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Remotely-sensed indicators for monitoring the general condition of "natural habitat" in watersheds: an application for Delaware's Nanticoke River watershed

Ralph W. Tiner*

US Fish and Wildlife Service, Northeast Region (Region 5), 300 Westgate Center Drive, Hadley, MA 01035, USA

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Abstract

Over the past two decades there has been increasing interest in developing indicators to monitor environmental change. Remote sensing techniques have been primarily used to generate information on land use/land cover changes. The US Fish and Wildlife Service has used this technology to monitor wetland trends and recently developed a set of remotely-sensed indicators to characterize and assess trends in the integrity of natural habitat in watersheds. The indices largely focus on the extent of "natural" cover throughout a given watershed, with an emphasis on locations important to fish, wildlife, and water quality. Six indices address natural habitat extent and four deal with human-caused disturbance. A composite index of natural habitat integrity combining the habitat extent and habitat disturbance indices may be formulated to provide an overall numeric value for a watershed or subbasin. These indices facilitate comparison between watersheds (and subbasins) and assesssment of trends useful for environmental monitoring. This paper describes the indices and presents an example of their application for characterizing and assessing conditions of subbasins within Delaware's Nanticoke River watershed.

Keywords: Natural habitat integrity; Watershed characterization; Nanticoke river watershed; Environmental indicators; Remotely-sensed indicators

1. Introduction

Loss and degradation of terrestrial and aquatic habitats and degraded water quality are major environmental concerns worldwide. Over the past two decades a variety of ecological indicators have been developed to document the current status and trends in natural resources. Such indicators can be used to provide information on environmental quality beyond traditional water quality indicators (e.g., temperature, pH, dissolved oxygen, chlorophyll, nutrients, suspended solids, salinity, trace metals, nitrates, various pesticides, and pathogens) and documenting land use trends. Ecological indicators include site-specific, field-derived metrics and landscape-level properties. Site-specific indicators include indices of biological integrity (IBIs) for assessing aquatic resources (e.g., Angermeier and Karr, 1986; Plafkin et al., 1989; US EPA, 1990; Karr and Chu, 1998), changes in plant community composition (including the invasion of exotic species) to identify possible disturbance (e.g., Ehrenfeld, 1983; Ehrenfeld and Schneider, 1991; Zampella and Ladig, 1997), and a hydrogeomorphic approach (HGM) for evaluating wetland functions and estimating changes in function from proposed

* Fax: +1 413 253 8482.
E-mail address: ralph_tiner@fws.gov (R.W. Tiner).

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dredge and fill projects (Brinson, 1993; Stevenson and Hauer, 2002). Land use has a major impact on both aquatic and terrestrial ecosystems. Many reports have addressed land use changes and some have focused on certain habitats such as wetlands (e.g., Tiner, 1984; Dahl and Johnson, 1991; Dahl, 2000), river corridors, and shoreline buffers (e.g., Lathrop and Bognar, 2001; Tiner et al., 2002). To estimate the ecological integrity of the interior Columbia River basin in the Pacific Northwest, Quigley et al. (2001) developed several "proxies" for ecological indicators that may be interpreted through remote sensing (e.g., percent of different land cover types and road density variables). Numerous wildlife habitat assessment procedures include geographic information system (GIS) analyses such as gap analysis for regional conservation assessments (Scott et al., 1993; Scott and Jennings, 1998) and studies of bird habitat trends (e.g., Dettmers and Bart, 1999).

There is a pressing need to develop environmental indicators that can be applied to large geographic areas on a periodic basis for evaluating, monitoring, and reporting on the status of natural resources regionally and globally. The H. John Heinz III Center for Science, Economics and the Environment (2002) report—"The State of the Nation's Ecosystems"—provides a national framework for creating an environmental report card for monitoring the status of America's ecosystems. It describes 103 strategic indicators for six ecosystems: (1) coasts and oceans (including estuaries and shorelines), (2) farmlands, (3) forests, (4) fresh waters (including freshwater wetlands and riparian habitat), (5) grasslands and shrublands, and (6) urban and suburban lands. For each of these ecosystems, habitat extent was identified as an important indicator, yet for most systems adequate data were not available for national reporting.

Through its National Wetlands Inventory Program, the US Fish and Wildlife Service has been tracking changes in wetland extent (Frayer et al., 1983; Tiner, 1984; Dahl and Johnson, 1991; Dahl, 2000) and building a national wetland geospatial database (http://wetlands.fws.gov). This work relies on remote sensing techniques (i.e., interpretation of aerial photographs) to document status and trends in wetland and deepwater habitats; these techniques are equally applicable for monitoring the condition of terrestrial habitats.

Human activities in and around wetlands and waterbodies have a significant impact on water quality and fish and wildlife habitat. For strategic planning and management, natural resource agencies need data on the status of river and stream corridors, wetlands, buffer zones, and the general environmental condition for entire watersheds. Numerous studies have documented the importance of maintaining vegetated buffers along streams and wetlands to fish and wildlife (Brinson et al., 1981; Keller et al., 1993; Osborne and Kovacic, 1993; Spackman and Hughes, 1995; Kilgo et al., 1998; Semlitsch and Jensen, 2001). The significance of vegetated riparian zones for improving water quality is also widely recognized (e.g., Lowrance et al., 1984; Peterjohn and Correll, 1984; Castelle et al., 1994; Desbonnet et al., 1994; Hill, 1996; Federal Interagency Stream Corridor Restoration Working Group, 1998; Wenger, 1999). Knowledge of the condition of wetland and stream buffers is also essential for locating possible sources of water quality degradation and sites for restoring riparian vegetation. Land-use disturbances in watersheds can have a significant negative impact on stream water chemistry and aquatic biota (Morgan and Phillipp, 1986; Ehrenfeld and Schneider, 1991; Pajak et al., 1994; Zampella, 1994; Zampella and Ladig, 1997).

