

**CLASSIFICATION AND PRIORITIZATION OF WATERSHEDS
FOR MONITORING, PROTECTION, AND RESTORATION
A Research and Outreach Prospectus of Advanced Mathematical, Statistical, and
Computational Approaches Using Pertinent Geospatial Information and Remote Sensing
CHARACTERIZATION, EVALUATION, AND VALIDATION OF
WATERSHED CHARACTERIZATION MODEL AND WATERSHED
PRIORITIZATION MODEL**

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Prospectus Summary

Natural resource managers need to be able to put watersheds into categories for several reasons, including identifying reference conditions, understanding the types of environmental degradation, designing monitoring studies, and narrowing the restoration options. For example, a defensible “bundling” of watersheds according to their characteristics, problems, and restoration feasibilities may allow “off-the-shelf” TMDL plans. We will develop, validate, and apply a hierarchical, geographically-independent classification of watersheds based on pre-existing environmental data. Although focused on the Mid-Atlantic Highlands, our scheme will be useful anywhere. Our project has three major parts. (1) Using multivariate statistics, we will build a Characterization Model to classify watersheds based on their natural features and observed stressors. (2) Using linear ordering and echelon analysis, we will build a Prioritization Model to classify basins according to disturbance, susceptibility to impairment, and feasibility of restoration, where the last includes technical and economic measures. Both the Characterization and Prioritization models will be validated with in-stream and terrestrial biotic data sets (e.g., IBIs). (3) We will compare the results of our taxonomies of watershed types and priorities to the findings of other classifications. Products include: synoptic GIS coverages of environmental data for the Mid-Atlantic Highlands, a model graphical and statistical process for classifying watersheds by their features and restoration priorities, a taxonomy of Mid-Atlantic watersheds, and a set of monitoring and restoration options for each watershed class that can assist managers in the development and implementation of TMDL plans.

Prospectus Research Description

1. Objectives

Introduction

An important purpose for a watershed classification system is to “support the design of efficient monitoring strategies, diagnose the causes of biological impairment, and prioritize watersheds for restoration.” Such a system should include conceptual models to explain and predict the relationships between land-use activities and the biological conditions within a watershed. We propose to develop and link conceptual and empirical watershed Characterization and Prioritization models for the Mid-Atlantic Highlands. We will validate a classification system that groups watersheds with similar physical characteristics and ecological stressors to provide scientifically defensible information and lead to “off-the-shelf” monitoring and management practices. This will provide managers with efficient tools to prioritize options and defend their decisions. To maximize the usefulness of our classification system, we will design a system that is hierarchical (for ease in setting management goals) and geographically independent (i.e., relevant to any temperate watershed).

The degradation of surface waters has spawned responses to remediate both point and nonpoint pollution [e.g., Clean Water Act of 1972 (CWA), Chesapeake Bay Agreement]. Through implementation of the CWA and derivative state laws, “fishable and swimmable” conditions have been restored in some areas. The original intent of the CWA “to restore and maintain the chemical, physical, and biological integrity of the Nation’s waters” [CWA 1972, Sec. 101(a)] is increasingly addressed as the USEPA encourages states to unify all three categories equally under a watershed umbrella. Threats to life, both human and other, continue to be major issues of concern. We, therefore, assume that the ultimate endpoints of management are to protect, maintain, and enhance both biological integrity and human quality of life in the study area.

Background Literature

Studies show conflicting results about the influence of catchment-wide conditions (Roth et al. 1996, Wang et al. 1997, Hunsaker and Levine 1995) versus riparian (Richards et al. 1996, Gregory et al. 1991) and local conditions (Hawkins et al. 2000) on in-stream biotic communities. Some of these differences have been attributed to studies’ scale (Lammert et al. 1997) and to the scale at which the driving causes are functioning (Frissel et al. 1986). Strong interactions between basin and local conditions exist, particularly in terms of channel morphology (Richards et al. 1997) and physical habitat (Imhof et al. 1996). Our approach considers surface waters and uplands, as well as their interface (Richards et al. 1996, Wardrop and Brooks 1998).

The ecological health of a watershed, then, reflects attributes of the transmission, storage, and release of water. The influences of climate, soils, and topography, for example, drive the channel’s hydrologic and fluvial geomorphologic processes (Leopold et al. 1964, Lotspeich 1980). These processes in turn affect water quality, flow regime, physical habitat, food and energy sources, and biotic interactions (Karr and Chu 1998), which collectively affect biotic

communities. The contributions of each of these factors will likely vary among ecoregions. For example, in the Southwest, groundwater and riparian vegetation may play larger roles in determining watershed condition than in the Adirondacks. To classify watersheds, we must identify the relative contributions of each attribute to the scale of interest which in turn will help managers understand the costs and benefits of management options (Claessen et al. 1994, Bradshaw 1998, Hawkins et al. 2000).

