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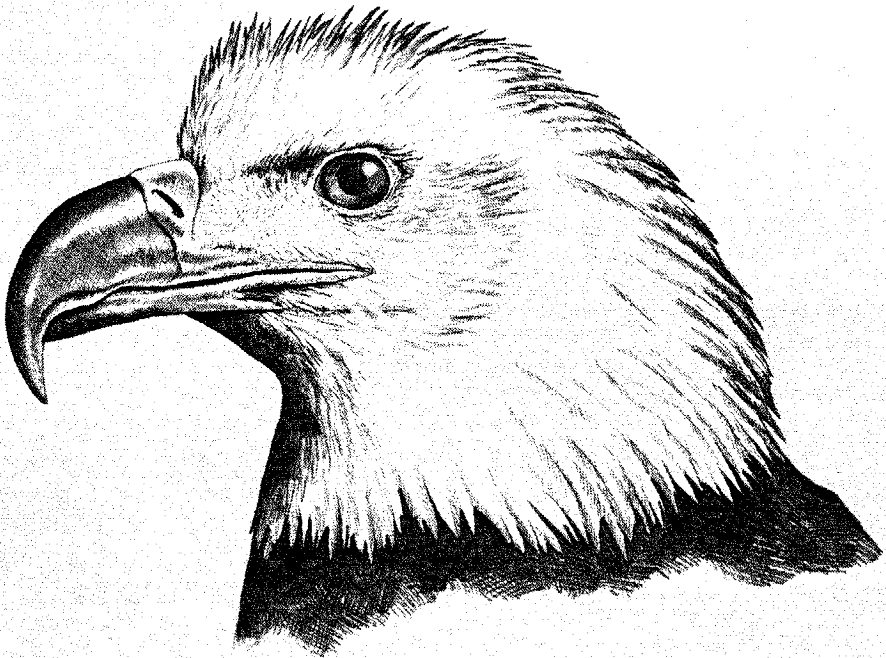

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HABITAT SUITABILITY INDEX MODELS: BALD EAGLE (BREEDING SEASON)

by

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PREFACE

This model was developed by the author as a result of his interest in, and experience with, the bald eagle. The U.S. Fish and Wildlife Service provided quality control, content reviews, and publication costs, but the fact that the model was completed is due primarily to the persistence and interest of the author.

This document is part of the Habitat Suitability Index (HSI) Model Series [Biological Report 82(10)], which provides habitat information useful for impact assessment and habitat management. Several types of habitat information are provided. The Habitat Use Information section is largely constrained to those data that can be used to derive quantitative relationships between key environmental variables and habitat suitability. This information provides the foundation for the HSI model and may be useful in the development of other models more appropriate to specific assessment or evaluation needs.

The HSI Model section documents the habitat model and includes information pertinent to its application. The model synthesizes the habitat use information into a framework appropriate for field application and is scaled to produce an index value between 0.0 (unsuitable habitat) and 1.0 (optimum habitat). The HSI Model section includes information about the geographic range and seasonal application of the model, its current verification status, and a list of the model variables with recommended measurement techniques for each variable.

The model is a formalized synthesis of biological and habitat information published in the scientific literature and may include unpublished information reflecting the opinions of identified experts. Habitat information about wildlife species frequently is represented by scattered data sets collected during different seasons and years and from different sites throughout the range of a species. The model presents this broad data base in a formal, logical, and simplified manner. The assumptions necessary for organizing and synthesizing the species-habitat information into the model are discussed. The model should be regarded as a hypothesis of species-habitat relationships and not as a statement of proven cause and effect relationships. The model may have merit in planning wildlife habitat research studies about a species, as well as in providing an estimate of the relative suitability of habitat for that species. User feedback concerning model improvements and other suggestions that may increase the utility and effectiveness of this habitat-based approach to fish and wildlife planning are encouraged. Please send suggestions to:

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CONTENTS

ACKNOWLEDGMENTS

Earlier drafts of this model were reviewed and commented on by Denis Case (Ohio Department of Natural Resources, Columbus, OH), Stanley Wiemeyer (U.S. Fish and Wildlife Service, Laurel, MD), and Keith Cline and Brian Millsap (Raptor Information Center, Washington, DC). They also provided additional data and literature on the bald eagle. Many people provided literature and unpublished data on different populations of the bald eagle: Jack Hodges (U.S. Fish and Wildlife Service, Juneau, AK), Mark Jenkins (Pacific Gas and Electric Co., San Ramon, CA), Jim Morash and Gary Strawn (West Virginia Department of Natural Resources, Elkins, WV), Peter Nye (New York State Department of Environmental Conservation, Delmar, NY), Dale Sheffer (Pennsylvania Game Commission, Harrisburg, PA), Gary Taylor (Maryland Wildlife Administration, Wye Mills, MD), Sylvia Taylor (Michigan Department of Natural Resources, Lansing, MI), and W. H. Taylor (Virginia Commission of Game and Inland Fisheries, Richmond, VA).

A later draft of this model was reviewed and commented upon by Dr. Robert Anthony (Oregon Cooperative Wildlife Research Unit, Corvallis, OR), Dr. Daniel James (U.S. Fish and Wildlife Service, Arlington, VA), John Mathisen (U.S. Forest Service, Cass Lake, MN), and Karen Steenhof (Bureau of Land Management, Boise, ID). Dr. Anthony, Mr. Mathisen, and Ms. Steenhof also provided additional literature. Much information on the measurement of lake productivity was provided by Richard A. Ryder (Ontario Ministry of Natural Resources, Thunder Bay, Ontario) and Dr. David Green (Cornell University, Biological Field Station, Bridgeport, NY). The generous and valuable assistance of these people is gratefully acknowledged.

The cover of this document was illustrated by Jennifer Shoemaker. Word processing was provided by Dora Ibarra, Elizabeth Barstow, and Patricia Gillis. Kay Lindgren assisted with literature search and acquisition.

BALD EAGLE (Haliaeetus leucocephalus)

HABITAT USE INFORMATION

General

The bald eagle (Haliaeetus leucocephalus) is a large predatory raptor that occurs "...primarily near seacoasts, rivers and large lakes, breeding in tall trees or on cliffs" (American Ornithologists' Union 1983:106). It is a common breeder throughout southeastern coastal Alaska (Robards and Hodges 1977) and is found in lesser numbers throughout Canada and the United States (DeGraaf et al. 1980). It winters primarily "...from southern Alaska and southern Canada southward" (American Ornithologists' Union 1983:106) near large, ice-free bodies of water (Steenhof 1978). After suffering precipitous declines over much of its range, the bald eagle population has recently exhibited signs of recovery (Hamerstrom et al. 1975; Grier 1982).

