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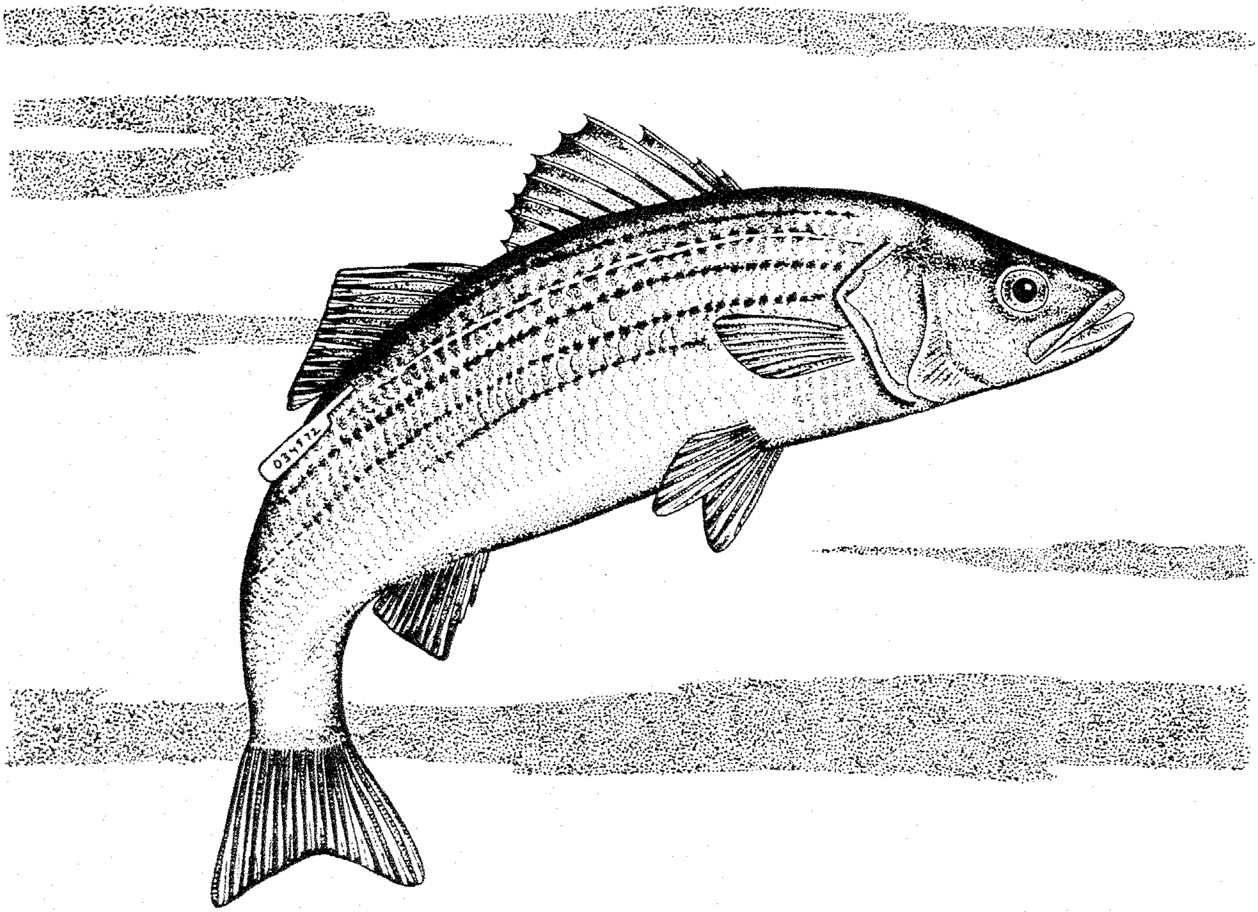
HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: INLAND STOCKS OF STRIPED BASS



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HABITAT SUITABILITY INDEX MODELS AND INSTREAM FLOW SUITABILITY CURVES: INLAND STOCKS OF STRIPED BASS

by

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PREFACE

The Habitat Suitability Index (HSI) models and instream flow Suitability Index (SI) curves presented in this publication aid in identifying important variables that determine the quality of striped bass habitat. Facts, concepts, and opinions obtained from published and unpublished reports, a Delphi panel of 18 striped bass experts/authorities, and the Striped Bass Committee, Southern Division, American Fisheries Society, are synthesized and presented in a format that can be used for habitat impact assessment and development of management alternatives.

Use of the HSI models with the Habitat Evaluation Procedures (HEP) or the SI curves with the Instream Flow Incremental Methodology (IFIM) requires project scoping, including the setting of clear study objectives. Armour et al. (in press)[1] present comparisons of the uses of HEP and IFIM for impact assessment and helpful recommendations for selecting the method most appropriate for achieving study objectives. If the HEP process is to be used, HSI model building techniques presented by the U.S. Fish and Wildlife Service (1981)[2] and the general guidelines for modifying HSI models and estimating variables presented by Terrell et al. (1982)[3] may be useful for simplifying and applying the HSI models to specific striped bass habitat assessment problems. Users of the SI curves for IFIM analyses should be familiar with the guide to stream habitat analysis (Bovee 1982)[4] and the user's guide to the physical habitat simulation system (Milhous et al. 1984).[5]

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[1]Armour, C. L., R. J. Fisher, and J. W. Terrell. In press. Comparison of the use of Habitat Evaluation Procedures (HEP) and the Instream Flow Incremental Methodology (IFIM) in aquatic analyses. U.S. Fish Wildl. Serv. FWS/OBS-84/11. 30 pp.

[2]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.

[3]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.

[4]Bovee, K. D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. Inf. Pap. 12. U.S. Fish Wildl. Serv. FWS/OBS-82/26. 247 pp.

[5]Milhous, R. T., D. L. Wagner, and T. Waddle. 1984. User's guide to the Physical Habitat Simulation System (Revised). Instream Flow Inf. Pap. 11. U.S. Fish Wildl. Serv. FWS/OBS-81/43. 475 pp.

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 the extent of the data base for 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 provide comments, suggestions, and field results that may help us increase the utility and effectiveness of this habitat-based approach to impact assessment. Please send commments to:

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STRIPED BASS (*Morone saxatilis* Walbaum)

INTRODUCTION

Habitat suitability information about striped bass and methods for applying the information are needed for water resource planning and management where the species is of concern. The purpose of this paper is to develop striped bass Habitat Suitability Index (HSI) models for use with the Habitat Evaluation Procedures (HEP) and Suitability Index (SI) curves for use with the Instream Flow Incremental Methodology (IFIM). HEP, which was first developed in 1976 (U.S. Fish and Wildlife Service 1980), is being applied Nationwide in both the public and private sectors (Schamberger and Krohn 1982) and is the most widely used evaluation technique by the U.S. Fish and Wildlife Service's Division of Ecological Services (Hardy 1981). IFIM, which became operational in 1978 (Bovee and Milhous 1978; Stalnaker 1978), was initially used for assessment of the effects of stream flow regimes on fish communities in streams in the western portion of the United States. It is now being used Nationwide for evaluating stream habitats and developing management recommendations and mitigating alternatives. There are several similarities and differences between the outputs and recommended uses of HEP and IFIM (Armour et al. in press). HEP is a generalized technique for use in terrestrial and aquatic habitats. IFIM is a specialized method designed for flowing water only.

Literature on striped bass is broad, resulting from over a century of investigations about a species that is generally characterized as being anadromous and is of great interest and importance to sporting, commerical, and scientific interests alike. A conservation measure for the fishery was enacted as early as 1639 (Pearson 1938). Fish culturists began attempts to propagate the species by the early 1880's (Worth 1884) in hopes of increasing its abundance in estuarine and riverine habitats. Freshwater reservoirs in New Jersey were stocked with striped bass as early as about 1935 (Surber 1958). Early reports on the life history of the striped bass (Scofield 1931; Pearson 1938; Merriman 1941; Raney 1952; Rathjen and Miller 1957), recent bibliographies (Pfuderer et al. 1975; Rogers and Westin 1975; Horseman and Kernehan 1976), and recent synopses (Westin and Rogers 1978; Hardy 1978; Setzler et al. 1980) are excellent sources of information about the species. The Striped Bass Committee, Southern Division, American Fisheries Society, identifies special study needs for striped bass, synthesizes information about introductions of the species into inland waters, and serves as a clearing house for information about striped bass in the Southeastern United States.

Even though the striped bass has been studied under a variety of laboratory and field conditions, there is a dearth of published information about the physio-chemical, biological, and hydrological parameters that limit the species in either lacustrine or riverine habitats. Where data are inadequate to develop SI curves for a species, opinions or best estimates of experts on the species can be used to develop the curves. However, opinions of experts on a question may differ, resulting in problems in deciding which opinion gives the best estimate. Generally, the consensus of a group of experts provides a more accurate response to a question than the response of a single expert (Fusfeld and Foster 1971). The Delphi technique, a method for developing a consensus among experts (Linstone and Turoff 1975; Zuboy 1981), was used to obtain opinions from 18 striped bass experts/authorities on the variables that determine habitat suitability for various life stages of striped bass, the general relationships between habitat suitability and certain important variables, and the general contents of this paper. Summaries of the steps used and results obtained from the Delphi technique will be presented by Crance (in prep.).

Terminology and criteria describing life stages of striped bass used in this publication are as follows. The egg stage begins with fertilization, ends at hatching, and includes embryonic development. The larval stage begins with hatching, ends at completion of fin formation, and includes yolk-sac, finfold, and post-finfold larvae. The juvenile stage begins on completion of fin formation (when the fish takes on the general appearance of mature fish) and ends at sexual maturity. The adult stage begins at sexual maturity and lasts until the fish dies. The spawning adult stage begins when the mature adult initiates spawning runs and ends when spawning is completed. Fingerlings are young juveniles, about 2.5 to 10 cm (1 to 4 inches) long.

HABITAT USE INFORMATION

General

Striped bass are tolerant of a variety of environmental conditions. They are found in marine, estuarine, riverine, and lacustrine habitats, depending on individual stocks, life stage, environmental variables, transplantations, and access to suitable spawning areas.

The Atlantic Coast range of the striped bass extends from the St. Lawrence River in Canada (Magnin and Beaulieu 1967) to the St. Johns River, Florida (McLane 1955), and on the Gulf of Mexico coast from the Suwanee River, Florida, to Lake Pontchartrain, Louisiana (Jordon 1884; Gowanloch 1933; Pearson 1938; Raney and Woolcott 1955; Barkuloo 1961; Brown 1965; Smith-Vaniz 1968; McIlwain 1968). Except for an occassional remnant population, native Gulf Coast striped bass no longer occur in their historical range, other than a small population in the Apalachicola River, Florida (Barkuloo 1961; Crateau et al. 1980, 1981; Wooley and Crateau 1983; Wooley in press).

The Pacific Coast range of the species, originally established with transplants from the East Coast, now extends from Barkley Sound, British Columbia, Canada, to 25 miles south of the California-Mexico border (Radovich 1961; Miller and Lea 1972).

The results of stocking striped bass in freshwater habitats were summarized by Surber (1958), Mensinger (1971), Bailey (1975), Gustaveson et al. (1980), Harper (1982), Whitehurst (1982), and Axon and Whitehurst (in press). Landlocked populations of this species complete their life cycle in freshwater habitats associated with Millerton Lake, California (Wydoski and Whitney 1979); Santee Cooper Reservoir, South Carolina (Scruggs and Fuller 1955; Scruggs 1957; Stevens 1958); Keystone Reservoir, Oklahoma (Mensinger 1971; Combs 1979); Kerr Reservoir, Virginia (Whitehurst 1982); the Colorado River and Lake Powell, Utah (St. Amant 1959; Gustaveson et al. 1980, in press; Persons and Bulkley 1982); and Lake Texoma, Oklahoma/Texas (Harper 1982).

Adults of coastal stocks typically are found in bays and waters around sandy beaches and shores (Pearson 1932; Bigelow and Schroeder 1953) with some water current (Hubback 1927; Raney 1952). They occur at depths from 0.6 m (2.0 ft) (Haddaway 1930) to 46 m (151 ft) (Nichols 1966). Generally, only mature or almost mature adults are found in marine waters, where they usually are confined to the neritic zone no more than 6 to 8 km (3.7 to 5 mi) offshore (Bigelow and Schroeder 1953). Adults from some coastal stocks undertake rather extensive coastal migrations (Merriman 1941; Vladykov and Wallace 1952; Chapoton and Sykes 1961; Clark 1968), while movements of adults from other coastal stocks are generally confined within estuaries or river systems (Scruggs and Fuller 1955; Raney 1957; Scruggs 1957; Clark 1968; Murawski 1969; Barkuloo 1970; Dudley et al. 1977) or limited mostly to rivers, deltas, and bays with some oceanic migrations (Talbot 1966; Chadwick 1967).

Mature adults typically exhibit annual spawning migrations and require rather specific riverine reproductive habitat. Spawning sites may be located just above the tide (Bieglow and Schroeder 1953) to as far as 320 km (199 mi) upstream above saltwater (Raney 1954), but are usually located within the first 40 km (25 mi) of a stream (Talbot 1966). Spawning sites are generally characterized by rapids, boulders, and strong currents (Norny 1882; Raney 1952; Mansueti and Hollis 1963; Talbot 1966). Eggs require suspension by currents for good survival and successful hatching (Stevens 1966; Talbot 1966; Bayless 1968).

Adults generally return to feeding grounds in open water areas of estuaries or reservoirs after spawning. However, Dudley et al. (1977) found that adults moved as far as 301 km (187 mi) upstream from the spawning area immediately after spawning and remained in riverine habitat at least 4 months. The tendency for the species to be more riverine in southern portions of its range is also supported by Raney (1952), Raney and Woolcott (1955), Barkuloo (1967), and Wooley and Crateau (1983). Adults landlocked in reservoir systems exhibit variable migration and distribution patterns.

Temperature has been reported to be a directive factor in habitat selection for juveniles and adults in some reservoirs (Coutant 1978, 1980; Schaich 1979; Waddle 1979; Coutant and Carroll 1980; Cheek 1982). Eggs generally hatch in riverine habitat, initial growth and development of larvae take place in the stream, and subsequent growth and development of larvae, juveniles, and adults occur in lacustrine habitat. Most landlocked stocks do not have access to suitable riverine habitat for reproduction and are sustained by stocking larvae or fingerlings. Bailey (1975) reported that striped bass survived "successfully" after being stocked in reservoirs where the annual range of temperature was 0 to 34° C (33 to 93° F), total hardness was 10 to 375 ppm, turbidity was 1.5 to 170 JTU, and the pH was 5.5 to 9.1.