Land use/cover changes and habitat disturbances can be evaluated in many ways. For example, the health and ecological condition of a watershed may be assessed by considering features such as the integrity of lotic (streamside) wetlands and vegetated stream corridors, the percent of land uses that may adversely affect water quality in the watershed, water quality based on chemical criteria, macroinvertebrate communities, fish communities, the percent of forest in the watershed, and the number of dams on streams. Recent work on assessing the condition of watersheds in the Pacific Northwest has focused on salmon (Naiman et al., 1992; Wissmar et al., 1994). Wang et al. (1997) found that in-stream habitat quality in Wisconsin declined when agricultural land use in a watershed exceeded 50%, while when only 10–20% of a watershed was urbanized, severe degradation occurred. A generally accepted rule of thumb is that stream health begins to decline when 10% of the land is impervious and becomes severely degraded when imperviousness exceeds 30% (McClintock and Cutforth, 2003). Managing the landscape around wetlands and aquatic habitats is vital to maintaining high quality sites and restoring degraded ones. Cost effective, rapid assessment measures need to be found that can be used to provide the public with information on the general status of "natural habitat." Governments committed to environmental protection could benefit from producing an environmental index (Gross National Natural Resources, GNNR) similar to the economic index (Gross National Product, GNP).

With widespread use of remote sensing and GIS technology for evaluating land use and habitat trends, a set of indicators of ecological condition could be derived to assess the current status and monitor trends of significant fish and wildlife resources. These indicators would not supplant more intensive, field-based indicators (e.g., IBIs and water chemistry parameters) or other GIS-based methods for conserving biodiversity (e.g., gap analysis), but they would be useful for tracking landscape-level changes in natural resources important for maintaining water quality and fish and wildlife habitat. These indicators could form the basis of a landscape-level assessment that provides a geospatial and statistical overview of significant land and water resources for a given watershed.

The purpose of this paper is to introduce a set of remotely-sensed indicators of "natural habitat integrity" developed to assess the general ecological condition of watersheds. Examples from a watershed study in Delaware, USA are given to illustrate their application.

2. Study area

The study area is the Delaware portion of the Nanticoke River watershed (Fig. 1). This 1266 km^2 drainage area encompasses about 25% of the state and drains into Chesapeake Bay, the largest estuary in the United States.

3. Methods

3.1. Building the geospatial database

Use of GIS for watershed analysis requires that map data be converted into a digital format for computer applications. Geospatial data are needed for three primary features: (1) land use/cover, (2) wetland and aquatic habitats, and (3) transportation routes. Soils data and historic maps are needed for predicting the historic extent of wetlands.

For the Nanticoke watershed, the following sources of geospatial digital data were available: (1) National Wetlands Inventory data from the US Fish and Wildlife Service (based on 1:24,000 maps derived from mostly early 1980s—1:58,000 color infrared photography), (2) State wetland data (based on digital orthophoto quarter-quads produced from spring 1992—1:40,000 color infrared photographs), (3) soil data from the USDA Natural Resources Conservation Service, (4) State land use and land cover data (mid-1990s data), and (5) US Geological Survey digital line graphs for roads and hydrography. The National Wetlands Inventory data were used as base data for wetlands and waterbodies since they are part of a national database and match up well with other national digital data, especially hydrology data from the US Geological Survey. The State's land use/cover data served as the foundation for nonwetlands (uplands). Other sources were used as collateral data to help improve the inventory of wetlands and deepwater habitats.

To produce more real-time assessment, existing information may need to be updated. For the Nanticoke project, digital wetland data were updated to 1998 through photointerpretation of spring 1998—1:40,000 black and white photography using a digital transfer scope. Wetlands were classified according to Cowardin et al. (1979) and Tiner (2000). The end-product was a more accurate, comprehensive, and up-to-date wetland database. The State's digital land use/cover data were similarly updated. Upland areas were classified according to Anderson et al. (1976) and aggregated into the following categories: developed land, agricultural land, forests, wetlands, transitional land (moving toward some type of development or agricultural use, but future status unknown), and water. Changes between "natural habitat," agriculture, and developed land were emphasized. Stream data based on 1:24,000 topographic maps were expanded to include a more complete assessment of ditches and channelized stream segments based on the digital hydro data.

3.2. Development of remotely-sensed natural habitat integrity indicators

For purposes of this type of analysis, "natural habitats" are defined as areas where significant hu-