Food

The preferred foraging habitats of the bald eagle are rivers, lakes, and estuaries (DeGraaf et al. 1980). Primary feeding areas are large bodies of open water. It is rarely associated with smaller streams or ponds (Leighton et al. 1979). In the Greater Yellowstone Ecosystem, "[a] stable food source, which was available from early spring, appeared to be the most important factor in breeding area selection" (Swenson et al. 1986:5). Swenson et al. (1986:43) further stated that "[d]ifferences in movements, breeding success, nest site selection, and nesting chronology among [the Yellowstone, Continental, and Snake] units were primarily due to differences in the amount and timing of food availability."

The bald eagle consumes a wide range of food items, from pied-billed grebes (Podilymbus podiceps) (Cline and Clark 1981) to bullheads (Ictalurus spp.) (Dunstan and Harper 1975) to sea otter (Enhydra lutris) pups (Sherrod et al. 1975). Bald eagles at Chesapeake Bay have been found to prey upon or take as carrion 45 species of birds, 11 species of mammals, 12 species of fish, and 5 species of turtles (Cline and Clark 1981). Bald eagles in Maine preyed upon or took as carrion at least 34 species of birds, 18 species of fish, 11 species of mammals, and 2 species of invertebrates (Todd et al. 1982). In Oregon, bald eagles fed on 16 species of fish, 46 species of birds, 20 species of mammals, and 2 invertebrate species (Frenzel 1984).

Although the staple of the bald eagle diet is fish (DeGraaf et al. 1980), their prey may be classified into three main types: live fish, live sea or water birds, and carrion. Fish composed 77% of the food item remains collected at bald eagle nests in interior Maine (Todd et al. 1982). Bald eagles nesting on offshore coastal islands fed primarily on seabirds and waterfowl. In northcentral Minnesota, the diet of breeding eagles was 90% fish (Dunstan and Harper 1975). Studies in Ohio showed that nesting bald eagles fed primarily on fish (Herrick 1924). At San Juan Island, Washington, fish composed 51% of the breeding season diet (Retfalvi 1970). Fish were also the most frequent prey of bald eagles in Chesapeake Bay (LeFranc and Cline 1983) and in Oregon (Frenzel 1984). In southeast New York, wintering bald eagles fed almost entirely on dead and dying alewives (Alosa pseudoharengus) that had passed through the turbines of hydroelectric generating stations (Nye and Suring 1978). In contrast, wintering eagles in Missouri fed primarily on dead and crippled Canada geese (Branta canadensis) (Griffin et al. 1982).

Bald eagle prey selection is determined largely by availability. Birds accounted for 68% and 47% of the diet of bald eagles in the Yellowstone and Continental Units, respectively, of the Greater Yellowstone Ecosystem, but fish made up 67% of the diet in the Snake Unit, in response to habitat differences and prey availability (Swenson et al. 1986). In Maine, eagles focused on the chain pickerel (Esox niger) spawning run in April, then on the sucker (Catostomus spp.) spawning run in May (Todd et al. 1982). Bald eagles in Missouri abandoned their primary prey, dead or crippled waterfowl, in favor of fish during years of heavy fish kill (Griffin et al. 1982). In Oregon, bald eagle diets varied both seasonally and geographically (Frenzel 1984). Wintering bald eagles in southeast New York readily fed upon deer (Odocoileus virginianus) carcasses on frozen reservoirs (A. Peterson, N.Y. State Department Environmental Conservation, Albany; unpubl.). In Washington, eagles fed heavily on road-killed animals (Retfalvi 1970).

Bald eagle nesting densities depend, in part, on total prey availability. At Besnard Lake, Saskatchewan, nesting densities were higher in areas of higher lake productivity (Gerrard et al. 1983), and eagle nesting densities in central Saskatchewan were significantly correlated with the commercial fish catch per hectare of surface water (Whitfield and Gerrard 1985). In California, there also appears to be a positive relationship between bald eagle nesting densities and lake or reservoir productivity (Detrich 1985).

Total prey availability is a function not only of foraging habitat productivity but also the size of the foraging habitat (i.e., total available prey = prey biomass/ha x size of foraging habitat). This is exemplified by the bald eagle's preference for large areas of open water for foraging. Bald eagles nesting in marine environs in New Brunswick were more successful than those occupying lake or river sites (Stocek and Pearce 1981). Lake habitats were also clearly preferred over river habitats. At the Pit River hydroelectric complex in California, bald eagles nested exclusively along reservoirs, although riverine habitats were available (BSAI 1985). Leighton et al. (1979) concluded that lakes <11 km in circumference did not constitute primary breeding habitat. Whitfield et al. (1974) concluded that lakes with <11.3 km of shoreline did not provide primary breeding habitat. The surface area of lakes with a circumference of 11 km varies with shoreline configuration, but cannot exceed 9.6 km² (for a circular lake). The smallest body of water reported to support one nesting pair of bald eagles is 8 ha (J. Mathisen, Chippewa National Forest, Cass Lake, MN; pers. comm.). It should be noted that bald eagles nesting on smaller water bodies may require other nearby lakes for additional foraging areas.

Although larger bodies of water appear to provide superior habitat to smaller ones (Whitfield et al. 1974; Leighton et al. 1979; Stoceck and Pearce 1981), increasing surface area beyond the 9.6 km² threshold does not appear to affect habitat suitability. For example, Lake Britton in northern California is a long and narrow reservoir with only 5.2 km² of surface area (BSAI 1985); however, it supports the highest density of nesting bald eagles in that state (if it were not so narrow, i.e., had a larger surface area, the same shoreline length could be more effectively used and might support an even greater density) (BSAI 1985; Detrich 1985). Also, in New York State, historical bald eagle nesting densities along Oneida Lake (207 km²) were at least as great as along the eastern shore of Lake Ontario (>15,000 km²) (Nye and Peterson 1980). Therefore, lakes with surface areas >10 km² (rounded from 9.6) appear to be of optimal size.

Water

No information pertaining to dietary water needs of the bald eagle was found in the literature.

Cover

Wintering bald eagles depend on suitable night and severe weather roosts in sheltered timber stands (Steenhof 1976). Although proximity to food sources is an important attribute (Keister and Anthony 1983), these roosts need not be close to water (Steenhof 1978). Roosts appear to be selected for protection from the wind (Steenhof 1978; Keister et al. 1985). However, the literature does not mention a dependence on cover during the breeding season. Cover requirements during the breeding season are assumed to be identical to reproduction requirements.

Reproduction

Although bald eagles will nest on the ground on isolated, treeless islands (Troyer and Hensel 1965) and occasionally on cliffs (Bull 1974; Brazil 1985), they prefer larger, dominant trees of a variety of species (Murphy 1965; Jaffee 1980; Lehman et al. 1980; Anthony and Isaacs 1981; Mosher and Andrew 1981; Mathisen 1983). The bald eagle prefers to nest in areas that are primarily mature or old-growth timber (Lehman et al. 1980; Anthony and Isaacs 1981; Anthony et al. 1982). Most nests in southeast Alaska were in old-growth forest where the average nest tree height was 29.4 m; no nests were found in second-growth trees (Robards and Hodges 1977). A mature vegetation structure was considered to be an important component of bald eagle breeding habitat in Maryland (Mosher and Andrew 1981). There, the average nest tree height was

29 m. The average nest tree height in Virginia was 30.1 m (Jaffee 1980). Nest trees were of an open, stable form providing easy access; the form was more important than the tree species in nest site selection.