Age, Growth, and Food

Merriman (1941), using the scale analysis method, estimated that a 29.5 kg (65 lb) striped bass was 29 to 31 years old. There are historic accounts of striped bass weighing 30 to 57 kg (66 to 126 lb) (Smith 1907; Bigelow and Welch 1925; Walford 1937; Merriman 1941).

Growth, food habits, and development rates of striped bass vary widely, depending on environmental and other conditions (Setzler et al. 1980). Mansueti (1958) gave a detailed account of the egg, larva, and young artifically spawned and hatchery-reared in water 16.7 to 17.2° C (62 to 63° F). Eggs hatched 36 to 48 hours after fertilization.

The duration of the larval stage ranges from about 23 days at 24° C (75.2° F) to 68 days at 15° C (59.0° F) (Rogers et al. 1977). A range of 18 to 21° C (64.4 to 69.8° F) appears to be optimal for growth from hatching through the yolk-sac stage.

The yolk-sac stage lasts 3 to 15 days (Mansueti 1958; Albrecht 1964; Doroshev 1970; Eldridge et al. 1977; Rogers et al. 1977). Mansueti (1958) reported that newly hatched larvae ranged from 1.9 to 3.7 mm TL; 10 to 15-day-old larvae were about 7.5 mm TL when the yolk-sac was fully absorbed.

Larvae generally form mouth parts at about 2 to 4 days of age or at lengths of 4.5 to 5.2 mm TL (Mansueti 1958; Tatum et al. 1966; Doroshev 1970). They begin feeding at about 5 to 8 days of age and 6 to 8 mm TL (Doroshev 1970; Humphries and Cumming 1973). Food availability during the first several days of feeding is a critical factor influencing survival of larvae (Miller 1977; Setzler et al. 1980; Cooper and Polgar 1981; Eldridge et al. 1981).

Pond-reared striped bass up to 10 mm TL generally prefer nauplii of copepods and cladocera (Sandoz and Johnston 1966; Humphries and Cumming 1972). They shift to larger zooplankton and microinvertebrates (Humphries and Cumming 1972), mainly copepods supplemented by cladocera and insects (Harper et al. 1969; Harper and Jarman 1972), at 10 to 30 mm TL. In ponds with an abundance of small forage fish, striped bass (at 30 to 60 mm TL) ate fewer copepods and more cladocerans and insects (Harper et al. 1969). At 60 to 69 mm TL, they began feeding on forage fish, and, at 100 mm TL, forage fish become an important food item.

Juveniles usually are opportunistic feeders (Merriman 1941; Morgan and Gerlach 1950; Johnson and Calhoun 1952; Raney 1952; Heubach et al. 1963; Stevens 1966; Hester and Stevens 1970; Ware 1971; Manooch 1973; Boynton et al. 1981). Utilization of fish in the diet of young-of-the-year striped bass probably depends on the availability of a suitable forage fish at the proper time and location (Markle and Grant 1970). Young-of-the-year striped bass in the Sacramento and San Joaquin River estuary fed mainly on invertebrates during the first winter and spring, changing to a diet of small fish the following summer (Stevens 1966). Gomez (1970) studied the food habits of young-of-the-year in Canton Reservoir, Oklahoma, and found that crustaceans and insects were a very significant part of the diet of striped bass 50 to 80 mm TL, gizzard shad (Dorosoma cpedianum) larvae were consumed by striped bass as early as 53 mm TL, and gizzard shad made up 15% of the diet of 66 mm TL striped bass. Morris and Follis (1978) reported that striped bass over 1-year old had reduced growth rates as shad (Dorosoma sp) declined in Lake E.V. Spence, Texas.

Adults also tend to be opportunistic feeders (Merriman 1941; deSylva 1973), but landlocked populations usually select clupeids or soft-rayed fish over other available food items. Striped bass in the Santee-Cooper Reservoir, South Carolina, fed heavily on mayfly nymphs during the spring months, but ate clupeid fishes almost entirely for the remainder of the year (Stevens 1958). Gizzard shad was the dominant food item for striped bass in Keystone Reservoir, Oklahoma (Mensinger 1971; Combs 1978). Ware (1971) found a preponderance of threadfin shad (Dorosoma petenense) and gizzard shad in the diet of striped bass 15 cm (6 inches) and larger from Florida lakes. Threadfin shad was the primary food item, both in frequency of occurrence and total volume, of adults from the lower Colorado River (Edwards 1974) and Lake Powell (Persons and Bulkley 1982). In the Illinois River, Oklahoma, striped bass 5 kg (11 lb) and larger fed heavily on rainbow trout (Salmo gairdneri) for the first week after the trout were stocked but gizzard shad made up 75% of their diet by number thereafter (Deppert and Mense 1979). Threadfin shad and American eel (Anguilla rostrata) were the major food items in stomachs of juveniles and adults from the Apalachiola River, Florida (Crateau et al. 1980, 1981). An abundance of small threadfin shad was considered critical for rapid growth of striped bass larger than 110 mm TL in Lake Powell (Gustaveson et al. 1980).

Adults may feed during spawning migrations (Morgan and Gerlach 1950; Trent and Hassler 1966; Persons and Bulkley 1982), but likely fast during spawning (Woodhull 1947; Morgan and Gerlach 1950; Hollis 1952; Stevens 1966; Trent and Hassler 1966; Manooch 1973).

Compared to natural coastal stocks, striped bass introduced into rivers and lakes likely grow faster, attaining an average length of about 25.4 to 27.9 cm (10 to 11 inches) the first year and 43.2 to 45.7 cm (17 to 18 inches) the second year (Scruggs 1957; Stevens 1958; Mensinger 1971; Ware 1971; Erickson et al. 1972). Juveniles, initially introduced into the Colorado River from California waters, grew an average of about 15.2 cm (6 inches) during the first year; river-spawned individuals grew to a mean of about 20.3 cm (8 inches) their first year (Edwards 1974). The mean fork length of age I and II striped bass from the Apalachicola River, Florida, was calculated to be 15.6 and 30.7 cm (6.1 and 12.1 inches), respectively (Crateau et al. 1981; Wooley and Crateau 1983). The length of striped bass from the Atlantic Coast at age I was roughly 12 cm (4.7 inches) and about 22 cm (8.7 inches) at age II (Merriman 1941). After age IV to VI, females grow faster than males (Robinson 1960; Mansueti 1961; Bason 1971).

Reproduction

Males may be sexually mature in 1 year; females in 3 years (Morgan and Gerlach 1950; Lewis 1962; Ware 1971). More commonly, however, males are sexually mature as 2-year-olds (Raney 1954; Mansueti 1956; Tagatz 1961; Mansueti and Hollis 1963; Ware 1971; Kohlenstein 1981) and females as 4- to 6-year olds (Scofield 1931; Vladykov and Wallace 1938; Merriman 1941; Jackson and Tiller 1952; Lewis 1962). The annual production of eggs increases with age and size of the female, ranging from about 65,000 as a 4-year-old to 4,500,000 as a 13-year-old (Jackson and Tiller 1952).

Streams suitable as striped bass reproductive habitat generally have a large volume of swift, turbulent water flowing over a substrate of rock and/or fine gravel (Pearson 1938; Raney 1952; Fish and McCoy 1959; Fish 1960; Mansueti and Hollis 1963; Kornegay and Humphries 1976; Combs 1979). The distance of the spawning site upstream from the river mouth varies by location and from year to year within the same river system. Spawning occurs 171.1 km (106 mi) upstream from the mouth of the Apalachicola River, Florida, (Crateau et al. 1980); 80 to 100 km (50 to 60 mi) above Santee-Cooper Reservoir, South Carolina (Scruggs 1957); 48 to 64 km (30 to 40 mi) above the headwaters of Kerr Reservoir, Virginia (Neal 1976); and 70 to 150 km (43 to 93 mi) above Keystone Reservoir, Oklahoma (Combs 1979). Persons and Bulkley (1982) reported that striped bass spawned in or near the mixing zone of Lake Powell, Utah, and the Colorado River. Gustaveson (in press) provided evidence of in-reservoir spawning by striped bass in Lake Powell.

Spawning is apparently cued to a rise in temperature in late winter or early spring (Hardy 1978) and also may be cued to the photoperiod (Crance in prep.). Spawning begins as early as mid-February or early March in Florida (Barkuloo 1961, 1970) and may last until early July (Raney 1954) in some locations, depending on latitude and other factors. Dudley and Black (1978) reported three spawning peaks during a season.

The low and high temperatures at which spawning occurred in the Roanoke River, North Carolina, during a 5-year period were 12.8° C (55° F) and 21.7° C (71° F), respectively (Shannon and Smith 1968). The optimal spawning temperatures were about 16.7 to 19.4° C (62 to 67° F). These ranges approximate temperature data associated with striped bass spawning reported by Calhoun et al. (1950), Farley (1966), and Talbot (1966).

Eggs are deposited near the water surface (Merriman 1941; Raney 1952). The incubation period is about 34 hours at 21° C (70° F) (Shannon and Smith 1968), 51.8 hours and 62 hours at 18° C (64.4° F) and 15.0° C (59.0° F), respectively (Rogers et al. 1977), and about 70 to 74 hours at 14.4 to 15.6° C (58 to 60° F) (Surber 1958).

General Habitat Requirements

Self renewing inland stocks of striped bass generally require two major types of habitat: (1) riverine habitat for reproduction; and (2) lacustrine or estuarine habitat for foraging, growth, and development by the larvae, juveniles, and adults.

Information about the relationships between striped bass habitat suitability and a few variables is substantial, but information for many variables is sparse. Available data indicate that dissolved oxygen concentration, water temperature, and velocity are the principal variables that limit riverine habitat suitability for striped bass; dissolved oxygen concentration and water temperature are the principal variables that limit lacustrine habitat suitability.

Food. Food availability may not directly limit the suitability of reproductive habitat because adults do not feed immediately before and during spawning (Woodhull 1947; Morgan and Gerlach 1950; Hollis 1952; Stevens 1966; Trent and Hassler 1966; Manooch 1973). However, their feeding habits during spawning runs are unclear. Larvae do not feed until they are 5 to 8 days of age (Doroshev 1970; Humphries and Cumming 1973) and may not begin to feed until they reach lacustrine or estuarine habitat.

Availability of prey (zooplankton) during the first few days of feeding is likely a critical factor influencing the survival of striped bass larvae (Miller 1977; Cooper and Polgar 1981; Eldridge et al. 1981). Miller (1977) reported that a minimum of 1,864 zooplankters per liter is required by larvae during initial feeding; however, striped bass larvae begin feeding and apparently survive in some waters in California, where average concentrations of zooplankton are much lower (Crance in prep.). A zooplankton density of 4,000/l or more was reported to be optimal for young juveniles.

Landlocked adults feed primarily on gizzard shad and/or threadfin shad (Stevens 1958; Mensinger 1971; Ware 1971; Edwards 1974; Bailey 1975; Weaver 1975; Combs 1978; Deppert and Mense 1979; Gustaveson et al. 1980; Persons and Bulkley 1982). The quantity of forage fish required likely depends on several interacting variables, including the size of the striped bass population to be sustained and the presence of other species that eat shad or that are eaten by striped bass. An established population of striped bass has been maintained in Arkansas waters where the clupeid standing crop average was as low as 22.4 kg/ha (20 lbs/acre), but a standing crop of about 84.1 kg/ha (75 lbs/acre) or higher is probably optimal (Crance in prep.).

Water flow. Diversions of instream flow may block spawning migrations or alter water depth, width, velocity, and/or other variables to levels critical for spawning and survival of eggs and larvae. Stable, high volume stream flow and water velocity during the spawning season probably enhance suitability of reproductive habitat by helping to stabilize the water temperature, facilitate the migration of spawning adults, suspend eggs until hatching, and buoy larvae until suspension can be maintained by swimming. Streams suitable for reproductive habitat generally are characterized as having large volumes of moving water (Pearson 1938; Raney 1954; Fish and McCoy 1959; Mansueti and Hollis 1963; Turner and Chadwick 1972) and uniform flows (Fish and McCoy 1959). High volume stream flow may result in the emigration of striped bass from the receiving reservoir if the reservoir has a short retention time.

Simultaneously rising discharges and water temperatures may have resulted in striped bass migrating upstream to spawning sites in the John H. Kerr Reservoir system, while very erratic stream flows, with or without rising temperatures, appeared to repel the fish (Neal 1976). Fish and McCoy (1959) concluded that a section of the Roanoke River became progressively more attractive to striped bass spawners as sustained minimum flows increased above 157 m^3/s (5,550 cfs) and that most of the spawners were driven out of the spawning area when minimum river flow decreased to 110 m^3/s (3,900 cfs). Successful spawning in the Apalachicola River, Florida, was associated with years when water flows of 255 to 8,213 m^3/s (9,000 to 290,000 cfs) occurred (Crance in prep.).

Suspended sediments and turbidity. Reports indicate that striped bass have a relatively high tolerance to silt-laden and turbid waters (Mansueti 1961, 1962; Talbot 1966) and that high concentrations of suspended sediments likely do not affect the eggs or larvae (Schubel and Wang 1973).

Sediment levels up to 500 mg/l did not affect the hatching success of eggs (Schubel and Wang 1973; Schubel and Auld 1974). However, sediment levels of 1,000 mg/l significantly reduced hatching success (Schubel and Auld 1974; Auld and Schubel 1978). Levels over 100 mg/l delayed hatching several hours (Schubel and Wang 1973). Morgan et al. (1973, 1983) concluded that hatch of striped eggs was not significantly affected by suspended sediment concentrations ranging from 20 to 2,300 mg/l, but embryo development was slowed significantly at concentrations above 1,300 mg/l.

The LC_{50} concentration of suspended sediments for striped bass larvae was 4,850 mg/l at 24 h and 2,800 mg/l at 48 h (Sherk et al. 1975). The mortality rate of yolk-sac larvae increased significantly when exposed to suspended sediment levels of 500 and 1,000 mg/l for 48 to 96 h (Auld and Schubel 1978).

Turbidity may indirectly benefit striped bass because it reduces light penetration (Crance in prep.). Intense light may be harmful to striped bass. In addition, gizzard shad and threadfin shad concentrate at times in warm, turbid water and become more vulnerable as prey.

