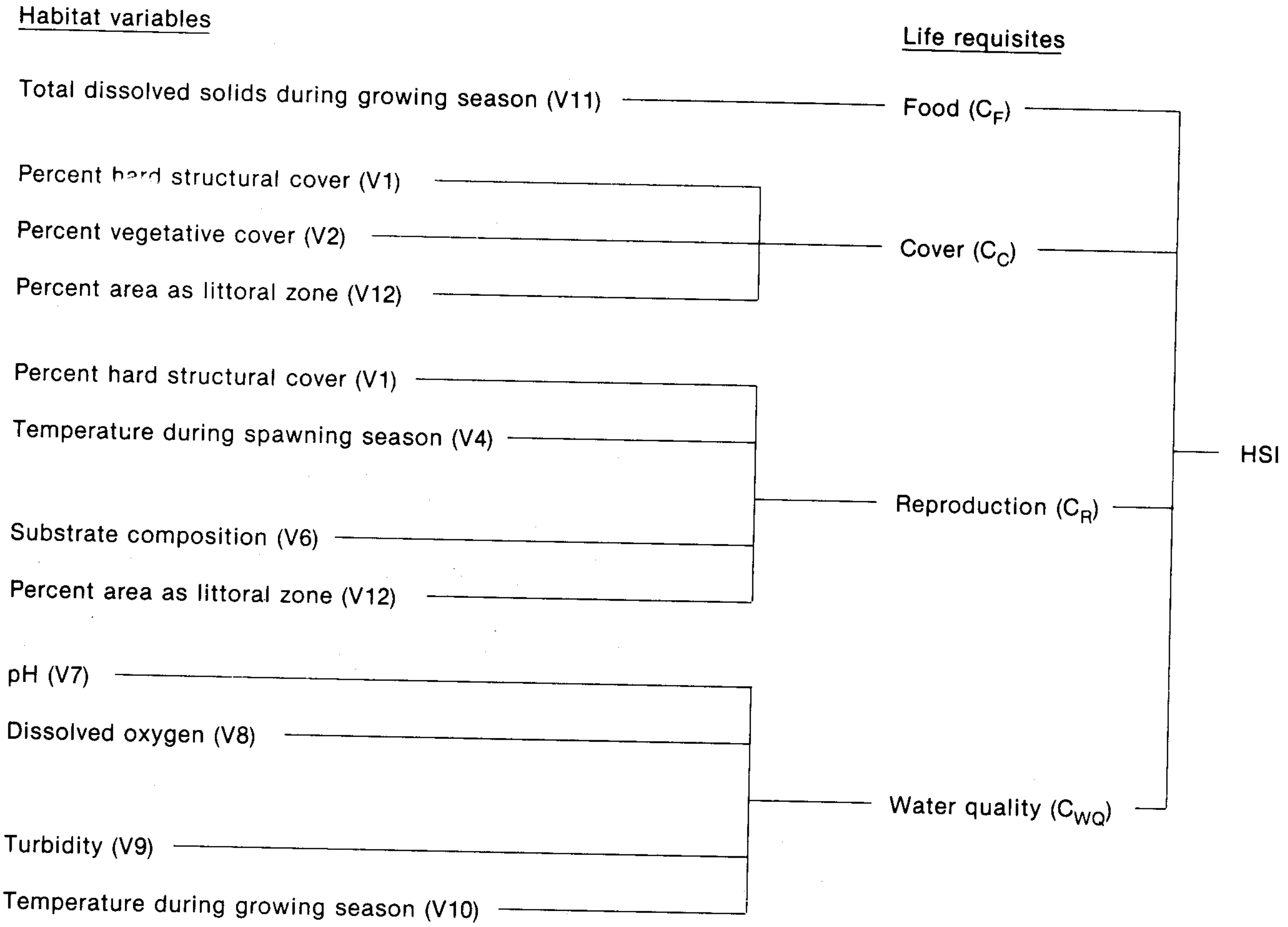


Figure 2. Habitat variables and life requisites in the lacustrine HSI model for the redbreast sunfish. HSI is equal to the lowest suitability index rating for a habitat variable.

Model Description—Riverine

Food and cover component. Percent of the habitat area composed of hard structural cover (V1) and vegetative cover (V2) were included because: (1) the distribution and abundance of the redbreast sunfish and other related species of centrarchids is closely associated with structural cover, and (2) vegetative cover provides an additional substrate to increase production of invertebrates that can be used as a food resource (Bass and Hitt 1974; Benke et al. 1979; Henry 1979; Benke et al. 1985). Although both cover types are used by redbreast sunfish, distinction is made because each provides different substrate for prey (vertebrate or invertebrate) utilization and secondary production (Benke et al. 1979; Henry 1979; Minshall 1984; Benke et al. 1985). Of the two cover types, hard structure appears to be more important to the redbreast sunfish as a food/cover source than does *in situ* vegetation.

Reproduction component. The percent of hard structural cover (V1) available in the habitat and benthic substrate composition characteristics (V6) were chosen as indicators of reproductive requirements of the redbreast sunfish because spawning generally occurs in areas adjacent to natural physical obstructions and redbreast sunfish select sand/gravel substrates for nest construction. Water temperature during spawning and embryonic development (V4) and current velocity (V5) were also included in this component due to their influence on nest site selection, nest integrity, the overall success of spawning, and their direct impact on the growth and survival of the embryos and larvae.

