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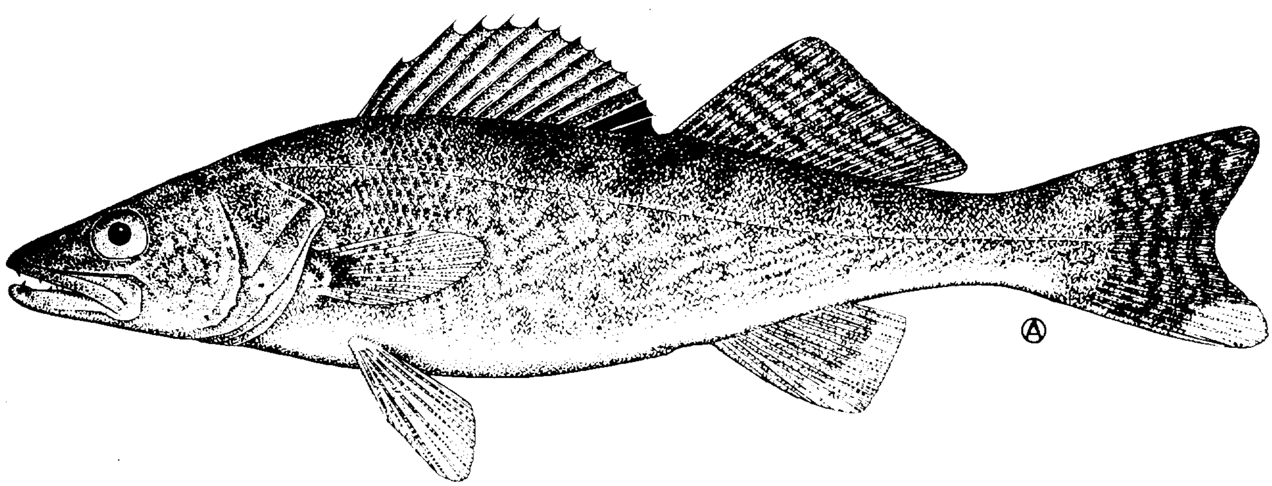
HABITAT SUITABILITY INFORMATION: WALLEYE



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April 1984

HABITAT SUITABILITY INFORMATION: WALLEYE

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PREFACE

The Habitat Suitability Index (HSI) models presented in this publication aid in identifying important habitat variables. Facts, ideas, and concepts obtained from the research literature and expert reviews are synthesized and presented in a format that can be used for impact assessment. The models are hypotheses of species-habitat relationships, and model users should recognize that the degree of veracity of the HSI model, SI graphs, and assumptions will vary according to geographical area and the extent of the data base for individual variables. After clear study objectives have been set, the HSI model building techniques presented in U.S. Fish and Wildlife Service (1981)[1] and the general guidelines for modifying HSI models and estimating model variables presented in Terrell et al. (1982)[2] may be useful for simplifying and applying the models to specific impact assessment problems. Simplified models should be tested with independent data sets, if possible. Statistically-derived models that are an alternative to using Suitability Indices to calculate an HSI are referenced in the text.

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

Results of a model performance test in a limited geographical area are summarized, but model reliability is likely to vary in different geographical areas and situations. The U.S. Fish and Wildlife Service encourages model users to provide comments, suggestions, and test results that may help us increase the utility and effectiveness of this habitat-based approach to impact assessment. Please send comments to:

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

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

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WALLEYE (*Stizostedion vitreum vitreum*)

HABITAT USE INFORMATION

General

The walleye is native to freshwater rivers and lakes of Canada and the United States, with rare occurrences in brackish water (Scott and Crossman 1973). In the United States, its native range occurs primarily in drainages east of the Rocky Mountains and west of the Appalachians; however, it has been widely introduced into reservoirs outside its native range (Colby et al. 1979). Walleye hybridize with sauger (*S. canadense*) and blue pike (*S. v. glaucum*) (Scott and Crossman 1973).

Age, Growth, and Food

Walleye live at least 17 years in cool northern waters (Momot pers. comm.); age VIII or younger fish were predominant in Tennessee impoundments (Hackney and Holbrook 1978). Males mature at age II to IV and females at age III to VIII (Scott and Crossman 1973; Colby et al. 1979). Growth of walleye depends primarily on food supply (Swenson and Smith 1976), temperature (Koenst and Smith 1976; Hokanson 1977), and population density (Carlander and Payne 1977; Kempinger and Carline 1977). In general, length of sexually mature walleye (age III+) is > 30 cm (Colby et al. 1979).

Walleye fry eat zooplankton and aquatic insects and start feeding on fish at 1.5 to 2.5 cm in length (Forney 1966; Bulkley et al. 1976). The diet of juvenile and adult walleye consists primarily of fish, but aquatic invertebrates, particularly mayfly larvae and crayfish, may be locally or seasonally important (Priegel 1963; Wagner 1972; Johnson and Hale 1977). In northern areas, age 0+ and 1+ yellow perch often account for a large portion of the diet in classic large, shallow perch-walleye lakes (Forney 1977; Kelso and Ward 1977). In the southern parts of the walleye range, clupeids and centrarchids often are most important (Miller 1967; Momot et al. 1977; Fitz and Holbrook 1978). Cannibalism may become significant when other prey are scarce (Chevalier 1973; Forney 1974).

Reproduction

The water temperature regime and the quality and quantity of suitable substrate are major factors affecting walleye reproductive success (Scott and Crossman 1973; Colby et al. 1979). Walleye spawn in spring during periods of rapid warming soon after ice break-up (Colby et al. 1979). Spawning is usually initiated at water temperatures of 7 to 9° C, with most spawning occurring in the range of 6 to 11° C (Scott and Crossman 1973). Preferred spawning habitats are shallow shoreline areas, shoals, riffles, and dam faces with rocky substrate and good water circulation from wave action or currents (Eschmeyer 1950; Johnson 1961; Colby et al. 1979). Lacustrine populations often migrate up rivers to spawn (Priegel 1970).

Walleye spawning activity occurs at night (Ryder 1977) and is often concentrated within a few days. Eggs are broadcast freely over the substrate and fall into cracks and crevices (Scott and Crossman 1973). Walleye do not provide any parental care (Balon et al. 1977).

Specific Habitat Requirements

Habitat requirements of walleye have been summarized in reviews in the PERCIS Symposium [J. Fish. Res. Board Can. 34(10) Oct. 1977] and by Kendall (1978), and Colby et al. (1979). Walleye are tolerant of a wide range of environmental conditions (Scott and Crossman 1973) but are generally most abundant in moderate-to-large lacustrine (> 100 ha) or riverine systems characterized by cool temperatures, shallow to moderate depths, extensive littoral areas, moderate turbidities, extensive areas of clean rocky substrate, and mesotrophic conditions (Kitchell et al. 1977; Leach et al. 1977). Kitchell et al. (1977) suggest that the littoral and sublittoral habitats occupied by walleyes in lakes are the equivalent of extensions of suitable riverine habitat into the lacustrine environment.

Walleye survival, growth, and standing crop have been related to the abundance and availability of the small forage fishes it utilizes as food (Jester 1971; Forney 1974; Swenson and Smith 1976; Momot et al. 1977; Groen and Schroeder 1978). Light conditions also are an important factor affecting walleye distribution, abundance, and feeding (Ryder 1977). Walleye survive and grow in a wide range of turbidities (Ali et al. 1977; Ryder 1977), but reach their highest abundance in moderately turbid conditions (Ryder 1968; Elsey and Thomson 1977; Kitchell et al. 1977; Ryder and Kerr 1978). Peak feeding occurs at water transparencies of approximately 1 to 2 m Secchi disk depths, with a great decrease in activity at < 1 or > 5 m Secchi disk depths (Ryder 1977). Walleye feed most actively under low light intensity. Lower standing crops of walleye in clear lakes may be at least partially attributable to the reduced length of time favorable for feeding (Ryder 1977; Swenson 1977). However, this relationship may not always hold in deep, clear lakes with adequate forage (e.g., cisco or whitefish, Coregonus sp.) available in deep water (Momot pers. comm.).

Walleye fry are photopositive until becoming demersal at lengths of 25 to 40 mm (Ney 1978). The demersal fry, juveniles, and adults are very photosensitive. They actively seek the shelter of dim light during periods of strong light intensities in clear waters (Scherer 1971; Ryder 1977). They are often found in deep or turbid water or in contact with the substrate under cover of boulders, log piles, brush, and dense beds of submerged vegetation during the day (Ryder 1977).

Walleye are generally most abundant in lakes or lake sections classified as mesotrophic (Regier et al. 1969; Kitchell et al. 1977; Leach et al. 1977; Schupp 1978). They are less abundant in oligotrophic conditions (usually dominated by salmonids) and in eutrophic conditions (usually dominated by centrarchids) (Kitchell et al. 1977). Eutrophication tends to significantly reduce habitat quality for walleye (Kitchell et al. 1977; Leach et al. 1977; Momot et al. 1977; Schupp 1978). Ryder et al. (1974) and Ryder and Kerr (1978), considering only Precambrian Shield lakes of the north temperate boreal forest zone, found walleye to be most abundant in lakes or lake sections with morphoedaphic indices (MEI) in the mesotrophic range of about 6.0 to 7.2. Carlander (1977), in contrast, found no correlation between MEI and walleye biomass in 23 lakes and reservoirs located over a broad geographic range. He concluded that the lack of correlation between biomass or yields of walleye and the usual indicators of productivity (e.g., MEI) was probably due to the fact that walleye populations do not bear a constant relationship to the total fish biomass or yield.

Walleye are commonly found in lakes with a pH ranging from 6.0 to 9.0; the species exhibits no behavioral changes when exposed to varying pH levels within this range (Scherer 1971). Lower pH levels (< 6.0) are associated with failures in reproduction (Anthony and Jorgenson 1977) and recruitment (Spangler et al. 1977). Higher pH levels (> 9.0) generally are unsuitable for most freshwater fish (McKee and Wolf 1963).

Adult. Adult walleye generally are found under cover in moderately shallow (< 15 m) waters during the day and move inshore at night to feed (Johnson and Hale 1977; Ryder 1977). Adults often are found in areas with slight currents (Ryder 1977), except during the winter when they tend to avoid turbulent areas (Colby et al. 1979). Using the velocity equation developed by Jones et al. (1974), the critical velocity (maximum velocity that can be sustained for 10 min) for adult walleye 30 cm in fork length is 74 cm/sec [critical velocity = $(13.07)L^{0.51}$, where L = fork length in cm].

Preferred (optimum) temperatures for growth of adults are 20 to 24° C (Dendy 1948; Ferguson 1958; Kelso 1972; Huh et al. 1976). Adults seem to avoid temperatures > 24° C, if possible (Fitz and Holbrook 1978). Kelso (1972) reported that growth in adults ceases at temperatures < 12° C. Upper lethal temperatures of 29 to 32° C were reported by Hokanson (1977), while Wrenn and Forsythe (1978) reported an upper lethal range of 34 to 35° C. Momot et al. (1977) attributed low survival and poor growth of age IV+ fish in a eutrophic central Ohio reservoir to absence of areas of summer habitat with cool (< 24° C) water and adequate (> 5 mg/l) dissolved oxygen.

Adult walleye can tolerate dissolved oxygen (DO) levels of 2 mg/l for a short time (Scherer 1971), but the greatest abundance of walleye occurs where minimum DO levels are greater than 3 to 5 mg/l (Dendy 1948). DO levels of < 1 mg/l are lethal (Scherer 1971).

Embryo. Highest embryo production and survival has been observed on clean gravel or rubble substrates (2.5 to 15 cm in diameter) (Johnson 1961). Survival also is good on dense mats of vegetation with adequate water circulation (Priegel 1970). Percent survival of embryos is greatly reduced on sand,

and survival of eggs deposited on soft muck and detritus is negligible (Johnson 1961; Priegel 1970). Years of highest embryo production in lakes are often associated with rising or stable spring water levels that increase the amount of littoral area available for spawning and prevent stranding of embryos (Johnson 1961; Chevalier 1977; Groen and Schroeder 1978).

Embryos require well-oxygenated water (Balon et al. 1977), and DO levels ≥ 5 mg/l are considered necessary for high survival and growth (Oseid and Smith 1971). DO levels ≤ 3.4 mg/l resulted in delayed hatching and a significant reduction in size at hatching (Colby and Smith 1967; Siefert and Spoor 1974). Streamflows and wind-generated currents in spawning areas must be sufficient for adequate circulation of oxygenated water around embryos (Priegel 1970). Positive correlations between spring river discharge and walleye year class strength have been reported for several rivers (Nelson and Walburg 1977; Spangler et al. 1977). The nonadhesive eggs can be dislodged from the substrate if stream flows or wind-generated currents are too high (Eschmeyer 1950; Priegel 1970). In the Great Lakes, the littoral substrate of exposed shoreline areas may be unsuitable for spawning due to strong wave action. Sedimentation (Benson 1968) and anoxia-producing pollutants (Colby and Smith 1967) are other factors that can reduce the availability of oxygen and, therefore, affect the survival of embryos.

Proper maturation of gonads in female walleyes requires minimum winter water temperatures of < 10° C (Hokanson 1977). Miller (1967) reported that walleyes failed to reproduce in a reservoir with minimum winter temperatures of 10 to 12.5° C. Embryos are adapted to steadily increasing water temperatures during the spring. Optimum temperatures are 6 to 9° C for fertilization and 9 to 15° C for incubation (Koenst and Smith 1976). Upper lethal (TL_{50}) temperatures for embryos are near 19° C (Smith and Koenst 1975). Eggs hatch in 14 to 21 days at temperatures of 8 to 15° C (Ney 1978). Steady spring warming rates of ≥ 0.28° C/day have been positively correlated with embryo and fry production (Busch et al. 1975). Poor survival of embryos is associated with cold water temperatures due to slow spring warming rates [< 0.18° C/day (Busch et al. 1975)], cold weather fronts (Busch et al. 1975), or release of cold reservoir water into tailwaters during spawning and incubation (Pfitzer 1967).