Salinity and total dissolved solids. Farley (1966) concluded that no significant spawning occurred during 1963 and 1964 in areas of the Sacramento-San Joaquin River systems in California where concentrations of total dissolved solids (TDS) were above 180 mg/l. In addition, TDS concentrations over 180 mg/l prevented striped bass from migrating above Stockton, California, in the San Joaquin River. Murawski (1969) noted that striped bass spawned in the Delaware River where the TDS concentration was 180 mg/l or less. Radtke and Turner (1967) concluded that 350 mg/l TDS was the critical concentration for blocking upstream spawning migrations. However, prespawning adults did not avoid 954 mg/l TDS in Keystone Reservoir, Oklahoma (Summerfelt and Moiser 1976), and adults migrated through waters in the Arkansas River tributary of Keystone Reservoir where the TDS level was 303 to 1,920 mg/l to reach spawning sites (Combs 1979).

Albrecht (1964) concluded that low salinity (920 to 948 mg/l chlorides) enhanced egg and larval survival and that moderate salinity (4,595 to 4,740 mg/l chlorides) was not detrimental. The idea that striped bass larvae do better in low salinity water than in fresh water is supported by Rathjen and Miller (1957), Tatum et al. (1966), Bayless (1972), Davies (1973), Shell (1974), and Lal et al. (1977). Rees (1977) found no overall difference in hatching success or fry survival among groups of eggs hatched at salinities of 0, 1,000, and 3,000 mg/l at 18.9° C (66.1° F). Morgan et al. (1981) noted that the effect of salinity on the development of striped bass is complex and that, although salinity does not directly influence percent hatch of eggs, there is a significant interactive effect of salinity and temperature on percent hatch, as well as on percent survival of larvae. Larvae held in water with salinity levels of 3,000 to 5,000 mg/l and then stocked in earthen ponds in Alabama, with the salinity level of the water between 3,000 to 8,000 mg/l, survived well (Crance in prep.).

Tagatz (1961) reported that juveniles survived abrupt transfers between salt and fresh water at temperature differences from 12.8 to 21.1° C (55 to 70° F), but were not tolerant to transfers from fresh water to salt water at 7.2° C (45° F). Adults were tolerant of abrupt changes between salt and fresh water at differences in temperature from 7.2 to 26.7° C (45 to 80° F).

pH. The tolerance range of larvae and young juvenile striped bass appears to be about pH 6 to 10 (Bonn et al. 1976; Regan et al. 1968; Shannon 1968; Bailey 1975); the optimum range is about pH 7.5 to 8.5 (Bogdanov et al. 1967; Davies 1973; Bonn et al. 1976). Rapid changes in pH can be lethal to young juveniles (Tatum et al. 1966). Regan et al. (1968) reported that mass mortality of larvae occurred within 4 hours after being subjected to a change in pH from 7.5 to 9.9. Doroshev (1970) reported 100% mortality of larvae subjected to a change of 0.8 to 1.0 pH units. Combs (1979) concluded that there was no relation between pH and striped bass production in the Arkansas River, Oklahoma, where the mean daily pH ranged from 7.3 to 8.5. The U.S Environmental Protection Agency (1976) recommended a pH range of 6.5 to 9.0 for freshwater aquatic life but cautions that the toxicity of some compounds, such as cyanide, increases as the pH is lowered and that the toxicity of ammonia may increase 10 times when the pH increases from 7.0 to 8.0.

Contaminant load. Quality criteria for freshwater aquatic life developed by the U.S. Environmental Protection Agency (1976), a review of EPA's criteria (Thurston et al. 1979), and quality criteria for water adopted by States are useful references for determining contaminant levels acceptable for striped bass habitats.

Physical barriers. Dams or other physical barriers that prevent fish passage may eliminate access to spawning habitat. Fishways have not proven satisfactory for striped bass (Talbot 1966).

Stream width. Extremely narrow streams can prevent adult striped bass from moving to spawning sites. However, width was not considered to be an important variable that determines riverine habitat suitability (Crance in prep.).

Stream length. If spawning occurs in riverine habitat, a minimum distance from the spawning site to lacustrine habitat is required (see section on minimum habitat size). This distance will vary, depending on climate, locale, density of eggs, and other factors.

Depth. The relationship of water depth to suitability of striped bass habitat is unclear (Crance in prep.). A minimum depth of 0.46 m (1.5 ft) is assumed to be needed for adults to swim upstream to spawning areas. Areas with depths of 1.8 to 2.1 m (6.0 to 7.0 ft) may be needed to provide temporary refuge from boat traffic and excessive current and sunlight. Spawning has been reported to occur in waters less than 1.8 m (6 ft) deep and at depths up to 15.2 m (50 ft). A depth range of about 1.8 to 9.1 m (6 to 30 ft) is assumed to be optimal for spawning. Extreme depths are not conducive to turbulence, which is usually associated with spawning areas.

If dissolved oxygen and water temperature levels are within suitable ranges, depths selected by striped bass in lacustrine habitats are determined to a large degree by food availability. Stratified lakes with a mean minimum depth less than about 6.1 m (20.0 ft) and unstratified lakes with a mean minimum depth less than about 1.8 m (6 ft) are likely to be unsuitable lacustrine habitat for juveniles and adults during summer. Juveniles are commonly caught in seinable waters 0.6 to 1.8 m (2 to 6 ft) deep (Crance in prep.).

Substrate. The relationship of substrate to suitability of striped bass habitat is unclear (Crance in prep.). Substrate is probably not a limiting factor except where eggs or larvae settle to the bottom. Substrate composed of particles large and/or dense enough that excessive amounts do not become suspended often is generally considered most suitable for spawning and egg incubation. However, spawning occurs over mud/silt in some coastal streams in Georgia and in Chesapeake Bay and over peat and sand substrate in California waters (Crance in prep.).

Data presented by Van Den Avyle and Higginbotham (1979) indicated that juveniles in a Tennessee lacustrine habitat preferred sand substrate during October and November but showed no preference for substrate type during other months. Shoreline seining for juveniles in Oklahoma reservoirs was most productive over sandy substrate (Mensinger 1971; Harper 1982).

Cover. The relationships between cover and suitability of striped bass habitat is unclear (Crance in prep.). Adults and larvae likely use instream cover for resting and protection. Streambank cover (trees or vegetation) provide shade, which may help to reduce excessive light penetration and buffer the water temperature.

Larvae and juveniles in lacustrine habitat are commonly found over sandy substrate in shallow water. They may use cover, such as submersed vegetation, for foraging and protection from predators. Harper (1982) reported that juveniles were found least frequently in vegetated coves. Adults are sometimes abundant in lacustrine habitat near submersed islands or shoals, large boulders, brush, overhanging ledges, and/or old river channels.

Riverine Habitat Requirements

Principal variables that determine the suitability of riverine habitat for striped bass are water temperature (V_1), dissolved oxygen concentration (V_2), and current velocity (V_3).

Water temperature (V_1). Water temperature regulates the activities of adults and the survival and development of eggs and larvae.

Spawning. Adults usually initiate spawning runs when temperatures reach 15 to 19° C (59 to 62° F) (Raney 1952). Both the initiation and duration of spawning are temperature-dependent (Calhoun et al. 1950; Rathjen and Miller 1957), and sudden drops in water temperature may interrupt spawning (Calhoun et al. 1950; Chadwick 1958; Mansueti amd Hollis 1963; Farley 1966; Combs 1979).

Kernehan et al. (1981) collected striped bass eggs in the vicinity of the Chesapeake and Delaware Canal where water temperatures ranged from 8.4 to 29.0° C (47.2 to 84.2° F), but they noted that most of the larvae produced in the area resulted from intensive spawning in water with temperatures of 13.5 to 18.0° C (56.3 to 64.4° F). Other temperature extremes reported for spawning were a low of 10° C (50° F) (Institute of Environmental Medicine 1973) and a high of 26.5° C (79.7° F) (Combs 1979). More commonly, spawning occurs within the range of about 12 to 23.9° C (54 to 75° F) (see Table 1).

Shannon and Smith (1968) did not observe spawning in the Roanoke River, North Carolina, when water temperatures were below 12.8° C (55° F) or above 21.7° C (71° F). McCoy (1959) reported a minimum spawning temperature of about 15° C (59° F) and a maximum of about 22° C (72° F). Combs (1979) reported that spawning began in the Arkansas River, Oklahoma, when the water temperature reached 15.5 to 18.5° C (59.9 to 65.13° F), slightly higher than initial spawning temperatures observed by Rathjen and Miller (1957), McCoy (1959), Hollis (1963, 1967), Kornegay and Humphries (1976), Marshall (1976), and Neal (1976). Stooksbury (1977) noted that striped bass spawned in J. Percy Priest Reservoir, Tennessee, at 15 to 17° C (59.0 to 62.6° F). The optimum temperature range for spawning appears to be about 17 to 20° C (63 to 68° F), based on reports by McCoy (1959) and Shannon and Smith (1968). However, the optimum spawning temperature range for striped bass in the Apalachicola River, Florida, appears to be slightly higher (Crateau et al. 1981). The minimum and maximum temperatures for spawning are about 12° C (54° F) and 24° C (75° F), respectively (Table 1).

Egg. The effects of temperature on hatching and incubation time are listed in Table 2. The lower and upper temperature limits for survival of eggs and resultant larvae are about 12.0° C (53.6° F) and 22.0° C (72.0° F), respectively. Eggs incubated at 21.0° C (70° F) hatched, and the fry survived for 3 days (Shannon and Smith 1968). However, when the incubation temperature nears 23.0° C (73° F) egg survival declines rapidly (Morgan and Rasin 1973), and resultant fry will not likely survive (Shannon and Smith 1968).

Table 1. Water temperatures associated with striped bass spawning.

Temperature °C	°F	State	Reference
Spawning occurred			
10.0	50.0	NY	Institute of Environmental Medicine (1973)
12.0 to 22.0	53.6 to 71.6	CA	Albrecht (1964)
12.2 to 21.0	54.0 to 70.0	VA	Tresselt (1952)
12.2 to 22.2	54.0 to 71.0	NJ	Murawski (1969)
12.8 to 21.7	55.0 to 71.0	NC	Shannon and Smith (1968)
14.4 to 20.6	58.0 to 59.0	NC	Kornegay and Humphries (1976)
14.4 to 22.2	58.0 to 72.0	NC	McCoy (1959)
14.4 to 23.3	58.0 to 74.0	VA	Neal (1976)
15.0 to 17.0	59.4 to 62.6	TN	Stooksbury (1977)
15.0 to 20.0	59.0 to 68.0	NJ	Rathjen and Miller (1957)
15.0 to 22.0	59.0 to 72.0	NC	Humphries (1966)
15.5 to 26.5	59.9 to 79.7	OK	Combs (1979)
16.1 to 23.9	61.0 to 75.0	FL	Crateau et al. (1980, 1981)
17.2 to 20.0	63.0 to 68.0	CA	Turner (1976)
17.0 to 23.0	62.6 to 73.4	GA	Dudley and Black (1978)
Spawning peak			
17.0 to 20.0	62.6 to 68.0	NC	McCoy (1959)
18.6 to 19.1	65.5 to 66.4	FL	Crateau et al. (1981)
Optimum spawning range			
16.7 to 19.4	62.0 to 67.0	NC	Shannon and Smith (1968)

Table 2. The effects of water temperature on striped bass eggs.

Temperature °C (°F)	Effect on eggs	Reference
10 (50)	Did not hatch	Morgan et al. (1981)
10.5 (51)	Did not hatch	Morgan and Rasin (1973)
11.0 (52)	Did not hatch	Morgan and Rasin (1973)
12 (53.6)	Seldom survived	Rogers et al. (1977)
< 12.2 (54)	Died rapidly	Barkuloo (1970)
12.8 (55)	Survived	Albrecht (1964)
14.4 to 15.5 (58 to 60)	Hatched 70-74 hours	Surber (1958)
15.6 (60)	Hatched 58 hours	Shannon and Smith (1968)
16.7 to 17.2 (62 to 63)	Hatched 48 hours	Mansueti (1958)
17.9 (64.3)	Hatched 48 hours	Pearson (1938)
21.0 (70)	Hatched 34 hours	Shannon and Smith (1968)
> 22.2 (72)	Died rapidly	Barkuloo (1970)
Approached 23.0 (73)	Mortality increased	Morgan and Rasin (1973)
22.2 (72)	None survived in salinities above 1000 ppm	Turner and Farley (1971)

According to Doroshev (1970) and Morgan et al. (1981), the optimum temperature range for best survival of striped bass eggs is about 17 to 20° C (62.6 to 68.0° F). However, Rogers et al. (1977) reported that egg survival was highest at 15 to 18° C (59 to 64.4° F). Bayless (1972) suggested that egg survival through hatching was best at 16.7 to 18.2° C (62 to 65° F). Rogers (1978) proposed a temperature of 18° C (64.4° F) as the physiological growth optimum for embryonic development and 18 to 21° C (64.4 to 70.0° F) for yolk-sac absorption.

Larval. Rogers et al. (1977) reported that the mean time between hatching and yolk absorption was 5.1 days at 21° C (69.8° F) and 8.3 days at 15° C (59° F). The duration of larval development (finfold plus post-finfold state) was about 24 days at 21° C (69.8° F) and 68 days at 15° C (59° F). Larvae may live within a temperature range of 12.8 to 23.9° C (55 to 75° F), but high mortality can be expected at 23.9° C (75° F) and above (Albrecht 1964). Temperatures below 10° C (50° F) and above 23° C (73.4° F) are apparently lethal to larvae (Doroshev 1970). Shannon and Smith (1968) reported 100% mortality of newly hatched larvae held at 23.3° C (74° F) for 70 hours; whereas, 100% of the larvae held at 21.1° C (70° F) for 76 hours survived. An optimal temperature range of 18 to 21° C (64.4 to 69.8° F) was reported for yolk-sac larvae (Rogers et al. 1977; Rogers 1978). Temperature ranges of 16 to 22° C (60.8 to 71.6° F) and 16 to 19° C (60.8 to 66.2° F) were reported to be favorable for striped bass larvae by Bogdanov et al. (1967) and Doroshov (1970), respectively. Results of a striped bass Delphi technique (Crance in prep.) indicated that larvae survival was good at temperatures as high as 24.4° C (76° F) in Alabama ponds, 25° C (77° F) in Chaptank River, Maryland, and 25.6° C (78° F) in South Carolina ponds; the ideal range for larvae in the Apalachicola River, Florida, was 18.3 to 22.2° C (65 to 72° F). Dey (1981) hypothesized that a sudden drop in water temperature from 15 to 12° C (59.0 to 53.6° F) in the Hudson River Estuary probably resulted in almost complete mortality of striped bass larvae. Boreman (1983) supported this hypothesis.

