A FLEXIBLE INDICATOR-BASED APPROACH TO ASSESSING THE ECOLOGICAL INTEGRITY OF SOUTH CAROLINA WATERSHEDS

John A. Kupfer and Peng Gao

AUTHORS: Dr. John Kupfer, Professor, Department of Geography, University of South Carolina, Columbia, SC 29208, kupfer@sc.edu; Peng Gao, Graduate Program, Department of Geography, University of South Carolina, Columbia, SC 29208

REFERENCE: *Proceedings of the 2008 South Carolina Water Resources Conference*, held October 14-15, 2008, at the Charleston Area Event Center

Abstract. Statewide assessment and reporting on watershed conditions may be facilitated by a framework that assembles and synthesizes information on ecological characteristics into a few easily-interpretable and scientifically-defensible measures. In much the same way that indicators of domestic production, inflation and unemployment are used to describe the general state of the nation’s economy, measures of the status and condition of water resources, plants, wildlife and other natural resources can be used to assess the ecological status of ecosystems, identify potential environmental problems, and monitor and evaluate the effectiveness of protective regulations and policies.

Our objective in this study was to quantify, evaluate and map measures of ecological integrity for watersheds in South Carolina. We calculated 51 indicators related to habitat fragmentation, conservation status, demography, urbanization, pollution and vulnerability to soil loss at the scale of 8-digit hydrologic units. Principle Components Analysis (PCA) identified five significant components that explained 74.4% of the variance in indicator values among watersheds. PCA Axes 1-5 corresponded to indicator groups associated with: 1) land use and priority species occurrences, 2) urban development and human stressors, 3) agricultural development and land protection, 4) riparian land use and stream impairment, and 5) agricultural conversion and abandonment. Next, we developed integrity and vulnerability scores for each watershed in the state by selecting metrics associated with each component and categorizing watersheds on the basis of the scores, proving a simple ranking of watersheds that may also be integrated with field-based surveys to serve as the basis for monitoring and reporting on a variety of watershed-level environmental management goals.

INTRODUCTION

Ecological indicators are quantitative measures that summarize more complex aspects of ecosystem composition, structure and function. They can be used to assess environmental conditions or monitor trends through time (Cairns et al., 1993) and may provide an early warning of human-caused environmental changes or reveal ecological responses to such changes (Hunsaker and Carpenter, 1990; Dale and Beyeler, 2001). Of particular interest has been the development of indicators assessing *ecological integrity*, the ability of an ecosystem to support and maintain an adaptive community of organisms with a characteristic physical structure, species composition, diversity, and functional organization.

Watershed integrity, which involves the integrity of riparian ecosystems and their adjacent local drainages, is a central focus in water resource management, sustainable land use planning, the acquisition, protection and restoration of critical ecosystems, and the monitoring and management of threatened and endangered species (e.g., Graf, 2001). Indicators can be particularly useful in detecting and evaluating human impacts in riparian and aquatic systems because of the diverse biological, chemical, hydrological and geophysical components that must be assessed and the complex linkages between terrestrial and aquatic systems. For example, the presence of indicator species, the amount of standing or downed woody debris, or the area of impervious surface in a surrounding watershed can be indicators of a wide range of ecosystem attributes and functions that may be too complex, difficult, or expensive to quantify.

Here, our objective was to develop a flexible, indicator-based approach for quantifying watershed integrity within South Carolina. We particularly emphasized basin-wide characteristics that affect the health and viability of riparian and aquatic systems. Performing a study of this nature makes it possible to determine which watersheds are of better quality and which may need more monitoring or perhaps remediation in the future. It also provides a general sense of the integrity of the environment in South Carolina. This may have ramifications in watershed and stream policies, as well as among other research programs regarding stream and watershed health.

METHODS

No single indicator can capture all aspects of integrity for an area so it is necessary to select a suite of complementary measures that effectively characterize the entire system yet are simple enough to be efficiently quantified and correspond to stated policy goals and research and management questions. Andreasen et al. (2001) suggested that indicators of ecological integrity should be comprehensive and multi-scaled, grounded in natural history, relevant and helpful, able to integrate concerns from aquatic and terrestrial ecology, and flexible and measurable. Numerous papers conducted at regional- and sub-regional scales give examples of indicators for watershed integrity (e.g., Gergel et al., 2002), and studies of deforestation and fragmentation provide additional metrics for consideration (e.g., Kupfer, 2006).