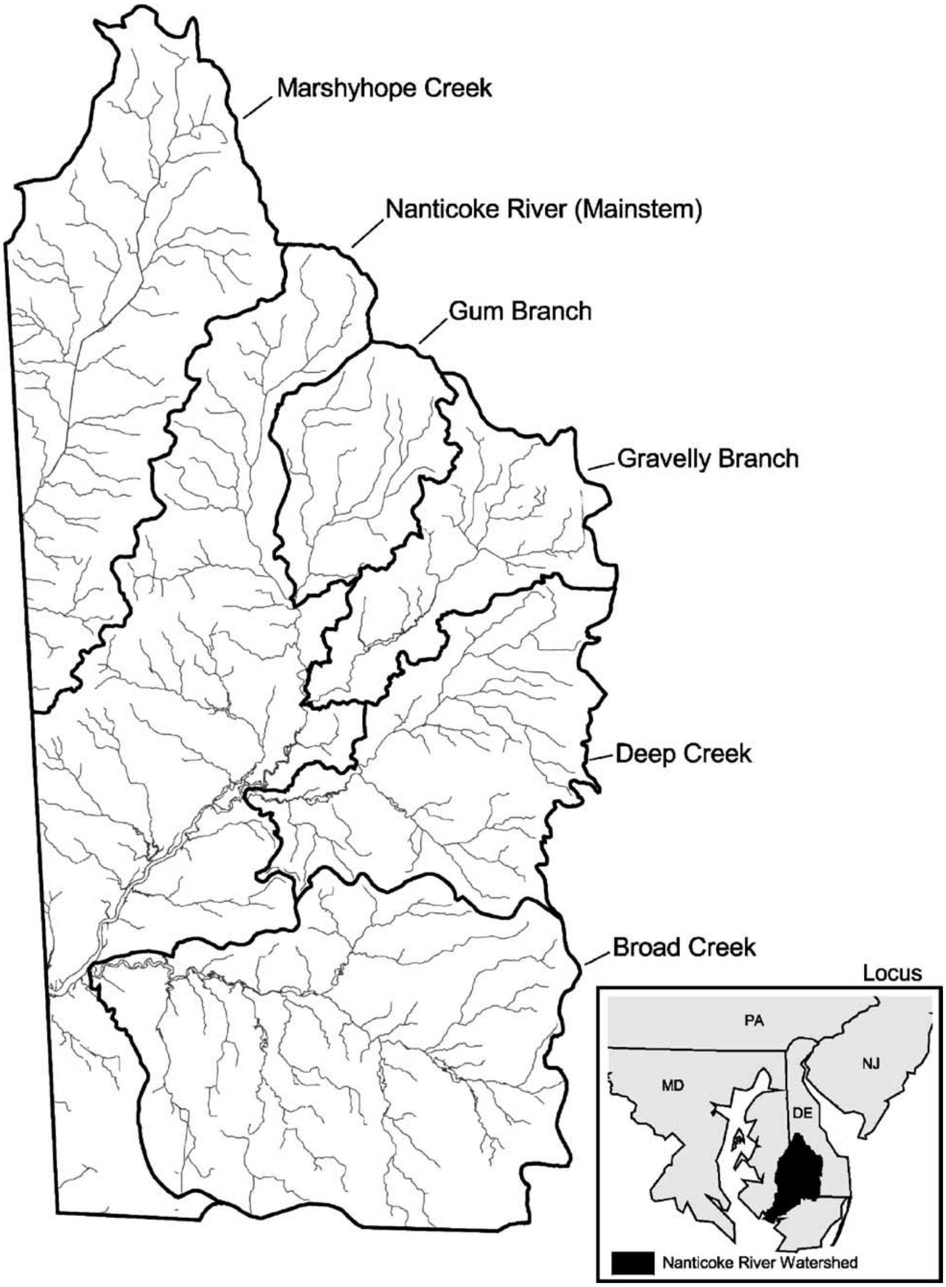

Fig. 1. Delaware's Nanticoke river watershed with subbasins designated.

man activity is limited to activities such as nature observation, hunting, fishing, or timber harvest, and where vegetation is allowed to grow for many years without annual harvesting of vegetation, fruits or berries for commercial purposes. Natural habitats are not restricted to pristine habitats; they include habitats ranging from pristine wilderness to wetlands now colonized by invasive species to commercial forests and wildlife management impoundments. They are not developed sites (e.g., impervious surfaces, lawns, cropland, pastures, or mowed hayfields) or areas subjected to heavy human traffic. They are essentially plant communities represented by forests, meadows, marshes, swamps, and shrub thickets where wildlife find food, shelter, and water. For this study, "natural habitat integrity" may be defined as the state of unbroken "natural habitats." For a watershed, natural habitat integrity can be measured by extent to which a watershed is represented by forests, grasslands, and other natural ecosystems (i.e. the area not developed for agriculture, transportation, urban life, and similar human activities). Natural habitat integrity is broadly defined as conditions where "natural habitat" is typically allowed to exist for many years, without great physical disturbance by humans.

To assess the overall ecological condition of watersheds, a set of largely remotely-sensed "natural habitat integrity indices" were developed. To be most useful for environmental monitoring, these indices had to meet four of the following requirements: (1) be derived from remotely-sensed data (aerial photos or satellite images) for contemporary data and from maps for historical data, (2) be suitable for frequent updating and rapid assessment, (3) consist of metrics that could efficiently and cost effectively be updated for large geographic areas, (4) present a broad view of the extent of "natural habitat," and (5) provide a historic perspective on the extent of wetlands and open waterbodies. Such indices would be coarse-filter variables for assessing the overall condition of watersheds. They are intended to augment, not supplant, other more rigorous, fine-filter approaches for describing the ecological condition of watersheds (e.g., IBIs for instream macroinvertebrates and fish and the extent of invasive species) and for examining relationships between human impacts and natural resources.

The variables chosen for indexing included: (1) extent of natural habitat, (2) condition of river and stream corridors, (3) condition of wetland buffers, (4) condition of pond and lake buffers, (5) present extent of wetlands relative to historic area, (6) present extent of standing waterbodies relative to historic area, (7) amount of stream channelization, (8) extent of river/stream damming, (9) the amount of wetland disturbance (e.g., drained, excavated, impounded, and farmed wetlands), and (10) the degree of habitat fragmentation by roads. These variables address watershed properties that are important for maintaining and improving fish and wildlife habitat and water quality. Riparian corridors are important habitats for resident and migratory species. Bird density in these zones may be twice that of adjacent uplands (Brinson et al., 1981). A 100 m-wide vegetated buffer was important for interior-nesting neotropical migrant birds in the Mid-Atlantic region of the US (Keller et al., 1993). A 10–30 m forested buffer can maintain stream temperatures vital to certain fish species (Osborne and Kovacic, 1993). Vegetated buffers around wetlands are also important for wildlife. Ninety-five percent of the breeding population of mole salamanders was found within 164 m of their natal vernal pool (Semlitsch and Jensen, 2001). Land use practices around wetlands may be as important to wildlife as the size of the wetland itself (Finlay and Houlahan, 1996). Vegetated buffers around all waterbodies help improve water quality. Desbonnet et al. (1994) suggested that a 45 m vegetated buffer should be adequate in most areas where sediment and adsorbed pollutants are major concerns. Historic trends in wetlands and waterbodies are of great interest to natural resource agencies and organizations. The other variables address significant alterations of rivers, streams, and wetlands plus habitat fragmentation by roads. Collectively, these variables represent features important to natural resource managers attempting to lessen the impact of human development on the environment.

Eleven indices were created to indicate the condition of watersheds: six addressing habitat extent, four dealing with habitat disturbances, and one composite index. The six "habitat extent indices" are natural cover, river-stream corridor integrity, vegetated wetland buffer integrity, pond and lake buffer integrity, wetland extent, and standing waterbody extent. The four "habitat disturbance indices" involve dammed stream flowage, channelized stream flowage, wetland disturbance, and habitat fragmentation by roads. The last index—"composite natural habitat integrity index"—is comprised of the weighted sum of all the other indices, with the disturbance indices subtracted from the habitat extent indices to yield an overall natural habitat integrity score for a watershed or subbasin for comparison with others. All indices have a maximum value of 1.0 and a minimum value of zero. For the habitat extent indices, the higher the value, the more habitat available. For the disturbance indices, the higher the score, the more disturbance.

The indices do not include certain qualitative information on the condition of existing habitats as reflected by the presence, absence, or abundance of invasive species or the degree of forest fragmentation, for example. The level of effort required to inject more qualititative data into the analysis may preclude the rapid assessment objective for this remotely-sensed ecological assessment. Weighting of natural woodlands versus commercial forests may be a practical option, but it was not explored. Another consideration would be establishment of minimum size thresholds to determine what constitutes a viable natural habitat for analysis (e.g., 0.04 hectare/0.1 acre patch of forest or 0.4 ha/1 acre minimum?). Other indices may also need to be developed to further aid in water quality assessments, such as an index of ditching density (for agricultural and silvicultural lands).