Based on indicators of biotic integrity, many Highlands streams are in poor condition (USEPA 2000). Both the abiotic (Poff and Ward 1990, Johnson et al. 1997) and biotic (Harding et al. 1998) conditions of an aquatic community are affected by historic and current characteristics of its basin. Within the Highlands, some of the main stressors to local streams are excess sediment, riparian degradation, mine drainage, acid deposition, excess nutrients, and exotic species (USEPA 2000). Region-wide stressors include loss of riparian habitat, farming in riparian areas and on steep slopes, road crossings, and forest fragmentation (Jones et al. 1997). Most streams are degraded by more than one stressor (Karr 1981, Minshall et al. 1983).

In light of multiple stressors, classification tools are useful to managers. These tools can be geographically dependent or -independent, hierarchical or non-hierarchical, incorporate a fixed or sliding scale, and based on structure or function (Detenbeck et al. 2000). Examples of hierarchical, geographically dependent classifications include ecoregions (Omernik 1987, Bryce and Clarke 1996), aquatic regions (Maxwell et al. 1995), and functional groupings (Hawkins et al. 2000). Maxwell et al. (1995) grouped watersheds by indicators of watershed function, including geoclimate, zoogeographic pattern, watershed morphology, and disturbance history. To reveal function in a geographically dependent scheme, The Nature Conservancy developed a nested framework for biotic and abiotic aquatic classification based on two landscape-level regions and two levels of smaller-scale habitat characterization (Lammert et al. 1997).

Geographically independent, hierarchical classifications rely on stream hydrogeomorphic (HGM) structure (Rosgen 1996) and wetland HGM function (Brinson 1993). Imnof et al. (1996) developed a scheme based on physical processes that drive fish abundance. Other examples classify watersheds based on water chemistry and/or temperature (e.g., Richards 1990, Seelbach et al. 1997, Momen and Zehr 1998), and hydrology and geomorphology and/or sediment size (e.g., Whiting and Bradley 1993, Seelbach et al. 1997).

Several *a posteriori* classifications attempt to assess relative risks. For example, one scheme generates a risk index for watersheds based on aerial photos, topographic maps, and rapid bioassessment (Bryce et al. 1999). Another approach maps predicted risk of drought damage due to changes in water withdrawal and soil and groundwater conditions (Claessen et al. 1994).

Ecosystems are also classified by measures of ecological resistance, or the ability of the system to withstand perturbation (Forman and Godron 1986). Resistance, plus resilience, which is the ability of a system to return to its original state after a disturbance (Gunderson 2000), are the primary determinants of ecosystem stability. Aquatic systems are dynamic, but if resistance is overwhelmed by disturbance, then its average long-term state changes (Reeves et al. 1995). Poff and Ward (1990) suggested that because stream communities reflect the history of disturbance

they are resistant. Others have suggested that resistance is enhanced by material retention (Minshall et al. 1983) or storage capacity (Detenbeck et al. 1998).

Objectives

To develop a standardized process for assessment and restoration, we propose to:

- develop a geographically-independent classification system that links watershed characterization and prioritization,
- use existing ecological data to validate this watershed classification system, and
- compare the rankings from our models to those of other regional studies.

Two major tasks will be (1) to compile existing data into a geographic information system (GIS) to characterize watersheds and describe a human disturbance gradient, and (2) to compile existing biological data to validate the geographic characterizations. Our validation will use data on multiple taxa to provide a diverse assessment of condition for each watershed. Additionally, we will compare the results of our characterization and prioritization models to the findings of other relevant regional studies. As a test of concept, we will apply our models to the data from the Mid-Atlantic Highlands (Fig. 1), but the process is potentially applicable worldwide.

The products of our research will include:

- A Watershed Characterization Model (WCM) that sorts watersheds into types based on their physical characteristics (e.g., soil type, climate). The WCM plots stressor resistance to measured levels of specific stressors to compare each watershed to reference condition.
- A Watershed Prioritization Model (WPM) that plots a given watershed's susceptibility to impairment from all stressors against a composite score of all stressors.
- A test of predictions from the WCM using multiple biological datasets from test watersheds.
- A restoration feasibility filter that potentially forms a third axis to the WPM.
- A comparison of WCM rankings to results of other classification schemes.