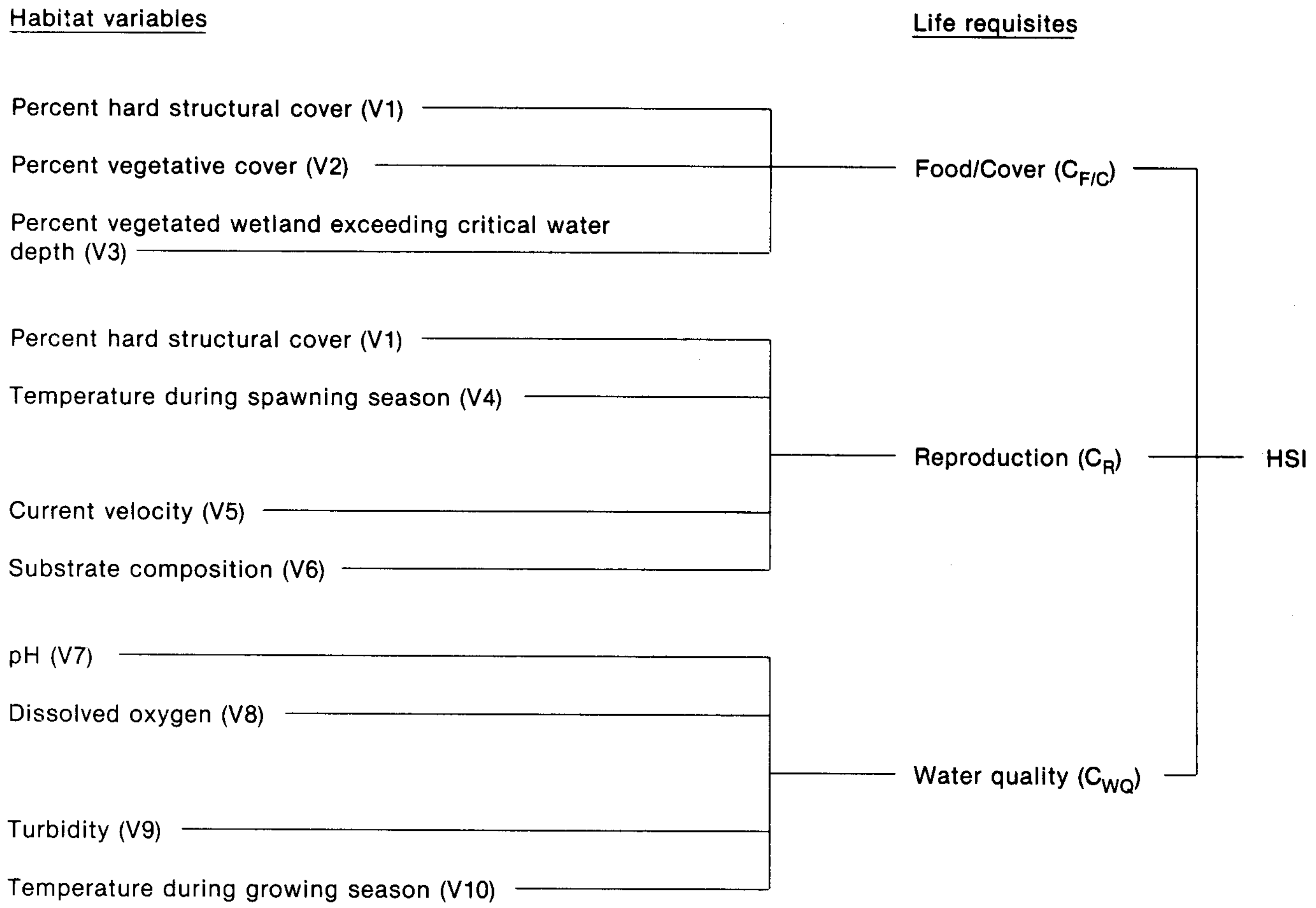


Figure 3. Habitat variables and life requisites in the palustrine HSI model for the redbreast sunfish. HSI is equal to the lowest suitability index rating for a habitat variable.

Water quality component. Dissolved oxygen (V8), pH (V7), and water temperature during the growing season (V10) were selected because these variables affect the growth, survival, and abundance of redbreast sunfish and related species. Turbidity (V9) is used in this model because of its influence on growth and abundance as indicated by studies on related species of centrarchids. Increased turbidity also reduces the growth of aquatic vegetation used by redbreast sunfish for shelter, reproduction, or as a substrate for food resource production. The influence of toxic substances on fish performances is not addressed by the model.

Other component. Stream width (V13) is important because the distribution and abundance of the redbreast sunfish differs between small headwater streams and large rivers.

Model Description—Lacustrine

Food component. Mean total dissolved solids (TDS) concentration during the growing season (V11) is used as an indicator of lacustrine productivity. Positive correlations between sunfish standing crop and TDS have been reported in several reservoir systems, presumably due to greater quantities and availability of food organisms being produced at higher TDS concentrations. It is assumed that TDS levels will be below those that can cause ion regulatory or osmoregulatory stress.

Cover component. The percent of hard structural cover (V1) and vegetative (V2) cover within a habitat are included in this component for the same reasons provided in the riverine model description. The percent of the lake classified as littoral zone (V12) is included because the redbreast sunfish generally occurs in nearshore habitats among natural physical obstructions and macrophytes.

Reproduction component. The percent of hard structural cover (V1), benthic substrate composition characteristics (V6), and temperature during the spawning season (V4) are included for the same reasons provided in the riverine HSI model. The percentage of littoral zone (V12) is included as a measure of the quantity of the total lake habitat available to the redbreast sunfish for spawning.

Water quality component. Same as described for the riverine model.