For this research, we calculated and assembled 51 indicators for 32 8-digit hydrologic unit watersheds that had all or a portion of their drainage lying within the border of South Carolina. If the watershed extended into an adjacent state, data for the entire watershed were used. Ideally, indicators should include those that address: 1) current conditions as well as vulnerability to future changes, and 2) biophysical conditions as well as relevant socio-economic characteristics. Data thus came from a range of sources and addressed: land use and land cover (the 1992 and 2001 National Land Cover Datasets), population density and change (the U.S. Census Bureau), habitat fragmentation (the National Atlas), road networks (the 2007 TIGER/Line file data set), Superfund sites, mines, potential pollution sources and discharges (the U.S. Environmental Protection Agency: EPA), hydrography, dams and diversions (the EPA and U.S. Geological Survey), soils (the Natural Resources Conservation Service), threatened and endangered species (the U.S. Fish and Wildlife Service) and conservation areas (the Southeast Gap Analysis program). For variables associated with land use and land cover, we calculated separate measures for the watershed as a whole and for areas within a 100 meter-wide riparian buffer along the length of all streams in the watershed. To screen for variables that provided no unique information, we examined pair-wise correlation coefficients between all candidate indicators; in cases where two indicators had a coefficient exceeding 0.90 or -0.90, one was removed. This resulted in a final list of 29 indicators.

An ideal set of indicators includes complementary measures that are independent of one another but yet can collectively quantify system characteristics. To assess redundancy among indicators and arrive at a complete but parsimonious set of indicators, we used principle components analysis (PCA) to identify common axes of indicators based on their values for the 32 watersheds. After discarding PCA axes that explained little variation in watershed-to-watershed characteristics, the result was a list of indicators and their associations with each PCA axis (*see* Riitters et al. 1995 *for a similar example*).

Using the results from the PCA, we selected two sets of five indicators, one comprised of indicators that were primarily indicative of current conditions and another that included variables associated with potential vulnerability to future changes. For each of the selected indicators, watersheds were classified into five groups using natural breaks defined by the Jenks's optimization method, an approach used by Heilman et al. (2002) to examine forest intactness. Each group was assigned an ordinal score ranging from 1 (lowest integrity; highest vulnerability) to 5 (highest integrity, lowest vulnerability), providing a relative ranking of all watersheds for each measure. We then summed the indicator values to arrive at final scores that summarized each watershed's: 1) current condition or integrity, and 2) potential vulnerability to future changes.

RESULTS

PCA Results

The PCA results identified five significant components that explained 74.4% of the variance in indicator values among watersheds. PCA Axis 1 was associated with a set of land use and priority species indicators, with high axis values distinguishing basins with large amounts of erodible soils, a high interior forest cover and low agricultural cover and numbers of threatened and endangered species (Table 1). PCA Axis 2 identified a group of indicators associated with urban development and human stressors, while PCA Axis 3 distinguished basins on the basis of agricultural development and land protection. PCA Axis 4 represented a set of indicators associated with riparian land use and stream impairment, and PCA Axis 5 distinguished basins on the basis of agricultural conversion and abandonment.

Watershed Integrity and Vulnerability

For each PCA Axis, we selected one variable associated with current ecological integrity to serve as a surrogate for the entire indicator group. We specifically chose: 1) percent of the basin containing interior forest (higher values = better integrity), 2) density of Resource Conservation and Recovery Act sites (lower values = better integrity), 3) percent agricultural cover in the watershed (lower values = better integrity), 4) road density within the riparian buffer (lower values = better integrity), and 5) percent agricultural cover in the riparian buffer that reverted to forest or wetlands from 1992-2001 (higher values = better integrity). As described above, basins were assigned a value of 1 (lowest integrity) to 5 (highest integrity) for each indicator using the natural breaks method, and these five values were summed to provide an

Table 1. Results from Principle Components Analysis (PCA) of ecological indicators in 32 South Carolina watersheds. Values indicate the strength of the relationship between the indicator and the axis scores.