Bald eagles in the Greater Yellowstone Ecosystem were flexible in their selection of nest sites, as long as a dependable food source was available in early spring (Swenson et al. 1986). Once this criterion was met, the eagles "... would nest...near either lakes or rivers, in either large, strong trees ...or small, weak trees..." (Swenson et al. 1986:41), although they tended to select the most desirable trees available. In comparison to surrounding trees, 38%, 44%, and 19% of the nest trees were categorized as larger (in diameter or height) in the Yellowstone, Continental, and Snake Units, respectively (Swenson et al. 1986). Sixty-two percent, 56%, and 71% of the nest trees were categorized as similar to surrounding trees in the three Units, respectively. Only 2 of the 56 nest trees were categorized as smaller than the surrounding trees.

Second-growth forest with a remnant (5% to 10%) old-growth component also may provide breeding areas. In Minnesota, State forestry laws of 1902 and 1908 required that 5% to 10% of the trees in the original forest stands be retained as seed trees (Juenemann and Frenzel 1972). These retained trees currently provide canopy discontinuity from the surrounding second-growth hardwoods and are strongly selected for by breeding bald eagles (Juenemann and Frenzel 1972; Mathisen 1983).

Some deforestation may occur without apparently affecting bald eagle densities. For example, in southern British Columbia, 21% of the study area had no old-growth trees, yet eagle density was not reduced from levels in northern British Columbia where 10% of the study area lacked old-growth (Hodges et al. 1984). Eagle densities in both areas matched those of undisturbed southeast Alaska. Although nesting density was greatly reduced in those plots of the study area without old-growth trees, densities in areas with at least some old-growth trees were higher than expected.

One of the most important characteristics of bald eagle nesting habitat is an open forest structure (Lehman et al. 1980; Anthony and Isaacs 1981; Mosher and Andrew 1981; Anthony et al. 1982). The average percent canopy closure at nests in Maryland was 61% (Mosher and Andrew 1981). In California, the canopy closure of the timber stand associated with the nest was usually <40% (Lehman 1979) and often <20% (Lehman et al. 1980). Bald eagles in the Pacific Northwest also nested in fairly open forests (Anthony et al. 1982) where the mean crown closure was <50% (Anthony and Isaacs 1981).

Bald eagles are primarily shoreline nesters (Hensel and Troyer 1964; Robards and King 1966; King et al. 1972; Gerrard et al. 1975; Grier 1977; Lehman et al. 1980; Hodges 1982; Mathisen 1983; Barber et al. 1985; Brazil 1985; Koonz 1985; Stocek 1985). Murphy (1965) listed proximity to water as the first requirement of an area as nesting habitat. The mean distance from water, however, varies between populations, from 36 m on Admiralty Island, Alaska (Robards and Hodges 1977), to over 707 m in Virginia (Jaffee 1980) to over 1.2 km in Oregon (Anthony and Isaacs 1981). Whitfield et al. (1974)

found that over 90% of all nests in their Manitoba and Saskatchewan study areas were within 182 m of a lake or river. Very few nests were found over 728 m from water. In this study and in Alaska (Robards and Hodges 1977), the number of nests dropped off sharply beyond 46 m from water. Bald eagles nested an average of 97.5 m, 199.8 m, and 552.5 m from water in the Yellowstone, Snake, and Continental Units, respectively, of the Greater Yellowstone Ecosystem (Swenson et al. 1986). In Maryland, Taylor and Therres (1981) did not consider land over 1.6 km from water to be suitable nesting habitat. Over 90% of all Maryland bald eagle nests were within 1.5 km of water. None of these studies, however, established a mean distance of land to water. Therefore, nest site preference may have been confounded with land and water distribution.

Bald eagles may show some reluctance to nest right at the shoreline. Even in relatively undisturbed areas of Alaska, the average distance of nest to water was 36 m (Robards and Hodges 1977). In addition, nests within 10 m of shore had a tendency to be used less than those nests over 10 m from shore. Both Robards and Hodges (1977) and Dixon (1909 cited by Bent 1937) suggested that protection from storms may be a reason for this avoidance of the immediate shoreline.

Special Considerations

Although the level of human disturbance often has no effect on the productivity of bald eagles at existing nest sites (Mathisen 1968; Grier 1969; Jaffee 1980; Stocek and Pearce 1981), eagles clearly prefer to nest in areas with little or no human disturbance (Fraser 1985). For example, bald eagle populations are densest in areas without significant human disturbance, such as southeast Alaska (Robards and Hodges 1977), and there they did not use areas of heavy human use. In Manitoba, there were significant numbers of nesting bald eagles on Lakes Winnipeg and Manitoba, except near extensive cottage development (Hatch 1985). Bald eagle densities on Besnard Lake, Saskatchewan, decreased in areas opened to recreational activity (Gerrard et al. 1985). The distance to a water body from bald eagle nests in the Greater Yellowstone Ecosystem tended to increase as the recreational use of the water body increased (Swenson et al. 1986). In Minnesota, human disturbance was related to lowered nest occupancy and productivity (Juenemann and Frenzel 1972). In coastal British Columbia, bald eagles were abundant except in heavily disturbed areas (Hodges et al. 1984). Bald eagles tended to nest away from human residential areas in Maryland (Taylor and Therres 1981). There, only two of 123 nests had residential development as the primary land use within 0.6 km of the nest. Taylor and Therres (1981) suggested that nesting bald eagles will tolerate low-density residential disturbance at distances greater than 1.2 km and medium- to high-density residential disturbances at greater than 1.8 km. A tendency of bald eagles to nest away from human activity was also noted in another quantitative study of bald eagle nesting habitat in Maryland (Mosher and Andrew 1981). Successful nest sites were located in more dense forest stands set back further from open water and forest openings than unsuccessful nests. All the bald eagle nests on Yellowstone Lake, Wyoming, were on the roadless south shore (Murphy 1965). The north shore is paralleled by a heavily traveled highway that permits access for a wide range of human recreational activities. The majority of bald eagle nests in Virginia were located in areas of light human use (Jaffee 1980). Jaffee (1980) suggested that bald eagles were relocating their nests in Virginia to avoid human disturbance associated with shorelines. Lehman et al. (1980) made a similar suggestion about bald eagles in California. These studies indicated that, although nesting bald eagles were not affected by low degrees of human disturbance, habitat suitability decreased as human disturbance increased. There were few reported instances of bald eagles nesting in medium- to high-density human residential areas, and the greatest densities were always reported in areas of minimal human activity.