Dissolved oxygen concentration (V_2). The U.S. Environmental Protection Agency (1976) recommended a dissolved oxygen concentration of 5.0 mg/l as the minimum level for maintaining good fish populations.

Adult. Areas of the Delaware River have been eliminated as striped bass spawning grounds due to low dissolved oxygen concentrations (Chittenden 1971a). Adults avoided water of 44% or less saturation in laboratory tests (Meldrim et al. 1974). It is assumed that dissolved oxygen concentrations suitable for egg survival, embryo development, hatching, and larval survival also are suitable for spawning adults.

Egg. Reductions in dissolved oxygen from 5 to 4 mg/l adversely affected the percent hatch of eggs and had a detrimental effect on larval survival (Turner and Farley 1971). Harrell and Bayless (1981) reported that normal development of striped bass embryos required a dissolved oxygen concentration ≥ 3.0 mg/l. Dissolved oxygen levels of 2.0 to 3.0 mg/l may have been responsible for the absence of striped bass eggs in areas of the Delaware River (Murawski 1969).

Larval. Dissolved oxygen concentrations of 2.0 mg/l and less are considered detrimental to striped bass larvae (Dorfman and Westman 1970; O'Mally and Boone 1972). Levels of 2.0 to 3.5 mg/l have been responsible for the absence of eggs and larvae in the Delaware River (Murawski 1969; Chittenden 1971a). Chittenden (1971b) concluded that larvae need a minimum level of 3.0 mg/l to survive. A level of 4.0 mg/l may be too low for successful reproduction (Talbot 1966). Even moderate reductions in dissolved oxygen concentrations (from 5.0 to 4.0 mg/l) may decrease the survival of eggs and larvae (Turner and Farley 1971).

Current velocity (V_3).

Adult. Water current probably is an attractant for striped bass that are preparing to spawn (Dickson 1958).

Egg. Striped bass eggs are semibuoyant. Without sufficient current, the eggs slowly settle to deeper water or the bottom and may suffocate due to a deficiency in dissolved oxygen (May and Fuller 1965). Continuous suspension and movement of eggs appear to be essential to survival and successful hatching in streams (Surber 1958; Fish and McCoy 1959; May and Fuller 1965; Barkuloo 1970). Albrecht (1964) and Bayless (1968) demonstrated, in the laboratory, that eggs not held in suspension could be hatched but success was limited. Eggs kept on the bottom during incubation had a poor chance of survival. Eggs probably hatched successfully in the absence of turbulent current in Lake Powell, Utah, where the dissolved oxygen concentration was 13.2 mg/l at the substrate surface where the eggs settled (Gustaveson et al. in press).

A minimum current velocity of about 30.5 cm/s (1 ft/s) is required to suspend striped bass eggs in freshwater (Albrecht 1964). However, the absolute minimum velocity required can be site and time specific, depending on the density of the water and the eggs. Water density varies with temperature, salinity, and total dissolved solids. Egg density varies with age and/or condition of the female and other factors (Schrader 1979). A velocity of 15 cm/s (0.5 ft/s) may keep eggs suspended once they become water hardened (Crance in prep.).

Surface water velocity in areas where striped bass eggs have been collected ranged from 12.2 to 88.4 cm/s (0.4 to 2.9 ft/s) in Virginia streams (Tresselt 1952), 18.3 to 88.4 cm/s (0.6 to 2.9 ft/s) in California waters (Albrecht 1964), and 50.0 to 83.5 cm/s (1.6 to 2.7 ft/s) in the Arkansas River, Oklahoma, where striped bass spawned 3 consecutive years (Combs 1979). Current velocity in the Roanoke River below Weldon, North Carolina, was about 49 cm/s (1.6 ft/s) near a major spawning area for striped bass (Dickson 1958). Spawning occurred in areas of the Santee River, South Carolina, where water velocity was less than 29.9 cm/s (0.98 ft/s) (Crance in prep.). Velocities of about 240 cm/s (7.9 ft/s) may create shears approaching the damaging range for eggs (Marcy 1971, 1973; Morgan et al. 1976). It was reported that eggs have been observed in water with velocities up to 270 cm/s (8.9 ft/s) and that a velocity of about 400 cm/s (13.1 ft/s) is likely the maximum for survival (Crance in prep.).

Larval. Larvae have little chance for survival if water currents are insufficient to keep them from settling to the bottom (Barkuloo 1970). Newly hatched larvae tend to settle to the bottom of an aquarium filled with un-agitated water despite swimming efforts to remain near the surface (Pearson 1938; Mansueti 1958). Larvae likely require currents or turbulence for up to 15 hours post-hatch (Meinz and Heubach 1978). Tests conducted by Morgan et al. (1976) indicated that eggs and larvae have about equal specific gravity. It is assumed that a minimum current velocity of 30.5 cm/s (1 ft/s), which is the velocity required to float eggs (Albrecht 1964), is necessary to bouy larvae until suspension can be maintained by swimming.

Current velocities higher than the minimum required to bouy eggs or larvae could be detrimental by moving eggs downstream into the slack water of a reservoir prior to hatching or by carrying larvae into slack water before they can maintain suspension by swimming. High velocity also may result in shear levels that damage eggs and/or larvae. Exposure of striped bass eggs to a shear level of 350 dynes/cm² killed 36% of the eggs in 1 minute, 69% in 2 minutes, and 88% in 4 minutes; exposure of larvae to 350 dynes/cm² killed 9.3% in 1 minute, 30.0% in 2 minutes, and 68.1% in 4 minutes (Morgan et al. 1976). Marcy (1971, 1973) and Morgan et al. (1976) presented information which indicated that a water velocity of about 240 cm/s (7.9 ft/s) created shears approaching the damaging range for striped bass eggs and larvae.

Lacustrine Habitat Requirements

Water temperature and dissolved oxygen concentration are the principal variables that determine suitability of lacustrine habitat for striped bass.

Water temperature (V_1, V_4, and V_5). Temperature preferences of striped bass likely vary by locale, apparently change with age and an increase in size (Schaich 1979; Coutant 1980, 1983; Coutant in press), and influence lacustrine habitat selection by juveniles and adults (Waddle 1979; Coutant and Carroll 1980; Cheek 1982).

Adult (temperature, V_5). The lower avoidance temperature by adults in Cherokee Reservoir, Tennessee, was about 18.5° C (65.0° F) (Schaich 1979). This was near the lower avoidance boundary for adults in coastal waters (Radovich 1963) but higher than temperatures of 13.9 to 17.2° C (57.0 to 63.0° F) in areas in the San Francisco Bay where many adults spend the summer (Crance in prep.).

Adults in Cherokee Reservoir avoided water above 25° C (77° F) (Waddle 1979; Schaich 1979); adults apparently avoided water temperatures of 24 to 25° C (75.2 to 77.0° F) in Watts Bar Reservoir, Tennessee (Cheek 1982). Merriman (1941) reported that adults avoided coastal waters above 25 to 27° C (77 to 80.6° F). Dudley et al. (1977) observed that adults in the Savannah River, Georgia, avoided temperatures over 26° C (78.8° F). Concentrations of adults were found in areas of Lake Whitney, Texas, in temperatures ranging from 27.5 to 29.0° C (81.5 to 84.2° F) when cooler water was available in the lake (Crance in prep.).

Summer habitat selected by adults in Tennessee Reservoirs indicate an average occupied temperature near 20° C (68° F) when warmer, oxygenated waters were available (Schaich 1979; Waddle 1979; Cheek 1982). Adults were found to occupy cool-water refuges (21.0° C; 69.8° F) in the Apalachicola River, Florida, during summer while surface water temperatures rose to 31° C (87.8° F) (Crateau et al. 1981; Wooley and Crateau 1983). It appears that the temperature niche for adult striped bass in lacustrine habitat may vary by several degrees (Crance in prep.). This may be due to a number of factors, including experimental variability, differences among fish stocks, geographic location, age of fish, and the ranges of water temperature and dissolved oxygen concentration available to the fish.

Juvenile (temperature, V_4). Juvenile striped bass select and grow optimally at higher temperatures than are optimal for eggs, larvae, or adults (Cox and Coutant 1981; Coutant in press). Juveniles can tolerate temperatures from 3 to 34° C (37.4 to 93.2° F) (Davies 1970). About 34.4 to 35° C (94 to 95° F) appears to be the upper lethal temperature range (Loeber 1951; Dorfman and Westman 1970). Growth apparently ceases at about 33.5° C (92.3° F) (Cox and Coutant 1981). Otwell and Merriner (1975) reported the greatest growth of juveniles at 24° C (75.2° F), which is within the range of 23.0 to 26.0° C (73.4 to 78.4° F) indicated as optimal for growth by Cox and Coutant (1981). Kellog and Gift (1983) reported that 26.9 to 30.3° C (80.5 to 86.6° F) was the optimum growth temperature range for striped bass that were 8.7 mm and 28.9 mm long at the start and end of the test period, respectively. However, it was reported that juveniles held in brackish water ponds in Alabama at 12 mg/l salinity and 33° C (91.4° F) actively fed and grew well (Crance in prep.).

Larval (temperature, V_1). Temperature requirements of striped bass larvae in lacustrine habitat are assumed to be equal to temperature requirements of larvae in riverine habitat. However, once larvae reach the lacustrine habitat, they are generally a few days older and are likely to survive and do well at slightly higher temperatures than they do at a younger age in riverine habitat.

Dissolved oxygen concentration (V_2). Dissolved oxygen concentration requirements for all life stages of striped bass are assumed to be equal whether they occur in lacustrine or riverine habitat.

Adult (dissolved oxygen, V_2). Refuges most frequently occupied by adults in Cherokee Reservoir, Tennessee, had 5 mg/l or more dissolved oxygen (Schaich 1979; Waddle 1979).

Juvenile (dissolved oxygen, V_2). Krouse (1968) observed no mortality of juveniles (2.8 to 13.0 cm TL; 1 to 4.4 inches) after 72 hours exposure to 5.0 mg/l dissolved oxygen. Mortality increased at 3.0 mg/l, and no fish survived at 1.0 mg/l. Chittenden (1971b) concluded that about 3.0 mg/l at 16.0° C (60.8° F) probably represents the minimum oxygen concentration for normal existence of juveniles and that 3.0 mg/l may be insufficient to maintain optimum populations of the species. Dorfman and Westman (1970) and Klyashtorin and Yarzhombek (1975) concluded that 4.0 to 4.5 mg/l can be considered the critical concentration of dissolved oxygen for young striped bass at 22° C (71.6° F).

Larval (dissolved oxygen, V_2). Egg and larval requirements for dissolved oxygen are assumed to be the same for both lacustrine and riverine habitats.

Special Considerations

Riverine habitat having a high HSI may not produce striped bass larvae, and a high HSI for lacustrine habitat does not necessarily indicate a high standing crop of striped bass. Numerous factors, including hatching success and survival of fry, spillway escapement, amount and availability of suitable forage, size and number of predators that feed on striped bass, stocking practices, and fishing pressure, can influence year-class size and abundance. Forage species eaten by juvenile and adult striped bass also are utilized by other prey species. The abundance of forage species is influenced by physiochemical variables, making their availability to striped bass uncertain.

High temperatures in the epilimnion and low dissolved oxygen concentrations in deep, cooler areas of a reservoir may bring about an environmental "squeeze" during warmer months, causing adult striped bass to seek refuge in relatively small, spring-fed coves or in tailwater areas (Coutant 1978; Schaich 1979; Waddle 1979; Cheek 1982). The "squeeze" may temporarily greatly reduce the volume and area of suitable habitat available to adults. While "squeezed" in the refuge, adults are highly vulnerable to parasites and diseases and to harvest by anglers. Inadequate food may result from increased competition for available forage, and fish may quit feeding and die due to the undesirable environmental conditions. Thermal stress and/or low levels of dissolved oxygen have been reported to result in mortality of adults in freshwater reservoirs (Axon and Whitehurst in press). Wooley and Crateau (1983) found that striped bass weighing 4.5 to 6.7 kg (9.9 to 14.8 lb), captured in cool-water refuges during the summer, showed a significant weight loss since the previous spring. However, adults weighing less than 4.5 kg (9.9 lb) had gained weight throughout the summer.

HABITAT SUITABILITY INDEX MODELS

Model Applicability

These models are not applicable to habitat overburdened with toxic chemicals or heated effluents or to rapidly fluctuating conditions, such as sudden changes in water temperature or river discharge during the spawning season. If contaminants are suspected to affect habitat suitability, guidelines on quality criteria for water are available from State water quality control agencies, the U.S. Environmental Protection Agency (1976), and Thurston et al. (1979).

Geographic area. The models generally are applicable to riverine or lacustrine habitat of striped bass throughout the 48 conterminous States. However, the models may require modification for use in some localized habitats.

Season. The riverine model is applicable during the spawning season; the lacustrine model is applicable during the period when habitat quality is expected to be critical for the life stage under consideration. Summer requirements of striped bass may not be adequately addressed for shallow, eutrophic, warmwater reservoirs or for coldwater lakes where winter ice or freeze-over occurs for several weeks. If a model is applied for a specific life stage, the HSI obtained will apply only to the season or period when the life stage of interest occurs.

Cover types. The lacustrine model is applicable to permanent freshwater reservoirs. The riverine model is most applicable to sections of streams that are utilized or likely to be utilized as striped bass reproductive habitat. This model could be applicable to a few mainstem reservoirs where water velocity and other requirements for spawning and hatching are within suitable ranges or to riverine habitat that striped bass occupy for reasons other than spawning, such as some estuarine streams.

Minimum habitat size. The minimum area of lacustrine habitat required to sustain a population of striped bass has not been established. The species is a pelagic feeder and probably prefers relatively large, deep, open water areas that are capable of supporting a clupeid forage base. The Striped Bass Committee, American Fisheries Society, considers the minimum habitat size to be 1,215 ha (3,000 acres) (Crance in prep.). Successful striped bass fisheries have been established in reservoirs ranging in size from 40.5 to 73,305 ha (100 to 181,000 acres) (Bailey 1975). The area and volume of lacustrine habitat utilized by adults during the warmest period of the year may be reduced greatly due to high temperatures in the epilimnion and low dissolved oxygen levels in deeper and cooler areas, coupled with a cool temperature preference by adults. Depth might be a limiting factor in lacustrine habitat if adult fish cannot retreat to a suitable depth to escape excessive light.