Rationale

In the Mid-Atlantic Highlands (Fig. 1), federal agencies such as the USEPA, Natural Resource Conservation Service, U.S. Geological Survey, U.S. Army Corps of Engineers, National Park Service, U.S. Fish and Wildlife Service, and others play regulatory, management, and funding roles that affect over 27 million people (USEPA 2000). The Highlands' five states (NY, PA, MD, WV, and VA) also regulate, manage, and fund myriad watershed activities. Nearly 300 counties, thousands of local governments, and hundreds of citizens' watershed associations and related groups need a logical system to understand issues, establish ecological and human health goals, tailor management approaches, and target resources for protection and restoration.

The Mid-Atlantic region contains over 25,000 stream miles designated as impaired (USEPA 2000). As required by the Clean Water Act, over 4,000 TMDL restoration plans are needed. A classification system that groups watersheds with similar features and problems would provide a scientifically defensible scheme to develop "off-the-shelf" monitoring and management practices. These methods could then be deployed proactively, potentially improving a stream's condition before TMDL development. For streams that may not receive TMDL remediation due to fiscal constraints, the stream's class would point to best management practices.

2. Approach

Study Area

The Mid-Atlantic Highlands includes parts of 6 ecoregions and 4 states (Fig. 1). Ecoregions define the study area in terms of natural potential and variability, and response to stressors (Bryce et al. 1999) and are useful in characterizing spatial patterns of water quality (Griffith et al. 1999, Omernik 1995).

The Highlands' ecoregions (Fig. 1) support some of the largest tracts and best examples of the Eastern Broadleaf Forest (Riitters et al. 2000). Trees, songbirds, land snails, salamanders, and freshwater mussels are highly diverse (Terwilliger 1991, Ricketts et al. 1999). The Highlands support many unique natural features, as well as national parks and national forests.

In addition, the Highlands are changing. Population growth threatens natural resources along interstate highways and around urban centers. Mountaintop mining fragments interior forest in West Virginia and Virginia, and surface and deep mining have led to chronic acid mine drainage in some areas. Invasive species and tree pathogens threaten oaks, beech, hemlock, and pines. Acid deposition, low-level ozone, and toxic ion deposition are also local stressors. Environmental stressors also affect the Highlands' socio-economic health through flooding, unplanned growth, lost economic development opportunities, and loss of farmlands.

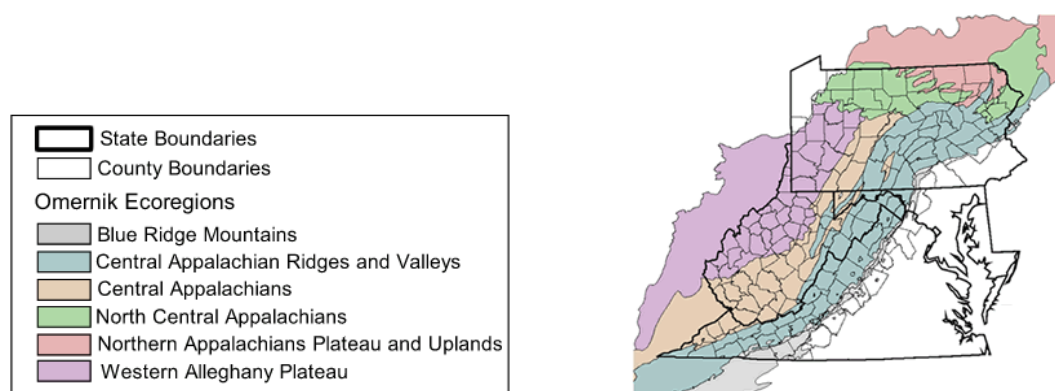


Figure 1. The Mid-Atlantic Highlands study area includes the mountains and valleys of Pennsylvania, Virginia, Maryland, and West Virginia, plus areas of continuous watersheds.

Finally, the Highlands is a desirable region in which to develop watershed classification models because of its multiple, spatially explicit biological datasets (Fig. 2). These can be used to validate *a priori* classifications. Particularly useful are EMAP (USEPA 2000) and landscape atlases (Jones et al. 1997), regional indicators of biological integrity (IBIs) such as the Bird Community Index (BCI) (O'Connell et al. 1998, 2000), an IBI for fish (McCormick et al. 2001), and other studies (Pan et al. 1999).