Fry. Stream velocities in spawning tributaries must be sufficient to transport fry downstream to lakes within the period of yolk-sac absorption (3 to 5 days) or fry will perish from lack of food (Priegel 1970). Fry will not begin to feed at temperatures < 15° C (Smith and Koenst 1975). Momot et al. (1977) reported that stocked walleye fry exhibited greater survival when there was a high availability of newly hatched gizzard shad (*Dorosoma cepedianum*) at time of stocking.

Optimum temperatures for growth of walleye fry are near 22° C (Kelso 1972; Huh et al. 1976; Koenst and Smith 1976). No growth occurs at temperatures ≤ 12° C or ≥ 29° C (Kelso 1972; Hokanson 1977). Upper lethal temperatures for fry are in the range of 31 to 33° C (Smith and Koenst 1976; Wrenn and Forsythe 1978). Conditions that reduce or retard growth (e.g., low temperature, low zooplankton abundance, and delayed hatching) can greatly affect fry overwinter survival because smaller fry experience more overwinter mortality than larger fry (Forney 1966).

Optimum DO concentrations for fry are ≥ 5 mg/l (Siefert and Spoor 1974). Moyle and Clothier (1959) reported that DO levels below 5 mg/l resulted in poor survival of stocked fry. Low DO levels also retard fry development (Oseid and Smith 1971) and reduce swimming ability (Siefert and Spoor 1974).

Fry can withstand only slight current velocities (Houde 1969). Walburg (1971) and Groen and Schroeder (1978) reported that high velocities near a reservoir outlet can result in significant fry losses, particularly if spawning occurs at the dam face.

Juvenile. Habitat requirements for juvenile walleye seem to be similar to those of adults (Colby et al. 1979). Using the previously described regression equation from Jones et al. (1974), the critical velocity for juveniles with a fork length of 20 cm is 60 cm/sec.

HABITAT SUITABILITY INDEX (HSI) MODELS

Model Applicability

Geographic area. This model is applicable to North American waters within the native and introduced range of walleye. The standard of comparison for each variable is the optimum value of the variable that occurs anywhere within this area. Optimum conditions will most likely occur in the northern United States, southern Canada, or within the median temperature envelope boundaries of percids, as defined by Hokanson (1977).

Season. The model provides an index for a riverine or lacustrine habitat based on its ability to support all life stages of walleye throughout the year.

Cover types. The model is applicable in riverine, lacustrine, and palustrine habitats, as described by Cowardin et al. (1979).

Minimum habitat area. Minimum habitat area is defined as the minimum area of contiguous, suitable habitat that is required to sustain a population. The minimum habitat area required by walleye populations is unknown, but relatively large lakes (> 100 ha) or river systems are more likely to provide adequate conditions for spawning (Kitchell et al. 1977; Leach et al. 1977). Self-sustaining walleye populations are generally rare in small lakes that are not connected to other lakes (Johnson et al. 1977). However, walleye are often abundant in small lakes (< 400 ha), where natural reproduction is supplemented by stocking (J. Lyons, pers. comm.; B. Johnson, pers. comm). Kitchell et al. (1977) noted that while walleye were present in many small (< 100 ha) lakes, they were abundant in only a few.

Verification level. The model represents our interpretation of how selected environmental factors limit potential carrying capacity. Portions of the model have been subjected to limited field application, by comparison with standing crop and catch per unit effort data. Reviewers of the model have recommended extensive testing and evaluation before accepting the model, or portions of the model, based on suitability index graphs as an accurate predictor of habitat quality. We agree with these recommendations.

Model Description

The Habitat Suitability Index (HSI) model that follows has two versions: riverine and lacustrine. These two versions condense the preceding observations into a set of measurable habitat variables. The model is structured to produce an index of walleye habitat quality between 0.0 (unsuitable) and 1.0 (optimum). A positive relationship between HSI and carrying capacity is assumed but has not been demonstrated. Habitat variables believed to be important in limiting distribution, abundance, or survival of walleye are included in the models. An assumed functional relationship between each habitat variable and habitat suitability is represented in a variable suitability index (SI) graph. It is assumed that SI ratings for different habitat variables can be compared. This is one of the weakest model assumptions. It is likely to be violated for some ranges of the selected variables because the impacts (e.g., changes in growth rates, survival rates, distribution, and abundance) measured by each variable are not directly comparable. The model is likely to provide the most accurate description of carrying capacity when all of the variables have extreme SI values; i.e., either near optimum or unsuitable.

Walleye habitat quality is represented by food, cover, water quality, and reproductive components. Variables that are thought to be direct or indirect measures of the relative ability of a habitat to meet these requirements are included in the appropriate component. Variables that affect habitat quality for walleyes, but do not easily fit into one of these four major components, are combined under the "other component" heading.

It should be noted that not all variables that potentially affect walleye populations are included in the models. Variables were not included if: (1) the variable was adequately measured by another variable(s); or (2) it would be difficult to measure the variable quantitatively [e.g., effects of inter- and intraspecific interactions on walleye biomass (Forney 1977)].

Model Description - Riverine

The structure of the riverine HSI model for walleye is presented graphically in Figure 1.

Food component. Average Secchi disk depth (V_1) is considered part of the food component because feeding activity is related to transparency (light) conditions. The optimum transparency range depicted in the graph is reasonably well defined in the literature from observations of conditions associated with

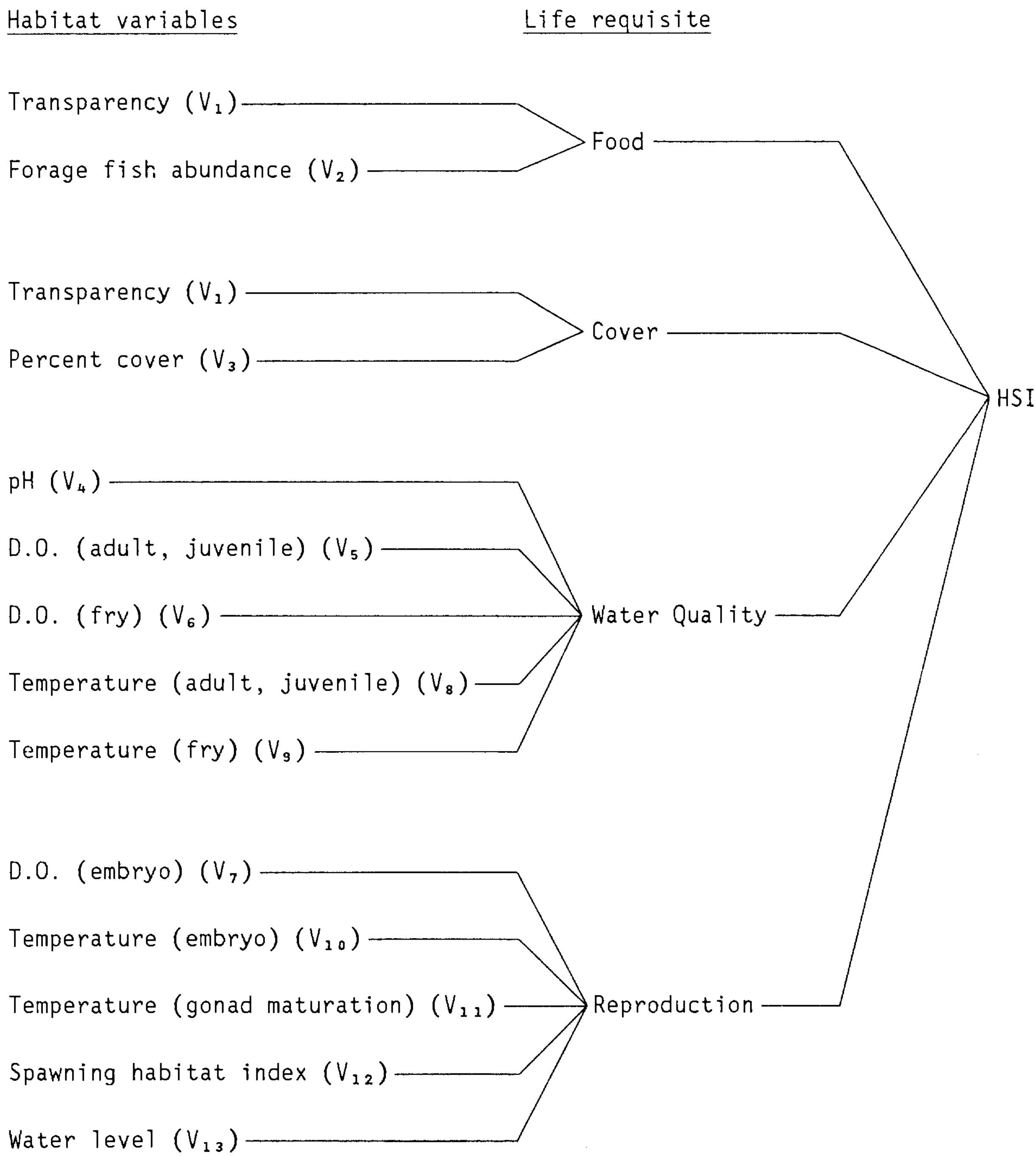


Figure 1. Tree diagram illustrating relationships between model variables, model components, and HSI for the walleye in riverine environments.

high feeding levels. Walleyes occur in very clear waters, although the time available for efficient foraging is reduced in those lakes that lack deep water and deep-water prey, such as cisco (Ryder 1977; Momot, pers. comm.). It was assumed that walleyes can find some shelter from light even in very clear waters, either in the form of cover or deep water; therefore, the descending limb of the graph remains above zero. Too much turbidity favors competitors, such as centrarchids (Kitchell et al. 1977), and apparently results in reduced feeding efficiency (Ryder 1977). Although some feeding probably occurs at high turbidity levels, the graph descends to 0 at very low Secchi disk depths, because it was assumed that clogging and abrasion of gills or high embryo mortality would occur at these levels.

The relative abundance of forage fishes (V_2) was included in this component because growth, food consumption, and standing crop of walleye are related to forage abundance. The index of relative abundance was measured in units of mg/m^3 of prey density, after Swenson and Smith (1976).

Variables V_1 and V_2 are assumed to be direct measures of food availability. Therefore, an increase in the suitability of either food component variable is assumed to increase the amount of available food by the same amount, regardless of the other food component variable rating. This assumption is expressed by combining variables through a simple arithmetic mean.

Cover component. The cover component was broken down into two subcomponent ratings, based on the amount of cover related to light conditions and cover in the form of physical shelter. Transparency (V_1) is included in a light intensity subcomponent because standing crop of walleye is reduced in: (1) clear water without sufficient water depth to provide cover from bright light; or (2) in very turbid waters where sauger (*S. canadense*) or centrarchids predominate (Leach et al. 1977; Ryder 1977). Percent of area with cover (V_3) is included in both subcomponents because cover is used both as an escape from intense light levels and as a resting area to avoid high water velocities.

The importance of percent cover (V_3) for shelter from light is assumed to vary. When transparency is too high to be optimum (Secchi disk transparency > 3.2 m), cover should become more important in determining habitat quality because the clearer the water, the greater the need to have cover to escape from high light intensities. These assumptions are quantified by combining the two variable ratings into a subcomponent of cover related to the ability of a water body to provide shelter from light. The coefficients in the equation quantify these subjective opinions; they are not the result of rigorous experimentation.

If the Secchi transparency is < 3.4 m (3.4 m rates an SI of 0.9), the subcomponent equals:

$$\frac{3V_1 + V_3}{4}$$

This equation reflects the greater importance of transparency (V_1) in determining habitat quality in terms of cover from light in waters that have near optimum or lower than optimum transparency levels. It could be argued that, when water transparency is too low to be optimum, percent cover should not be included in a subcomponent rating depicting cover from light. Percent cover was left in the equation because transparency levels can be variable and cover can occasionally become important in water that normally has transparency levels too low to be optimum. If the Secchi transparency is greater than 3.4 m, the SI rating is less than 0.9 and is determined from the descending limb of the SI curve for V_1. In this situation, the subcomponent equals:

$$\frac{3V_1 + NV_3}{3 + N}$$

where $N = [10(1\text{-SI of } V_1)]$. The second equation provides the same answer as the first equation when V_1 has an SI of 0.9. It predicts a slower drop in suitability when increasing transparency is associated with high cover ratings than when it is associated with low cover ratings. The equation thus quantifies the assumption that cover is more important for shelter from light when the water is too clear to be optimum.

Water quality component. Dissolved oxygen (V_5, V_6) and temperature (V_8, V_9) levels for adults-juveniles and fry, respectively, as well as pH (V_4), are included because these water quality parameters affect growth, survival, or feeding (or all three) in walleye. Suboptimum levels of these variables are defined primarily from well-documented negative impacts that do not appear to be mitigated by a higher suitability of other variables. This, and the fact that the dependency of dissolved oxygen requirements on temperature is included in the variable definition, justifies combining these variables into a subcomponent rating by selecting the lowest variable rating.

Reproduction component. Dissolved oxygen (V_7), mean weekly temperatures in spring (V_{10}), and minimum winter water temperatures (V_{11}) are included in this component because they can be limiting factors to successful embryo survival or gamete development. Quantity (percent riffles in riverine situations or littoral area in lacustrine situations) and quality (substrate type) of spawning habitat have been shown to affect embryo survival and production and, therefore, are included in a spawning habitat index (V_{12}) based on the product of quantity (percent riffle or littoral area > .3 m but < 1.5 m deep) and quality (determined from a substrate index) of spawning habitat. Model users may want to modify the depth criteria based on available data for local walleye populations.

In order to interpret the spawning habitat index, it is necessary to assume some optimum quantity of spawning habitat needed to ensure maximum reproductive success. This quantity is likely to vary for different types of water bodies in different geographic areas, and the impact of a change in spawning area is likely to be difficult to evaluate. For example, Busch et al. (1975) found that, while suitable spawning habitat (and walleye populations) in western Lake Erie had been substantially reduced from historical levels, the remaining spawning reef area of 51.3 to 110.4 ha (depending on water level) was still capable of producing strong year classes of walleye in the western basin. However, the limited spawning habitat appeared to be a factor in making spawning success more vulnerable to variations in weather. A high value (20%) was selected as the optimum proportion of a water body that should meet the criteria for spawning. Model users should critically evaluate the suggested percentage and modify it based on local data. Multiplication of the derived spawning substrate index (e.g., 0.20) by the maximum possible spawning substrate index (e.g., 200, derived by multiplying 100% rubble times the proposed weighting factor of 2) obtainable for a specified area resulted in a product of 40 (see spawning habitat index V_{12}). Therefore, 40 was defined as the optimum value of the spawning habitat index (V_{12}) and a suitability index of 1.0 was assigned to all spawning habitat indices ≥ 40. A spawning habitat index of 0 was equated to an HSI of 0 because 0 was believed to represent conditions where the likelihood of successful reproduction is nil (e.g, 100% silt = spawning habitat index of 0).