Model Description—Palustrine

Food and cover component. Food and cover variables are identical to those described in the riverine model. An additional variable, percent vegetated wetland exceeding a minimum critical water depth (V3), is also included because redbreast sunfish require a minimum depth within the macrophyte beds if they are to be utilized for shelter, feeding, or reproduction. This variable also provides a measure of wetland permanency for all life history stages of the redbreast sunfish.

Reproduction component. Same as described for the riverine model.

Water quality component. Same as described for the riverine model.

HSI Determination

We believe that environmental conditions represented by suitability indices (SI's) below 1.0 are sufficient to prevent maximum standing crops from occurring regardless of the value of the other habitat variables. We assume, therefore, that the most limiting factor (i.e., the variable with the lowest SI) defines the upper limit, in terms of proportion of maximum standing crop, for redbreast sunfish populations in the aquatic system being evaluated. Thus, determination of the HSI for each model type equals:

HSI (Riverine) = Minimum SI of [V1, V2, V4, V5, V6, V7, V8, V9, V10, V13]

HSI (Lacustrine) = Minimum SI of [V1, V2, V4, V6, V7, V8, V9, V10, V11, V12]

HSI (Palustrine) = Minimum SI of [V1, V2, V3, V4, V5, V6, V7, V8, V9, V10]

If the above assumption is true and limiting environmental conditions during the time period the standing crop was produced are accurately represented by model input data, then the relationship of HSI to actual observed standing crops will be as shown in Figure 4.

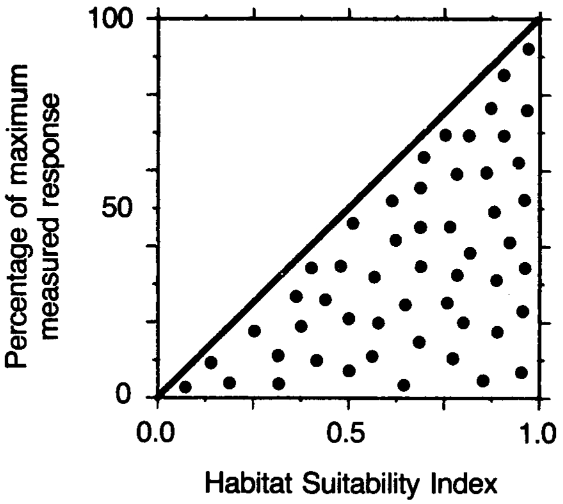


Figure 4. Assumed relationship of HSI to percent of maximum standing crop, or other response assumed to represent carrying capacity.

For aquatic environments receiving cooling system water from nuclear power plants, nuclear reactors, or conventional coal power generating facilities, the SI values for V4 and V10 should be calculated from annual temperature profiles, instead of seasonal periods in the life history of the species. Water temperatures in portions of some aquatic environments may exceed critical lethal levels even during winter, so application on a year-round basis is necessary. For these special cases, we assume carrying capacity is dependent on the proportion of the aquatic system that is within certain temperature limits and thus useable by the species. Thus, the overall SI for V4 and V10 in these disturbed habitats is the weighted arithmetic mean of the products obtained when individual habitat areas are multiplied by both the SI for the area and a weighting factor for the temporal duration of those environmental conditions. For example, if an entire lake was being evaluated as potential habitat, and 40% of the lake had completely unsuitable (i.e., SI = 0) temperatures during the growing season (e.g., a 240-day period each year), while the other 60% had an SI of 0.1 for 170 days and an SI of 0.2 for 70 days, then the SI for V10 for the entire lake would be computed as follows:

$$SI = \frac{(240 \text{ days} \times 0.0 \times 40\%) + (170 \text{ days} \times 0.1 \times 60\%) + (70 \text{ days} \times 0.2 \times 60\%)}{(240 \text{ days} \times 40\%) + (170 \text{ days} \times 60\%) + (70 \text{ days} \times 60\%)}$$

$$SI = 0.08$$

While formulated for thermally disturbed systems, weighting by time and area also can be applied to natural aquatic habitats. The above example used an agricultural growing season (average number of days between last spring frost and first fall frost) representative of the southeastern U.S. as the basis for the calculations, because agricultural growing season is anticipated to be related to suitable water temperatures for fish growth in unimpacted systems. When heated effluents are released on a year-round basis, the weighting factor for time could be 365 days.

Suitability Index (SI) Graphs for Model Variables

Suitability index graphs are based on the responses of redbreast sunfish and other centrarchids to habitat parameters presented in the habitat use section. The responses (e.g., growth, survival) are not the same for all variables. The suitability index ranges from 0.0 (unsuitable) to 1.0 (optimal) and was derived using the rationale presented in Table 1 for the 13 model variables.

Model variables emphasize the extreme, rather than the average, conditions for most habitat parameters, because we assume that extreme conditions will most often limit the carrying capacity of the habitat. Some flexibility is provided in model variable definitions because fish can avoid, or withstand, short-term, localized, unsuitable conditions. Gilbert (1984) found that HSI models based on SI's that had flexible definitions of habitat variables were generally better predictors of fish standing crops than similar HSI models with stringent, inflexible definitions.

Table 1. Sources of information and rationale used in the construction of the suitability index graphs for the redbreast sunfish. Habitat classified as "excellent" has a suitability index of 0.8 to 1.0, "good" 0.5 to 0.7, "fair" 0.2 to 0.4, and "poor" 0.0 to 0.1.