Logging operations can be very intensive, and this degree of human activity may lower nesting productivity (Anthony and Isaacs 1981). Carefully controlled selective timber harvest, however, need not lower habitat suitability (Lehman et al. 1980). Selective logging during the fall and winter was considered a necessary and appropriate bald eagle management tool in California because eagles there preferred to nest in ponderosa pine (Pinus ponderosa), a shade intolerant species (Lehman et al. 1980; Burke 1983).

Bald eagles may be more prone to nest desertion early in the nesting cycle than late in the cycle (Mathisen 1968) and will react differently to different types of disturbance. For example, existing cropland was considered an acceptable component of bald eagle nesting habitat in Maryland (Taylor and Therres 1981). However, the authors noted that cropland itself is unsuitable bald eagle nesting habitat. Intensive agriculture in Ohio was not thought to disturb some nesting bald eagles (D. Case, Ohio Department of Natural Resources, Columbus, Ohio; pers. comm.). In addition, disturbances that eagles may not directly recognize as human, such as railroads, planes, and unused buildings, may be tolerated.

HABITAT SUITABILITY INDEX (HSI) MODEL

Model Applicability

Purpose. This model differs from the standard HSI model. Most HSI models are designed to quantify the impacts of development projects for mitigation planning or to predict benefits of various habitat management programs. The bald eagle HSI model may be used for assessment of impacts, but will be of little use in mitigation or management studies due to the model variables. Variables used in this model to assess habitat suitability either are not likely to change due to management (e.g., area of water body, morphoedaphic index), or are likely to change slowly over time as a result of management (e.g., the amount of mature forest available for nest sites). Management of bald eagle nesting habitat currently consists primarily of nest site protection. For example, the management strategy for the bald eagle at Chippewa National Forest in Minnesota is primarily land-use restrictions in the vicinity of nests, along with biological monitoring (Mathisen et al. 1977). Therefore, the primary uses of this model may differ from those of other HSI models. This model may be most useful in comparing the suitability of many different areas at one point in time for site protection, or as a tool in recovery planning to locate optimum areas for bald eagle reintroduction or protection.

Geographic area. This HSI model has been developed for application to habitats in that portion of North America north of the 37th parallel, which runs from Norfolk, Virginia, to San Jose, California (Figure 1). Because the bald eagle nests across the continent in a variety of ecoregions, and is so mobile, no attempt was made to delineate a discrete breeding range within this area.

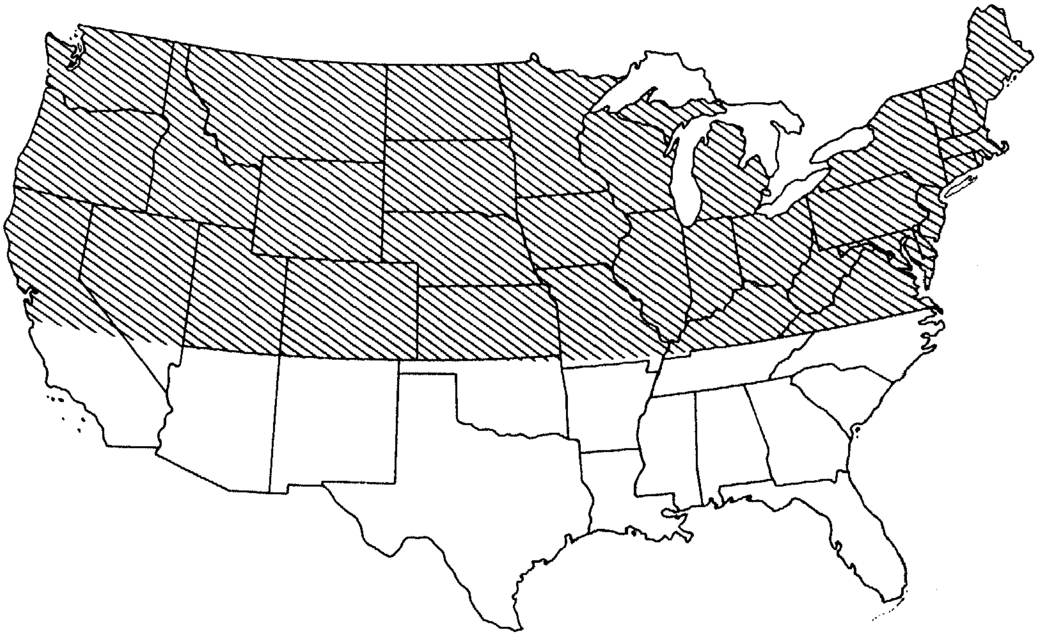


Figure 1. Geographic applicability of the bald eagle HSI model.

Season. This model was developed to evaluate the potential quality of nesting habitat for the bald eagle. It is not intended to assess the quality of fall and winter habitat.

Cover types. This model was developed to evaluate habitat in the Lacustrine (L) and Estuarine (E) cover types (terminology follows that of U.S. Fish and Wildlife Service 1981). These cover types include a 1.5-km strip of land that borders the open water or adjoining emergent or scrub-shrub wetlands. This model does not provide a means of evaluating riverine and marine cover types because data on the morphoedaphic index (a major factor in determining food suitability with this model) was not found for these cover types.

Minimum habitat area. Minimum habitat area is defined as the minimum amount of contiguous habitat that is required before an area will be occupied by a species. The smallest body of water occupied by one pair of nesting bald eagles is 8 ha. Therefore, the minimum size of an evaluation area is assumed to be a body of water with a surface area of 8 ha surrounded by a 1.5-km strip of land.

Verification level. Earlier drafts of this model were reviewed by the following individuals:

Dr. Robert Anthony, Oregon Cooperative Wildlife Research Unit, Corvallis, OR

Mr. Denis Case, Ohio Department of Natural Resources, Columbus, OH

Mr. Keith Cline, Raptor Information Center, Washington, DC

Dr. Daniel James, U.S. Fish and Wildlife Service, Arlington, VA

Mr. John Mathisen, U.S. Forest Service, Cass Lake, MN

Mr. Brian Millsap, Raptor Information Center, Washington, DC

Ms. Karen Steenhof, U.S. Bureau of Land Management, Boise, ID

Mr. Stanley Wiemeyer, U.S. Fish and Wildlife Service, Laurel, MD

Comments by the reviewers were incorporated into the model and resulted in several significant improvements. The current model has not been field tested and empirical relationships between model outputs and measures of bald eagle habitat suitability are unknown.

Model Description

Overview. The breeding season HSI model for the bald eagle considers food, reproduction, and human disturbance as the primary components of breeding habitat. The HSI value considers the quality and availability of nesting sites and the availability of prey. Because eagle prey is primarily derived from aquatic systems, total prey availability is assumed to depend upon the size and productivity of the associated water body. Optimal nesting habitat is assumed to be characterized by: (1) a large foraging area with high fish production, (2) the presence of mature trees for nest sites, and (3) minimal human disturbance. Cover requirements during the breeding season are assumed to be adequately evaluated by the criteria used to evaluate reproductive requirements.

The following sections describe the logic used and the assumptions made to translate the habitat information for the bald eagle to the variables and equations used in the model. The suitability levels of variables and relationships between variables are also described.