3.3. Habitat extent indices

These indices mainly attempt to provide an assessment of the amount of natural vegetation or natural habitat that occurs in a watershed, including strategic locations important for water quality and aquatic/wetland wildlife.

The *Natural Cover Index* (I_{NC}) is based on the proportion of a watershed that is represented by natural vegetation; it provides information on how much of a watershed is not developed and may be serving as important wildlife habitat.

$$I_{NC} = \frac{A_{NV}}{A_W},$$

where A_{NV} (area in natural vegetation) equals the area of the watershed's land surface in natural vegetation and A_W is the total land surface area of the watershed.

The *River-Stream Corridor Integrity Index* (I_{RSCI}) provides information on the status of vegetated riparian corridors.

$$I_{RSCI} = \frac{A_{VC}}{A_{TC}}$$

where A_{VC} (vegetated river-stream corridor area) is the area of the river-stream corridor that is colonized by natural vegetation and A_{TC} (total river-stream corridor area) is the total area of the river-stream corridor. The width of the river-stream corridor may be varied to suit project goals, but a 200-meter corridor (100 m on each bank of the river or stream) is the recommended minimum. Note that these corridors include banks of impounded sections of rivers and streams, so that a continuous river or stream corridor is evaluated. It might be worthwhile to separate linear segments (streams) from polygonal segments (rivers) as the latter may be more frequently surrounded by wetland rather than upland, especially in tidal reaches. For the Nanticoke watershed, the index was applied to nontidal rivers for assessing the composite natural habitat integrity index, but it may be applied to tidal portions when evaluating the entire watershed. Also, if desirable, impounded sections could be culled out and included in the pond/lake buffer integrity index.

The *Wetland Buffer Integrity Index* (I_{WB}) provides information on vegetated buffers around vegetated wetlands that are important for wildlife and for reducing impacts to wetland water quality from surface runoff.

$$I_{WB} = \frac{A_{VB}}{A_{TB}},$$

where A_{VB} (area of vegetated buffer) is the area of the buffer zone that is in natural vegetation and A_{TB} is the total area of the buffer zone (excluding water). Buffer width can be varied according to regional needs and conditions. For the Nanticoke watershed, a 100 m buffer (recommended minimum) was examined.

The *Pond and Lake Buffer Integrity Index* (I_{PLB}) documents the extent of natural vegetation in a zone surrounding these waterbodies that is important for both water quality and aquatic life (buffer from impacts associated with adjacent urban/suburban development, agriculture, and other human actions). Buffer width can be varied according to regional needs and conditions; 100 m buffer was used for the Nanticoke study.

$$I_{PLB} = \frac{A_{VB}}{A_{TB}},$$

where A_{VB} (area of vegetated buffer) is the area of the buffer zone that is in natural vegetation and A_{TB} is the total area of the buffer zone.

The *Wetland Extent Index* (I_{WE}) compares the current extent of vegetated wetlands (excluding nonvegetated, open-water wetlands) to the estimated historic extent.

$$I_{WE} = \frac{A_{CW}}{A_{HW}}$$

where A_{CW} is the current area of vegetated wetland in a watershed and A_{HW} is the historic vegetated wetland area in the watershed. The I_{WE} is an approximation of the extent of the original wetland acreage remaining in a watershed. Farmed wetlands are included where cultivation is during droughts only, since they are likely to support natural vegetation during normal and wet years. Where farmed wetlands are cultivated more or less annually such as in much of the Northeast region, they are not included in the area of vegetated wetland, since they lack natural vegetation in most years and only minimally function as wetland. Commercial cranberry bogs are excluded since they are not considered natural habitats.

The Standing Waterbody Extent Index (I_{SWE}) addresses the current extent of standing fresh waterbodies (e.g., lakes, reservoirs, and open-water wetlands–ponds) in a watershed relative to the historic area of such features.

$$I_{SWE} = \frac{A_{CSW}}{A_{HSW}},$$

where A_{CSW} is the current standing waterbody area and A_{HSW} is the historic standing waterbody area in the watershed. From a practical standpoint, this index is estimated. For most areas, including the Nanticoke watershed, a net gain in ponds and impoundments has occurred over time. Every national wetland trend study for the US (Frayer et al., 1983; Tiner, 1984; Dahl and Johnson, 1991; Dahl, 2000) has shown an increase in pond area as ponds are constructed for a multitude of purposes. For these situations, the I_{SWE} value is 1.0+ indicating a gain in this aquatic resource and no specific calculations necessary; a value of 1.0 is then used for determining the Composite Natural Habitat Integrity Index for the study area. In geographic areas where significant loss of open water has occurred, an estimate will need to be derived from available sources (including historic maps).

3.4. Habitat disturbance indices

A set of four indices have been developed to address alterations to natural habitats. For these indices, a value of 1.0 is assigned when all of the streams or existing wetlands have been modified.

The *Dammed Stream Flowage Index* (I_{DSF}) highlights the direct impact of damming on rivers and streams in a watershed.

$$I_{DSF} = \frac{L_{DS}}{L_{TS}},$$

where L_{DS} is the length of perennial streams impounded by dams (combined pool length) and L_{TS} is the total length of perennial streams in the watershed (including the length of in-stream pools). Note that the total stream length used for this index will be greater than that used in the channelized stream length index, since the latter emphasizes existing streams and excludes dammed segments. For the Nanticoke project, this index was applied only to linear streams (not rivers); in the future, this index should be expanded to include the entire river-stream length (i.e., the Dammed River-Stream Flowage Index).

The *Channelized Stream Length Index* (I_{CSL}) is a measure of the extent of stream channelization within a watershed.

$$I_{CSL} = \frac{L_{CS}}{L_{TS}}$$

where L_{CS} is the channelized stream length and L_{TS} is the total stream length for the watershed. The index will usually emphasize perennial streams as it did for the Nanticoke study, but it could include intermittent streams, if desirable. The total stream length does not include the length of: (1) artificial ditches excavated in farm fields and forests, (2) dammed sections of streams, and (3) polygonal portions of rivers. Channelization of the latter may be represented by a separate index or preferably combined with this index to form a Channelized River-Stream Length Index.