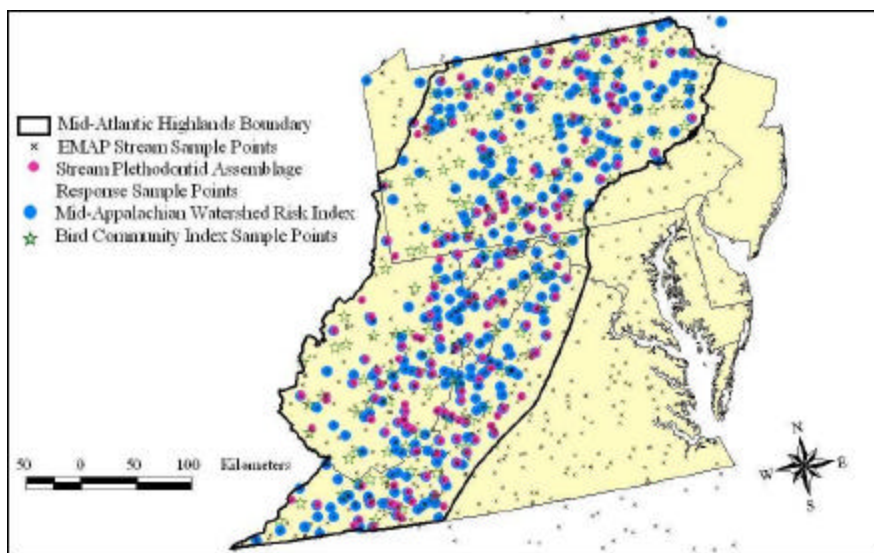


Figure 2. Examples of spatially explicit biological datasets from the Mid-Atlantic Highlands.

Procedures

We will develop and validate two models: (1) one to characterize watersheds based on resistance to stressors and actual levels of stressors (WCM), and (2) another to prioritize the potential for restoration to benefit managers (WPM). We will use data from multiple taxa to apply several IBIs as a test of the characterization and prioritization models. Finally, we will compare our results to other classifications.

Watershed Characterization Model (WCM)

We will first assemble data on the physical attributes of watersheds that are independent of human activity. For example, human actions generally cannot alter the hydrogeomorphology (HGM) pervasive in a watershed (Brinson 1993). In contrast, riparian buffer width is a human-mediated attribute. Examples of human-independent physical attributes of watersheds include climate, aspect, slope, stream sinuosity, size, water source, bedrock, and soil type. We will identify a suite of physical attributes to characterize any temperate watershed on Earth. Specific values for attributes will differentiate watersheds of different ecoregions, types, and scales.

We will use multivariate statistical tools (e.g., cluster analysis) to group watersheds with similar physical attributes. Watersheds falling in clusters that share similar attributes will be identified as specific watershed “types.” Tran et al. (2001) clustered and ranked 123 Highlands watersheds into 7 classes of vulnerability by using self-organizing maps (SOM) (Kohonen 1984). The physical attributes under consideration will involve large data sets of multivariate and univariate indicators of nominal, ordinal, counts or continuous nature. Appropriate data structures and algorithms for mining these geospatial indicators data will be adapted and fine-tuned.

Next, we will compile an exhaustive list of potential watershed stressors in the study region. Again, the stressors should be relevant in any watershed at any scale. Based on work by Adamus and Brandt (1990), we will likely consider enrichment/eutrophication, biological oxygen

demand, contaminants, acidification, sedimentation, turbidity, vegetation alteration, thermal alteration, hydrologic modification, and habitat fragmentation, among others. The magnitude of these and many stressors can be interpreted with remotely sensed data.

The WCM will plot the location of each watershed on axes of modeled resistance and levels of empirically measured stressors. We will rank watershed types on their likely resistance to stressors based on literature and professional judgment. For example, watershed types underlain by limestone should be more resistant to acidification than watersheds on sandstone or shale. For some stressors, the resistance of watershed types will be quantified at interval or ordinal scales. Every watershed within a given class, regardless of observed stressor levels, will be assigned the same resistance rank (or range of ranks) for a given stressor.

Next, we will assemble data on actual levels of stressors in given watersheds. For each stressor resistance level identified, the WCM requires an empirical measure of that stressor, e.g., mean pH of headwater streams. The user will not have to collect original data—the stressors should be easily determined synoptically in a GIS.

Our goal is to develop a watershed classification system that is both scientifically defensible and user-friendly. Because our process relies on remotely sensed data compiled into GIS data layers, we will generate synoptic coverage for the study area. To date, we have identified approximately 25 publicly available GIS databases with direct applicability to this project. Once we have completed the exercise for the smallest delineated watersheds that are available digitally [e.g., 12-14 digit hydrologic unit code (HUC)], we will explore how a watershed's class changes during aggregation to 11- and then 8-digit HUCs. This will be accomplished with appropriate tools in hierarchical structures analysis and adapting some of them for this specific context.

As part of the process to develop the WCM, we will apply it to a sample of test watersheds in the Highlands. Figure 3 illustrates schematically how the WCM might be envisioned. Note in 3a-c that watersheds all occupy the same level of resistance to each stressor. The measured stressor levels for $p1-4$ differentiate the watersheds. For each watershed type, reference watersheds will have the lowest levels of measured stressors. Regardless of resistance, which is based on physical characteristics, the least stressed watersheds represent the reference condition. Thus, in 3d, both $p1$ and $q1$ represent reference watersheds. Watersheds $p2-p4$ and $q2-q4$ are classed in terms of their numeric deviation from reference.