Water level during the spawning period (V_{13}) is also included in this component because the water level can affect the area and type of substrate available for spawning; it has also been related to year-class strength. A suboptimum water level fluctuation was assumed to consistently have a negative impact on reproductive success; this is especially so because walleye spawning is restricted to a relatively short time period in the spring.

Compensation among reproduction variables was considered unlikely; therefore, the lowest variable rating among the combined variables was selected as the subcomponent value.

HSI calculation. The HSI was defined as the minimum value for any component SI because "suboptimum" conditions for a component were assumed to represent conditions that have measurable negative impacts on individuals and thus limit carrying capacity even when other conditions are optimum.

Model Description - Lacustrine

The structure of the lacustrine HSI model for walleye is shown in Figure 2. The model includes the components from the riverine model, with an "other" component added to the model.

"Other" component. A measure of the trophic status of a lake (V_{14}) is assumed to be a general determinant of habitat suitability for walleye because abundance of walleye often has been related to trophic conditions. Trophic status is a composite variable that includes many of the factors that appear

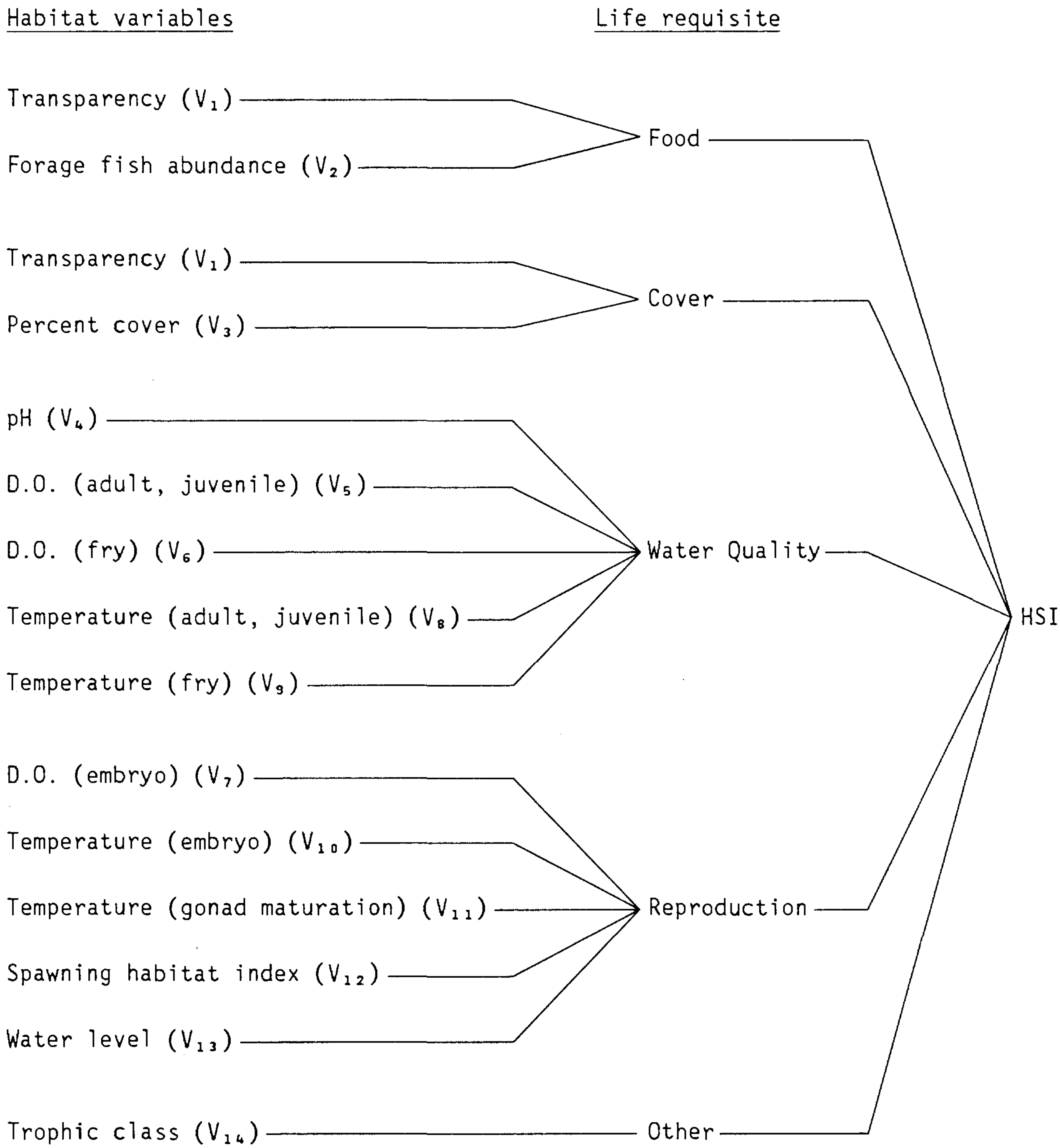


Figure 2. Tree diagram illustrating relationships between model variables, model components, and HSI for walleye in lacustrine environments.

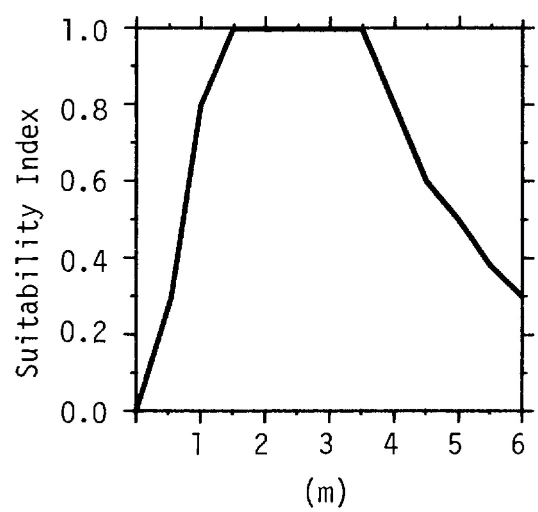
to affect walleye population levels and is, therefore, assumed to have an impact on carrying capacity. Trophic status is considered a potentially useful variable for predicting the suitability of future habitat conditions for walleye populations in some types of lakes. However, the variable may be biased towards Canadian shield lakes and inadequately represent excellent walleye lakes that are large and relatively eutrophic but do not stratify for extended periods of time. The trophic status variable is in the model in order to call attention to a variety of environmental variables that may be useful in providing a very general description of walleye habitat quality. Users should evaluate the accuracy of the trophic status definition they select under environmental conditions similar to those where the model will be applied.

HSI Calculation

The HSI was defined as the minimum component value for the same reasons described for the riverine model.

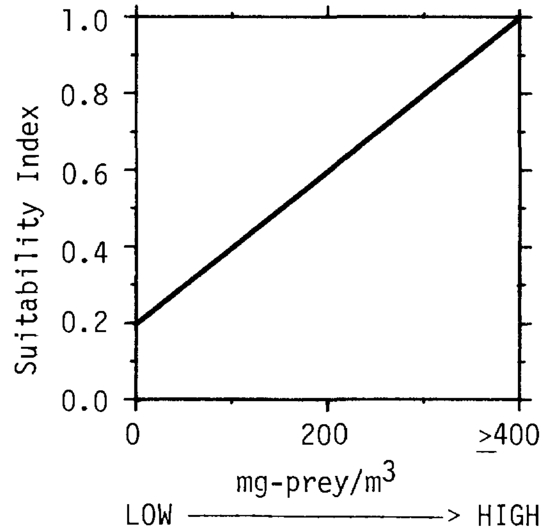
Suitability Index (SI) Graphs for Model Variables

Suitability index graphs pertain to riverine (R) or lacustrine (L) habitats or both.

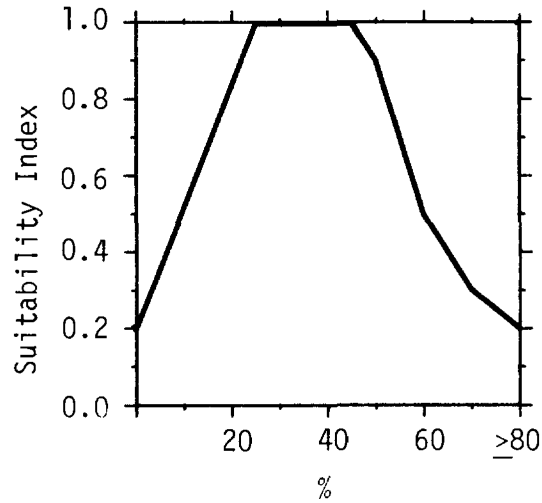
Habitat	Variable		Suitability graph
R,L	V_1	Average transparency (Secchi depth) during summer.	

R,L V_2 Relative abundance of small (< 12 cm) forage fishes during spring and summer (fry, juvenile, and adult).

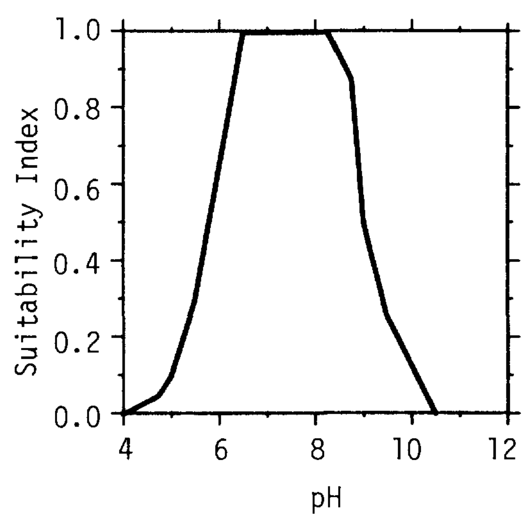
Note: SI for this variable for predicted or future conditions can be based on standing crop predictive models, such as those presented by Aggus and Morais (1979).



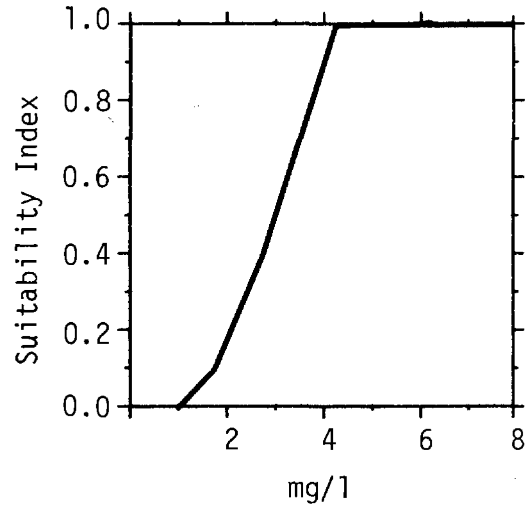
R,L V_3 Percent of water body with cover (boulders, log piles, brush, submerged vegetation) and adequate dissolved oxygen (> 3 mg/l) during the spring and summer (fry, juvenile, and adult).



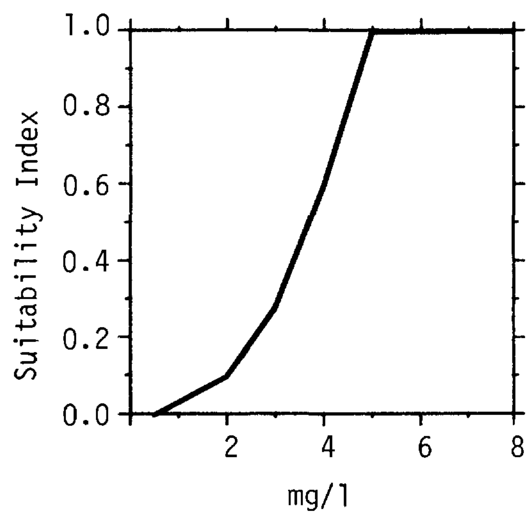
R,L V_4 Least suitable pH during the year.



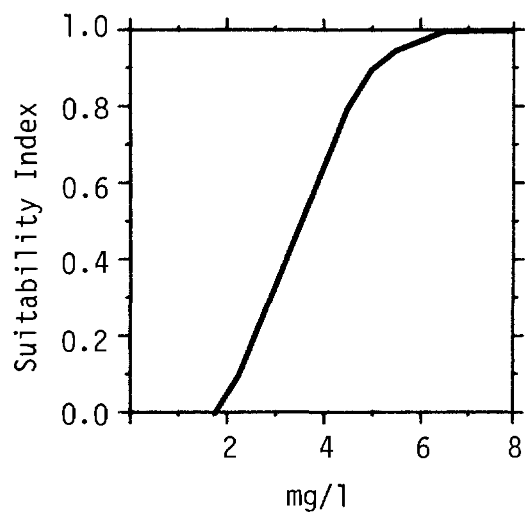
R,L V_5 Minimum dissolved oxygen level in pools and runs (R) or above thermocline (L) in summer (adult and juvenile).