The *Wetland Disturbance Index* (I_{WD}) focuses on alterations (diking, impounding, ditching, excavating, or farming) within existing wetlands.

$$I_{WD} = \frac{A_{DW}}{A_{TW}},$$

where A_{DW} is the area of disturbed or altered wetlands and A_{TW} is the total wetland area in the watershed. Wetlands are represented by both vegetated and nonvegetated (e.g., shallow ponds) types including natural and created wetlands. Since the focus of analysis is on natural habitat, diking and excavating wetlands (or portions thereof) are viewed as adverse actions. It is recognized that many such wetlands serve as valuable wildlife habitats (e.g., waterfowl impoundments), despite such alteration.

The *Habitat Fragmentation/Road Index* (I_{HF}) attempts to address habitat fragmentation by roads and reflects degradation of water quality, and terrestrial and aquatic ecosystems from associated development.

$$I_{HF} = \frac{A_R}{A_W} \times 16,$$

where A_R is the area of roads (interstates, state/county and other roads) and A_W is the total land area of the watershed. Since road area will never equal 100% of a watershed and all the other indices have a maximize value of 1.0, a multiplier was needed to increase the index value to a maximum level of 1.0 for use in the composite natural habitat integrity index. A multiplier of 16 was established based on examination of road density in a portion of Jersey City, NJ, an urban area with extremely high road density (0.06 road area/city area). Multiplying the road area by 16 would yield an index value near 1.0 (the estimated maximum road area/unit area). If this multiplier yields an index value greater than 1.0, use 1.0 for the value when computing the composite index. (Note: This would only happen if an entire watershed or subbasin had higher road density than the portion of Jersey City, NJ sampled which would be a rare situation.) If the composite index is not calculated, then the index could stand alone without the multiplier.

While limited to road fragmentation, this index serves a surrogate for habitat fragmentation and degradation. Two watersheds may have the same amount of natural habitat, but one may have many roads and the other few. Although not the only human action that causes habitat fragmentation, road density is closely correlated to degraded ecosystems (Miller et al., 1996; Quigley and Arbelbide, 1997; Forman and Alexander, 1998; Forman, 2000; Trombulak and Frissell, 2000). More detailed assessments of habitat fragmentation, including mean patch size, patch density, edge density, and total core area, could be performed, if necessary.

For the Nanticoke project, the following estimated road widths were used to calculate A_R: interstates (two lanes/direction)—12.1 m, state roads (two lanes; 1 lane/direction)—12.1 m, county/local roads (two lanes; 1 lane/direction)—11.5 m, and dirt roads (two lanes)—6.7 m (Kevin Canning, Delaware Department of Transportation, personal communication 2003). Road widths were applied to lengths of each road type to calculate the area of roads for the study area.

3.5. Composite Natural Habitat Integrity Index

The *Composite Natural Habitat Integrity Index* (I_{CNHI}) is a combination of the preceding indices that seeks to express the overall condition of a watershed in terms of the relative intactness of natural plant communities and waterbodies, without reference to specific qualitative differences. From a practical standpoint, the value of calculating a composite index is that it yields a single number that can represent the condition of natural habitats for a watershed for use in comparison with other watersheds. Three significant drawbacks must be noted: (1) the actual number depends on the weighting scheme, (2) the weighting schemes may be subjective (as in the present study), and (3) reducing all the indices to a single number may lead to overlooking the significance of the individual indices. It should therefore be emphasized that the scores for the other indices are valuable indicators themselves and whenever a composite index is reported, the scores for individual indices should also be stated. Variations of I_{CNHI} may be derived by considering buffer zones of different widths (e.g., $I_{CNHI\,100}$ or $I_{CNHI\,200}$) and by applying different weights to individual indices or by separating or aggregating various indices (e.g., stream corridor integrity index, river corridor integrity index, or river-stream corridor integrity index). Users can modify these values according to their needs.

For the Nanticoke watershed study, the following formula was used:

$$\begin{aligned} I_{CNHI\,100} = {} & (0.5 \times I_{NC}) + (0.125 \times I_{RSCI\,200}) \\ & + (0.125 \times I_{WB\,100}) + (0.05 \times I_{PLB\,100}) \\ & + (0.1 \times I_{WE}), + (0.1 \times I_{SWE}) \\ & - (0.1 \times I_{DSF}) - (0.1 \times I_{CSL}) \\ & - (0.1 \times I_{WD}) - (0.1 \times I_{HF}), \end{aligned}$$

where the condition of a 100 m buffer is used throughout.

In this formula, the natural cover index was given as much weight as all the habitat extent indices combined, and the each of the disturbance indices was assigned a weight of 0.1. Others may choose to devise other weighting schemes or simply omit the composite index as the individual indices provide more specific assessments of habitat condition. When comparing two or more watersheds, the same formula must be used for obvious reasons.

4. Results

From the data collected and analyzed, a series of maps can be prepared that highlights numerous features. These features include wetland type, extent of natural habitat vs. developed and agricultural lands (Fig. 2), the nature of buffers around wetlands, ponds, rivers, and streams, altered wetlands, potential wetland and stream buffer restoration sites, and the extent of stream channelization and damming.

The values of the eleven indices for Delaware's Nanticoke River are given in Table 1. Since a pristine watershed has an composite index value of 1.0 for natural habitat integrity, the Nanticoke's composite index of 0.29 indicates a significantly stressed watershed due to human actions. Examination of the individual indices shows where the stresses are. Nearly two-thirds of the vegetated wetland buffer and 61% of the pond and lake buffers have been developed in this largely agricultural watershed. All the ponds are artificial and most are probably surrounded by cropland. The index values show that this watershed has lost 59% of both its natural habitat and its original wetland area, while 79% of its streams have been channelized and 71% of its current wetlands are altered by ditches, diking, excavation, or farming. There were 2694.4 km of roads in the watershed for a road density of 2.13 km/km^2 (high density according to Quigley et al. (2001)). This high road density led to a considerable habitat frag-