Variable	Sources of information and rationale
V1	A large amount of physical obstruction in the habitat is assumed to be suboptimal because it: (1) interferes with visual predatory behavior; (2) provides excessive refugia, through structural complexity, which limits accessibility to potential invertebrate prey species, and, consequently, reduces population growth parameters due to increased foraging costs (Crowder and Cooper 1979, 1982); and (3) can reduce the amount of suitable spawning habitat to a level that may negatively affect adult-larvae recruitment dynamics. Based on available information for other centrarchids, 25-70% hard structural cover (e.g., logs, stumps, root masses, rocks) is estimated to be the most productive habitat for this species. Extreme conditions (less than 5% and greater than 90% hard structure cover) may still provide valuable habitat, but growth, survival, and reproduction are probably limited under these physical habitat conditions to the extent that standing crop would be reduced.
V2	The amount of vegetative cover is important for the same reasons provided in the hard structural cover section. A different functional relationship is expected, however, because utilization of this cover type is assumed to be secondary to the use of hard structural cover. It probably has greater importance as an additional substrate to increase invertebrate secondary productivity that can be used as a food resource than as shelter (Bass and Hitt 1974; Sandow et al. 1974; Benke et al. 1979; Henry 1979; Benke 1984; Benke et al. 1985). Excessive amounts of vegetative cover may reduce redbreast sunfish populations.
V3	In river-swamp systems (palustrine), extensive macrophyte growth can develop along shallow channel margins, to the extent of choking the waterway and acting as a sediment trap. To be utilized as a source of cover by, and provide food resources for, redbreast sunfish, there must be a critical minimum depth of water overlying the sediments. Water depths <10 cm contain few juvenile and adult fish (Aho and Anderson, pers. obs.) and are rated poor. Although these shallow areas may be used as nursery areas for larvae upon hatching, when all life history stages are collectively examined, water depths <10 cm are rated as poor habitat for fish utilization. The occurrence and abundance of redbreast sunfish increases with depth, and optimal conditions are presumed where species usage and abundance are highest. Additionally, if nesting takes place among, or adjacent to, these vegetated

Table 1. (Continued)

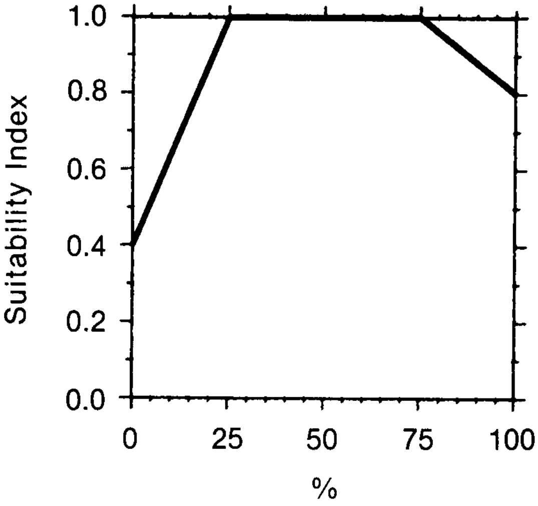
Variable	Sources of information and rationale
	areas, some minimal depth is necessary based on observations of nest site selection. Most redbreast sunfish nests have been found in waters exceeding 25 cm in depth, thus, 20 cm is a conservative estimate of the depth level required to provide adequate spawning habitat for the redbreast sunfish. The depth of water also provides a measure of the degree of wetland permanency, which is critical to fish utilization and secondary production.
V4	Specific information correlating water temperatures with maximal embryonic development and survival are lacking for the redbreast sunfish. It is assumed, however, that temperature requirements for growth and survival are more similar to those reported by Kelly (1968) and Coutant (1977) for largemouth bass than the requirements given by Clugston (1966) and Banner and Van Arman (1973) for bluegill. This assumption is based on observations made in thermally impacted reservoirs on the Savannah River Plant, where bluegills construct nests in areas of higher temperatures along a thermal gradient than do either largemouth bass or redbreast sunfish (Clugston 1973; Siler 1975; Aho and Anderson, pers. obs.). Therefore, temperatures corresponding to periods of maximum spawning activity (20–25 °C) (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974) and optimal temperatures for incubation of largemouth bass eggs (21–27 °C) are regarded as being optimum. Temperatures outside of this range are considered less suitable and values <15 °C and >32 °C, which result in greatly reduced embryonic development and survival, are rated poor.
V5	Nest establishment and integrity and egg, embryo, and larval survival are several of the major determinants of the distribution and abundance of the redbreast sunfish. Current velocities corresponding to the mean value for nest site construction (Davis 1972) are rated as optimum. Adults and juveniles have greater ability to maintain position in the stream than the larval stages; thus, they are more tolerant of variations in flow regime. Velocities up to 35 cm/s are considered to be good for adults and juveniles because of highest abundance of fish in this range. Current velocities up to 20 cm/s are considered optimal for the fry and embryo stages. Reduction in species abundance occurs in streams having average velocities >35 cm/s (Bass and Hitt 1974; Sandow et al. 1974) and represent habitats rated as fair to poor.
V6	The availability of suitable nesting substrate is recognized as being a major factor affecting reproductive success of centrarchid fishes (Breder 1935; Kramer and Smith 1962; Muncy et al. 1979). Redbreast sunfish appear to require a mixture of sand and gravel to spawn successfully (Davis 1972; Bass and Hitt 1974; Sandow et al. 1974). Similar to bluegills (Stevenson et al. 1969), nests located on sand or gravel substrates produced the greatest number of larvae. Silt or substrates with high organic composition (probably having a high oxygen demand and little interstitial water flow) are regarded as being poor habitats for reproduction, based on the effects of low dissolved oxygen concentrations on egg and embryo survival and development of related species as reported by Siefert et al. (1974), Eipper (1975), and Muncy et al. (1979). Reductions in survival of the embryonic stages can also be affected by the composition of the sand/gravel mixtures used in nest construction (Bain and Helfrich 1983). Our best estimate of optimal benthic substrate is that more than 40% of the substrate (at preferred spawning depths) should consist of a mixture of predominately coarse sand and gravel (substrate classes as defined by Cummins 1962). The fish should be able to sweep away fine layers of silt to utilize underlying sand and gravel, but we could not find any description of how deep a layer could be swept away.
V7	No data are available on specific negative impacts of pH on growth, survival, and reproduction of the redbreast sunfish. They have been collected in streams with a pH range of 4.8 to 8.4 in North Carolina, indicating this range is suitable for the occurrence of natural populations. Optimal pH range is assumed to be the range in which growth and abundance have been reported to be good in southeastern coastal plain habitats (6.5–8.5) (Bass and Hitt 1974; Sandow et al. 1974; Michaels et al. 1981). This range falls within values cited for many different species of freshwater fish (Stroud 1967). Regarding long-term exposure, pH values <4.0 or >10.0 are likely to reduce the probability of long-term survival of the population and are rated poor.
V8	Dissolved oxygen (DO) concentrations (>5.0 mg/l) corresponding to highest growth (Stewart et al. 1967; Dourdoroff and Shumway 1970) are deemed excellent. DO concentrations between 2.0 and 5.0 mg/l are associated with avoidance behavior and moderate reductions in growth rates and survival for other centrarchids [e.g., 3.0 mg/l at 20 °C for warmouth (Larimore 1957); <5 mg/l for largemouth bass (Katz 1959; Whitmore et al. 1960; Petit 1973)] and are classified as good to fair habitats. Extended exposure to DO levels below 2.0 mg/l greatly reduces the survival of smallmouth and largemouth bass embryos (Siefert et al. 1974; Eipper 1975) and are considered poor.