Food component. Bald eagle breeding habitat suitability is strongly influenced by the availability of live or carrion prey, primarily fish or aquatic birds. Specifically, the amount of open water in the evaluation area and its productivity are of major importance in determining the total amount of food available to a population of eagles.

Since nesting bald eagles prey largely on aquatic or aquaphilic species, habitat suitability generally increases with the amount of open water. It was noted previously that areas with <8 ha (0.08 km^2) of open water are not known to constitute bald eagle habitat. Habitat suitability increases from zero below this size to optimal for bodies of water with surface areas ≥10 km^2 (Figure 2a). For estuarine cover types, the suitability index (SIV1) is assumed to be optimal (=1.0) for the amount of foraging habitat.

For the purposes of this model, emergent and scrub-shrub wetlands adjacent to open water also should be considered foraging habitat (as opposed to nesting habitat) due to documented eagle use of these habitats. Foraging in emergent or scrub-shrub wetlands, however, is apparently coincidental to the primary feeding strategies of fishing and shoreline scavenging, because bald eagles have not been observed hunting in emergent or scrub-shrub wetlands that are located far from large, open water bodies. Therefore, emergent or scrub-shrub wetlands that are not associated with open water should not be considered foraging habitat.

The productivity of the water body is the second aspect that is of importance in determining food availability. Specifically, food availability and, hence, habitat suitability, increase with productivity. A reasonable measure of the productivity of lentic aquatic systems can be obtained from the morphoedaphic index (Ryder 1965, 1978, 1980; Jenkins 1982) in terms of fish biomass density or potential fish yield (lbs/acre). The morphoedaphic index (MEI), where

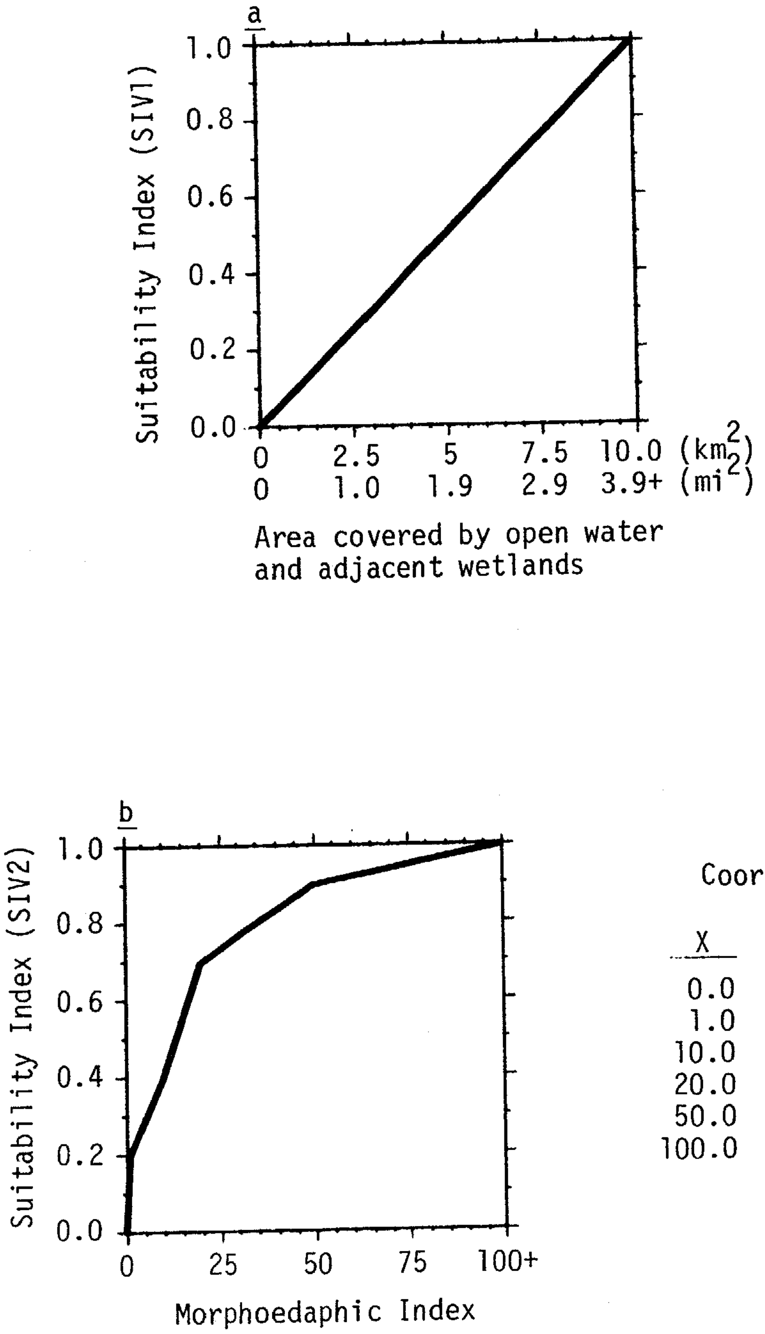
$$\text{MEI} = \frac{\text{total dissolved solids (ppm)}}{\text{mean depth (feet)}}$$

has been used to explain differences in bald eagle nesting densities (Gerrard et al. 1983; Detrich 1985). Detrich (1985) used a modified form where

$$\text{MEI} = \frac{\text{conductivity (micromhos)}}{\text{mean depth (cm)}}$$

Fish biomass density and, hence, habitat suitability are assumed to increase with the MEI as a function of the data curves generated by Ryder (1965) and Jenkins (1982) and as described by Ryder (R. A. Ryder, Ontario Ministry of Natural Resources, Thunder Bay, Ontario; pers. comm.) (Figure 2b).

Ryder et al. (1974) note that certain conditions may cause the MEI to yield misleading results. Very shallow lakes, with a mean depth <3 m, may contain lowered fish biomass because of winterkill. Also, lakes with very high TDS levels often have limited fish populations, although the precise reason for this is unclear (Schlesinger and Regier 1982). It is often thought,



Coordinates

X	Y
0.0	0.0
1.0	0.2
10.0	0.4
20.0	0.7
50.0	0.9
100.0	1.0

Figure 2. Relationships between variables used to evaluate suitability of water bodies as bald eagle habitat and suitability indices for the variables.

however, that highly productive systems have marginal habitat for some fish species because of anoxic hypolimnions or reduction of "liebensraum" (Ryder, pers. comm.). Ryder states that fish crops increase rapidly with the MEI to about 40, and show little improvement between MEI's of 40 and 100. Beyond an MEI of 100, Ryder states that the MEI-fish crop relationship often breaks down because of the conditions noted above.

Provided that all criteria for use are heeded, the MEI can be applied to freshwater or brackish ecosystems (Ryder, pers. comm.). However, in this model, comparisons of HSI between the two types may not be made because the salinity of estuaries and, therefore, TDS differs from that of lake water.