Table 1
Scores for natural habitat integrity indices for the Nanticoke watershed

Index (code)	Computation	Score
Natural cover (I_{NC})	51813 ha of natural vegetation/126582 ha of land in watershed	0.41
River-stream corridor Integrity ($I_{RSCI200}$)	11369 ha of natural vegetation/19143 ha of buffer	0.59
Vegetated wetland Buffer (I_{WB100})	11647 ha of natural vegetation/32125 ha of upland buffer	0.36
Pond/lake buffer (I_{PLB100})	996 ha of natural vegetation/2545 ha of upland buffer	0.39
Wetland extent* (I_{WE})	24091 ha of wetlands/58255 ha of hydric soil map units	0.41
Standing waterbody Extent (I_{SWE})	Historic gains from impoundment and pond construction	1.0+
Dammed stream Flowage (I_{DSF})	28.2 km dammed/918.9 km of perennial nontidal rivers and streams	0.03
Channelized stream Length (I_{CSL})	700.5 km of channelized/890.7 km of nontidal rivers and streams	0.79
Wetland disturbance (I_{WD})	22076 ha of altered wetlands/31308 ha of wetlands	0.71
Habitat fragmentation By roads (I_{HF})	3081 ha of roads/126582 ha of area × 16	0.38
Composite (I_{CNHI})**	(0.5 × 0.41) + (0.125 × 0.59) + (0.125 × 0.36) + (0.05 × 0.39) + (0.1 × 0.41) + (0.1 × 1.0) − (0.1 × 0.03) − (0.1 × 0.79) − (0.1 × 0.71) − (0.1 × 0.38) = 0.485 − 0.191 =	0.29

All buffer widths are 100 m; buffer area does not include open water.
* Estimated from hydric soil data available for 85% of the watershed.
** $I_{CNHI} = (0.5 \times I_{NC}) + (0.125 \times I_{RSCI200}) + (0.125 \times I_{WB100}) + (0.05 \times I_{PLB100}) + (0.1 \times I_{WE}) + (0.1 \times I_{SWE}) - (0.1 \times I_{DSF}) - (0.1 \times I_{CSL}) - (0.1 \times I_{WD}) - (0.1 \times I_{HF})$.

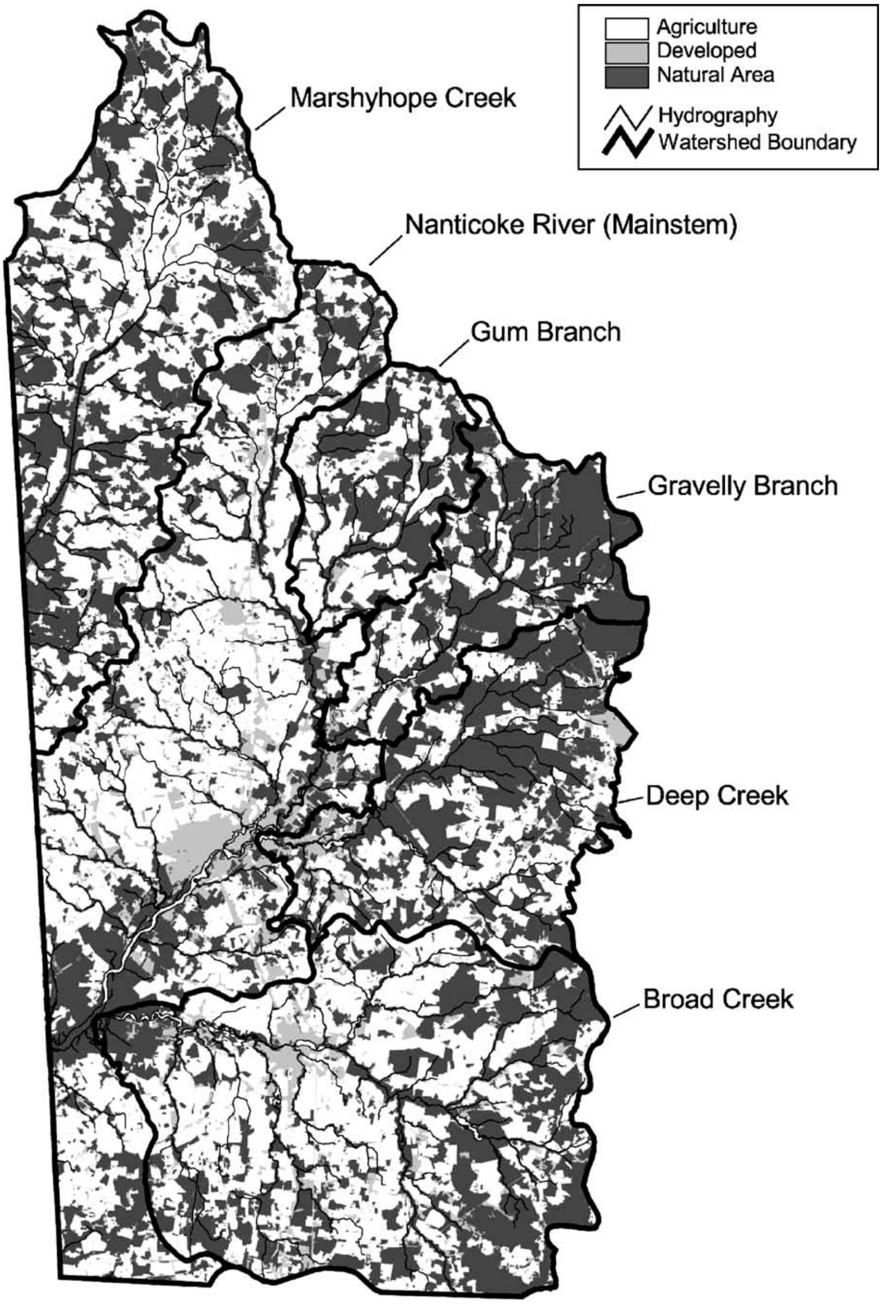

Fig. 2. Extent of developed, agricultural, and natural habitat areas in Delaware's Nanticoke River watershed.

mentation. Forty-one percent of the land in the watershed is covered with natural vegetation, while 50% is in agriculture, and 9% is developed. If the response of this watershed to farming and development is similar to that of Wisconsin watersheds studied by Wang et al. (1997), significant degradation of water quality and aquatic habitat can be expected for the Nanticoke, since they found that watersheds with more than half

Table 2
Summary statistics for land use and landcover in subbasins of the Nanticoke watershed

Subbasin	Area of land use/cover types in hectares (percent of total subbasin)			
	Developed (%)	Agriculture (%)	Natural vegetation* (%)	Water (%)
Broad Creek	2801 (9)	15484 (51)	11999 (39)	395 (1)
Deep Creek	1519 (9)	6336 (39)	8424 (51)	147 (1)
Gravelly Branch	607 (6)	3040 (31)	6200 (63)	57 (<1)
Gum Branch	422 (5)	3754 (48)	3629 (46)	18 (<1)
Marshyhope Creek	1017 (4)	13755 (54)	10418 (41)	50 (<1)
Nanticoke Mainstem	4646 (12)	21376 (57)	11143 (30)	564 (1)

* Includes pine plantations and other commercial forests.