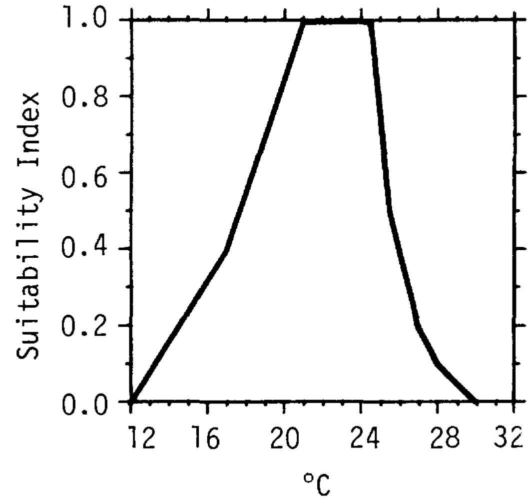
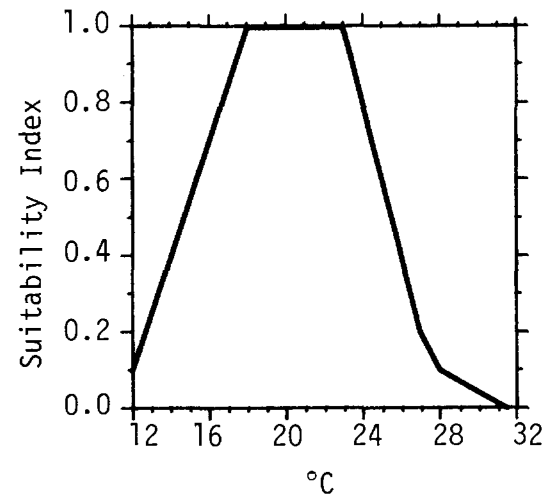
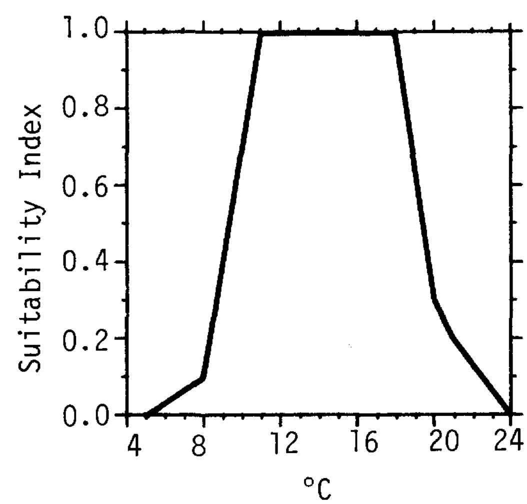


R,L V_6 Minimum dissolved oxygen level during summer-fall along shallow shoreline areas (fry).

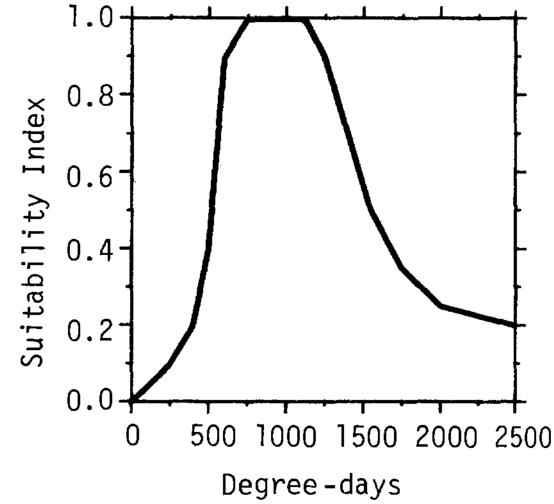


R,L V_7 Minimum dissolved oxygen level measured in spawning areas during spring (embryo).



R,L	V_8	Mean weekly water temperature in pools (R) or above thermocline (L) during summer (adult and juvenile).	
R,L	V_9	Mean weekly water temperature in shallow shoreline areas during late spring-early summer (fry).	
R,L	V_{10}	Mean weekly water temperature during spawning in spring (embryo).	

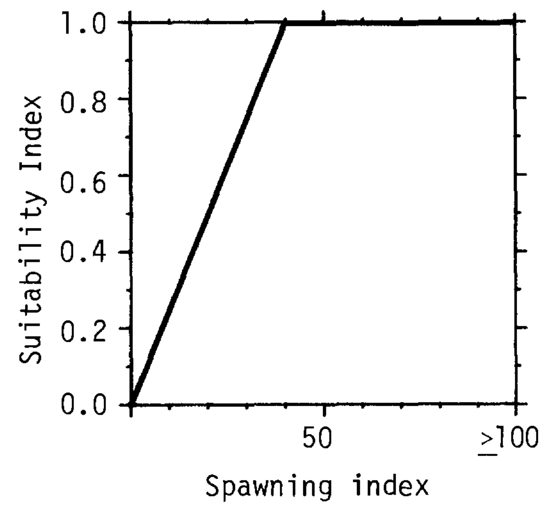
R,L V_{11} Degree days between 4 and 10° C from October 30 to April 15. (Calculate by multiplying water temperatures in the range of 4 to 10° C by number of days that are in this temperature range. For example, 160 days of 6° C = 960 degree-days = SI of 1.0).



R,L V_{12} Spawning habitat index.

Calculated by multiplying the proportion of the water body composed of riffle or littoral areas > 0.3 m but < 1.5 m deep by the substrate index where the substrate index is defined by the following equation:

Substrate Index = 2(% gravel/rubble 2.5 to 15 cm in diameter) + (% boulders/bedrock) + 0.5(% sand) + 0.5(% dense vegetation) + 0(% silt/detritus).

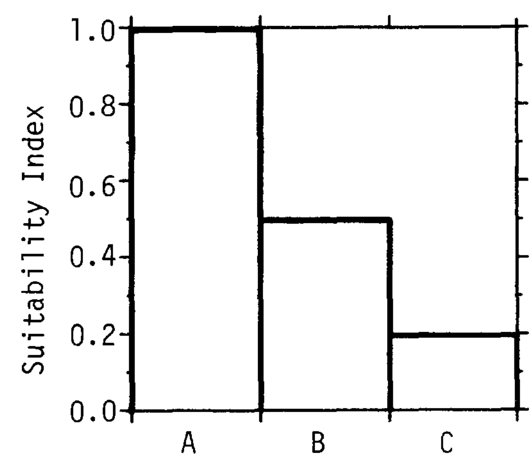


R,L V_{13} Water level during spawning and embryo development (embryo).

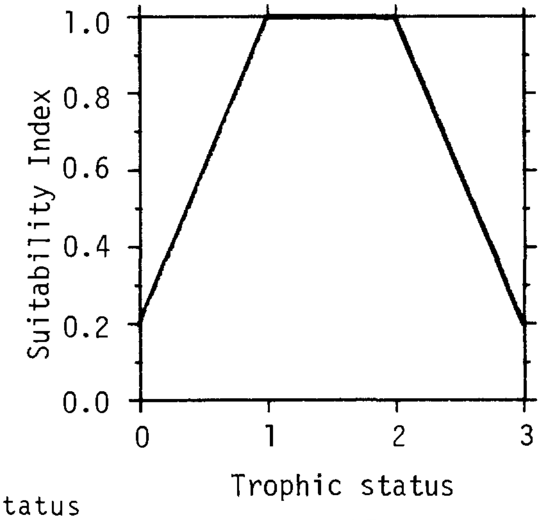
A) Rising or normal and stable: abundance of shallow shoreline or shoal areas for spawning.

B) Low: many spawning areas are exposed, and never inundated.

C) Fluctuating: fluctuations sufficient to alternately expose and flood spawning areas.



L	V_{14}	Trophic status of lake or lake section.
Note:	The following list of parameter levels can be used to classify a water body according to trophic status (adapted from Leach et al. 1977).	



Parameter	Trophic status 0-1 (Oligotrophic)[1]	1-2 (Mesotrophic)	2-3 (Eutrophic)
Primary production rate	low	moderate	high
Organic matter in sediments	low	moderate	high
Hypolimnetic O_2 loss	low	moderate	high
Nutrient loading rates (phosphorus, nitrogen)	low	moderate	high
Morphoedaphic index (MEI) (metric)	< 5.9	6.0-7.2	> 7.3
Transparency (Secchi depth)	high (> 6 m)	moderate (1-6 m)	low (< 1m)

[1]For actual values of these parameters for each trophic status, refer to Leach et al. (1977). Values may differ by geographic location.

Riverine Model

This model attempts to describe life requisite requirements separately and consists of four components: Food, Cover, Water Quality, and Reproduction. Rationale for the form of the equations is the same as that for the riverine model.

(1) Food (C_F)

$$C_F = \frac{V_1 + V_2}{2}$$

(2) Cover (C_C)

C_C = the lowest of the subcomponent ratings for cover from the appropriate C_L, where:

$$C_L = \frac{3V_1 + V_3}{4}$$ when Secchi transparency is ≤ 3.4 m

$$C_L = \frac{3V_1 + NV_3}{3 + N}$$ when Secchi transparency is > 3.4 m
$N = [10(1\text{-SI of } V_1)]$

(3) Water Quality (C_{WQ})

C_{WQ} = the lowest of V_4, V_5, V_6, V_8, or V_9

(4) Reproduction (C_R)

C_R = the lowest of V_7, V_{10}, V_{11}, V_{12}, or V_{13}

(5) HSI determination

HSI = the lowest of C_F, C_C, C_{WQ}, or C_R

Sources of data and a synopsis of the assumptions made in developing suitability indices are presented in Table 1.

Table 1. Sources of information and assumptions used in construction of the suitability index graphs are listed below. "Excellent" habitat for walleye was assumed to correspond to an SI of 0.8 to 1.0, "good" habitat to an SI of 0.5 to 0.7, "fair" habitat to an SI of 0.2 to 0.4, and "poor" habitat to an SI of 0.0 to 0.1.

Variable	Assumptions and sources
V_1	Transparency levels of 1 to 3 m Secchi disk depths were considered excellent because feeding activity in the light-sensitive walleye is highest under moderately turbid conditions (Ryder 1977). Secchi depths < 1 m or > 5 m were deemed fair because feeding activity is greatly reduced in very turbid or very clear waters.
V_2	High abundance of forage fishes was considered excellent because strong year-classes of walleyes develop when small forage fishes are both abundant and available (Jester 1971; Forney 1977). Groen and Schroeder (1978) reported that walleye abundance in Kansas reservoirs increased substantially following implementation of water management plans that provided higher water levels in the spring and also resulted in increased habitat and production of forage fishes. Low forage fish production or availability at the time walleye fry switch to piscivory results in increased cannibalism (Forney 1977) and reduced recruitment and growth of walleye populations (Momot et al. 1977) and, therefore, was considered to provide only "fair" habitat conditions. Forage abundance was defined in units of mg/m^3, based on the work of Swenson and Smith (1976) and Swenson (1977) who showed that walleye prey consumption rate was low at prey densities $< 50\ mg/m^3$, but increased with increasing prey densities and stabilized at prey densities $> 400\ mg/m^3$.
V_3	There are no quantitative data relating amount of cover to walleye standing crop or abundance. However, walleye of all sizes strongly favor shelter or dim light during the day (Scherer 1971) and are often found under cover of boulders, logs, brush, or submerged vegetation during periods of high light intensity (Ryder 1977). Thus, areas with sparse cover are assumed to be less suitable as walleye habitat. Too much vegetation is assumed to reduce habitat suitability by reducing foraging ability (Swenson 1977).

Table 1. (continued).

Variable	Assumptions and sources
V_4	pH levels in the range of 6.0 to 9.0 are considered good-excellent. Levels within this range correspond to optimal pH levels for freshwater fish in general (McKee and Wolf 1963). Also, walleye exhibit no behavioral responses to pH changes within this range. pH levels < 5.5 are deemed poor because walleye spawning ceases at a pH ≤ 4.0 (Anthony and Jorgensen 1977) and because pH levels ≤ 5.5 are thought to be responsible for recruitment failures in walleye populations (Spangler et al. 1977).
V_5	D.O. concentrations identified by Davis (1975) as optimum for Canadian nonsalmonid freshwater fish populations (≥ 5.5 mg/l) are considered excellent. Concentrations that resulted in stress (< 3 mg/l) or loss of equilibrium (0.6 mg/l) in walleye in the laboratory (Scherer 1971) are deemed poor.
V_6	D.O. concentrations of 3 to 5 mg/l are considered fair because Moyle and Clothier (1959) reported poor survival of stocked walleye fry within this range. D.O. concentrations < 3 mg/l are considered poor because Siefert and Spoor (1974) reported that walleye larvae raised at 2.4 and 1.9 mg/l were noticeably weak swimmers.
V_7	D.O. concentrations near saturation (> 6 mg/l) are considered excellent because embryos require well-oxygenated water for successful hatching (Colby and Smith 1967; Priegel 1970; Balon et al. 1977). Concentrations < 3 mg/l are considered poor because the size of walleye fry at hatching was significantly reduced at < 3.4 mg/l (Siefert and Spoor 1974).
V_8	Temperatures $< 12°$ C are considered poor because growth does not occur at these temperatures (Kelso 1972). Temperatures $\geq 30°$ C are lethal (Koenst and Smith 1976) and, therefore, also are deemed poor. "Excellent" habitat suitability is defined as those temperatures (20 to 24° C) that correspond to the highest growth rate (Kelso 1972; Smith and Koenst 1975) and highest abundance (Dendy 1948; Ryder 1977). Temperatures of 25 to 30° C are considered fair to poor because walleyes appear to exhibit a strong aversion to water temperatures $> 24°$ C (Fitz and Holbrook 1978).

Table 1. (continued).

Variable	Assumptions and sources
V_9	Upper lethal temperatures for walleye fry [31.6° C (Smith and Koenst 1975); 32 to 33° C (Wrenn and Forsythe 1978)] are deemed poor, as are temperatures below those needed to initiate feeding in fry in the laboratory [15° C (Smith and Koenst 1975)]. Temperatures identified as preferred [20.6 to 23.2° C (Ferguson 1958)] or as optimum for growth [22° C (Huh et al. 1976; Koenst and Smith 1976)] are considered excellent. Temperatures near 16° C and 28° C are considered fair because growth is slow at these temperatures (Huh et al. 1976).
V_{10}	Temperatures corresponding to the TL_{50} maximum (19.2° C) and minimum (< 6.0° C) (Smith and Koenst 1975) are deemed poor. Temperatures corresponding to the highest percent hatch rate of walleye embryos in the laboratory [9 to 15° C (Koenst and Smith 1976)] are considered excellent.
V_{11}	The shape of this SI graph was based primarily on temperature requirements for gonad maturation in yellow perch (<u>Perca flavescens</u>), a percid often sympatric with walleye that also requires winter temperatures < 10° C for proper gonad maturation (Hokanson 1977). Gonad maturation is a function of temperature and time (Jones et al. 1974; Hokanson 1977); therefore, chill duration (measured in degree-days) was used as the measure of suitability. Chill durations are only calculated for temperatures < 10° C because no viable spawnings occurred in yellow perch held at ≥ 12° C and Miller (1967) reported that walleye failed to reproduce in a California reservoir with minimum winter water temperatures of 10 to 12.5° C (Hokanson 1977). A chill duration of > 2,000 degree-days is assumed to be of poor suitability because only a small percentage of yellow perch reared at 10° C for 200(= 2000 degree-days) or 240(= 2400 degree-days) days spawned successfully (Jones et al. 1974). A chill duration of 740 to 1110 degree-days is deemed excellent because Jones et al. (1974) reported that optimum conditions for gonad maturation in yellow perch occurred when the fish were exposed to 4 to 6° C temperatures for 185 days(= 740 to 1110 degree-days) starting October 30. A chill duration of 360 degree-days is considered the lower limit for gonad maturation because only limited viable spawnings occurred in yellow perch held at a minimum of 12° C, except for those held 45 days at 8° C(= 360 degree-days) (Jones et al. 1974; Hokanson 1977). It should be noted that these laboratory results may not be directly applicable to field situations, particularly when dealing with populations near or beyond the southern limit of the natural walleye range (Clugston et al. 1978).