	PCA Axis				
	1	2	3	4	5
# priority plant spp.	**-0.90**				
# priority animal spp.	**-0.90**				
% of basin with highly erodible soils	**0.86**				
% interior forest	**0.78**				
Density of dams / stream length	**0.71**				
% high quality farmland in basin	**-0.62**				
Toxic Release Inventory sites		**0.92**			
% urban cover		**0.90**			
Density RCRA sites		**0.86**			
Population density change: 1990-2000		**0.76**			
Density NPDES sites		**0.72**			
Density of CERCLIS sites		**0.68**			
Density of PCS sites		**0.63**			
% urban cover in riparian buffer		**0.62**			
Population in 2000		**0.59**			
Road density		**0.53**			
% agricultural cover			**0.92**		
% agricultural cover in riparian buffer			**0.88**		
% of basin in GAP protection status 1-3			**-0.69**		
Density of impaired streams				**0.90**	
% forest in riparian buffer				**-0.64**	
Road density in riparian buffer				**0.66**	
% natural cover converted to human land use: riparian				**0.54**	
% agricultural cover converted to natural cover: riparian					**0.72**
% natural cover converted to human land uses					**-0.64**
% agricultural cover converted to natural cover					**0.81**
Eigenvalue	**8.94**	**4.70**	**4.39**	**2.37**	**1.92**
% Variance Explained	**29.8**	**15.7**	**14.6**	**7.9**	**6.4**
Cumulative Variance	**29.8**	**45.5**	**60.1**	**68.0**	**74.4**

Table 2. Calculation of watershed integrity values for three basins based on rank orders for five ecological indicators. Indicators are: 1) % of the basin classified as interior forest, 2) density of Resource Conservation and Recovery Act sites, 3) % agricultural cover in the watershed, 4) road density within the riparian buffer, and 5) % agricultural cover in the riparian buffer that reverted to forest or wetlands from 1992-2001.

	Ecological Indicator					
	1	2	3	4	5	Total
Lynches River	1	4	1	3	2	11
Stevens River	4	5	4	4	4	21
Wateree River	3	3	4	3	3	16

overall integrity value ranging from 5-25 (Table 2). These were mapped to display the relative integrity of watersheds throughout the state (Figure 1).

We similarly selected five indicators associated with watershed vulnerability to future change, including: 1) number of threatened and endangered fish and wildlife species (lower values = lower vulnerability), 2) percent of the basin with highly erodible soils (lower values = lower vulnerability), 3) population density change from 1990-2000 (lower values = lower vulnerability), 4) percent of the basin which has permanent protection from conversion of natural land cover (GAP management status 1-3) (higher values = lower vulnerability), and 5) percent of forested area in the basin that was converted to agriculture or development from 1992-2001 (higher values = higher vulnerability). Each basin was again assigned a value of 1 (highest vulnerability) to 5 (lowest vulnerability) for each indicator, and the values were summed to produce a measure of relative vulnerability to changes in integrity for watersheds throughout the state (Figure 2).

Finally, categorizing watersheds into high or low

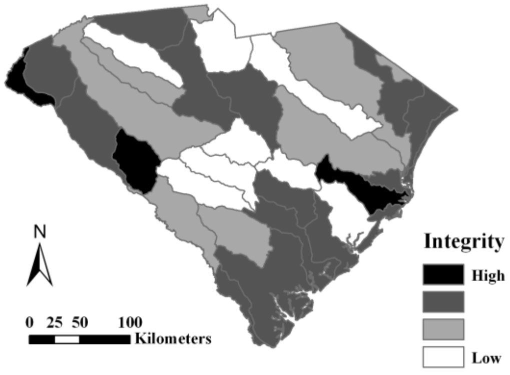

Figure 1. Map of current watershed integrity scores based on cumulative ordinal ranks for five indicators of all watersheds in South Carolina.