Table 3
Condition of the 100 m buffer along streams in each subbasin for five cases: (1) perennial rivers and streams only (excluding tidal reach), (2) perennials and tidal, (3) perennials, intermittents, and ditches, (4) perennials including tidal, plus intermittents and ditches, and (5) perennial streams only. Buffer data address the land portion of the buffer and do not include open water areas

Subbasin	Percent of Buffer in "natural vegetation"				
	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 4 (%)	Case 5 (%)
Broad Creek	58	59	42	43	59
Deep Creek	65	64	48	48	65
Gravelly Branch	80	80	61	61	81
Gum Branch	73	73	49	49	73
Marshyhope Creek	54	54	37	37	54
Nanticoke Mainstem	51	53	32	34	50

of their acreage in agriculture experienced significant declines of in-stream habitat quality versus watersheds with less agriculture and more forest.

Applying the indices to subbasins within the Nanticoke watershed offers a comparative analysis useful for detecting problems within the watershed. Tables 2–8 summarize vital statistics for each subbasin. Wetlands represent 17–37% of the subbasins (Broad Creek—21%; Deep Creek—29%; Gravelly Branch—37%; Gum Branch—28%; Marshyhope Creek—32%; Nanticoke Mainstem—17%). The road density in each subbasin was the following: Broad Creek—2.16 km/km^2, Deep Creek—2.06, Gravelly Branch—2.08, Gum Branch—1.86, Marshyhope Creek—1.66, and Nanticoke Mainstem—2.52. These densities are all considered high by Quigley et al. (2001). From the indices and land use/cover data generated for the entire watershed, it is apparent that this watershed is heavily impacted by human activities, namely agriculture (Fig. 2). While all subbasins appeared to be significantly stressed due to land use, channelization, wetland alteration, and habitat fragmentation, Gravelly Branch, with a composite index value of 0.47, appears to be in noticeably better condition than the other subbasins (Table 8).

Table 4
Percent of the 100 m buffer along ponds/lakes and wetlands that are in "natural vegetation" for each subbasin

Subbasin	Percent of Buffer in "natural vegetation"	
	Pond/lake buffer (%)	Wetland buffer (%)
Broad Creek	42	40
Deep Creek	41	41
Gravelly Branch	57	49
Gum Branch	44	46
Marshyhope Creek	37	28
Nanticoke Mainstem	34	31

5. Discussion

Human alteration of the landscape is a major force adversely impacting aquatic and other wildlife habi-

Table 5
Disturbance values for streams and extent of ditching in each subbasin of the Nanticoke river watershed

Subbasin	Channelized stream (% of total)* (km)	Flowing perennial streams* (km)	Dammed stream (% of total)** (km)	Perennial streams** (km)	Ditches (km)
Broad Creek	123.7 (59)	209.8	12.8 (6)	221.9	402.9
Deep Creek	112.2 (88)	128.3	5.0 (4)	131.7	230.2
Gravelly Branch	59.5 (89)	67.0	5.3 (7)	72.0	123.2
Gum Branch	56.0 (96)	58.1	–	58.1	88.3
Marshyhope Creek	176.5 (94)	187.8	–	187.8	522.9
Nanticoke Mainstem	172.2 (75)	229.0	5.0 (2)	233.9	436.6

Note that totals do not always add up due to computer round-off procedures.
* Excludes tidal reach, impounded segments, and intermittent streams.
** Excludes tidal reach and intermittent streams.

Table 6
Extent of altered wetlands in each subbasin

Subbasin	Ditched area (ha)	Farmed area (ha)	Impounded area (ha)	Excavated area (ha)	Total wetland area altered (% of wetlands)
Broad Creek	3519	284	81	97	3980 (63)
Deep Creek	3201	218	47	42	3508 (73)
Gravelly Branch	1953	70	25	10	2058 (56)
Gum Branch	1762	16	3	11	1792 (81)
Marshyhope Creek	6543	385	<1	15	6944 (87)
Nanticoke Mainstem	3320	367	14	94	3795 (61)

tat through outright destruction and degradation. Current species extinction rates surpass those determined from the geologic record (Probst and Crow, 1991). The amount, type, and extent of natural habitat are important environmental indicators for natural resource managers and conservationists. Fragmentation of remaining habitat by roads and other development creates significant problems for maintaining biological

Table 7
Extent of roads (area in ha and length in km) in each subbasin and percent of subbasin covered by roads (interstate, state, county/local, and dirt roads)

Subbasin	Area and length of roads					
	Interstate area (length)	State area (length)	County/local area (length)	Dirt area (length)	Total area (length)	Percent of basin
Broad Creek	34.2 (28.2)	7.9 (6.6)	702.2 (610.6)	6.4 (9.6)	750.7 (655.0)	2.5
Deep Creek	6.4 (5.3)	36.0 (29.8)	328.5 (285.7)	9.3 (13.8)	380.2 (334.6)	2.3
Gravelly Branch	0.0 (0)	14.5 (12.0)	199.7 (173.6)	12.8 (19.1)	227.0 (204.7)	2.3
Gum Branch	0.0 (0)	0.0 (0)	164.0 (142.5)	1.8 (2.7)	165.8 (145.2)	2.1
Marshyhope Creek	9.0 (7.4)	10.1 (8.3)	454.9 (395.5)	3.9 (5.9)	477.9 (417.1)	1.9
Nanticoke Mainstem	77.0 (63.6)	17.2 (14.2)	980.8 (852.9)	4.6 (6.9)	1079.6 (937.6)	2.9

Table 8
Remotely-sensed natural habitat integrity indices for each subbasin in the Delaware portion of the Nanticoke River watershed

Subbasin	Remotely-sensed Natural Habitat Integrity Indices										
	I_{NC}	$I_{RSCI200}$	I_{WB100}	I_{PLB100}	I_{WE}	I_{SWE}	I_{DSF}	I_{CSL}	I_{WD}	I_{HF}	$I_{CNHI100}$
Broad Creek	0.40	0.59	0.40	0.42	0.45	1.0	0.06	0.59	0.63	0.40	0.32
Deep Creek	0.52	0.64	0.41	0.41	0.43	1.0	0.04	0.87	0.73	0.37	0.35
Gravelly Branch	0.63	0.80	0.49	0.57	0.52	1.0	0.07	0.89	0.56	0.37	0.47
Gum Branch	0.46	0.73	0.46	0.44	0.35	1.0	0.00	0.96	0.81	0.34	0.33
Marshyhope Creek	0.41	0.54	0.28	0.37	0.38*	1.0	0.00	0.94	0.87	0.30	0.26
Nanticoke Mainstem	0.30	0.53	0.31	0.34	0.36*	1.0	0.02	0.75	0.61	0.46	0.23

Note: The River-Stream Corridor Index includes the tidal reach.