The minimum length of stream required for riverine reproductive habitat can be roughly estimated by calculating the product of current velocity and hatching time. The minimum length of stream required is about 52.6 km or 32.7 miles (48 h x 30.5 cm/s or 1 ft/s) if eggs must float for 48 hours (approximate time for hatching at optimum water temperature) before hatching, a minimum current velocity of 30.5 cm/s (1 ft/s) is required for egg flotation, and eggs move downstream at current velocity. However, this estimate may not represent the actual minimum stream length required because: (1) eggs do not move at current velocity; (2) water temperature may vary enough between stream sections to alter hatching time; (3) suspension of the newly hatched embryo may be required for about 15 hours post-hatch, increasing the distance required; and (4) the role of currents within reservoirs, especially headwater areas, is unknown.

Verification level. Neither model has been field tested. Hypothetical data sets were generated (Tables 3 and 4) and used to test the assumptions that HSI's obtained by using the models are reasonable and acceptable.

Eighteen striped bass experts/authorities, who participated in a Delphi exercise to develop striped bass habitat suitability information (Crance in prep.), reviewed a draft of this paper. The reviewers provided substantial ideas and suggestions that were incorporated, where appropriate, into the model building effort.

Field use of models. The level of detail for a particular model application depends on time, money, and accuracy constraints. Detailed field sampling of all of the variables that affect striped bass habitat will provide the most reliable and replicable HSI's. Use of previously collected data for any of the variables may result in satisfactory application of the models. Temperature, dissolved oxygen, and stream velocity data required for the models are likely to have been published or be available from natural resource agencies. Suggested techniques for measuring model variables and references to consult for more details are listed in Table 5. Subjective estimates of any or all variables can be made in order to reduce the amount of time required to apply the models. When subjective estimates are used, they should be made or confirmed by experienced striped bass experts. Use of subjective estimates decreases reliability and replicability and should be accompanied by appropriate documentation on the method of HSI determination and quality of the data used in the models.

Interpreting Model Outputs

Initially, the objective is that the HSI's for striped bass habitat obtained using the models are correlated with an expert's ranking. Ideally, HSI outputs would have a direct linear relationship to carrying capacity. This relationship is assumed but has not been tested.

The proper interpretation of the model output is one of comparison. Habitats with high HSI's would, on the average, be expected to have higher standing crops of striped bass or the potential to support more striped bass than those with a lower HSI. The correlation between population size and HSI has not been tested. Factors not included in the HSI models may have a significant effect on population size.

The models cannot be expected to discriminate among different habitats with high resolution at this stage of development because they depend on untested assumptions and known oversimplifications. Interactions among model variables and species both play a role in determining habitat suitability for striped bass; however, these influences are not considered in the model. It is suggested that the HSI outputs be interpreted as indicators or predictors of high (0.8 to 1.0), medium (0.5 to 0.7), low (0.2 to 0.4), or unsuitable (0.0 to 0.1) striped bass habitat. Neither model will provide an HSI of 1.0 if any model component is not within the optimum value for the life stage being considered.

Table 3. Artificial data sets developed to illustrate how suitability indices (SI), component indices (C), and the habitat suitability index (HSI) are calculated using the riverine habitat variables and model equations.

Variable	Data set 1		Data set 2		Data set 3		Data set 4	
	Data	SI	Data	SI	Data	SI	Data	SI
Temperature (V_1) °C	14.5	0.8	17.0	1.0	21.0	0.7	18.5	1.0
Dissolved oxygen (V_2) mg/l	6.0	1.0	4.2	0.6	4.0	0.5	7.0	1.0
Current velocity (V_3) cm/s	55.0	1.0	40.0	0.5	213.0	0.2	15.0	0
C_{WQ}		0.8		0.5		0.2		0
HSI		0.8		0.5		0.2		0

C_{WQ} = lowest SI = HSI

Table 4. Artificial data sets developed to illustrate how suitability indices (SI), component indices (C), and the habitat suitability index (HSI) are calculated using the lacustrine habitat variables and model equations.

Variable	Data set 1		Data set 2		Data set 3		Data set 4	
	Data	SI	Data	SI	Data	SI	Data	SI
Temperature (V_1) °C (larval)	14.9	0.9	17.0	1.0	21.0	0.7	21.5	0.5
Dissolved oxygen (V_2) mg/l (larval)	7.0	1.0	6.0	1.0	5.0	1.0	4.0	0.5
Temperature (V_4) °C (juvenile)	21.5	0.9	20.0	0.8	30.0	0.5	30.5	0.4
Dissolved oxygen (V_2) mg/l (juvenile)	6.0	1.0	7.0	1.0	4.9	0.8	3.4	0.2
Temperature (V_5) °C (adult)	18.0	1.0	17.0	0.8	28.0	0.4	29.0	0.2
Dissolved oxygen (V_2) mg/l (adult)	5.5	1.0	4.4	0.7	4.0	0.5	2.5	0
<u>Component SI</u>								
C larval		0.9		1.0		0.7		0.5
C juvenile		0.9		0.8		0.5		0.2
C adult		0.9		0.8		0.4		0

C = lowest SI for component
No overall lacustrine HSI calculated
Component HSI = component C

Table 5. Descriptions of and suggested measurement techniques for variables used in riverine and lacustrine HSI models for striped bass.

Habitat	Variable	Variable description	Suggested technique	Reference source
Riverine or lacustrine	V_1	Average mean daily temperature at midafternoon: riverine habitat during spawning; selected lacustrine habitat during larvae development (larvae).	Existing data, literature, or field sampling of representative reaches of stream using thermometers.	American Public Health Association (1981); Theurer and Voos (in prep.).
Riverine or lacustrine	V_2	Minimum dissolved oxygen concentration near sunrise: riverine habitat during spawning; selected lacustrine habitat throughout year (adults, juveniles, or larvae).	Existing data, literature, or field sampling of representative reaches of stream using the Winkler or idometric method and its modifications or electrometric methods.	American Public Health Association (1981).
Riverine	V_3	Average mean daily current velocity in water column: riverine habitat during spawning.	Existing data, literature, or field measurements of representative reaches of stream, using current meter.	Boyer (1964); Carter and Davidian (1965); Smoot and Novak (1968); Bovee and Milhous (1978).
Lacustrine	V_4	Average mean daily water temperature at midafternoon in selected lacustrine habitat during growing season (juveniles).	Existing data, literature,or field sampling of representative areas of reservoir using thermometers.	American Public Health Association (1981).
Lacustrine	V_5	Average mean daily water temperature at midafternoon in selected lacustrine habitat during warmest months (2.3 to 4.5 kg, or 5 to 10 lb adults).	Existing data, literature, or field sampling of representative areas of reservoir using Winkler or idometric method and its modifications or electrometric methods.	American Public Health Association (1981).

Model Description

The assumed relationships among model variables, components, and the HSI for the riverine model and the lacustrine model are illustrated in Figure 1 and Figure 2, respectively. The models are structurally simple and can be modified as needed for special situations and as additional information, including results of field tests to develop specific utilization curves, becomes available. The riverine model produces an HSI between 0 and 1 for overall riverine (reproductive) habitat quality. The lacustrine model produces an HSI between 0 and 1 for each of three life stages (adult, juvenile, and larvae) in reservoirs. A positive relationship between HSI and carrying capacity is assumed. However, the models are habitat models, not population models, and their ability to predict production or population levels of striped bass is unknown .

The suitability index (SI) graphs (see pages 29 and 30) included reflect the author's subjective integration of the literature, expert opinion, personal experience, and reviewer comments. They represent assumed functional relationships between a variable and habitat suitability for a particular life stage and should be regarded as tentative and open to modification. Documentation of the assumptions and rationale for including variables in the models and for developing the SI curves for the variables follow.

Riverine model. Suitability of riverine habitat for spawning adults, eggs and larvae is directly related to water temperature (V_1), dissolved oxygen concentration (V_2), and stream velocity (V_3).

Temperature (V_1). Spawning generally occurs at temperatures near 18° C (65° F). Optimal survival and development of eggs and larvae occur within the range of 15 to 20° C (59 to 68° F). Spawning, egg survival and hatching success, and survival and growth of larvae are reduced at temperatures outside this range. Therefore, these three life stages were combined for the water temperature component of the model, and a single temperature SI graph provided to determine the temperature SI (SI_1) for riverine habitat.

Dissolved oxygen (V_2). No significant difference appears to exist in the dissolved oxygen requirement for adult, egg, and larval life stages or between riverine and lacustrine habitats. Levels of 5 mg/l and above are optimal for these three life stages. Spawning activities and survival of eggs and larvae are reduced when dissolved oxygen levels are below 5 mg/l. The minimal level for normal development of eggs and embryos is about 3 mg/l. Mortality of juveniles occurs at 3 mg/l, and no juveniles survive at 1 mg/l. It is assumed that air-saturated waters are optimal and that supersaturated waters are unsuitable. Adult, egg, and larval life stages were combined for the dissolved oxygen concentration component of the model, and a single SI graph provided to determine the dissolved oxygen SI (SI_3) for both riverine and lacustrine habitat.

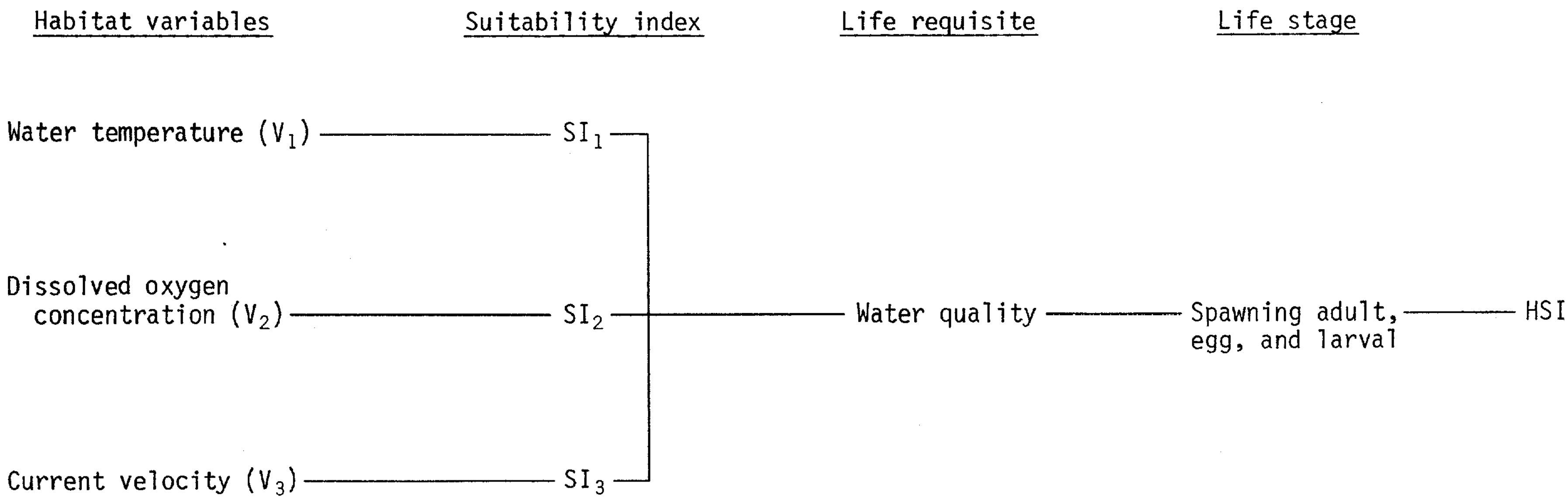


Figure 1. Tree diagram illustrating relationships of habitat variables and water quality in the riverine HSI model for striped bass.

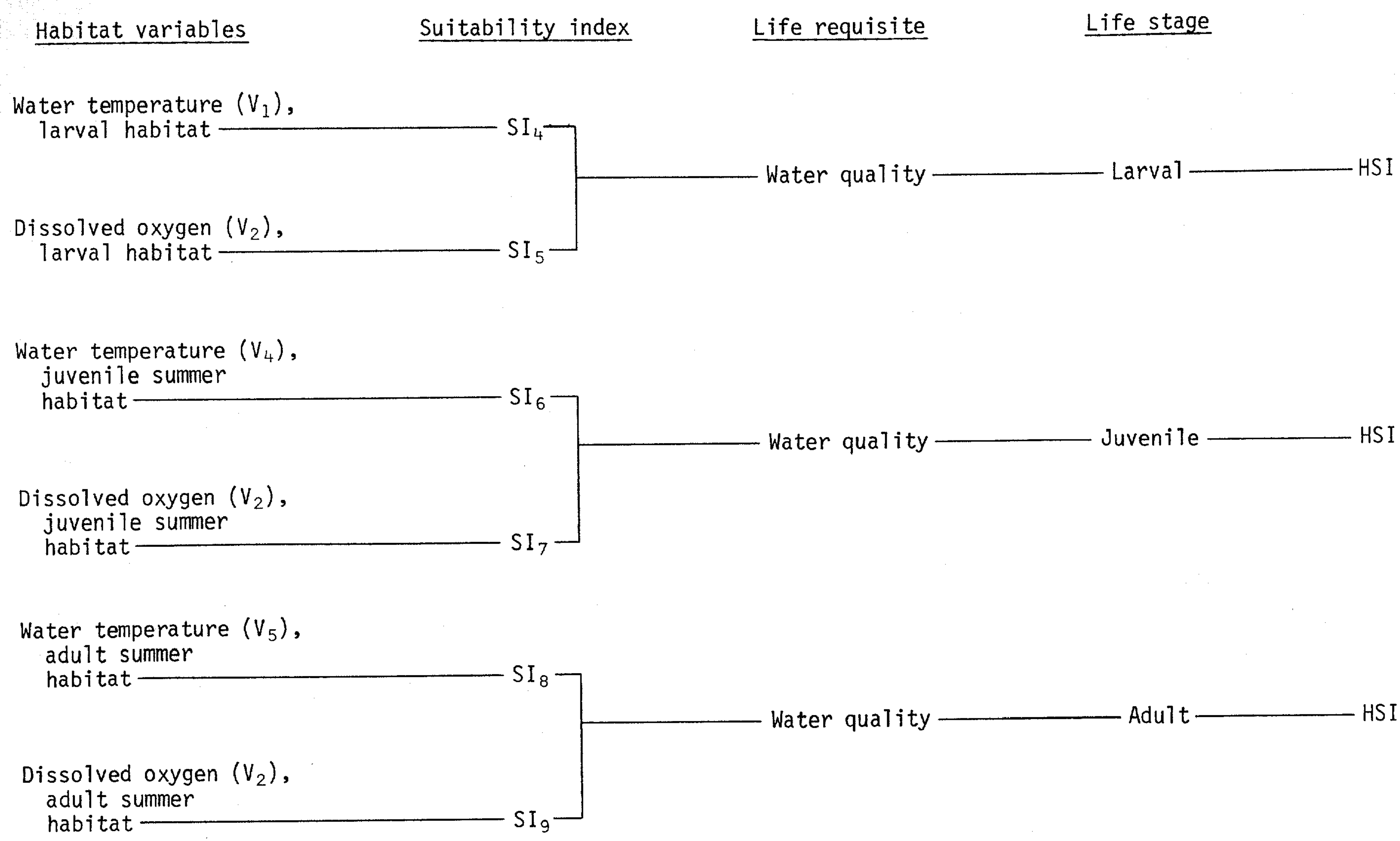


Figure 2. Tree diagram illustrating relationships of habitat variables and water quality in the lacustrine HSI model for striped bass.