Table 1. (Concluded)

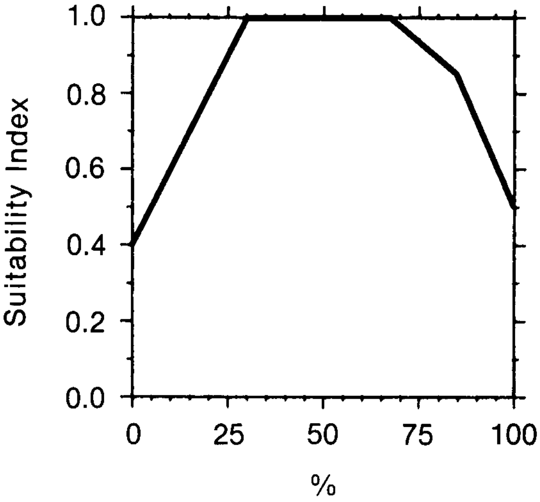
Variable	Sources of information and rationale
V9	Low to moderate turbidity levels are rated excellent because many species of sunfish, including the redbreast sunfish, attain their highest growth rates in clear water (Jenkins et al. 1955; Bass and Hitt 1974). They are also abundant in tannin-stained waters and marshes (Sandow et al. 1974; Germann et al. 1975; Benke et al. 1979; Michaels et al. 1981), sluggish streams, backwaters, and lakes (Moyle 1976; Smith 1979; Trautman 1981). Turbidities exceeding 100 JTU's begin to negatively impact growth and abundance of other centrarchids (i.e., warmouth, green sunfish, bluegill, and largemouth bass) (Jenkins et al. 1955; Buck 1956; Cross 1967; Moyle and Nichols 1973; Pflieger 1975; Smith 1979) and are rated only good to fair.
V10	Water temperatures corresponding to optimal growth and survival of adult, juvenile, and fry life history stages of the redbreast sunfish are not known. Optimal water temperatures are assumed to be similar to those of other centrarchids. For example, growth and survival are regarded as being good in the range of 18-32 °C, but maximal values for both of these responses have been observed at temperatures of 25-30 °C for largemouth bass, bluegill, and green sunfish (Hart 1952; Strawn 1961; Banner and Van Arman 1973; Beitinger et al. 1975; Coutant 1975a,b, 1977; Coutant and Cox 1976; Brungs and Jones 1977; Lemke 1977; Venables et al. 1978; Magnuson and Beitinger 1979; Wrenn and Grannemann 1980; Coutant and DeAngelis 1984). Temperatures <15 °C and >35 °C are rated poor because population performance measures of many species of centrarchids are either greatly reduced or mortality increases at these temperatures.
V11	For most lacustrine systems, low concentrations of total dissolved solids (TDS) indicate low productivity, whereas extremely high levels may induce osmoregulatory stress or ion regulation problems for many organisms. For reservoir sport fishes, including several species of sunfishes but not redbreast sunfish, a positive curvilinear relationship between standing crop and TDS has been demonstrated (Jenkins 1976). TDS levels correlated to maximum sportfish standing crops for midwestern reservoirs range from 100 to 400 ppm and are rated as optimum habitat. However, comparable TDS values are rare in southeastern lentic habitats unless turbidity is high. The proposed relationship is likely to be a conservative estimate of maximum performance within the natural range of the redbreast sunfish. Further work is necessary to verify if a TDS-standing crop relationship exists.
V12	In ponds and lakes, redbreast sunfish frequent shallow water and are usually associated with areas of vegetation or hard structural cover. Based on relationships observed for other centrarchids (e.g., green sunfish, Moyle and Nichols 1973; Stuber et al. 1982), 35% of the benthic substrate should have either hard structure or vegetation as cover types. The optimal percentage of littoral zone is then represented by the value that results when 35% of the total pond or lake's bottom is covered and 80% cover exists within any given area of the water body. Depending on geographic location (north vs. south) or the presence of environmental stress (e.g., thermal effluent additions), too extensive a littoral zone may, however, lower habitat quality, since this species, and other centrarchids, uses deep water in the summer to escape high water temperatures and in the winter to form large aggregations (Breder and Nigrelli 1935; Emig 1966). Too much vegetation associated with the littoral zone may also affect the foraging success and, hence, growth rates and body-size fecundity relationships.
V13	The distribution and abundance of redbreast sunfish varies according to stream width. Abundance is highest in streams of intermediate size and therefore they are rated as optimum habitat. Declines in abundance have been recorded in larger rivers (Chable 1947; Bass and Hitt 1974; Sandow et al. 1974). Suboptimum, but still "good" habitat conditions, are assumed to exist when stream width surpasses some threshold value (e.g., 30 meters).