It is important to locate each watershed for each stressor in the WCM graphs so watershed types with different resistances can be compared and prioritized. Each watershed will receive a separate WCM score for each individual stressor under consideration. For example, a manager of a large county might weigh options for watersheds of multiple types. The impairment of each, accounting for resistance, should be considered. In Figure 3d, $q1$ is in “better” condition than $p1$ because $q1$ has higher resistance and similar measured stress than $p1$. Is $q2$ in better condition than $p1$ due to $q2$'s greater resistance? The answer lies in $q2$'s condition relative to reference state for watersheds of type q . The WCM permits the ranking of $q2$ relative to reference for all “ q ” watersheds. If $q2$ is numerically within, say, 60% of reference, and $p1$ lies within the reference bounds for “ p ” watersheds, then $p1$ is considered in better condition than $q2$, even

though q_2 has higher resistance. We will most likely apply a contour analysis to test watersheds to determine each watershed's deviation from a reference state.

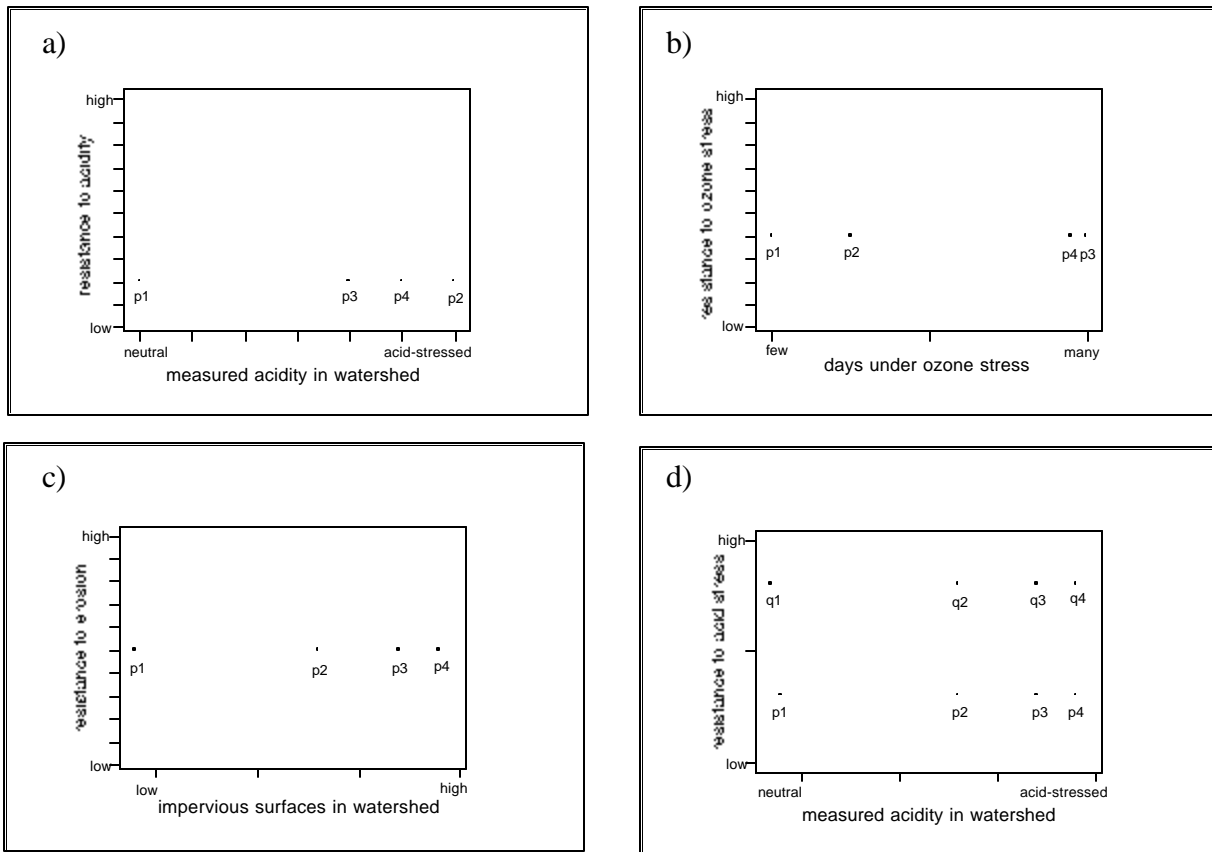


Figure 3. Hypothetical schematic representation of the WCM. Graphs a, b, and c illustrate the placement of four watersheds of type “p” relative to resistance and measurement of three potential stressors. Four watersheds of a different type (“q”) are illustrated in d.