Velocity (V_3). Newly hatched eggs require a minimum current velocity of about 30.5 cm/s (1 ft/s) for flotation. Water velocity less than 30.5 cm/s (1 ft/s) may buoy water-hardened eggs but eggs in all stages may occur in a stretch of stream simultaneously. Few, if any, eggs that settle to the bottom will survive, presumably due to a deficiency in dissolved oxygen. In addition, few larvae survive if they are not buoyed during approximately the first 15 h posthatch. Assumptions relative to velocity are: (1) the minimum velocity required to suspend eggs is about 30 cm/s (1 ft/s), and the same velocity is necessary for successful spawning and hatching; (2) velocities of 50 to 122 cm/s (1.6 to 4.0 ft/s) are optimal; (3) suitability decreases as velocity increases above 122 cm/s; and (4) velocities above about 400 cm/s (13.1 ft/s) are unsuitable. Streams must be of sufficient length to allow eggs to hatch and larvae to attain self-buoyancy under the existing temperature, velocity, and other conditions before reaching slack water in the reservoir. Velocity requirements for spawning, eggs, and larvae appear to be about equal, and these three life stages were combined for the velocity component of the model and a single velocity SI graph is provided to determine the current velocity SI (SI_3) for riverine habitat.

The variable in the riverine HSI model with the lowest SI is assumed to be the limiting factor. Therefore, overall riverine habitat suitability is determined as follows:

HSI (riverine) = Lowest of the following variables: SI_1, SI_2, or SI_3

Lacustrine model. Suitability of lacustrine habitat for larvae, juveniles, and adults is directly related to water quality, and water quality is primarily determined by water temperature and dissolved oxygen concentration.

Water quality determines habitat suitability independently for each life stage component of the lacustrine model because temperature preferences of striped bass change with age.

Larval. Survival and growth of striped bass larvae are generally optimal within the temperature range of 15 to 20° C (59 to 68° F) and are reduced at temperatures below and above this range. The temperature SI (SI_4) for juveniles does not take into account that older larvae or larvae of all ages in some habitats survive and do well in slightly higher temperatures. Therefore, the temperature SI curve for larvae may need to be modified to be useful for the population of interest.

It is assumed that temperatures and dissolved oxygen levels suitable for larvae in riverine habitat are suitable for larvae in lacustrine habitat and that the SI graphs used to determine the temperature and dissolved oxygen SI's for larvae in riverine habitat can be used to determine the SI's (SI_4 and SI_5) for larvae in lacustrine habitat. (See sections on temperature and dissolved oxygen under Riverine Model.) Dissolved oxygen requirements are assumed to be the same for all life stages. Therefore, the dissolved oxygen SI graph developed is for all life stages.

Juvenile. Juvenile striped bass generally tolerate temperatures from 3 to 34° C (37.4 to 93.2° F) and select and grow optimally within the range of 22.0 to 28.0° C (71.6 to 82.4° F). Growth decreases outside this optimal range and ceases at about 33.5° C (92.3° F). Death occurs near 34.4° C (94° F).

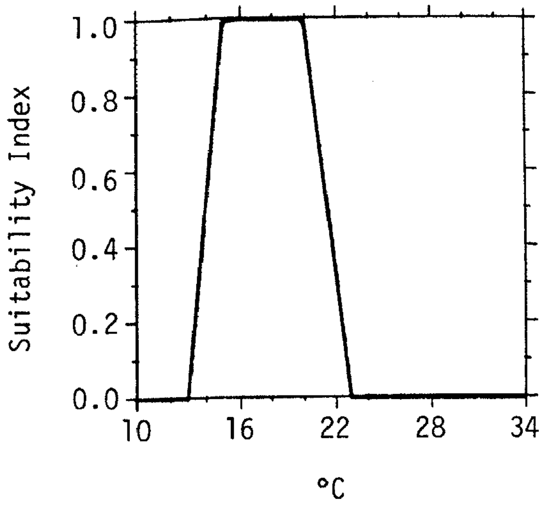
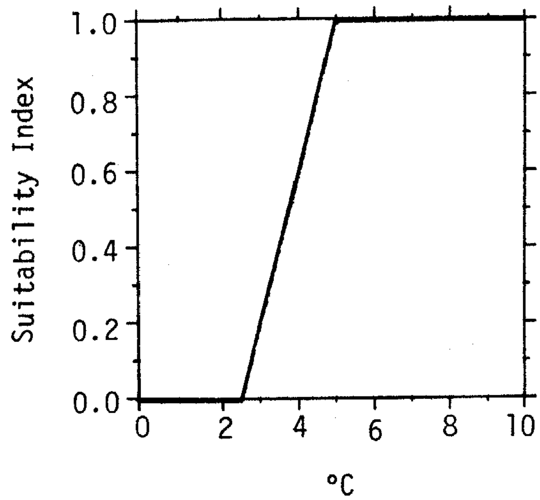
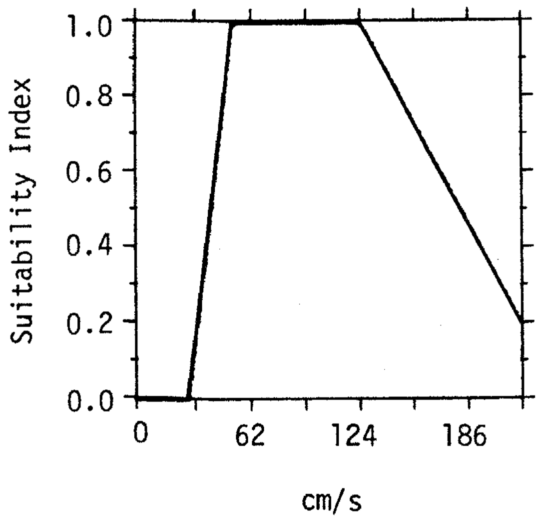
The dissolved oxygen SI (SI_7) graph for juveniles is based on the assumption that all life stages have equal dissolved oxygen requirements.

Adult. Adult striped bass in reservoirs generally exhibit a temperature preference of about 20° C (68° F) during summer months, but the optimum temperature may vary from 18 to 24° C (64.4 to 75.2° F). The lower avoidance temperature boundary is near 16° C (60.8° F); the upper avoidance boundary is about 25° C (77° F). It is assumed that adults survive in reservoirs at temperatures outside of these avoidance boundaries but that summer habitat suitability decreases. The temperature SI graph (SI_8) developed for adult striped bass in lacustrine habitats is assumed to represent preferences of medium weight adults (5 to 10 lb). It does not take into account temperature preferences reported for adults in Lake Whitney, Texas, or the San Francisco Bay area. Also, the optimum range and the upper temperature range for SI = 0 may be too high for some reservoirs. The temperature SI curve for adults may need to be modified to be applicable to the specific size of striped bass and the population of interest.

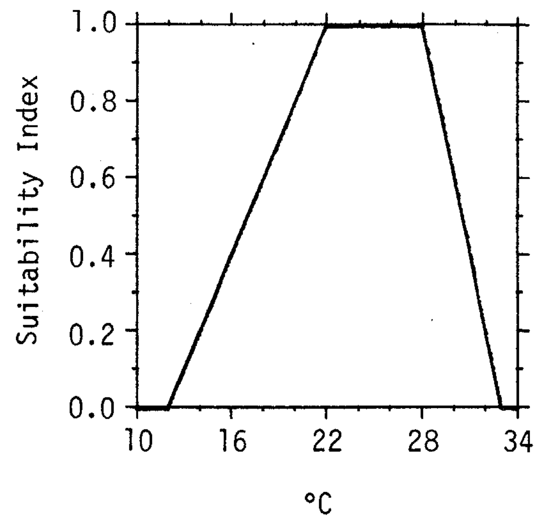
The dissolved oxygen curve for adults (SI_9) was based on the assumption that all life stages of striped bass have the same dissolved oxygen requirements.

Suitability Index (SI) Graphs for Model Variables

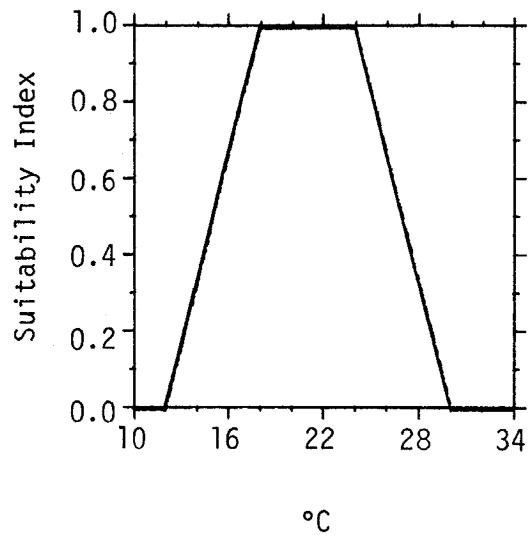
This section contains suitability index curves and equations to quantitatively describe the relationships discussed in the previous sections. The curves provide a graphic representation of the relationships between various measurements of habitat variables and habitat suitability. The riverine curves and equations can be used to produce an overall HSI for striped bass reproductive habitat. The lacustrine curves and equations can be used to produce an HSI for each of the three life stages that occur in lacustrine habitat.

Habitat	Variable		Suitability graph
Riverine (R), Lacustrine (L)	V_1	Average mean daily water temperature at midafternoon: riverine habitat during spawning; lacustrine habitat during larval development (larvae).	
R,L	V_2	Minimum dissolved oxygen concentration near surface: riverine habitat during spawning; lacustrine habitat throughout year (adults, juveniles, or larvae).	
R	V_3	Average mean daily current velocity in water column: riverine habitat during spawning.	

L V_4 Average mean daily water temperature at midafternoon: lacustrine habitat during growing season (juvenile).



L V_5 Average mean daily water temperature at midafternoon: lacustrine habitat during warmest months (adults, medium weight).



ADDITIONAL HABITAT MODELS

A habitat suitability index model developed by Bain and Bain (1982) is available for coastal stocks of striped bass. The riverine portion of their model may be applicable to riverine habitat for inland stocks.

INSTREAM FLOW INCREMENTAL METHODOLOGY

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

The output generated by the PHABSIM component of IFIM can be used for several IFIM habitat display and interpretation techniques, including:

1. Habitat Time Series. Determination of impact of a project on a species' life stage habitat by imposing project operation curves over baseline flow time series conditions and integrating the difference between the corresponding times series;

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

3. Optimization. Determination of flows (daily, weekly, and monthly) that minimize habitat reductions for a complex of species and life stages of interest.

Suitability Index Curves Used in IFIM

PHABSIM utilizes Suitability Index (SI) curves that describe the instream suitability of the habitat variables most closely related to stream hydraulics and channel structure (e.g., velocity, depth, substrate, cover, and temperature) for each major life stage of a given fish species (e.g., spawning, egg incubation, larval, juvenile, and adult). The Western Energy and Land Use Team has designated four categories of curves and standardized the terminology pertaining to the curves. The designation of a curve as belonging to a particular category does not imply that there are differences in the quality or accuracy of curves among the four categories.

Category one curves are the most common type presently available for use with IFIM. Category one curves have, as their basis, one or more literature sources. Some may be derived from general statements made in the literature about fishes (e.g., rainbow trout spawn in gravel; fry prefer shallow water). Others may come from literature sources which include variable amounts of field data [e.g., from a sample size of 300, fry were observed in velocities ranging from 0 to 0.9 m (0 to 3.0 ft/s), and 80% were found in velocities less than 30.5 cm/s (1.0 ft/s)]. Other category one curves may be based entirely on professional opinion obtained by using the Delphi technique [e.g., an expert believes that velocities ranging from 30.5 to 244 cm/s (1.0 to 8.0 ft/s) are necessary for successful spawning of striped bass]. Most category one curves are the result of a combination of sources; an individual curve may include information from the literature, combined with field data, and smoothed or modified using professional judgement. Category one curves usually are intended to reflect general habitat suitability throughout the entire geographic range of the species and throughout the year, unless they are identified as being applicable only to a given area or season. In the latter case, curves developed for a specific area or stream may not accurately reflect habitat utilization in other areas. Curves meant to describe the general habitat suitability of a variable throughout the entire range of a species may not be as sensitive to small changes of the variable within a specific stream (e.g., rainbow trout generally utilize silt, sand, gravel, and cobble for spawning substrate, but utilize only cobble in Willow Creek, Colorado).

Category two curves are derived from frequency analyses of field data and basically are curves fit to a frequency histogram. Each curve describes the observed utilization of a habitat variable by a life stage of the evaluation species. Category two curves, unaltered by professional judgement or other sources of information, are referred to as utilization curves. When modified by judgement, they are considered category one curves. Utilization curves from one set of data are not applicable for all streams and situations (e.g., a depth utilization curve from a shallow stream cannot be used for the Missouri River). Category two curves, therefore, are usually biased because of limited habitat availability. An ideal study stream would have all substrate and cover types present in equal amounts; all depth, velocity, and percent cover intervals available in equal proportions; and all combinations of all variables in equal proportions. Utilization curves from such a perfectly designed study theoretically should be transferable to any stream within the geographical range of the species. Curves from streams with high habitat diversity are generally more transferable than curves from streams with low habitat diversity. Users of category two curves should first review the stream description to see if conditions are similar to those present in the stream segment to be investigated. Some variables to consider include stream width, depth, discharge, gradient, elevation, latitude and longitude, temperature, water quality, substrate and cover diversity, fish species associations, and data collection descriptors (e.g., time of day, season of year, sample size, and sampling methods). If one or more factors deviate significantly from those of the proposed study site, curve transference is not advised, and the investigator should develop his or her own curves.