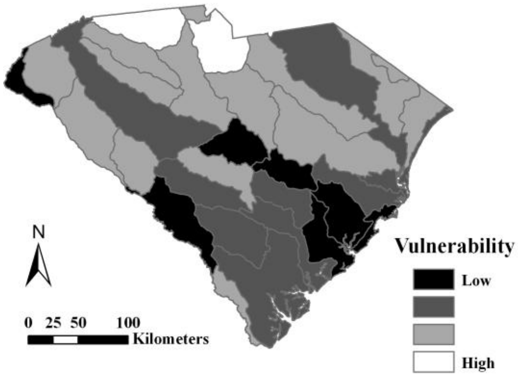

Figure 2. Map of watershed vulnerability to future changes. Scores are based on ordinal ranks for five indicators for all watersheds in South Carolina.

classes in terms of current integrity and vulnerability (high = watersheds with above median indicator values) revealed some general patterns in watershed conditions (Figure 3). For example, watersheds with the highest current integrity and lowest vulnerability to change are generally Coastal Plain systems, particularly those associated with the ACE (Ashepoo-Combahee-Edisto) Basin. Of perhaps greater interest from a management standpoint are those watersheds with high integrity but also high vulnerability: the Middle and Upper reaches of the Savannah, the Broad-Wateree system, and the Little Pee Dee and Waccamaw Rivers.

DISCUSSION AND CONCLUSIONS

In this paper, we have presented the results of just one potential set of analyses of watershed integrity based on the selection of a set of indicators. However, the implementation of these indicators is flexible such that stakeholders can examine individual indicators of interest or composite the indicators by summing / averaging the relative values for any desired subset of selected indicators to create an overall relative index of ecosystem integrity. Indeed, a long-term objective of this research is to implement the indicators through both an interactive, web-based interface and through standard GIS query processes, allowing decision makers to compare the relative integrity of different watersheds and weigh the effects of potential management actions. Further, although the results of these analyses were summarized by 8-digit watersheds, the methodology is flexible in that it can be implemented at finer or coarser spatial scales, depending on the needs of potential end users.

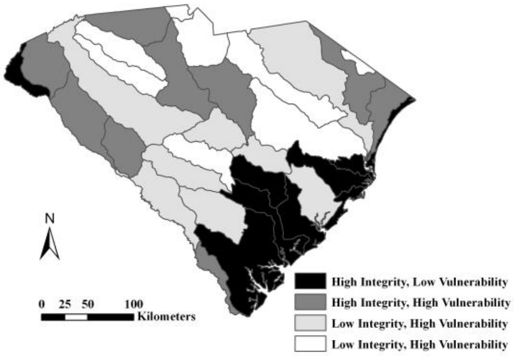

Figure 3. Classification of South Carolina watersheds on the basis of the integrity and vulnerability indicator values.

LITERATURE CITED

Andreasen, J.K., R.V. O’Neill, R. Noss and N.C. Slosser. 2001. Considerations for the development of a terrestrial index of ecological integrity. *Ecological Indicators* 1: 21-35.

Cairns, J., P.V. McCormick and B.R. Niederlehner. 1993. A proposed framework for developing indicators of ecosystem health. *Hydrobiologia* 236: 1-44.

Dale, V.H. and S.C. Beyeler. 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators* 1: 3-10.

Gergel, S.E., M.G. Turner, J.R. Miller, J.M. Melack and E.H. Stanley. 2002. Landscape indicators of human impacts to riverine systems. *Aquatic Sciences* 64: 118-128.

Graf, W.L. 2001. Presidential Address: Damage control: Restoring the physical integrity of America’s rivers. *Annals of the Association of American Geographers* 91: 1-27.

Heilman, G.E., J.R. Strittholt, N.C. Slosser and D.A. Dellasala. 2002. Forest fragmentation of the conterminous United States: assessing forest intactness through road density and spatial characteristics. *BioScience* 52: 411-422.

Hunsaker, C.T. and D.E. Carpenter (eds.). 1990. *Environmental Monitoring and Assessment Program: Ecological Indicators*. Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC.

Kupfer, J. 2006. National assessments of forest fragmentation in the US. *Global Environmental Change* 16: 73–82.

Riitters, K.H., R.V. O’Neill, C.T. Hunsaker, J.D. Wickham, D.H. Yankee, S.P. Timmons, K.B. Jones and B.L. Jackson. 1995. A factor analysis of landscape pattern and structure metrics. *Landscape Ecology* 10: 23-39.