Variable

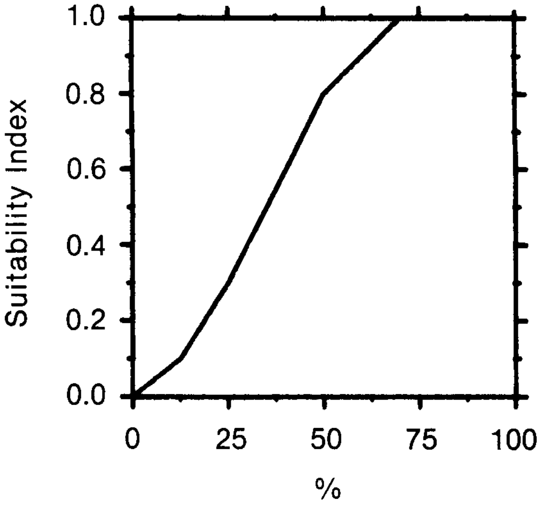
V1 Percent hard structure cover during average spring-summer water levels.



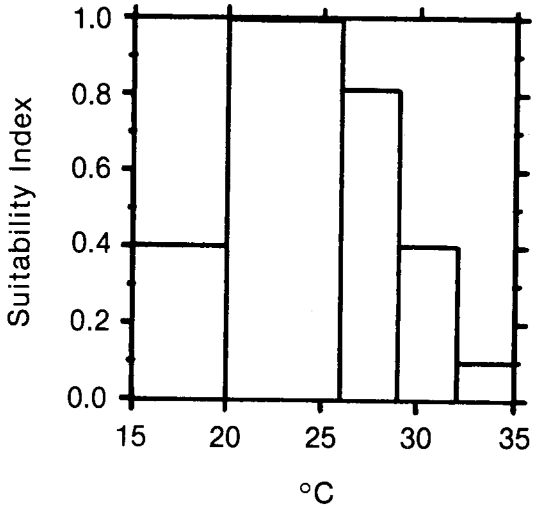
V2 Percent vegetative cover during average spring-summer water levels.



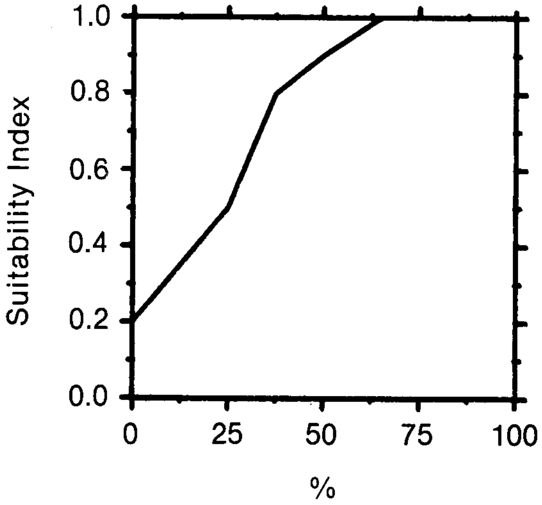
V3 Percent of vegetated wetland with a depth ≥20 cm (palustrine habitats).



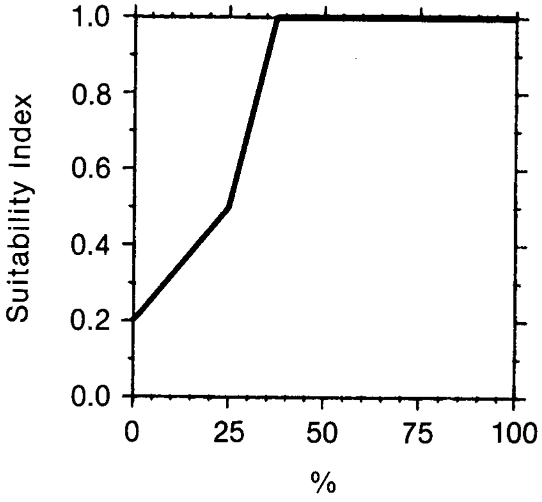
V4 Maximum water temperature at preferred spawning depth (0.2-1.5 m) sustained for at least one week during the spawning season (embryo).



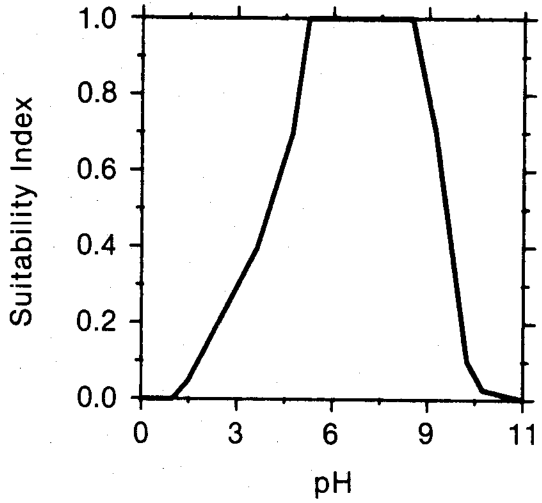
V5 Percent of stream area during spawning season that has a current velocity ≤20 cm/s and is at least 20 cm in depth.