* Calculations based on part of subbasin where digital soils data were available (37% of Marshyhope Creek subbasin and 92% of the Nanticoke River Mainstem subbasin).

diversity (Harris, 1984; Saunders et al., 1991). Dove (2001) provides an extensive literature review on assessing the impact of landscape changes on habitat suitability for birds. Out of 15 variables, Robbins et al. (1989) identified percent forest as most often related to relative abundance of birds, while Robinson et al. (1995) detected a stronger correlation between percent forest cover and nesting for many birds than correspondence with percent forest interior and mean forest patch size. Dove (2001) recommended that patch variables (e.g., mean patch size, patch density, edge density, and total core area) be evaluated rather than rely on a single variable such a percent forest cover, but recognized that use of a broader set of landscape metrics is complicated by their high degree of correlation (e.g., multicollinearity), especially when considering habitat suitability for particular bird species. These fragmentation metrics are important for forest nesting birds and can be determined from the dataset created for the Nanticoke project.

In evaluating the ecological integrity of the interior Columbia River basin, Quigley et al. (2001) identified percent cover by several land cover types and road density as significant indicators (proxies for field-based measures related to ecological integrity). Five land cover types were evaluated: dry forest, moist forest, dry grass or shrub, agricultural land, and juniper/sagebrush. Two categories of road density were considered: low density ($<0.43\,km/km^2$) and moderate or greater density ($>0.43\,km/km^2$), although a total of six classes were evaluated (none = $<0.01\,km/km^2$, very low = 0.01–0.06, low = 0.06–0.43, moderate = 0.43–1.06, high = 1.06–2.92, and extremely high = >2.92). The $0.43\,km/km^2$ road density was determined by a previous study (Lee et al., 1997) to be a threshold for identifying areas with high aquatic habitat degradation. After reading the interior Columbia River basin paper, I added a road density index to the habitat disturbance indices, since there is a positive correlation between road density and habitat fragmentation and degradation and it could be easily determined through GIS analysis.

The US Environmental Protection Agency (2003) published state water monitoring and assessment program guidelines. Among the recommended core water quality indicators are several that can be monitored, at least in part, by remote sensing techniques: (1) condition of biological communities, (2) habitat assessment, (3) landscape conditions, and (4) wetland hydrogeomorphic settings/functions (Machung and Forgione, 2002; Tiner, 2002). The third indicator was recommended for all four categories of designated uses (aquatic life & wildlife, recreation, drinking water, and fish/shellfish consumption). The remotely-sensed natural habitat integrity indicators represent metrics that can be used by states to help monitor and assess water quality for reporting purposes.

Land management agencies also need information like those expressed by the natural habitat integrity indices. For example, the US Department of Agriculture (Committee of Scientists, 1999) in examining stewardship of national forests and grasslands recommended using ecological integrity as a measure of ecological condition to help guide management policies. Ryder and Kerr (1989) stressed the need for basin-wide environmental assessments.

Use of the remotely-sensed indicators for monitoring purposes requires periodic updates of two basic sources of information: (1) land use/cover data (including roads) and (2) wetland/deepwater habitat data (including stream data). Land use/cover data are typically updated by state natural resource agencies and possibly by federal agencies. While there are limitations to what can be interpreted through remote sensing (e.g., Tiner, 1999), current technologies should provide sufficient data to generate reasonably accurate values for the indices for many areas. Afterall the focus is on natural areas and not on specific plant communities. These indices represent useful information for resource managers to support their efforts to conserve the nation's natural resources and to advise the public on the changing status of America's natural lands. Once the digital databases are created, it should be cost-effective to update the data and produce updated findings.It must be emphasized that these remotely-sensed indices represent a first-cut at evaluating the condition of natural resources and human impacts. From the water resource standpoint, the indices do not account for direct discharges, groundwater inputs, the effects of groundwater withdrawals, or air pollution (e.g., acid rain) on aquatic systems because these impacts are not photointerpretable. Consequently, there may not be a direct relationship between these indices and existing water quality, but they do account for several important features that affect water and habitat quality. For example, appropriately managed riparian zones can potentially mitigate for poor land use practices to benefit fish and are worthy sites for restoration and protection (Wilkin and Hebel, 1982; Rabeni, 1992, respectively).

For future projects, especially for those in agricultural areas, it may be worth developing an index that addresses the extent of drained land on the landscape. Drainage ditches and tile drains "short circuit" the groundwater system and move nutrient-rich and chemical-laden surface water runoff directly to streams, resulting in significantly reduced water quality (Hamilton, 2002). This index (Drained Land Index) would be computed based on the area of drained land versus the total land area of the watershed.

6. Conclusion

Remotely-sensed indices of natural habitat integrity provide a framework for large-scale, level-one environmental assessments. Collectively, they represent a landscape-level assessment that can be readily updated and therefore can serve as an effective monitoring tool for natural resource agencies and organizations. The natural habitat integrity indices can be used to develop "habitat condition profiles" for individual watersheds at varying scales (i.e., subbasins to major watersheds) and for comparative analysis. Further investigations comparing field-based, water quality indicators (e.g., IBIs for macroinvertebrates or fish, or water quality parameters) with these landscape-level indicators may reveal correlations that can be used to improve land and water resource management. The indices can be used as one set of indicators for reports on the state-of-the environment by various levels of government or by concerned organizations (e.g., watershed associations). Data collected to generate these indices can be displayed in graphic or map form to illustrate status and trends in significant natural resources. They may also be used to identify and help prioritize potential areas for ecological restoration (e.g., wetlands, stream channels, riparian corridors, and vegetated buffer zones), while highlighting areas that need to be conserved. This type of analysis presents a holistic view of watersheds. It can help target ecological restoration of whole systems and help restorationists develop watershed-based restoration strategies. Finally, the remotely-sensed indices of natural habitat integrity provide information that can be used as an educational tool for helping the public better understand human impacts on the natural environment.

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