Validation of WCM

With suites of IBIs available in the Highlands, we will validate the WCM with real biological data – a key endpoint of management objectives. We will test the predicted placement of test watersheds in the WCM graphs for individual stressors against empirical values for IBIs that specifically address those stressors. For example, the Bird Community Index (O’Connell et al. 2000) is particularly sensitive to land cover disturbance, but largely insensitive to stress from eutrophication. Individual WCM results for instream stressors will be tested with IBIs designed to respond to instream stressors (e.g., McCormick et al. 2001). We will also include indicators under development, e.g., a regional IBI for forested headwaters (Brooks et al. 1998) and an index of stream plethodontid assemblage (Rocco and Brooks 2000). Where data are unavailable, we may use modeled vertebrate distributions (Pennsylvania Gap Analysis Project, Myers et al. 2000) and state breeding bird atlases (e.g., Brauning 1992). Decision rule thresholds will likely vary by

scale and IBI. Specific hypotheses will take the form of “IBIs indicate high integrity under low levels of empirically measured stressors” and *vice versa*.

Watershed Prioritization Model (WPM)

We will design a WPM that incorporates summary measures of condition and overall assessments of human disturbance (Figure 4). The x-axis of the WPM will be a composite index of overall anthropogenic disturbance. The human disturbance gradient combines landscape metrics (e.g., proportional land cover, contagion) and site-specific data on stressors (Adamus and Brandt 1990, Karr and Chu 1999, USEPA 2000). The y-axis will be the composite deviation from reference for each watershed over all stressors. This axis can be regarded as “susceptibility to impairment.” The WPM is independent of geography and scale, and designed to be simple, adaptable, and useful by managers.

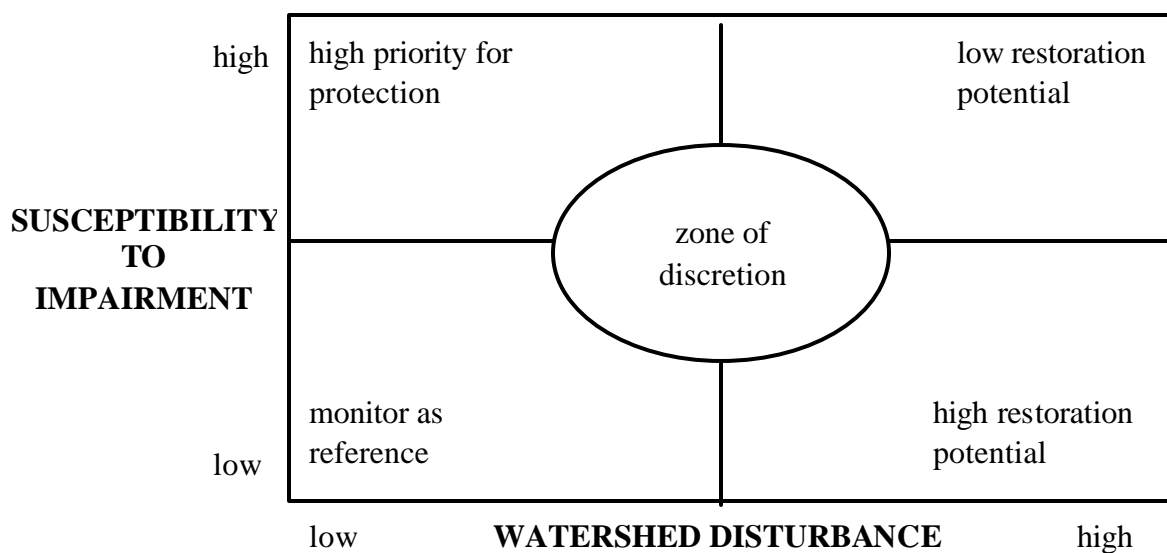


Figure 4. The Watershed Prioritization Model (WPM) plots composite scores for overall watershed condition (susceptibility) against overall watershed disturbance to guide management activity. For example, watersheds in the top left are not disturbed, but are susceptible to disturbance. Such watersheds would be considered priorities for protection.

Also part of the WPM is a Feasibility of Implementation analysis, potentially expressed as a 3rd axis on the WPM graph. This is a new index of technical and economic constraints. For example, if a point source of acid mine drainage creates a biological void, it may not be feasible to treat the contamination with current technology nor be economically reasonable to try. By using such an empirically based index, managers can assess the available technology and estimated costs, and then assign a relative ranking to a project. Thus the two axes of the WPM provide guidance on the remediation needs of individual watersheds, while the Feasibility of Implementation suggests specific actions with a high probability of success.