The suitability of the food component (SIF) is assumed to be best represented by the geometric mean of the two variables used to evaluate this component, as in Equation 1. This is intended to reflect the compensatory nature between lake size and lake productivity. Specifically, it is assumed that the food resources in lakes from 0.08 - 10 km² are not most efficiently used by eagles due to their territorial requirements. It is assumed, following the discussion of Detrich (1985), that smaller lakes often have opposing shorelines <0.5 km apart and that the presence of a pair of eagles on one shore may preclude use of the other shore by other eagles. On larger lakes (>10 km²), it is assumed that lake geometry does not affect habitat use and that the SI is primarily determined by the MEI. Equation 1 yields a food suitability index of 0.0 for lakes ≤8 ha. For lakes >8 ha, the food suitability index determined by Equation 1 is a function both of area and MEI, but the index will be closer to the lower of the two inputs (i.e., SIV1 and SIV2). Note that the area of foraging habitat in estuarine cover types is assumed to be optimal (i.e., SIV1 = 1.0).

$$SIF = (SIV1 \times SIV2)^{1/2} \qquad (1)$$

Reproduction component. Although individual pairs or remnant populations of bald eagles will nest in second-growth timber or largely deforested areas, the species clearly prefers, and reaches its greatest densities in, large areas of undisturbed, mature or old-growth timber, with an open and discontinuous canopy. This habitat type provides an abundance of the eagle's preferred nesting sites, i.e., tall, dominant trees, regardless of species, with an open structure and stable limbs allowing easy approach from the air. Second-growth forests, with a remnant (5% to 10%) old-growth component intermixed, also can provide for nesting requirements. Dense stands of even-aged, small, second-growth timber without a remnant old-growth component do not provide the relatively open canopy structure bald eagles need. The species rarely nests in this seral stage. Productivity of more exposed nests may be affected by increased vulnerability to storm damage. Susceptibility to human disturbance also may increase with visibility or accessibility of the nest.

Suitable bald eagle nesting habitat within lacustrine or estuarine habitats is assumed to be a function of the amount of mature, open canopy forest cover within the evaluation area. Because the majority of bald eagle nests of all populations are within 1.5 km of shore, the evaluation area for this component is the land area within 1.5 km of the edge of the water or associated herbaceous or shrub wetland. Optimum conditions for reproduction are assumed to occur when mature timber exceeds 75% of the land area. Smith (1974) defined undisturbed (i.e., mature) temperate forest generally as uneven aged, having a discontinuous canopy >20 m high. However, the height and structure of mature forests will vary with the forest type. Hence, the user should establish a definition of maturity for the forest cover in the evaluation area. The silvicultural definition of rotation age maturity is not appropriate for the purposes of this model, because it refers to the concepts of financial maturity and return on investment (Smith 1962). Habitats where mature forest cover is <75% of the land area are assumed to be suboptimal (Figure 3). Because bald eagles are territorial, with widely spaced nests even under optimum conditions, it is assumed that some deforestation within an evaluation area may occur without reducing the suitability index for the reproduction component. In this model, the suitability index for bald eagle reproduction (SIR) is estimated by only one variable, the proportion of potential nesting area in mature timber, and is equal, therefore, to SIV3 (from Figure 3).

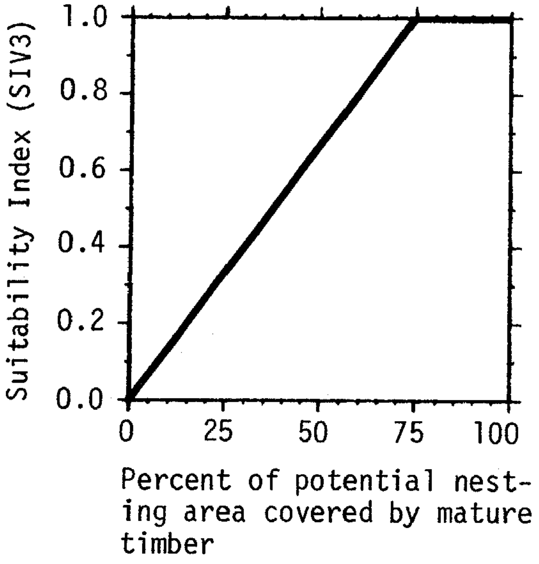


Figure 3. The assumed relationship between the amount of mature timber within 1.5 km of a shoreline and suitability of the habitat for bald eagle nesting.

Human disturbance component. Bald eagle populations reach their greatest densities in areas of minimal human activity. They are found in reduced densities in areas of moderate human use and are not found at all in areas of heavy human use. They prefer to nest at least 1.0 km from human residences and will nest farther from shore to avoid shoreline disturbances. Where human disturbance is severe, nesting success may be affected, and the area may be abandoned entirely. Although remnant populations often are not affected by existing levels of human disturbance, the potential carrying capacity of their habitat has been reduced through human presence and activities. The precise effect of human disturbance on bald eagle carrying capacity is not known and is, therefore, difficult to evaluate.

Human presence in bald eagle nesting habitat falls primarily into four categories: (1) agriculture, (2) urbanization, (3) recreational development, and (4) logging. Most agricultural operations are not human intensive and their effect on carrying capacity most likely is felt via attendant deforestation, not via the human presence *per se*. For this reason, agriculture is considered to be an impact upon the reproduction component. Urbanization and recreational development can both be measured by the density of houses, buildings, or campsites. Medium- and high-density residential areas are defined as areas where lot frontage is ≤33 m (New York State 1974). Medium-density residential areas along a lakeshore would then have buildings at a density of 30 per kilometer of shoreline (Figure 4). This corresponds to 20 buildings per square kilometer of the reproduction area. Habitat suitability is assumed to be optimal where there are no buildings or campsites and unsuitable where there are >20 buildings or campsites per square kilometer of upland (Figure 4).

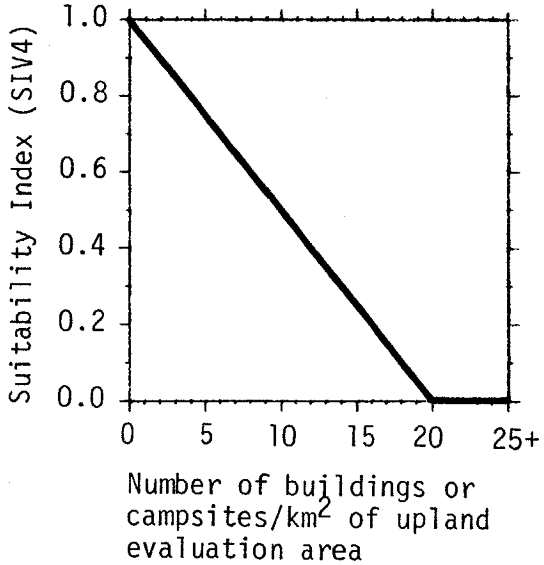


Figure 4. Assumed relationship between housing or campsite density and habitat suitability for the bald eagle.