Table 1. (continued).

Variable	Assumptions and sources
V_{12}	A rubble-gravel substrate is assumed to be excellent as spawning habitat for walleye because: (1) gravel and rubble are preferred for spawning when available (Eschmeyer 1950; Priegel 1970; Nelson and Walburg 1977); (2) Chevalier (1977) reported that walleye eggs are most abundant on beaches with gravel, rubble, or shingle rock; (3) Johnson (1961) reported that percent survival of walleye eggs was highest on gravel-rubble substrate; and (4) the addition of gravel and rubble to marginal walleye spawning areas is followed by increased egg deposition and survival (Johnson 1961; Newburg 1975). Substrates where O_2 is low and/or water circulation is poor (i.e., sand, silt, and detritus) are associated with low embryo survival (Johnson 1961; Colby and Smith 1967; Benson 1968; Priegel 1970) and are deemed poor. Mats of dense vegetation are considered to be moderately suitable because Priegel (1970) found good survival of walleye eggs in dense grass-sedge vegetation with good water circulation. Weighting factors used in the substrate index equation were based on documented survival of embryos in the order: gravel-rubble ≥ gravel-sand > sand > silt-detritus (Johnson 1961; Priegel 1970).
V_{13}	A positive correlation between spring water levels and year-class strength of walleye was reported by Chevalier (1977). Stable or rising spring water levels result in more successful reproduction in walleye by increasing the availability of spawning and rearing habitat (Chevalier 1977; Groen and Schroeder 1978). Therefore, stable or rising water levels are considered excellent. Low water levels are considered fair because Johnson (1961) and Chevalier (1977) reported that low water levels decrease availability of spawning habitat by exposing shallow rocky shoreline areas and shoals. Reservoirs with rapidly fluctuating spring water levels are considered poor because sudden drawdowns can interrupt spawning activity and lead to stranding and dessication of eggs (Groen and Schroeder 1978). Also, high discharge rates accompanying rapid drawdown can result in a significant loss of age 0 and older walleye (Walburg 1971; Groen and Schroeder 1978). The degree of lake drawdown necessary to expose spawning areas is likely to vary, depending on the depth of major spawning areas. If site specific data are lacking, a drop of ≥ 0.3 m from normal elevation should be defined as "low" because Johnson (1961) and Chevalier (1977) reported that the majority of walleye spawn at depths of 0.3 m or less.

Table 1. (concluded).

Variable	Assumptions and sources
V_{14}	Walleye are most abundant in waters classified as mesotrophic; i.e., those waters with moderate fertility and moderate turbidity (Regier et al. 1969; Kitchell et al. 1977; Schupp 1978). Schupp (1978) reported that walleye abundance and growth in a large heterogenous Minnesota lake was greatest in lake sections characterized by mesotrophic conditions. Walleye are less abundant in deep, clear, unproductive lakes and in shallow, highly productive areas. Kitchell et al. (1977) and Leach et al. (1977) proposed the assumption that habitat quality for walleye populations is related to the trophic conditions present in the lake or lake section, with mesotrophic status most likely to represent optimum conditions. Therefore, it is assumed that the more eutrophic or oligotrophic a water body is, the less suitable it is as walleye habitat. The trophic classification system of Leach et al. (1977) was revised for use as a guide in classifying a water body as oligo-, meso-, or eutrophic.

Lacustrine Model

This model utilizes the life requisite approach and consists of five components: Food, Cover, Water Quality, Reproduction, and Other.

(1) Food (C_F)

$$C_F = \frac{V_1 + V_2}{2}$$

(2) Cover (C_C)

$$C_C = \frac{3V_1 + V_3}{4}$$ when Secchi transparency is ≤ 3.4 m

$$C_C = \frac{3V_1 + NV_3}{3 + N}$$ when Secchi transparency is > 3.4 m where N = [10(1-SI of V_1)]

(3) Water Quality (C_{WQ})

C_{WQ} = the lowest of V_4, V_5, V_6, V_8, or V_9

(4) Reproduction (C_R)

C_R = the lowest of V_7, V_{10}, V_{11}, V_{12}, or V_{13}

Note: The variables in this component should be measured in tributaries if that is where reproduction primarily occurs.

(5) Other (C_{OT})

$C_{OT} = V_{14}$

(6) HSI determination

HSI = the lowest of C_F, C_C, C_{WQ}, C_R, or C_{OT}

Sources of data and assumptions made in developing the suitability indices are presented in Table 1.

Application of Lacustrine Model

Two modified versions of the lacustrine HSI model were applied to 10 lakes in Iowa, Wisconsin, and Minnesota using environmental and fish population data provided by Nickum (pers. comm.). Environmental data were used to estimate five model variables: V_1, V_3, V_4, V_{12}, and V_{13} (Table 2). The original model structure was retained, with the HSI defined as the lowest SI of the cover component (derived from V_1 and V_3), V_4, V_{12}, or V_{13}. The second modified model had the same structure, except that variables directly related to reproductive success (V_{12} and V_{13}) were excluded.

The first modified model assigned only a "good" rating to an Iowa lake with a standing crop of 38.7 fish/ha. However, this lake is stocked with walleye fry, which could negate the impact of the availability of spawning habitat on standing crop. The second modified model (HSI' in Table 2) excluded variables related directly to reproductive success and resulted in a high HSI for the lake with the high standing crop. Both of the tested HSI models assigned high HSI's to Wisconsin and Minnesota lakes with high and low standing crops and fair (0.2) and excellent (0.8) HSI's to two Minnesota lakes that apparently contained no walleye.

The test results are consistent with the assumption that the type of HSI model tested can predict an upper limit to population levels but not a lower limit. High HSI's were associated with both high and low standing crops; low HSI's were associated only with low standing crops. Lakes with very similar habitat conditions (e.g., Wisconsin lakes 4 and 5), as rated by the model variables, had very different walleye population densities. This seems to indicate that additional factors not included in the model were influencing population levels.

The test results indicate that the SI of 0.7 assigned to 15% cover may be either too low or that the combined effect of cover and light transparency are incorrectly depicted in the model. This conclusion is based on the fact that lake number three, which had the highest standing crop, had 15% cover. Therefore, the curve (V_3) should probably be modified so that 15% cover receives an SI of 1.0.

Interpreting Model Outputs

The models described above are generalized descriptions of habitat requirements for walleye and are unlikely to discriminate among different habitats with a high level of accuracy or precision at this stage of development. Each model variable is considered to have some effect on carrying capacity for walleye, and the suitability index graphs depict this assumed effect. However, the graphs are derived from a series of untested assumptions and have unknown accuracy in depicting habitat suitability for walleye. The model assumes that each model component alone can limit walleye production,

Table 2. Suitability indices for walleye in selected lakes.

Lake number and State	Standing crop fish/net	Standing crop fish/ha	V_1 Secchi transp. Data	V_1 SI	V_3 % cover Data	V_3 SI	V_4 Least suitable pH Data	V_4 SI	V_{12} Spawning habitat index Data	V_{12} SI	V_{13} Water level during spawning Data	V_{13} SI	HSI[a]	HSI'[b] without V_{12} and V_{13}
1 IA	-	38.70	2.9	1.00	50.0	0.90	7.2	1.0	125.5	1.0	2	0.5	0.50	0.98
2 IA	-	2.60	0.5	0.30	5.0	0.35	8.1	1.0	50.0	1.0	1	1.0	0.31	0.31
3 WI	-	63.00	2.7	1.00	15.0	0.70	7.4	1.0	112.5	1.0	1	1.0	0.90	0.90
4 WI	-	1.70	1.5	1.00	6.0	0.40	6.4	1.0	66.0	1.0	1	1.0	0.85	0.85
5 WI	-	12.10	2.7	1.00	7.0	0.40	7.0	1.0	58.0	1.0	1	1.0	0.85	0.85
6 MN	26.69	-	3.8	0.80	50.0	0.90	8.0	1.0	135.0	1.0	1	1.0	0.84	0.84
7 MN	6.37	-	0.9	0.70	15.0	0.70	-	-	17.5	0.4	1	1.0	0.40	0.70
8 MN	0.00	-	7.5	0.30	3.0	0.30	-	-	105.5	1.0	1	1.0	0.30	0.30
9 MN	15.00	-	2.7	1.00	61.0	0.50	-	-	50.5	1.0	2	0.5	0.50	0.87
10 MN	0.00	-	1.1	0.85	15.0	0.70	-	-	110.0	1.0	1	1.0	0.81	0.81

[a] HSI = Lowest of cover component (as defined in text using V_1 and V_3), V_4, V_{12}, or V_{13}.

[b] HSI' = Lowest of cover component (as defined in text using V_1 and V_3) or V_4.

[c] Fry stocked.

[d] Value estimated based on pH of similar lakes.

but this has not been tested. A major weakness of the models is that, while model variables may be necessary to determine the suitability of habitat for walleye, they may not be sufficient. Therefore, high HSI's may be associated with low or zero standing crops, as well as high standing crops. It should be remembered that lakes unsuitable for walleye reproduction may support a walleye fishery through supplemental stocking with fry.

Model outputs should be interpreted as indicators (or predictors) of excellent (0.8 to 1.0), good (0.5 to 0.7), fair (0.2 to 0.4), or poor (0.0 to 0.1) habitat for walleye. The output of the models provided should be most useful in comparing different habitats. If two study areas have different HSI's, the one with the higher HSI is expected to have the potential to support a larger walleye population. The models also provide the basic framework for incorporating new model hypotheses or other site-specific factors that affect habitat suitability for walleye. Users should recognize that carrying capacity is a concept not a measurable response for which one can build a falsifiable predictive model. Users conducting impact assessments requiring major model improvements and testing should concentrate on building a falsifiable model. The model should use a clearly documented chain of logic to predict a measurable response (e.g., growth) that is acceptable for judging a selected impact.

ADDITIONAL HABITAT MODELS

Model 1

Where water quality is not limiting, optimum riverine habitat for walleye is characterized by the following conditions: moderate-to-large river size; cool temperatures (average summer temperature from 20 to 24° C; winter temperatures < 10° C); mesotrophic conditions; high abundance of rocky shoal and shoreline areas for spawning; and high abundance of small forage fishes:

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

Model 2

Where water quality is not limiting, optimum lacustrine habitat for walleye is characterized by the following conditions: moderate-to-large lake size (> 100 ha); cool temperatures (as in Model 1 above); mesotrophic conditions; abundance of rocky shoal and shoreline areas for spawning; and high abundance of small forage fishes:

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

Model 3

Aggus and Morais (1979) and Aggus and Bivin (1982) developed regression equations relating walleye standing crop or harvest in reservoirs to easily measured environmental variables. These authors discuss procedures for using the equations, as well as limitations of the models.

Model 4

Prentice and Clark (1978) presented a walleye population dynamics model (WALLEYE) for predicting walleye stocking success based on reservoir habitat conditions and predator abundance. The model was developed from data on 17 Texas reservoirs. Model simulations showed good agreement with actual walleye population abundance data. WALLEYE can provide information on potential success of walleye introductions and evaluate the need for, and success of, habitat improvements.

INSTREAM FLOW INCREMENTAL METHODOLOGY (IFIM)

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

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

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

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

Suitability Index Graphs as Used in IFIM

PHABSIM utilizes Suitability Index graphs (SI curves) that describe the instream suitability of the habitat variables most closely related to stream hydraulics and channel structure (velocity, depth, substrate, temperature, and cover) for each major life stage (spawning, egg incubation, fry, juvenile, and adult) of a given fish species. The specific curves required for a PHABSIM analysis represent the hydraulic-related parameters for which a species or life stage demonstrates a strong preference (i.e., a pelagic species that only shows preferences for velocity and temperature will have very broad curves for depth, substrate, and cover). Instream Flow Information Papers 11 (Milhous et al. 1981) and 12 (Bovee 1982) should be reviewed carefully before using any curves for a PHABSIM analysis. SI curves used with the IFIM that are generated from empirical microhabitat data are quite similar in appearance to the more generalized literature-based SI curves developed in many HSI models (Armour et al. 1983). These two types of SI curves are interchangeable, in some cases, after conversion to the same units of measurement (English, metric, or codes).

SI curve validity is dependent on the quality and quantity of information used to generate the curve. The curves used need to accurately reflect the conditions and assumptions inherent to the model(s) used to aggregate the curve-generated SI's into a measure of habitat suitability. If the necessary curves are unavailable or if available curves are inadequate (i.e., built on different assumptions), a new set of curves should be generated (data collection and analyses techniques for curve generation will be included in a forthcoming Instream Flow Information Paper).

There are several ways to develop SI curves. The method selected depends on the habitat model that will be used and the available database for the species. The validity of the curve is not obvious and, therefore, the method by which the curve is generated and the quality of the database are very important. Care also must be taken to choose the habitat model most appropriate for the specific study or evaluation; the choice of models determines the type of SI curves that will be used. For example, in an HSI model, a SI curve for velocity usually reflects suitability of average channel (stream) velocity (i.e., a macrohabitat descriptor); in an IFIM analysis, SI curves for velocity are assumed to represent suitability of the velocity at the point in the stream occupied by a fish (i.e., a microhabitat descriptor) (Armour et al. 1983).