V6 Percent bottom area (during spawning season) at preferred spawning depth (0.2-1.5 m) composed primarily of coarse sand or fine gravel (0.1-0.5 cm diameter particle size).

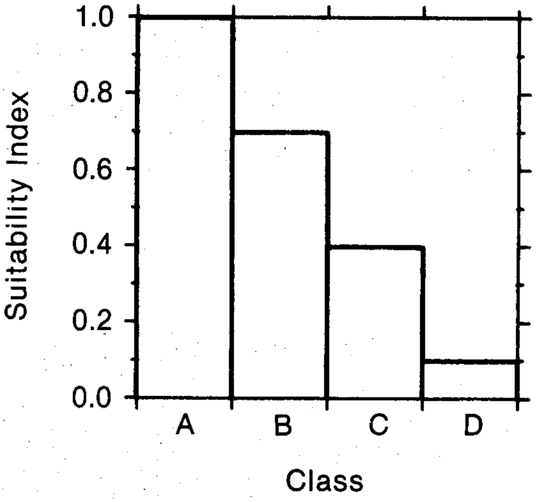


V7 Least suitable pH during spawning and growing season.

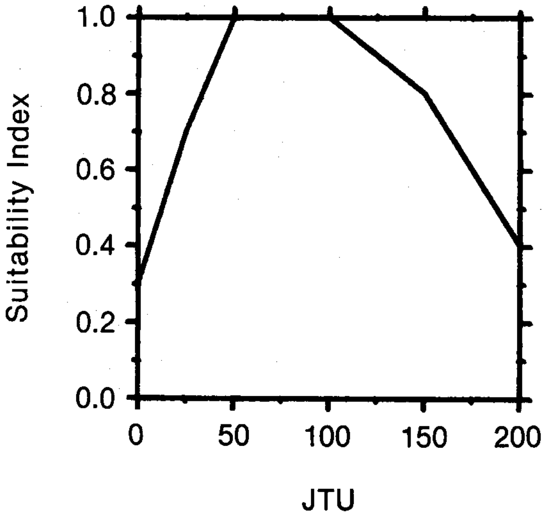


V8 Minimum dissolved oxygen range during spawning and growing season.

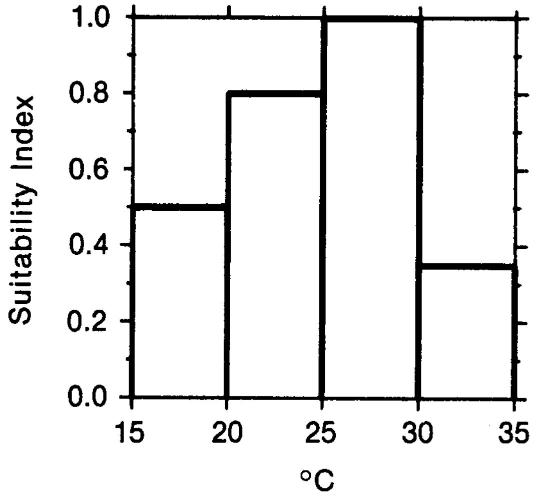
A. Seldom below 5.0 mg/l
B. Usually between 3.0 and 5.0 mg/l
C. Usually between 1.5 and 3.0 mg/l
D. Often below 1.5 mg/l



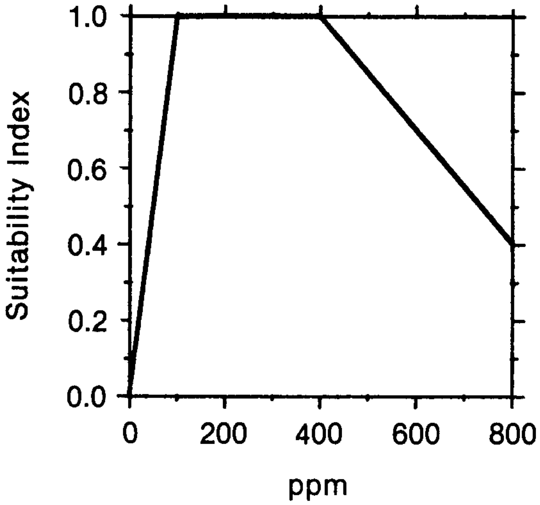
V9 Maximum monthly average turbidity during spawning and growing season.



V10 Maximum weekly water temperature (1-2 m deep) sustained during growing season (adult, juvenile, larvae).

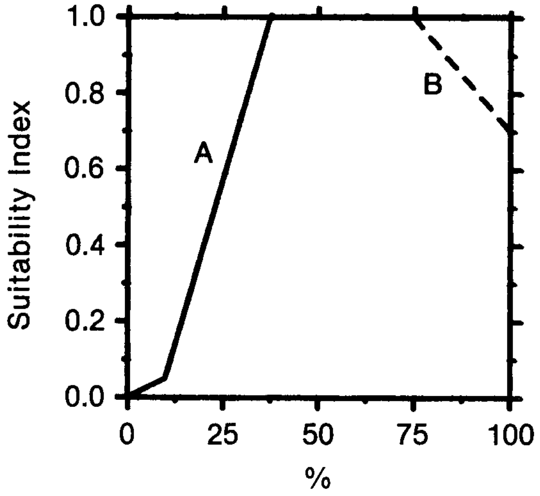


V11 Mean total dissolved solids concentration of surface waters (1-2 m deep) during growing season.