The distribution and uses of the buildings or campsites, as well as the season of use, will affect the amount of their disturbance. If all the buildings or campsites are distributed evenly along the shoreline, so as to preempt the most desired nesting and perching sites, their impact will be greater than if they are tightly clustered and removed from the shoreline.

The human presence associated with logging may be significant and could cause large reductions in habitat suitability. However, this form of human disturbance has been studied only with respect to impacts upon productivity at individual nest sites. Because productivity varies between and within eagle populations, regardless of nesting density, productivity data alone cannot be used to reliably support habitat suitability models that are based upon nesting density. No information was located in the literature that documented a correlation between logging intensity over a large area (i.e., more than a single nest site) and nesting density in the same area. For this reason, the human disturbance associated with logging operations, although important, cannot be reliably included in this model and must be considered as a separate process.

The overall suitability index for the human disturbance (SIHD) component is estimated by the suitability index determined for building or campsite density (i.e., SIHD = SIV4).

Building density may not be the most precise indicator of human disturbance under certain conditions (e.g., heavy boat traffic only). To be a useful habitat assessment tool, however, the model variables must be easily measurable and applicable to the range of conditions within the model's geographic area of applicability. Building density, therefore, is used as a surrogate measure of human disturbance, because it is an easily measured indicator of long-term human land use.

HSI determination. The overall habitat suitability index is a function of the food, reproductive, and human disturbance components. Any of the components may be the most limiting factor in a given situation. Under pristine conditions, where the reproductive and human disturbance components are optimum, the overall habitat suitability will be determined by the food component which is, in turn, a function of the foraging area and the MEI. Under other conditions, the potential food base may be capable of supporting a higher density of bald eagles than is actually realized, as a result of less than optimum conditions for nesting sites and disturbance potential. It is assumed that the food component is of greater importance alone than either of the other components alone, unless one of the other components is 0.0. The reproductive and human disturbance components are combined via a geometric mean which yields a combined suitability value of 0.0 if either of the inputs is 0.0, and a value closer to the lower of the input values if both are >0.0. The resulting suitability value is multiplied by the food suitability index to yield the overall habitat suitability index (Equation 2). This relationship is based on the assumption that the food suitability value defines the upper level of potential suitability that will be realized only when the reproductive and human disturbance components are optimum. Values less than optimum for the reproductive and human disturbance components will lower the overall value from the maximum set by the food component suitability. In the extreme situation, none of the potential food will be used by eagles when either or both of the reproductive or human disturbance components equals 0.0. It should be noted that the product resulting from Equation 2 will be lower than any individual input if the combined reproductive/disturbance input and the food input are <1.0, because decimals are being multiplied. This is intended and follows the logic that the combined reproductive/disturbance component is a modifier of the maximum suitability determined by the food component.

$$\text{HSI} = (\text{SIR} \times \text{SIHD})^{1/2} \times (\text{SIF}) \qquad (2)$$

Because the HSI equation is geometric, and uses values <1.0, the HSI score will generally be <1.0, and will often be <0.5. This will be particularly true when cold, oligotrophic lakes are evaluated. The assignment of an HSI value <0.5 to a wilderness lake with perhaps a healthy eagle population may seem illogical. However, it should be remembered that the HSI is designed to reflect habitat suitability by the density of eagles along the shoreline. Oligotrophic, wilderness lakes may have quite healthy populations of eagles, but at lower densities than can be expected around more productive lakes.

Application of the Model

Summary of model variables. This model provides criteria to evaluate the suitability of bald eagle nesting habitat in lacustrine or estuarine cover types. The relationships of the habitat variables to an HSI are shown in Figure 5. Definitions of habitat variables and suggested measurement techniques (Hays et al. 1981, unless noted otherwise) are shown in Figure 6.

The presumed relationship between each habitat variable and habitat suitability has been described and documented. This provides some insights that can be used to tailor the model to fit study constraints and local bald eagle breeding characteristics. Due to the large breeding range of the bald eagle, it is expected that model alterations will be necessary.

Because many of the data used in applying this model are derived from remote sensing, it is essential that the user visit the evaluation area to ensure that all remote sensing data are accurate. This is necessary to properly define the occurrence and limits of mature forest and to accurately record the type and intensity of human disturbance. This model should not be applied solely on the basis of remote sensing data, no matter how recently collected.

Model assumptions. A number of significant assumptions were made in the development of this HSI model for the bald eagle. The major assumptions are as follows:

1. Mature forested stands with minimal human disturbance are required for nesting by bald eagles. However, optimal nesting conditions can exist as long as >75% of potential nesting area is in mature timber.

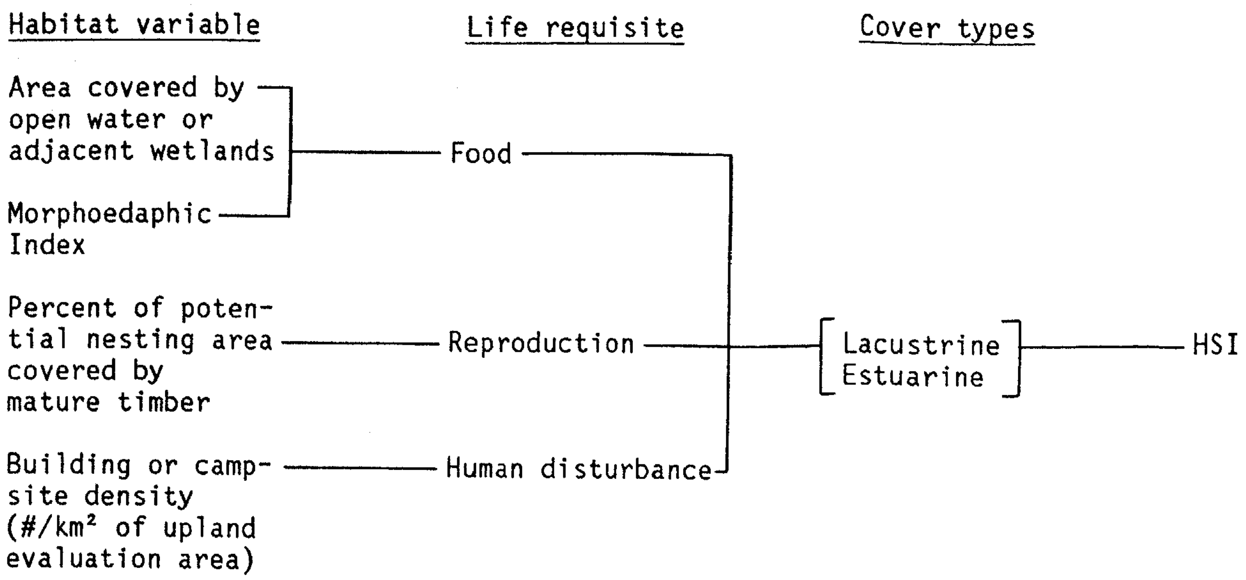


Figure 5. Relationships of habitat variables, life requisites, and cover types in the bald eagle HSI model.