A system with standard terminology has been developed for classifying SI curve sets and describing the database used to construct the curves in IFIM applications. The classification is not intended to define the quality of the data or the accuracy of the curves. There are four categories in the classification. A literature-based (category one) curve is a generalized description or summary of habitat preferences based data found in the literature. This type of curve usually is based on information in published references on the upper and lower limits of a variable for a species (e.g., juveniles are usually found at water depths of 0.3 to 1.0 m). Unpublished data and expert opinion also can be used to develop these curves. Occasionally, the reference also contains information on the optimum or preferred condition within the limits of tolerance (e.g., juveniles are found at water depths of 0.3 to 1.0 m, but are most common at depths from 0.4 to 0.6 m). Virtually all of the SI curves published in the HSI series for depth, velocity, and substrate, are category one curves.

Utilization curves (category two) are based on a frequency analysis of fish observations in the stream environment with the habitat variables measured at each sighting [see Instream Flow Information Paper 3 (Bovee and Cochnauer 1977) and Instream Flow Information Paper 12 (Bovee 1982:173-196)]. These curves are designated as utilization curves because they depict the habitat conditions a fish will use within a specific range of available conditions. Because of the way the data are collected for utilization curves, the resulting function represents the probability of occurrence of a particular environmental condition, given the presence of a fish of a particular species, $P(E|F)$. Utilization curves are generally more precise for IFIM applications than literature-based curves because they are based on specific measurements of habitat characteristics where the fish actually occur. However, utilization curves may not be transferable to streams that differ substantially in size and complexity from the streams where the data were obtained.

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

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

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

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

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

Availability of Graphs for Use in IFIM

Table 3 lists the SI curves available for an IFIM analysis of walleye habitat. All curves should be reviewed before use to determine applicability.

Category two SI curves for adult velocity and substrate (Fig. 3), juvenile velocity, depth, and substrate (Fig. 4), and fry velocity, depth, and substrate (Fig. 5) were generated as a result of frequency analyses of raw data collected

Table 3. Availability of curves for an IFIM analysis of walleye habitat.

	Velocity	Depth	Substrate[a]	Temperature[b]	Cover[b]
Spawning	Use SI curve, Fig. 6.	Use SI curve, Fig. 6.	Use SI curve, Fig. 6.	Use SI curve for V_{10}.	No curve available.
Egg incubation	Use SI curve, Fig. 6.	Use SI curve, Fig. 6.	Use SI curve, Fig. 6.	Use SI curve for V_{10}.	No curve available.
Fry	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Use SI curve, Fig. 5.	Use SI = 1.0 for 12-29° C (see text, page 9).[c]	Use SI curve for V_3.
Juvenile	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve, Fig. 4.	Use SI curve for V_3.
Adult	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	Use SI curve, Fig. 3.	Use SI curve for V_3.

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

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

[b]When use of SI curves is prescribed, refer to the appropriate curve in the HSI model section.

[c]Use SI = 1.0 if the habitat variable is optimal; if the habitat variable is less than optimal, the user must determine, by judgement, the most appropriate SI.

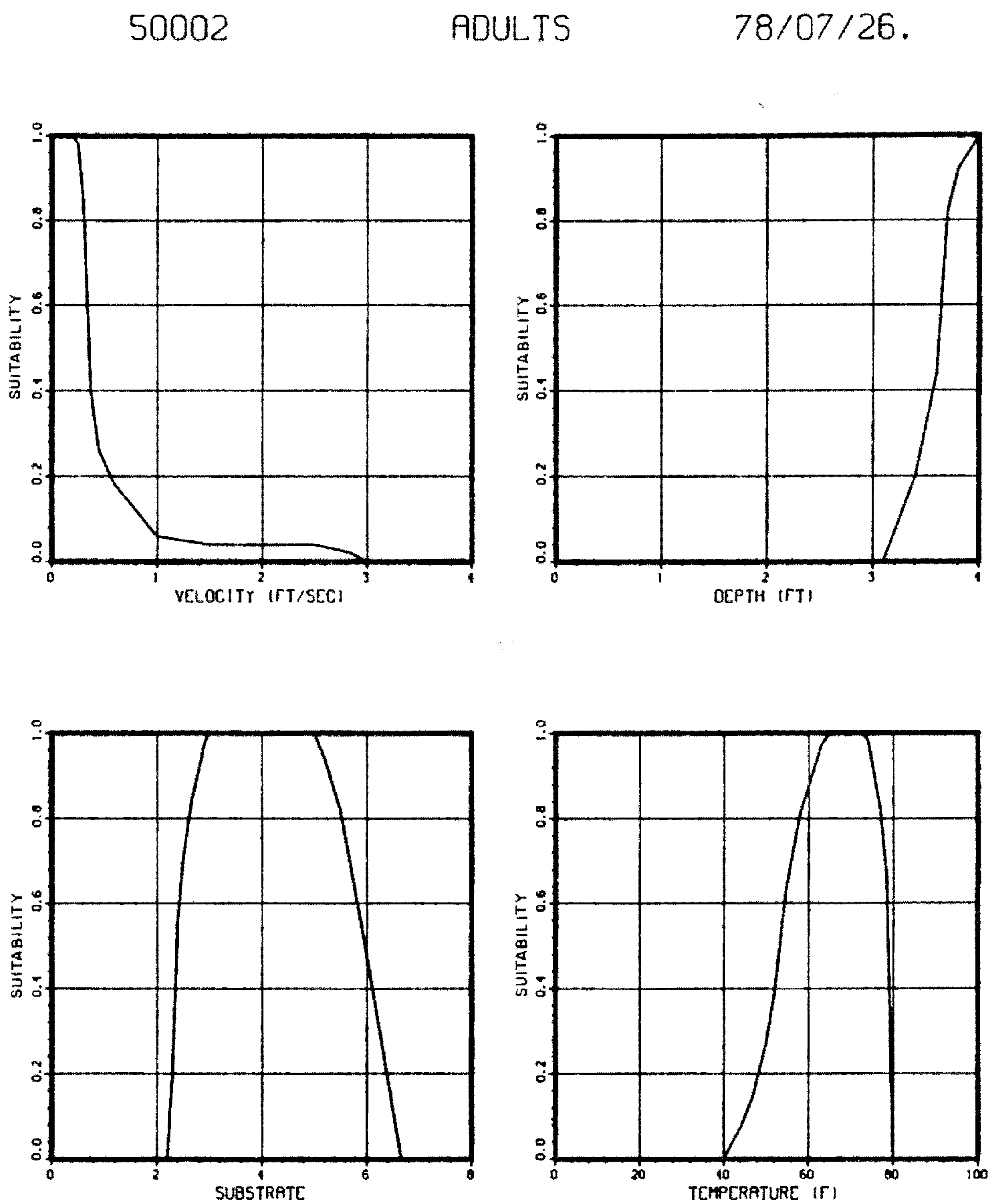


Figure 3. SI curves for adult walleye habitat (Kallemeyn and Novotny unpubl. data; Coutant 1977).

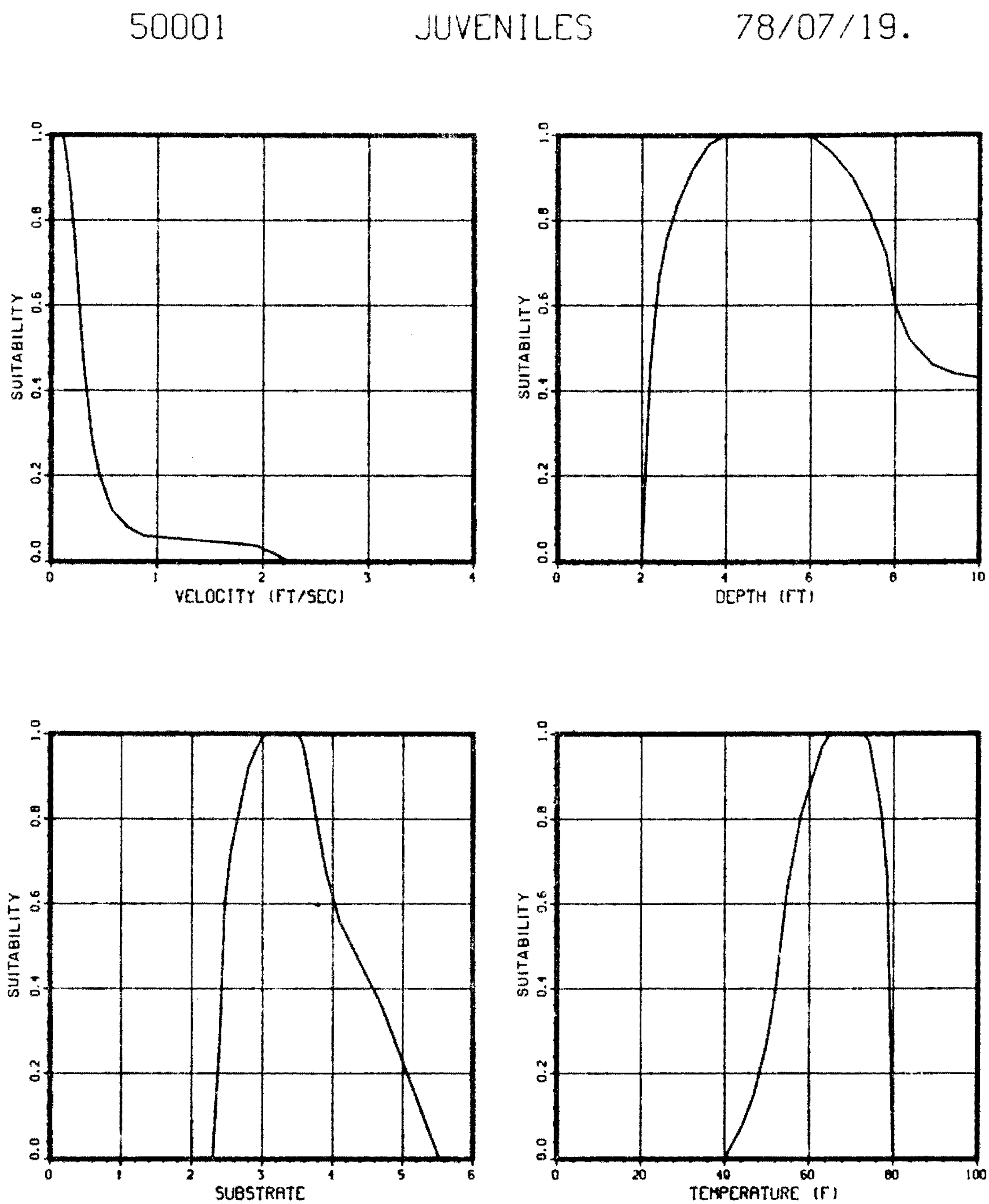


Figure 4. SI curves for juvenile walleye habitat (Kallemeyn and Novotny unpubl. data; Coutant 1977).

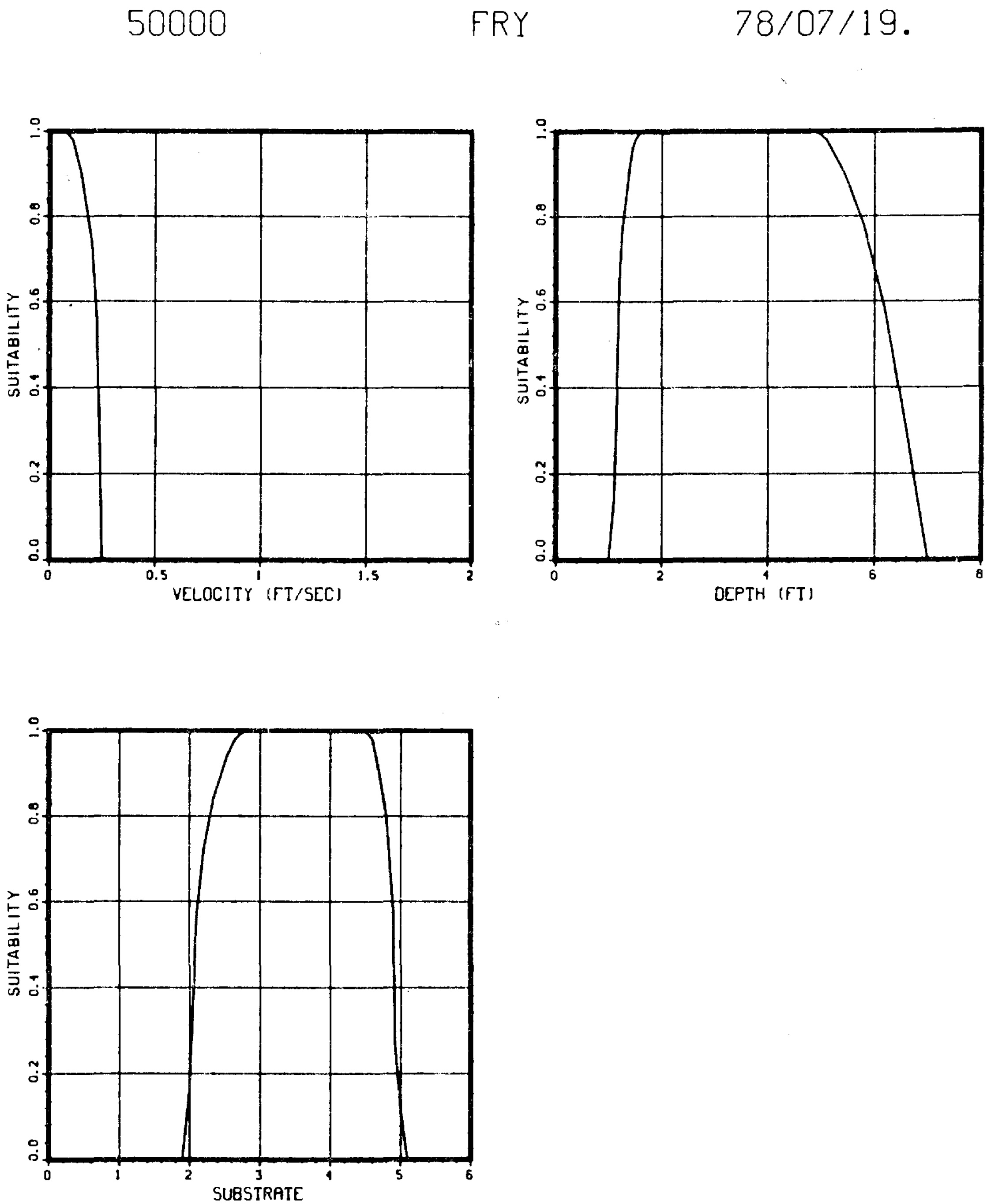


Figure 5. Category two SI curves for walleye fry habitat (Kallemeyn and Novotny unpubl. data).

by Kallemeyn and Novotny (unpubl. data). Kallemeyn and Novotny sampled the Missouri River at each of four stations for 4 days every 4 weeks from 29 March to 4 November 1976. Three stations were on unchannelized sections of river located on the South Dakota/Nebraska border, one below the Fort Rendall Dam and two below the Gavins Point Dam. The fourth station was on a channelized section of river on the Iowa/Nebraska border below Sioux City. Sampling gear included gill nets, trammel nets, hoop nets, seines, a drop trap, an electroshocker, and plankton nets. A total of 20 fry, 48 juveniles, and 41 adult walleye were collected and the data used in frequency analyses.