Validation of WPM

We will use composite IBIs to validate the WPM, much like validating the WCM. For the WPM, predicted composite IBIs will be high for watersheds in the bottom left of the WPM graph, low for those in top right, and show mixed results in top left and bottom right. Our validation will assess the degree to which predicted and actual composite IBI scores agree in different regions of the WPM graph.

Comparisons to Other Studies

We will compare the rankings from our watershed characterization and prioritization models to those from other regional studies. We will use several statistical methods to assess similarity, several of which are described below.

Analysis

Our project requires the manipulation of disparate data sets at various scales. During this process, we will use metadata and maintain records of how various indices are combined to ensure the analyses can be dissected to understand the implications for decision-making. The Penn State and CVI teams have extensive experience with stakeholders (Constantz 2000). We will use this collective expertise to inform managers of the benefits and consequences of using this approach. By involving stakeholders early in our project (Constantz 1997, Collins et al. 1998), we will enhance the odds they will be used.

The defining thrust of this project is to classify and prioritize watersheds in response to multi-criteria. To prioritize and rank means to linearize. Rather than derive a composite index, we will prioritize the watersheds without having to integrate the indicators. This is now possible, and the approach is relatively novel and innovative. Our analysis team has developed it successfully for nationwide prioritization for UNEP with land, air, and water indicators measuring the human environment interface at national level (Patil 2001a, Patil and Taillie, 2001a). Also see Hasse Workshop (2001) held in Munich, Germany to help improve decision support in water quality management and the management of environmental chemicals using Hasse diagram techniques.

We address the question of ranking a collection S of elements when a suite of indicator values is available for each member of the collection (Patil 2001ab, Patil and Taillie 2001abcd). The elements can be represented as a cloud of points in a multidimensional space (Filar and Ross 2001), but the different indicators typically convey different comparative messages and there is no unique way to rank the elements. We take the view that the relative positions in indicator space determine only a *partial ordering* (Fishburn 1985, Neggers and Kim 1998, Trotter 1992) and work with Hasse diagrams (Neggers and Kim 1998, Di Battista et al. 1999) of partial order to study the collection of all rankings that are consistent with the partial order. Such rankings are called *linear extensions* of the partial order. We then ask how many linear extensions assign rank 1 to a given element? How many assign rank 1 or rank 2, etc.? This associates a cumulative rank frequency distribution to each element and the “stochastic ordering” of cumulative distribution functions provides a new partial order on S , which *extends* (is consistent with) the original partial order. We call this process for extending the partial order the *cumulative rank frequency (CRF) operator*. Repeated application of the CRF operator eventually results in a *linear ordering* of S (Figure 5). The number of linear extensions is typically too large for complete enumeration.

However, Markov Chain Monte Carlo (MCMC) methods allow us to *estimate* the rank frequency distributions needed to apply the CRF operator. See Aldous (1987) and Brightwell and Winkler (1991) for further elaboration.

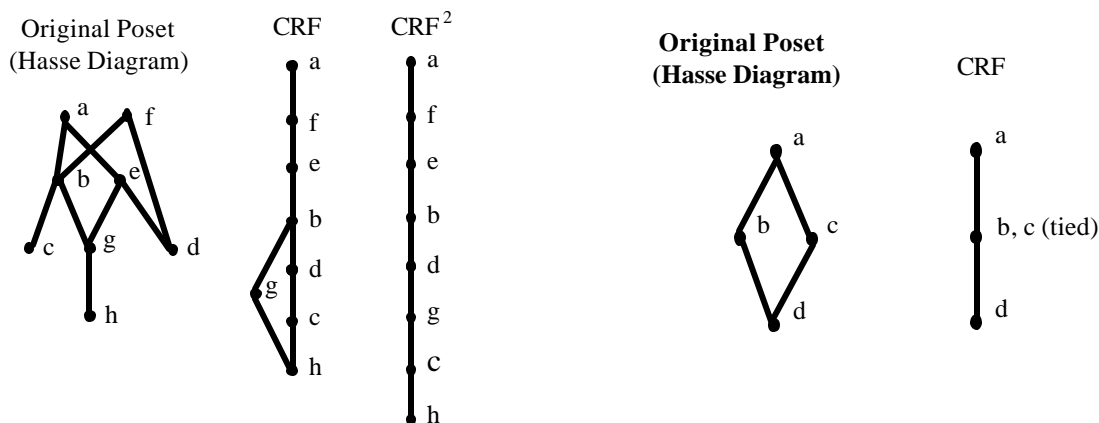


Figure 5. The three diagrams on the left show the linearizing effect of the CRF operator. The two diagrams on the right show how ties can emerge during linearization. A poset is a partially ordered set.