Category three curves are derived from utilization curves that have been corrected for environmental bias and, therefore, represent the preference of the species. Habitat utilization data and habitat availability data must simultaneously be collected from the same area in order to generate a preference curve. Habitat availability information should reflect the relative amount of different habitat types in the same proportions as they exist throughout the stream study area. A curve is then developed for the habitat frequency distribution in the same way as for fish utilization observations and the equation coefficients of the availability curve subtracted from the equation coefficients of the utilization curve, resulting in preference curve coefficients. Theoretically, cateogry three curves should be unconditionally transferable to any stream although this has not been validated. At present, very few category three curves exist because most habitat utilization data sets are without concomitant habitat availability data sets. In the future, investigators will be encouraged to collect habitat availability data.

Category four curves (conditional preference curves) describe habitat preferences as a function of interaction among variables. For example, fish depth utilization may depend on the presence or absence of cover or velocity utilization may depend on time of day or season of year. Category four curves are just beginning to be developed and are still largely conceptual.

IFIM analyses may utilize any or all categories of curves, but category three and four curves would yield the most precise results. Category two curves yield accurate results if they are transferable to the stream segment under investigation. If no category three or four curves are available and category two curves are not transferable for a particular application, category one curves may be the better choice. A basic assumption of the IFIM is that the evaluation species exhibits a describable preference/avoidance behavior for one or more of the microhabitat variables of depth, velocity, substrate, and cover.

Availability of Striped Bass SI Curves for Use in IFIM

The availability of SI curves for use in an IFIM analysis of striped bass riverine habitat is summarized in Table 6. The curves are category one curves and should be considered for interim use until new information, such as data obtained from field studies directed toward habitat suitability studies, is available. The curves are based on a combination of expert opinion, published and unpublished reports, and the author's judgement. The relationship of velocity, depth, substrate, cover, and temperature to habitat suitability for spawning, egg incubation, larvae, juveniles, and adults was given special consideration throughout the curve development process (Figs. 3-7). Each variable should be considered for each life stage, and variable SI curves not included in this report may need to be developed if the variable/life stage is important or an analysis of the effects of the variables on the habitat for a life stage is a study objective. SI curves for dissolved oxygen concentration were not included because it was assumed that this variable is not a problem when the temperature is within a suitable range. If dissolved oxygen is an important factor for riverine habitat suitability, the dissolved oxygen SI curve component (V_2) of the riverine HSI model can be used in an IFIM analysis for the habitat of each life stage of striped bass.

Some of the SI curves in Figures 3 through 7 are the same as the SI curves included for an HSI analysis. The rationale for these curves was included in the HSI section of this paper. Some of the SI curves in Figures 3 through 7 were based primarily on the opinion of participants in the Striped Bass Delphi exercise (Crance in prep.).

Spawning. The SI curves for striped bass spawning (Fig. 3) are for IFIM analyses of riverine spawning habitat during the spawning season, which is some time between February and July, depending on the locale. Spawning occurs near the surface, and eggs incubate while suspended by water currents. Therefore, spawning and egg incubation habitats are considered separately.

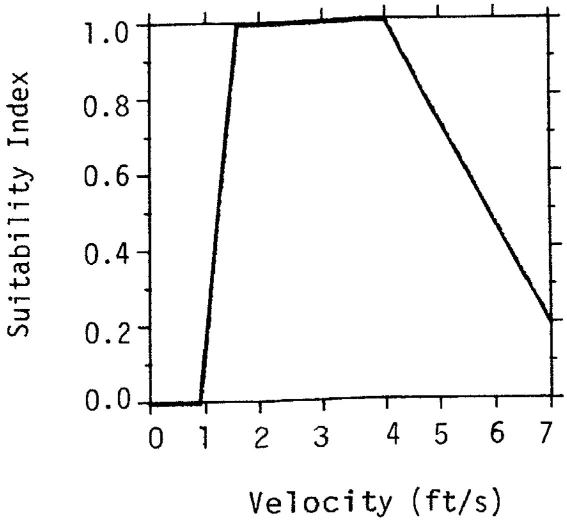
Velocity. Adults have been observed to cease spawning and leave the spawning site when water flow suddenly decreases. Therefore, it is assumed that water velocity is critical for spawning. The precise suitability range is unclear, but it is assumed to be similar or equal to the velocity suitability range for eggs and larvae. The velocity curve developed as a component (V_3) of the HSI riverine model is the basis for the velocity SI curve for spawning.

Table 6. Availability of SI curves for use with IFIM analysis of striped bass riverine habitat.

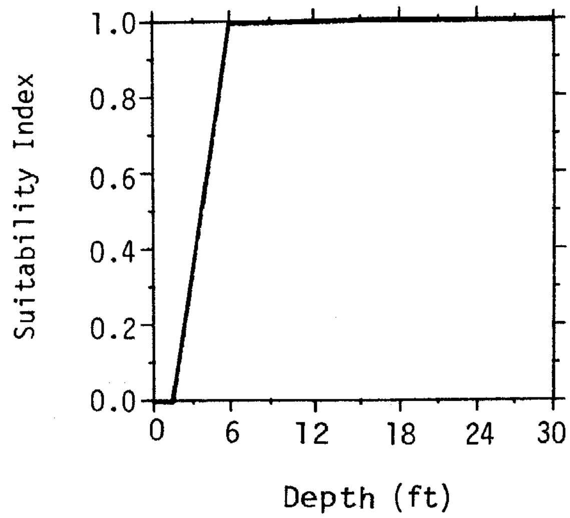
Activity/ life stage	Velocity	Depth	Substrate	Cover	Temperature
Spawning	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	Curve not necessary.	Curve not necessary.	Use SI curve, Fig. 3.
Egg incubation	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Curve not necessary.	Use SI curve, Fig. 4.
Larval	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Curve not available.	Use SI curve, Fig. 5.
Juvenile	Curve not available.	Use SI curve, Fig. 6.	Curve not available.	Curve not available.	Use SI curve, Fig. 6.
Adult	Curve not available.	Use SI curve, Fig. 7.	Curve not available.	Curve not available.	Use SI curve, Fig. 7.

Coordinates

x (ft/s)	y (SI)
0.0	0.0
0.9	0.0
1.64	1.0
4.0	1.0
7.0	0.2
13.2	0.0
100.0	0.0



x (ft)	y (SI)
0.0	0.0
1.4	0.0
6.0	1.0
30.0	1.0
100.0	0.0



It is assumed that substrate is unimportant to or not used by striped bass for spawning and, therefore, a substrate SI curve for spawning is not necessary.

Figure 3. SI curves for IFIM analyses of striped bass riverine spawning habitat.

It is assumed that cover in unimportant to or not used by striped bass for spawning and, therefore, a cover SI curve for spawning is not necessary.

Coordinates

x (°F)	y (SI)
0.0	0.0
55.4	0.0
59.0	1.0
68.0	1.0
73.4	0.0
100.0	0.0

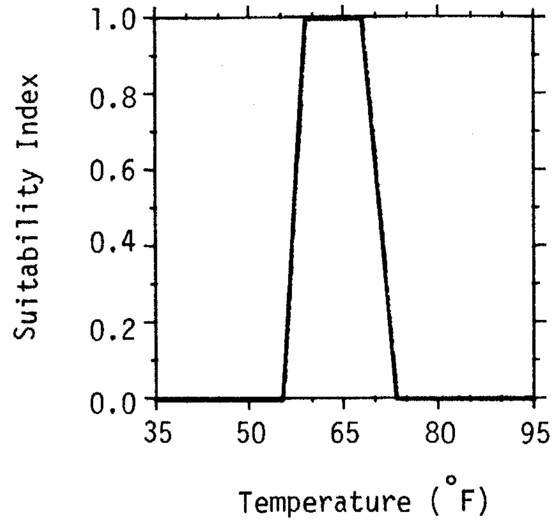


Figure 3. (concluded).

Depth. Assumptions used to develop the SI depth curve for spawning were: (1) the minimum suitable depth for unimpeded movement by adult striped bass is 0.45 m (1.5 ft); (2) depths of 1.83 to 9.1 m (6 to 30 ft) are optimum for spawning; and (3) turbulence is associated with areas considered good striped bass spawning habitat but extreme depths are not conducive to turbulent water. Therefore, spawning habitat suitability likely decreases as depth increases above some point, presumably about 9.1 m (30 ft), and continues to decrease with increased depth, reaching medium suitability at about 15.2 m (50 ft) and becoming unsuitable for spawning at 30.5 m (100 ft).

Substrate. Striped bass spawn over a variety of substrates. Therefore, substrate is not considered an important variable in determining spawning habitat suitability.

Cover. It is assumed that striped bass do not utilize cover for spawning and that a cover SI curve for spawning is not necessary.

Temperature. The initiation and duration of spawning by striped bass are temperature-dependent. The temperature curve developed as a component (V_1) of the riverine HSI model was the basis for the SI temperature curve for spawning.

Egg incubation. The SI curves for striped bass egg incubation (Fig. 4) are for IFIM analyses of riverine habitat where eggs incubate. Normally, eggs move with the current and hatch in the water column in about 34 to 74 hours, depending on the temperature. The length of stream over which incubation occurs varies, depending on water temperature, velocity, and other factors.

Depth. The precise water depth crucial for egg incubation is unclear. However, a depth SI curve was developed based on the assumptions that: (1) depths less than 0.45 m (1.5 ft) are unsuitable for egg incubation habitat; and (2) depths of 1.83 m (6 ft) and over provide optimum suitability.

Substrate. Eggs normally incubate while suspended in the water column by currents. Therefore, substrate type does not become a limiting factor to egg incubation except where eggs settle to the bottom. If the eggs sink to the substrate, the chances of survivial are greatly reduced, presumably due to siltation and a deficiency in dissolved oxygen. The substrate SI curve for egg incubation was based on the assumption that siltation rates are higher, dissolved oxygen concentration lower, and survival rates of eggs lower if the dominate substrate type consists of particles smaller than sand. Sand and larger particles are assumed to be optimum substrate composition.

Coordinates

x (ft/s)	y (SI)
0.0	0.0
0.9	0.0
1.64	1.0
4.0	1.0
7.0	0.2
13.1	0.0
100.0	0.0

x (ft)	y (SI)
0.0	0.0
1.4	0.0
6.0	1.0
30.0	1.0
100.0	0.0

x (code)	Particle size	y (SI)
1	Plant detritus/organic material	0.1
2	Mud/soft clay	0.4
3	Silt (< 0.062 mm)	0.6
4	Sand (0.062 to 2 mm)	1.0
5	Gravel (2 to 64 mm)	1.0
6	Cobble/rubble (64 to 250 mm)	1.0
7	Boulder (250 to 4,000 mm)	1.0
8	Bedrock (solid rock)	1.0

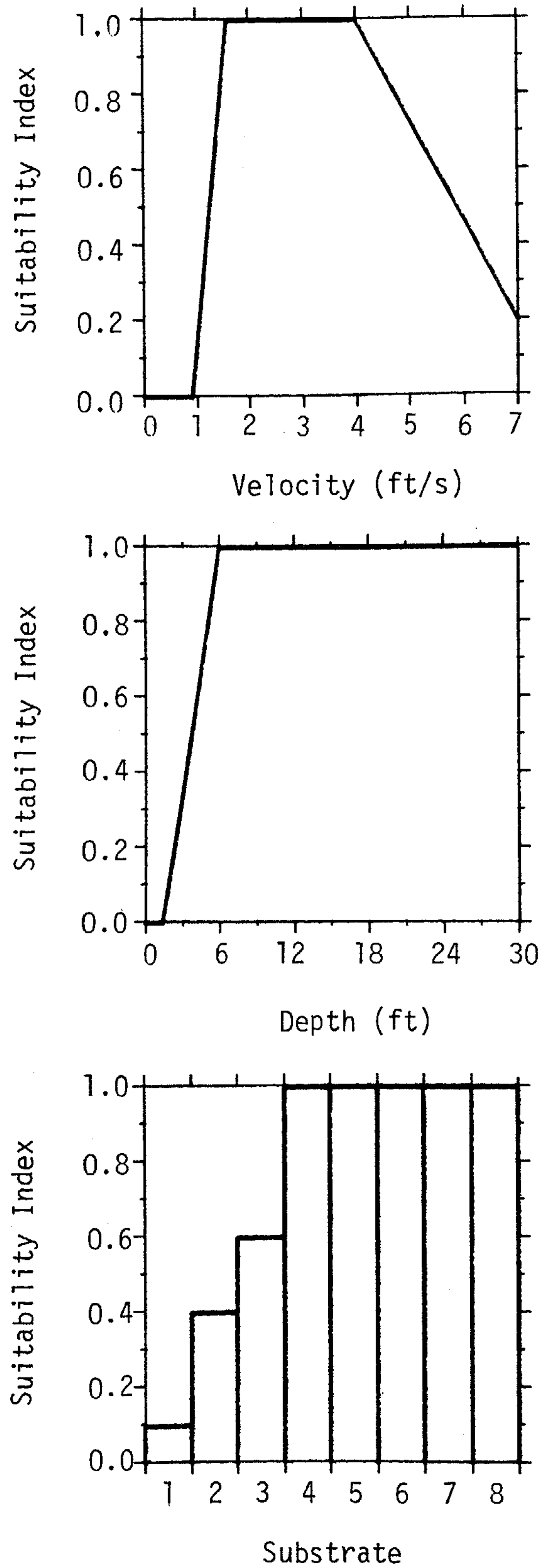


Figure 4. SI curves for IFIM analyses of striped bass riverine habitat for egg incubation.

It is assumed that cover is unimportant to striped bass egg incubation and, therefore, a cover SI curve for egg incubation is not necessary.

Coordinates

x (°F)	y (SI)
0.0	0.0
55.4	0.0
59.0	1.0
68.0	1.0
73.4	0.0
100.0	0.0

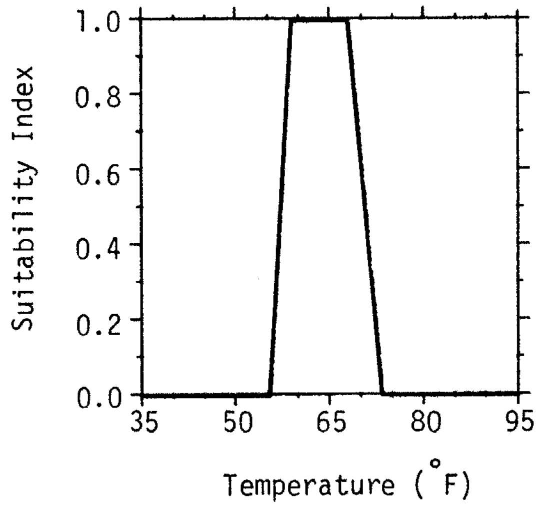


Figure 4. (concluded).