Habitat types identified in the unchannelized sections of the Missouri River included main channel, main channel border, sandbar, chute, backwater, pool, and marsh; those in channelized sections of the river included main channel, spur dike, notched spur dike, notched wing dike, revetment, and notched revetment. During the study, channel widths ranged from 300 to 1,500 m ($\bar{x}$ = 640 to 760 m), depths ranged from 0.0 to 8.0 m ($\bar{x}$ < 2.0 m), daily mean discharges ranged from 872 to 1,104 m^3/sec ($\bar{x}$ ~ 1,105 m^3/sec), surface velocities ranged from 0.0 to 2.1 m/sec, the gradient was approximately 0.2 m/km, surface water temperatures ranged from 3.5 to 27.5° C, turbidity ranged from 2.3 to 33.0 JTU's, and conductivity ranged from 550 to 780 µmhos/ cm. The substrate consisted primarily of sand, but silt was dominant in backwater and marsh areas.

The category two SI curve for spawning velocity (Fig. 6) was generated from a frequency analysis of raw data (Graham unpubl. data) collected from below the intake diversion (river mile 71.1) on the Yellowstone River in Montana from 18 April to 6 May 1977. A total of 230 eggs were collected at night from four transects located on a 3/4 mile gravel bar. Collections were made using a 20-inch square net for kick sampling. During the study, flows ranged from 5,900 to 10,600 CFS, velocities sampled ranged from 0.7 to 3.9 fps, depths sampled ranged from 1 to 3 ft, substrate observed was predominantly gravel and cobble with some sand, and temperatures ranged from 52 to 53° F.

The category two SI curve for spawning depth (Fig. 6) was derived from frequency analyses of the raw data collected by Graham (unpubl. data) and the data collected by Kallemeyn and Novotny (unpubl. data). The SI curve for spawning substrate (Fig. 6) is a category one curve and was generated as a result of information obtained from Graham's unpublished data and articles published by Kallemeyn and Novotny (1977), and Newburg (1975). The category one curve for adult temperature preferences (Fig. 2) was derived from information in a publication by Coutant (1977); the assumption was made that juvenile walleye prefer the same temperatures as adults.

The SI curve for adult walleye depth utilization (Fig. 2) was generated from a frequency analysis of the data collected by Kallemeyn and Novotny (unpubl. data) and data collected by Russell (unpubl. data). Russell used scuba diving to observe walleye adults in 36 pools within 39 mi of the Current River, between Van Buren and Doniphan in Carter and Ripley counties of Missouri, during 6 days in 1970 and 1971. Approximately 613 walleye were observed, weighing from 1 to 10 lbs. Pool lengths ranged from 75 to 450 ft,

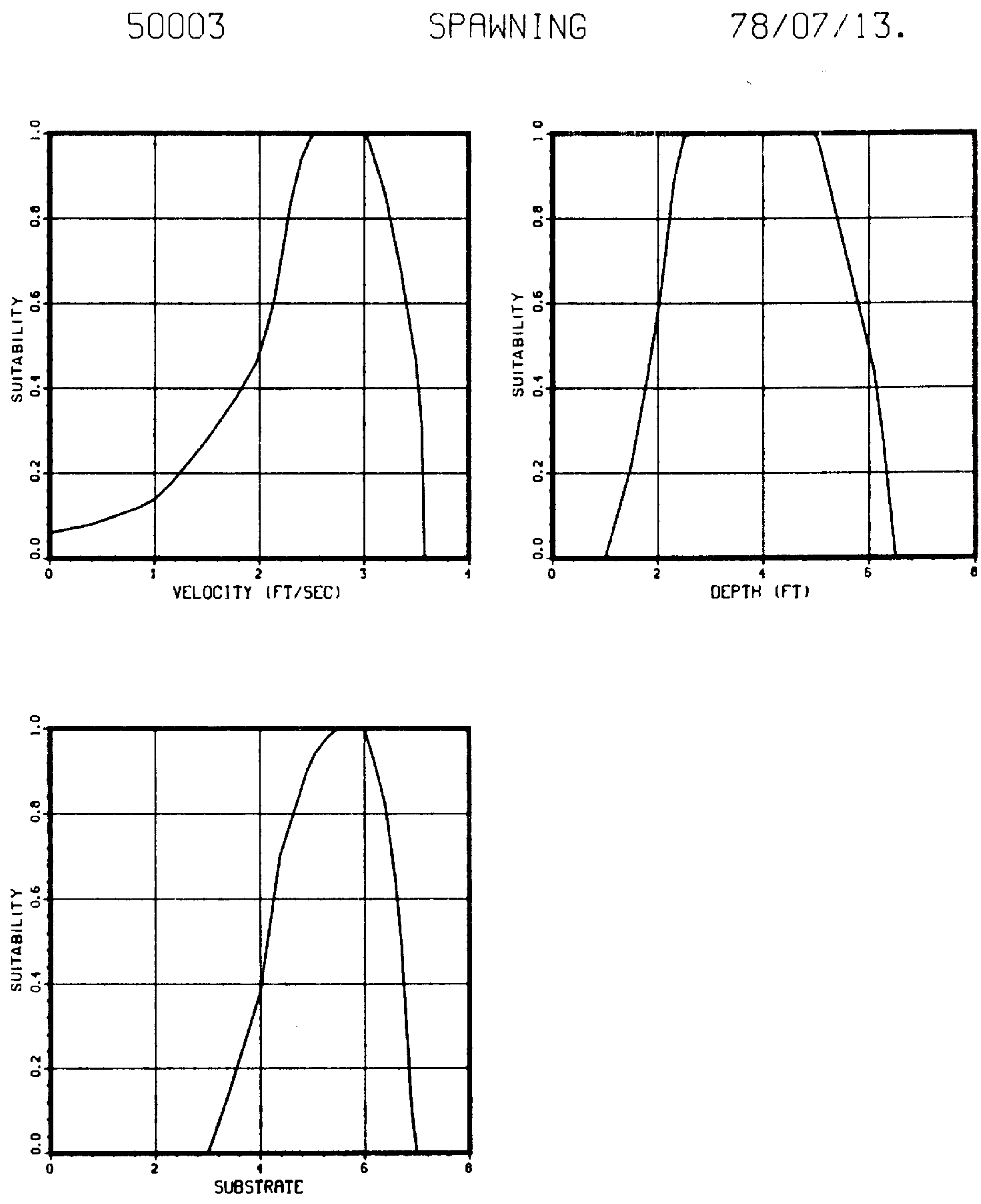


Figure 6. SI curves for walleye spawning habitat (Graham unpubl. data; Kallemeyn and Novotny unpubl. data; Kallemeyn and Novotny 1977; Newburg 1975).

and maximum pool depths ranged from 8 to 18 ft. Walleye congregated in pools during the day and moved into the shallows to feed at night in these sample areas. Therefore, users of the SI curve for adult depth utilization should be aware that the curve represents daytime resting habitat.

REFERENCES

Aggus, L. R., and D. I. Morais. 1979. Habitat suitability index equations for reservoirs based on standing crop of fish. Natl. Reservoir Res. Prog. Rep. to U.S. Fish Wildl. Serv. 120 pp.

Aggus, L. R., and W. M. Bivin. 1982. Habitat suitability index models: Regression models based on harvest of coolwater and coldwater fishes in reservoirs. U.S. Fish Wildl. Serv. FWS/OBS-82/10.25. 38 pp.

Ali, M. A., R. A. Ryder, and M. Anctil. 1977. Photoreceptors and visual pigments as related to behavioral responses and preferred habitats of perches (Perca spp.) and pikeperches (Stizostedion spp.). J. Fish. Res. Board Can. 34(10):1475-1480.

Anthony, D. D., and C. R. Jorgensen. 1977. Factors in the declining contributions of walleye (Stizostedion vitreum vitreum) to the fishery of Lake Nipissing, Ontario 1960-76. J. Fish. Res. Board Can. 34(10):1703-1709.

Armour, C. L., R. J. Fisher, and J. W. Terrell. 1983. Comparison and recommendations for use of Habitat Evaluation Procedures (HEP) and the Instream Flow Incremental Methodology (IFIM) for aquatic analyses. Draft rep. U.S. Fish Wildl. Serv., Western Energy and Land Use Team, Fort Collins, CO. 42 pp.

Balon, E. K., W. T. Momot, and H. A. Regier. 1977. Reproductive guilds of percids: results of the paleogeographical history and ecological succession. J. Fish. Res. Board Can. 34(10):1910-1921.

Benson, N. G. 1968. Review of fishery studies on Missouri main stem reservoirs. U.S. Fish Wildl. Serv. Res. Rep. 71. 61 pp.

Bovee, K. D. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12. U.S. Fish Wildl. Serv. FWS/OBS-82/26. 248 pp.

Bovee, K. D., and T. Cochnauer. 1977. Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments: fisheries. Instream Flow Information Paper 3. U.S. Fish Wildl. Serv. FWS/OBS-77/63. 39 pp.

Bulkley, R. V., V. L. Spykermann, and L. E. Inmon. 1976. Food of the pelagic young of walleyes and five cohabiting fish species in Clear Lake, Iowa. Trans. Am. Fish. Soc. 105(1):77-83.

Busch, W. D. N., R. L. Scholl, and W. L. Hartman. 1975. Environmental factors affecting the strength of walleye (Stizostedion vitreum vitreum) year-classes in western Lake Erie 1960-70. J. Fish. Res. Board Can. 32(10):1733-1743.

Carlander, K. D. 1977. Biomass, production, and yields of walleye (Stizostedion vitreum vitreum) and yellow perch (Perca flavescens) in North American lakes. J. Fish. Res. Board Can. 34(10):1602-1612.

Carlander, K. D., and P. M. Payne. 1977. Year-class abundance, population, and production of walleye (Stizostedion vitreum vitreum) in Clear Lake, Iowa, 1948-74, with varied fry stocking rates. J. Fish. Res. Board Can. 34(10):1792-1799.

Chevalier, J. R. 1973. Cannibalism as a factor in the first year survival of walleye in Oneida Lake. Trans. Am. Fish. Soc. 102(4):739-744.

______________. 1977. Changes in walleye (Stizostedion vitreum vitreum) population in Rainy Lake and factors in abundance 1924-75. J. Fish. Res. Board Can. 34(10):1696-1702.

Clugston, J. P., J. L. Oliver, and P. Ruelle. 1978. Reproduction, growth, and standing crops of yellow perch in southern reservoirs. Pages 89-99 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11. 437 pp.

Colby, P. J., and L. L. Smith, Jr. 1967. Survival of walleye eggs and fry on paper fiber sludge deposits in Rainy River, Minnesota. Trans. Am. Fish. Soc. 96(3):278-296.

Colby, P. J., R. E. McNicol, and R. A. Ryder. 1979. Synopsis of biological data on the walleye Stizostedion v. vitreum (Mitchill 1818). Contribution 77-13, Ontario Ministry Nat. Resources, Fish. Res. Sect. Food and Agriculture Organization of the United Nations. 123 pp.

Coutant, C. C. 1977. Compilation of temperature preference data. J. Fish. Res. Board Can. 34(5):739-746.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish Wildl. Serv. FWS/OBS-79/31. 103 pp.

Davis, J. C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Board Can. 32:2295-2332.

Dendy, J. S. 1948. Predicting depth distribution of fish in three TVA storage-type reservoirs. Trans. Am. Fish. Soc. 75(1945):65-71.

Elsey, C. A., and R. T. Thomson. 1977. Exploitation of walleye (Stizostedion vitreum vitreum) in Lac Des Mille Lacs, Northern Ontario, by commercial and sport fisheries 1958-1975. J. Fish. Res. Board Can. 34(10):1769-1773.

Eschmeyer, P. H. 1950. The life history of the walleye, (Stizostedion vitreum vitreum), Mitchell, in Michigan. Mich. Dept. Conserv., Inst. Fish. Res. Bull. 3. 99 pp.

Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Board Can. 15(4):607-624.

Fitz, R., B., and J. A. Holbrook,II. 1978. Sauger and walleye in Norris Reservoir, Tennessee. Pages 11-82 in R. L. Kendall (ed.) Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

Forney, J. L. 1966. Factors affecting first-year growth of walleyes in Oneida Lake, New York. New York Fish and Game J. 13(2):146-147.

___________. 1974. Interactions between yellow perch abundance, walleye predation, and survival of alternate prey in Oneida Lake, New York. Trans. Am. Fish. Soc. 103(1):15-24.

___________. 1977. Evidence of inter- and intraspecific competition as factors regulating walleye (Stizostedion vitreum vitreum) biomass in Oneida Lake, New York. J. Fish. Res. Board Can. 34(10):1812-1820.

Graham, P. Unpublished field data collected below the intake diversion (river mile 71.1) on the Yellowstone River in Montana, from 18 April to 6 May 1977. Montana Dept. Fish Game, Miles City, MT.

Groen, C. L., and T. A. Schroeder. 1978. Effects of water level management on walleye and other coolwater fishes in Kansas reservoirs. Pages 278-283 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

Hackney, P. A., and J. A. Holbrook, II. 1978. Sauger, walleye, and perch in the southeastern United States. Pages 82-83 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

Hokanson, K. E. F. 1977. Temperature requirements of some percids and adaptations to the seasonal temperature cycle. J. Fish. Res. Board Can. 34(10):1524-1550.