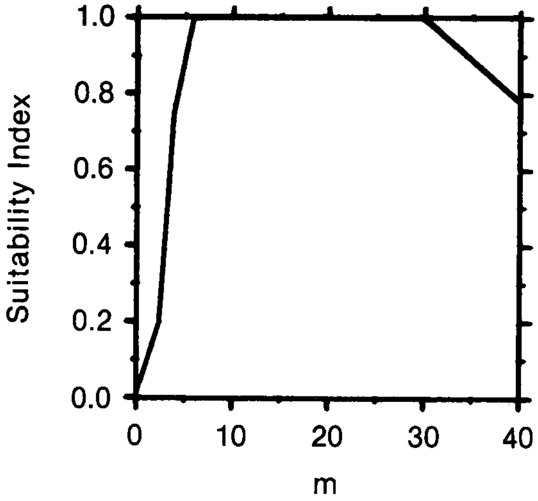


V12 Percent littoral zone area at average summer water level.

A. Southern areas
B. Northern areas



V13 Mean stream width at average summer flow.



Interpreting Model Outputs

The model has not been rigorously tested in the field to compare model outputs to species or population responses such as growth, survival, standing crop, or production. Rigorous testing should be conducted before the model is used to justify decisions. The variables selected are based on commonly measured aquatic habitat characteristics. Preliminary use of the model (Prescott Brownell, letter dated 14 Jan 86) has indicated that most variables can easily be estimated in field situations, but there are some problems estimating substrate-related variables when the water is turbid or site access is difficult. Depending on local conditions, the variable definitions may be refined to reflect constraints on sampling water quality or substrate or to incorporate additional knowledge of the species' habitat requirements.

The HSI's generated by using all (or some) of the model variables should be interpreted as ratings of the potential of an area of habitat to support a resident, self-sustaining population of redbreast sunfish. We do not expect that selection of the lowest SI value for a sample site will, in fact, result in a model that will accurately predict actual standing crop or secondary production, because habitat variables alone do not determine population levels. We recognize the importance of potential biotic interactions (e.g., predation, intra- and interspecific competition within and between the sunfishes and other members of the fish assemblage) in influencing potential patterns of distribution and abundance. However, as the physical habitat forms the template to which the animal must also respond, habitat factors known to affect performance of populations or individuals are being used in a model assumed to predict habitat-induced population limits. The accuracy of the model-generated HSI as a predictor of habitat-induced population limits is currently unknown and may vary between different geographical areas. Our extensive use of data for other centrarchid species probably will reduce model accuracy.

The model, however, can be evaluated with field measurements from environments that include the range of variables found in the proposed area of application to determine which, if any, model variables are important in limiting population levels. For example, Nelson and Miller (1984) used principal component analysis to identify HSI model variables that explained variation in standing crops of three species of centrarchids. These variables were then used as the basis of a simplified model with improved resolution properties for predicting standing crop. Layher and Maughan (1985) used standing stock estimates to develop individual SI graphs. Given the appropriate information on population dynamics and habitat featues, a multivariate approach should be a useful means to examine these complex macrohabitat properties, possibly through path analysis (c.f. Shively and Jackson 1985).

ADDITIONAL HABITAT MODELS

If predictions of actual, rather than maximum expected population levels, are required for HSI determination, the selection of additional statistical models, weighting of specific variables, or the choice of additional variable measurements may be important. For example, Li et al. (1984) used stepwise discriminant analysis to predict three levels of fish standing crop. Layher (1985) formulated SI graphs from standing crop data for channel catfish (*Ictalurus punctatus*) to predict effects of changes in flow on standing crop. Rabern (1984) predicted standing crops of southeastern stream fish directly from habitat data, bypassing altogether the development of suitability indices.

Foltz (1982) presented regression equations for predicting fish species diversity and catch per unit effort (CPUE) of all fish species combined, using a data set gathered from 1st, 2nd, and 3rd order steams in the Piedmont area of the Savannah River drainage. Redbreast sunfish were only a minor (≤1.0% by number) component of the fish captured in these streams. However, positive correlations of stream width and percent rubble to CPUE existed for the more common species, including several species of centrarchids. We expect a similar pattern (to a point) of a positive effect on redbreast sunfish populations with increasing stream width and the occurrence of greater substrate heterogeneity. Consideration of these trends has been used in the development of SI curves for V6 and V13.

INSTREAM FLOW INCREMENTAL METHODOLOGY

At the time of the development of this report (June 1986), no SI curves for use with the Instream Flow Incremental Methodology (IFIM) were available; however, a Delphi exercise for constructing curves has been initated. Guidance and examples of techniques for developing SI curves for use with IFIM are provided by Bovee and Cochnauer (1977), Stalnaker (1979), Baldridge and Ames (1982), Orth and Maughan (1982), Orth et al. (1982), Hamilton and Nelson (1984), Moyle and Baltz (1985), and Bovee (in preparation). The above references should be useful in designing a field study to develop curves and as an aid in interpreting habitat ratings derived from the SI curves. However, IFIM should not be used by individuals who have not received formal training in the use of the methodology. Use of the curves and IFIM to quantify habitat changes is critiqued by Patten (1979), Mathur et al. (1985), and Moyle and Baltz (1985).

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A review and synthesis of existing information were used to develop a Habitat Suitability Index (HSI) model and instream flow suitability curves for the redbreast sunfish (Lepomis auritus). The model consolidates habitat use information into a framework appropriate for field application, and is scaled to produce an index between 0.0 (unsuitable habitat) and 1.0 (optimum habitat). HSI models are designed to be used with Habitat Evaluation Procedures previously developed by the U.S. Fish and Wildlife Service.

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