2. Mature forest stands within 1.5 km of a body of water ≥8 ha provide optimal nesting conditions regardless of stand composition.
3. Immature forest stands provide no nesting habitat.
4. The extent and influence of human disturbance can be estimated by an estimate of building or campsite density.

The first assumption will probably be valid in most applications of this model. Under certain conditions, however, bald eagles will nest on the ground or on cliffs. This typically occurs on isolated, uninhabited islands where trees are scarce or absent. Under these circumstances, the model should be modified to include potential cliff or ground nests.

The second and third assumptions also should be valid in most applications of this model. However, certain monotypic stands may not provide optimal nesting conditions at maturity, if the tree species' terminal branching structure is too fine or fragile to support eagle nests. Some immature forest stands that are approaching maturity may contain scattered individual trees that, due to site advantage, possess size and form suitable for nesting. If either circumstance occurs, the model should be modified to reflect the relative presence or absence of nesting sites.

Variable (definition)	Cover types	Suggested technique
Area covered by open water or adjacent wetlands (the absolute area being evaluated that consists of open water plus the herbaceous and shrub wetlands that are immediately adjacent to open water; herbaceous and shrub wetlands that are not adjacent to open water should not be included in determination of area for this variable.)	L	Remote sensing, topographic map, dot grid, published data.
Morphoedaphic Index [A ratio relating the productivity of a water body as measured by total dissolved solids to the mean depth of that water body using the following formula: Morphoedaphic Index (MEI) = $\frac{\text{total dissolved solids}}{\text{mean depth}}$ where total dissolved solids (TDS) is measured in parts per million and mean depth is measured in feet].	L,E	TDS meter, conductivity meter, laboratory analysis, soundings, published data, (Hamilton and Bergersen, n.d.). (NOTE: Conductivity measurements must be converted to TDS before determination of MEI.)
Percent of potential nesting area covered by mature timber (an estimate of the proportion of a 1.5 km wide band of land, surrounding the cover type being evaluated, that is covered by mature forest; characteristics defining mature forest, such as height and density of trees, must be defined by the model user).	L,E	Remote sensing, direct observation, dot grid, topographic map.

Figure 6. Definitions of habitat variables and suggested measurement techniques.

Variable (definition)	Cover types	Suggested technique
Building or campsite density (the number of campsites, houses, or other permanent dwellings per km² of upland evaluation area based on the 1.5 km wide strip of land surrounding the aquatic cover type being evaluated).	L,E	Remote sensing.

Figure 6. (Concluded)

The fourth assumption is perhaps the assumption that will most often be invalid. The impact of humans on nesting bald eagles involves many types and intensities of disturbances. The use of building or campsite density as the single estimator of the impact of human disturbance obviously simplifies a very complex problem. Other means of assessing human disturbance on a local basis may be preferable to building or campsite density.

There are factors other than habitat that affect the carrying capacity of an area for bald eagles, including climate and environmental contaminants. These factors should be considered as possible sources of variation when model outputs are compared to populations in different habitats in widely separated areas.

Climate affects virtually all living organisms. As the mean temperature decreases, breeding seasons become shortened and energetics becomes an increasingly important factor. Wetmore and Gillespie (1976) found a significant correlation between mean April temperature and osprey (Pandion haliaetus) productivity in Labrador and northeastern Quebec. Leighton et al. (1979) found a significant correlation between April temperature and bald eagle nesting density in Saskatchewan. Their data indicated that, whereas local climatic and geographic features may cause variation, in general, bald eagle reproduction becomes difficult, if not impossible, where the mean April temperature is <-7 °C. Where mean April temperature is >10 °C, bald eagles begin nesting earlier to avoid extreme summer temperatures; this behavior is exhibited by bald eagles nesting in the southeastern United States (Bent 1937).

Climate also affects bald eagle prey availability. Total annual fish production is positively correlated with annual temperature on a global basis (Schlesinger and Regier 1982). Although climate was not a significant factor in fish production within the north-temperate climatic region (Matuszek 1978), there can be large differences in annual fish production between north-temperate and south-temperate lakes with similar morphoedaphic indices (Schlesinger and Regier 1982).

Persistent environmental contaminants are another factor, but are not included as a habitat component in this model for two reasons. First, the contaminant burden in eagle populations is a function of wintering habitat as well as breeding habitat and cannot be accurately measured by analysis of breeding habitat alone. Second, the effect of persistent environmental contaminants on eagles has been measured by its effect upon nesting productivity, not directly on nesting density. However, nesting density has been affected where contamination was severe for prolonged periods (S. N. Wiemeyer, Patuxtent Wildlife Research Center, Laurel, MD; pers. comm.). In these cases, reproduction was inadequate to maintain stable populations and contaminants caused direct mortality to eagles. For the same reasons discussed earlier concerning logging impacts, the impact of persistent environmental contaminants upon habitat suitability cannot be reliably included in this model and must be considered as a separate process. Persistent environmental contaminants, however, have had marked effects on many raptor populations (Hickey 1969; Porter and Wiemeyer 1969; Redig 1979), including the bald eagle (Hamerstrom et al. 1975; Wiemeyer et al. 1984). Thus, the level of environmental contaminants in the nesting area should be considered in conjunction with any habitat analysis. Few controlled studies of the relationships between dietary levels of contaminants and reproductive success have been conducted. However, a very general pattern has been observed regarding dietary concentrations of DDE, which is now the most frequent source of chemically-induced reproductive disruptions (Wiemeyer, pers. comm.). This pattern can be used as a preliminary guide to suggest effects on productivity. When the wet weight dietary concentration of DDE in prey tissue is <0.1 ppm, no effect on raptor productivity is expected. Between 0.1 and 0.5 ppm, there may be some residue accumulation and minor effects. Between 0.5 and 3 ppm, there may be some eggshell thinning and reproductive problems. When DDE concentrations in prey tissues are consistently above 3 ppm, there may be occasional adult mortality and a severe reduction or complete failure in productivity. Other persistent contaminants also may cause adverse effects on bald eagle populations (Wiemeyer, pers. comm.). Contaminant ecologists should be consulted when such contaminants are detected in prey items. The potential effects of nonpersistent but moderately to highly toxic contaminants should not be overlooked.

SOURCES OF OTHER MODELS

Two HSI models have been developed for Alaska (Steenhof, in press). Both models rely on subjective characterization of habitat types and appear to measure the suitability of individual nest sites, rather than larger areas of habitat.

Taylor and Therres (1981) used the physical characteristics of known bald eagle nesting habitat in Maryland to construct a computer-generated prediction of suitable habitat in Maryland. They evaluated land use, cover type, disturbance, and distance to feeding areas. Their system measured many different areas at a single point in time. The biological data used in their model supports this HSI model and was used to document some of the assumptions contained herein.

Two additional HSI models are currently being developed for use in Montana (Steenhof, in press).

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

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