Houde, E. D. 1969. Sustained swimming ability of larvae of walleye (Stizostedion vitreum vitreum) and yellow perch (Perca flavescens). J. Fish. Res. Board Can. 26(6):1647-1659.

Huh, H. T., H. E. Calbert, and D. A. Stuiber. 1976. Effects of temperature and light on growth of yellow perch and walleye using formulated feed. Trans. Am. Fish. Soc. 105(2):254-258.

Jester, D. B. 1971. Effects of commercial fishing, species introductions, and drawdown control on fish populations in Elephant Butte Reservoir, New Mexico. Pages 265-285 in G. E. Hall (ed.). Reservoir fisheries and limnology. Am. Fish. Soc. Spec. Publ. 8.

Johnson, B. 1983. Personal communication. Univ. Wisconsin, Cent. Limnology, Madison.

Johnson, F. H. 1961. Walleye egg survival during incubation on several types of bottom in Lake Winnibigoshish, Minnesota, and connecting waters. Trans. Am. Fish. Soc. 90(3):312-322.

Johnson, F. H., and J. G. Hale. 1977. Interrelations between walleye (Stizostedion vitreum vitreum) and smallmouth bass (Micropterus dolomieui) in four northeastern Minnesota Lakes, 1948-69. J. Fish. Res. Board Can. 34(10):1626-1632.

Johnson, M. G., J. H. Leach, C. K. Minns, and C. H. Olver. 1977. Limnological characteristics of Ontario Lakes in relation to associations of walleye (Stizostedion vitreum vitreum), northern pike (Esox lucius), lake trout (Salvelinus namaycush), and smallmouth bass (Micropterus dolomieui). J. Fish. Board Can. 34(10):1592-1601.

Jones, D. R., J. W. Kiceniuk, and O. S. Bamford. 1974. Evaluation of the swimming performance of several fish species from the MacKenzie River. J. Fish. Res. Board Can. 31(10):1641-1647.

Kallemeyn, L. W., and J. F. Novotny. 1977. Fish and fish food organisms in various habitats of the Missouri River in South Dakota, Nebraska, and Iowa. U.S. Fish Wildl. Serv. FWS/OBS-77/25. 100 pp.

Kallemeyn, L. W., and J. F. Novotny. Unpublished field data collected from four stations on the Missouri River in South Dakota, Nebraska, and Iowa from 29 March to 4 November 1976. N. Central Reservoir Invest. Yankton, SD.

Kelso, J. R. M. 1972. Conversion, maintenance, and assimilation for walleye (Stizostedion vitreum vitreum), as affected by size, diet, and temperature. J. Fish. Res. Board Can. 29(8):1181-1192.

Kelso, J. R. M., and F. J. Ward. 1977. Unexploited percid populations of West Blue Lake, Manitoba, and their interactions. J. Fish. Res. Board. Can. 34(10):1655-1669.

Kempinger, J. J., and R. F. Carline. 1977. Dynamics of the walleye (Stizostedion vitreum vitreum) population in Escanaba Lake, Wisconsin 1955-72. J. Fish. Res. Board Can. 34(10):1800-1811.

Kendall, R. L. (ed.). 1978. Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11. 437 pp.

Kitchell, J. F., M. G. Johnson, C. K. Minns, K. H. Loftus, L. Grieg, and C. H. Olver. 1977. Percid habitat: the river analogy. J. Fish. Res. Board Can. 34(10):1936-1940.

Koenst, W. M., and L. L. Smith, Jr. 1976. Thermal requirements of the early life history of walleye (Stizostedion vitreum vitreum) and sauger (Stizostedion canadense). J. Fish. Res. Board Can. 33(5):1130-1136.

Leach, J. H., M. G. Johnson, J. R. M. Kelso, J. Hartmann, W. Numann, and B. Entz. 1977. Responses of percid fishes and their habitats to eutrophication. J. Fish. Res. Board Can. 34(10):1964-1971.

Lyons, J. 1983. Personal communication. Univ. Wisconsin. Cent. Limnology, Madison.

McKee, J. E., and H. W. Wolf. 1963. Water quality criteria. State Water Quality Control Board. Sacramento, CA. Publ. 3A. 548 pp.

Nickum, J. G. 1983. Personal communication. Leader, Iowa Cooperative Fishery Research Unit, Ames.

Milhous, R. T., D. L. Wegner, and T. Waddle. 1981. User's guide to the Physical Habitat Simulation System. Instream Flow Information Paper 11. U.S. Fish Wildl. Serv. FWS/OBS-81/43. 273 pp.

Miller, L. W. 1967. The introduction, growth, diet, and depth distribution of walleye, Stizostedion vitreum (Mitchill), in El Capitan Reservoir, San Diego County. Calif. Res. Agency, Dept. Fish Game, Inland Fish. Br., Admin. Rep. 67-10. 13 pp.

Momot, W. T. 1983. Personal communication. Dept. Biol., Lakehead Univ., Thunder Bay, Ontario.

Momot, W. T., J. Erickson, and F. Stevenson. 1977. Maintenance of a walleye, (Stizostedion vitreum vitreum) fishery in a eutrophic reservoir. J. Fish. Res. Board Can. 34(10):1725-1733.

Moyle, J. B., and W. D. Clothier. 1959. Effects of management and winter oxygen levels on the fish population of a prairie lake. Trans. Am. Fish. Soc. 88(3):178-185.

Nelson, W. R., and C. H. Walburg. 1977. Population dynamics of yellow perch (Perca flavescens), sauger (Stizostedion canadense) and walleye (S. vitreum vitreum) in four main stem Missouri River reservoirs. J. Fish. Res. Board Can. 34(10):1748-1763.

Newburg, H. J. 1975. Evaluation of an improved walleye (Stizostedion vitreum) spawning shoal with criteria for design and placement. Minn. Dept. Nat. Res. Invest. Rep. 340. 39 pp.

Ney, J. J. 1978. A synoptic review of yellow perch and walleye biology. Pages 1-12 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

Oseid, D. M., and L. L. Smith, Jr. 1971. Survival and hatching of walleye eggs at various dissolved oxygen levels. Prog. Fish-Cult. 33(2):81-85.

Pfitzer, D. W. 1967. Evaluations of tailwater fishery resources resulting from high dams. Pages 477-488 in Reservoir fishery resources symposium. Am. Fish. Soc. Publ., Univ. Georgia, Athens.

Prentice, J. A., and R. D. Clark, Jr. 1978. Walleye fishery management in Texas - a systems approach. Pages 408-416 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

Priegel, G. R. 1963. Food of walleye and sauger in Lake Winnebago, Wisconsin. Trans. Am. Fish. Soc. 92(3):312-313.

__________. 1970. Reproduction and early life history of the walleye in the Lake Winnebago region. Wisconsin Conserv. Dept. Tech. Bull. 45. 105 pp.

Regier, H. A., J. C. Applegate, and R. A. Ryder. 1969. The ecology and management of the walleye in western Lake Erie. Great Lakes Fish Comm. Tech. Rep. 15. 101 pp.

Russell, T. R. Unpublished field data collected from the Current River between Van Buren and Doniphan, Missouri, in 1970 and 1971. State of Missouri Project F-1-R-21, Study S-10, Job 2.

Ryder, R. A. 1968. Dynamics and exploitation of mature walleye, Stizostedion vitreum vitreum, in the Nipigon Bay region of Lake Superior. J. Fish. Res. Board Can. 25(7):1347-1376.

__________. 1977. Effects of ambient light variations on behavior of yearling, subadult, and adult walleyes (Stizostedion vitreum vitreum). J. Fish. Res. Board Can. 34(10):1481-1491.

Ryder, R. A., and S. R. Kerr. 1978. The adult walleye (Stizostedion v. vitreum) in the percid community - a niche definition based on feeding behavior and food specificity. Pages 39-51 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

Ryder, R. A., S. R. Kerr, K. H. Loftus, and H. A. Regier. 1974. The morphoedaphic index, a fish yield estimator - review and evaluation. J. Fish. Res. Board Can. 31:663-688.

Scherer, E. 1971. Effects of oxygen depletion and of carbon dioxide buildup on the photic behaviour of the walleye (Stizostedion vitreum vitreum). J. Fish. Res. Board Can. 28:1303-1307.

Schupp, D. H. 1978. Walleye abundance, growth, movement, and yield in disparate environments within a Minnesota lake. Pages 58-65 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish Soc. Spec. Publ. 11.

Scott, W. B., and E. J. Crossman. 1973. Freshwater Fishes of Canada. Fish. Res. Board of Canada, Ottawa. Bull. 184. 966 pp.

Siefert, R. E., and W. A. Spoor. 1974. Effects of reduced oxygen on embryos and larvae of the white sucker, coho salmon, brook trout, and walleye. Pages 487-495 in J. H. S. Blaxter (ed.). The early life history of fish. Springer-Verlag, New York.

Smith, L. L., Jr., and W. M. Koenst. 1975. Temperature effects on eggs and fry of percoid fishes. U.S. Environ. Protection Agency. Ecol. Res. Ser. EPA-660/3-75-017. 91 pp.

Spangler, G. R., N. R. Payne, G. K. Winterton. 1977. Percids in the Canadian waters of Lake Huron. J. Fish. Res. Board Can. 34(10):1839-1848.

Swenson, W. A. 1977. Food consumption of walleye (Stizostedion vitreum vitreum) and sauger (S. canadense) in relation to food availability and physical conditions in Lake of the Woods, Minnesota, Shagawa Lake, and western Lake Superior. J. Fish. Res. Board Can. 34(10):1643-1654.

Swenson, W. A., and L. L. Smith, Jr. 1976. Influence of food, competition, predation, and cannibalism in walleye (Stizostedion vitreum vitreum). J. Fish. Res. Board Can. 30(9):1327-1336.

Wagner, W. C. 1972. Utilization of alewives by inshore piscivorous fishes in Lake Michigan. Trans. Am. Fish. Soc. 101(1):55-63.

Walburg, C. H. 1971. Loss of young fish in reservoir discharge and year-class survival, Lewis and Clark Lake, Missouri River. Pages 441-448 in G. E. Hall (ed.). Reservoir fisheries and limnology. Am. Fish. Soc. Spec. Publ. 8.

Wrenn, W. B., and T. D. Forsythe. 1978. Effects of temperature on production and yield of juvenile walleyes in experimental ecosystems. Pages 66-73 in R. L. Kendall (ed.). Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

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16. Abstract (Limit: 200 words)

The habitat suitability index (HSI) models presented in this publication aid in identifying important habitat variables for the walleye (Stizostedion vitreum vitreum). Information obtained from the research literature and expert reviews are synthesized into models which present hypotheses of species - habitat relationships.

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

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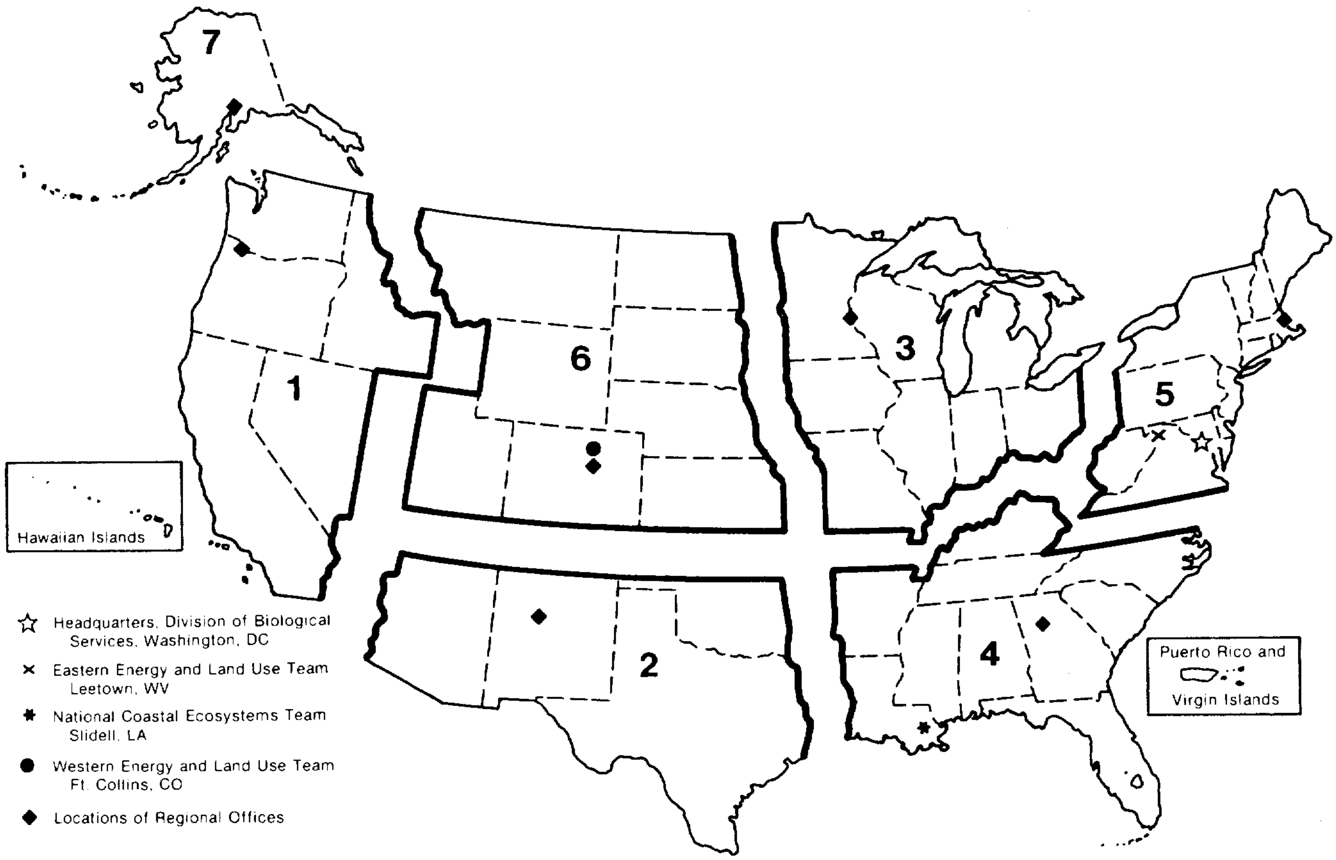

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