Cover. It is assumed that cover is unimportant for striped bass egg incubation and that a cover SI curve for egg incubation is not necessary.

Temperature. Incubation of striped bass eggs is temperature-dependent. The temperature SI curve for egg incubation is based on the temperature SI curve developed as a component (V_1) of the riverine HSI model.

Larvae. The SI curves for striped bass larvae (Fig. 5) are for IFIM analyses of riverine habitat where larvae are commonly found.

Velocity. The velocity curve developed as a component (V_3) of the HSI model was the basis for the larval velocity SI curve.

Depth. The depth SI curve for larvae was based on the same assumptions as the depth SI curve for egg incubation. It is assumed that equal depths have equal SI's for larvae and eggs.

Substrate. Newly hatched larvae have about the same density as eggs. They require a current for suspension until bouancy can be maintained by swimming. It is assumed that equal substrate types have equal SI's for larvae and eggs.

Cover. It is assumed that larvae utilize potholes, rocks, rubble, overhanging vegetation (shade), and other cover forms for protection from predators and excessive light and for resting. However, no SI curve for cover was developed because several methods are used to describe cover and there is a sparseness of information on cover use by larvae. A cover SI curve for larvae should be developed if a complete IFIM analysis of larvae riverine habitat is required.

Temperature. The temperature curve developed as component V_1 of the HSI model was the basis for the larval SI temperature curve.

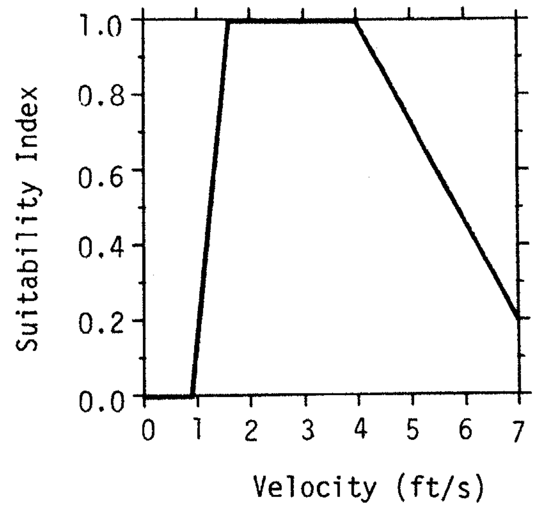
Juvenile. SI curves for striped bass juveniles (Fig. 6) are for IFIM analyses of riverine habitat where juveniles are commonly found. Only depth and temperature SI curves are available for juvenile riverine habitat, and they are based on scanty information. SI curves for velocity, substrate, and cover need to be developed if a complete IFIM analysis of juvenile riverine habitat is required.

Velocity. Insufficient information was available to develop a velocity SI curve for juveniles.

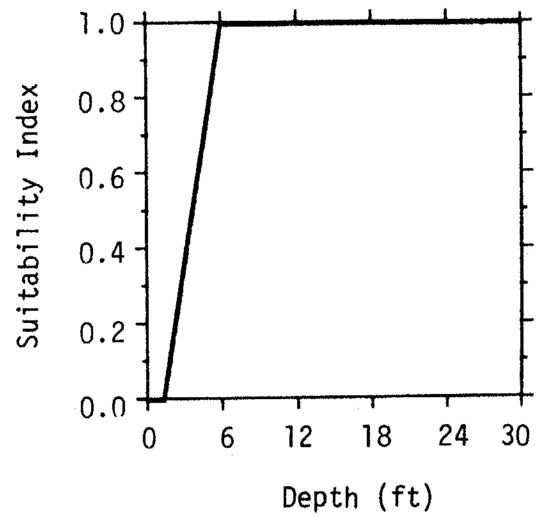
Depth. The depth SI curve for juveniles was based on the same assumptions as the depth SI curve for adults [i.e., a minimum depth of 1.83 m (1.5 ft) is required for unimpeded movement, and depths of 1.83 to 9.1 m (6 to 30 ft) provide optimum suitability]. The curve does not take into account that many juveniles in some lacustrine and estuarine habitats are captured at depths less than 1.83 m (6 ft) (Crance in prep.).

Coordinates

x (ft/s)	y (SI)
0.0	0.0
0.9	0.0
1.64	1.0
4.0	1.0
7.0	0.2
13.1	0.0
100.0	0.0



x (ft)	y (SI)
0.0	0.0
1.4	0.0
6.0	1.0
30.0	1.0
100.0	0.0



x (code)	Particle size	y (SI)
1	Plant detritus/organic material	0.1
2	Mud/soft clay	0.4
3	Silt (< 0.062 mm)	0.6
4	Sand (0.062 to 2 mm)	1.0
5	Gravel (2 to 64 mm)	1.0
6	Cobble/rubble (64 to 250 mm)	1.0
7	Boulder (250 to 4,000 mm)	1.0
8	Bedrock (solid rock)	1.0

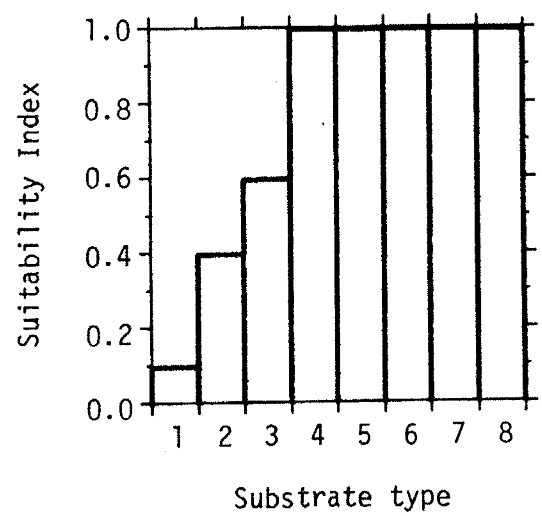


Figure 5. SI curves for IFIM analyses of striped bass riverine habitat for larvae.

A cover SI curve for larval striped bass is not available. Information on the relationship of the variable to larval habitat suitability was insufficient to develop a curve.

Coordinates

x (°F)	y (SI)
0.0	0.0
55.4	0.0
59.0	1.0
68.0	1.0
73.4	0.0
100.0	0.0

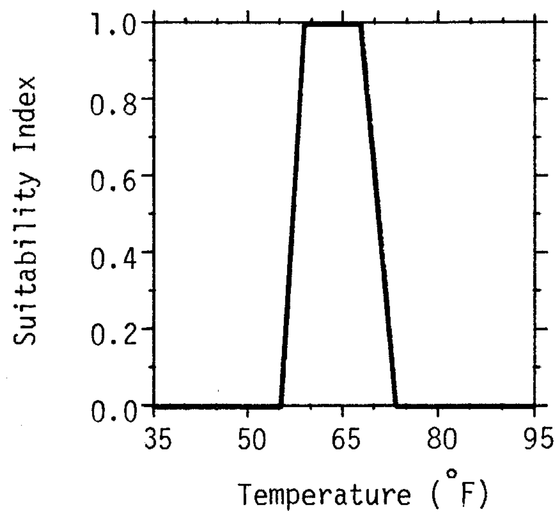
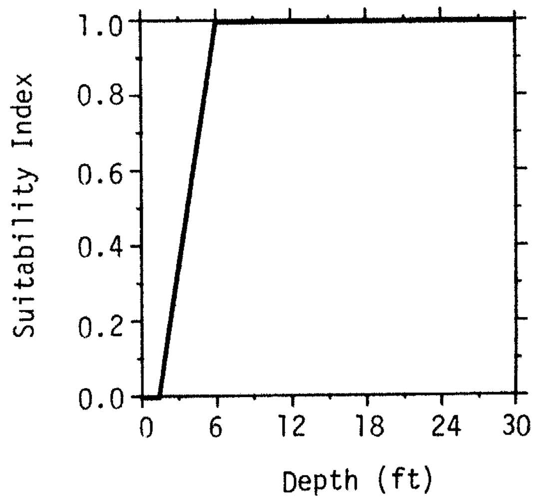


Figure 5. (concluded).

A velocity SI curve for juvenile striped bass is not available. Information on the relationship of the variable to juvenile habitat suitability was insufficient to develop a curve.

Coordinates

x (ft)	y (SI)
0.0	0.0
1.4	0.0
6.0	1.0
30.0	1.0
100.0	0.0



A substrate SI curve for juvenile striped bass is not available. Information on the relationship of the variable to juvenile habitat suitability was insufficient to develop a curve.

Figure 6. SI curves for IFIM analyses of striped bass riverine habitat for juveniles.

A cover SI curve for juvenile striped bass is not available. Information on the relationship of the variable to juvenile habitat suitability was insufficient to develop a curve.

Coordinates

x (°F)	y (SI)
0.0	0.0
53.6	0.0
71.6	1.0
82.4	1.0
91.4	0.0
100.0	0.0

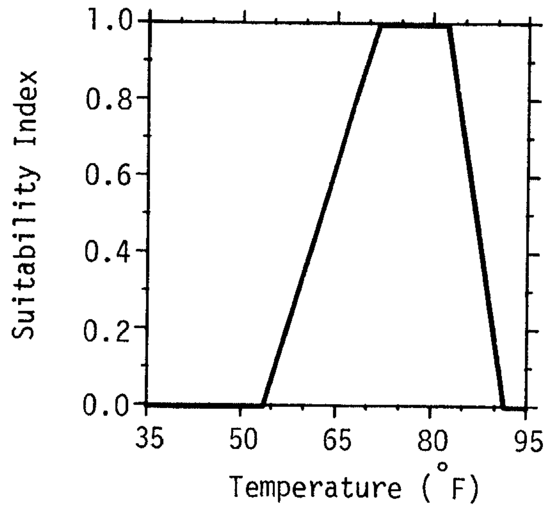


Figure 6. (concluded).

Substrate. The suitability of substrate for juvenile riverine habitat is unclear. No SI curve was developed.

Cover. Cover utilization by juveniles in riverine habitat is unclear. Therefore, no SI curve was developed.

Temperature. The temperature SI curve for juveniles in riverine habitat was based on the temperature SI curve developed as component V_4 of the lacustrine HSI model.

Adults. The SI curves for striped bass adults (Fig. 7) are for IFIM analyses of riverine habitat where nonspawning adults are found. Only depth and temperature SI curves are available. SI curves for velocity, substrate, and cover will need to be developed for a complete IFIM analysis of nonspawning adult riverine habitat.

Velocity. Insufficient information was available to develop a velocity SI curve for adult striped bass.

Depth. The depth SI curve for adults was based on the assumptions that: (1) a minimum depth of 0.45 m (1.5 ft) is required for unimpeded movement by adults; and (2) depths of 1.83 to 9.1 m (6 to 30 ft) are optimum.

Substrate. Insufficient information was available to develop a substrate SI curve for adult striped bass.

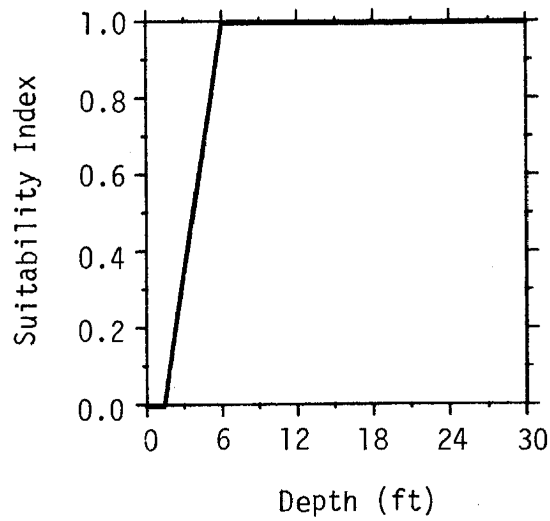
Cover. Insufficient information was available to develop a cover SI curve for adult striped bass.

Temperature. The temperature SI curve for adults was based on the temperature SI curve (V_5) developed as a component of the lacustrine HSI model.

A velocity SI curve for adult striped bass is not available. Information on the relationship of the variable to adult habitat suitability was insufficient to develop a curve.

Coordinates

x (ft)	y (SI)
0.0	0.0
1.4	0.0
6.0	1.0
30.0	1.0
100.0	0.0



A substrate SI curve for adult striped bass is not available. Information on the relationship of the variable to adult habitat suitability was insufficient to develop a curve.

Figure 7. SI curves for IFIM analyses of striped bass riverine habitat for adults.

A cover SI curve for adult striped bass is not available. Information on the relationship of the variable to adult habitat suitability was insufficient to develop a curve.

Coordinates

x (°F)	y (SI)
0.0	0.0
53.6	0.0
64.4	1.0
75.0	1.0
86.0	0.0
100.0	0.0

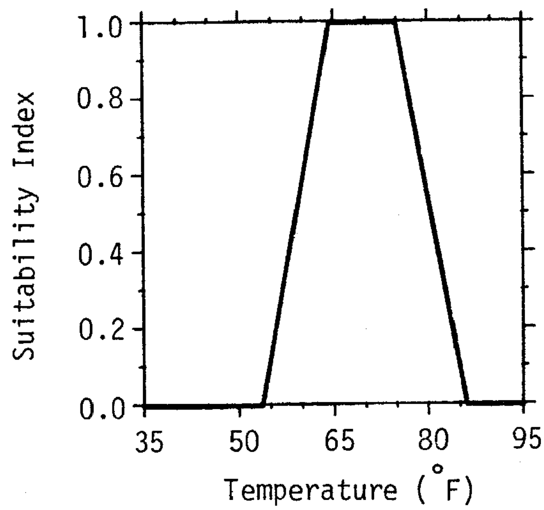


Figure 7. (concluded).

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The Habitat Suitability Index (HSI) models and instream flow Suitability Index (SI) curves presented in this publication aid in identifying important variables that determine the quality of striped bass habitat. Facts, concepts, and opinions obtained from published and unpublished reports, a Delphi panel of 18 striped bass experts/authorities, and the Striped Bass Committee, Southern Division, American Fisheries Society, are synthesized and presented in a format that can be used for habitat impact assessment and development of management alternatives.

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