Hasse diagram and CRF linearization methods will be employed to achieve the following goals:

WCM validation. IBI and WCM concordance will be studied via the Hasse diagram representing the partial order determined jointly by the two measures. Perfect concordance corresponds to a linear Hasse diagram. Departure from linearity, in the form of a more complex Hasse diagram, signifies some breakdown in concordance. Complexity of the Hasse diagram will be assessed by the number of iterations of the CRF operator needed to achieve linearity. Intermediate Hasse diagrams produced during linearization will identify watersheds and watershed groups responsible for any non-concordance. The same general approach can be used for WPM validation.

Overlaying “Condition” contours on WCM graphs. How do we compare the condition of q_2 and p_1 (for example) in Figure 3? For each graph, the stressor levels and the resistance levels induce a partial order on the watersheds. The resulting Hasse diagram is linearized to give a joint stressor-resistance ranking that guides contour determination. Comparison of these contours with empirical IBI contours provides a visual WCM validation. Normally, the CRF operator is applied to the uniform distribution on the set of linear extensions. But other (weighted) probability distributions can be used if one wants to differentially weight stressor and resistance in determining final rankings. The choice of weights requires input from subject-matter specialists, however.

Composite rankings for WPM axes. The susceptibility and disturbance axes in the WPM (Figure 4) are a composite of land cover measures and various WCM-derived measures. One approach

Figure 6. (a) Echelon decomposition of a surface and (b) associated echelon tree.

A major question concerning quantitative spatial variables with respect to many applications is whether there are substantial sectors of the surface having particularly high or particularly low values relative to the mean level. An echelon family is seen as a candidate for focus if the probability of its extent receiving observed amounts is less than the criterion under a random distribution of quantity over area. Echelons may also be determined after filtering the surface variable to smooth local variability. The degree of change in the echelon structure as a result of filtering is indicative of the sensitivity or insensitivity to errors in the data. Filtering strategies will be explored for the purpose of assessing robustness of spatial structure to errors in the surface variable. Echelons also facilitate comparative study of spatial complexity as expressed by a suite of echelon indicators. Each indicator can be treated as a synthetic sensor band. These pseudo-sensor bands can be assembled as synthetic multi-band complexity image datasets for the region in question. Segmentation of the synthetic multi-band data will extract prevailing patterns of complexity among the several indicators of ecosystem health.

Regional spatial pattern and distribution of the watershed priority classification will be analyzed using echelons. The “condition” ranking and the “protection-restoration” ranking used in WPM boundary determination provide a pair of surface variables. Each of these variables can be reversed providing four surfaces for echelon analysis. The peaks of these surfaces correspond respectively to the four corners of the WPM graph.

3. Expected Results or Benefits

Benefits

We will develop three tools to support decision-making by natural resource managers: (1) a Characterization Model to place any watershed in the context of its potential reference condition; (2) a Prioritization Model to guide specific management decisions based on susceptibility to impairment; and (3) a Prioritization Model extension that provides a feasibility analysis (both economic and technological) for specific management options.

Recipients

State water managers allocate limited resources to implement federal laws. Local officials must respond to citizen concerns about threats from development and a desire to protect aquatic habitats. Our scheme will address the needs of both by providing general watershed models that can be dissected into component indices for diagnosis.

Solutions

Our approach to watershed classification and prioritization is ultimately based on objectively defined physical attributes of watersheds plotted against empirical measurements of actual stressors. Because watersheds are prioritized relative to their specific approximation of reference condition for their type, watersheds of multiple types and susceptibilities to impairment can be directly compared in a decision matrix. Thus, our models are truly geographically independent

and can be potentially adapted for use in any temperate freshwater system worldwide. The WCM and WPM provide specific aid to the management decision process that can benefit managers at multiple scales anywhere stressor data are available on specific watersheds. Moreover, our development and validation of these models with real biological data from the Mid-Atlantic Highlands will provide specific detail as a proof-of-concept to attach confidence bounds on the management actions our models may suggest.

4. General Information

Management and Personnel

Dr. Brooks (PSU) and Dr. Constantz (CVI) will serve as Project Co-Directors, ensuring data collection and analyses are timely and appropriate. Dr. Patil (PSU, assisted by Dr. Taillie, Dr. Myers, and B. Freed) will serve as Director of Analysis, ensuring appropriate use of quantitative and statistical methods. P. Kinder (CVI, assisted by M. Sherald, P. Claggett, and E. Clifton) will acquire and compile GIS data sets. Dr. Myers and J. Bishop (PSU) will coordinate with CVI to access extensive GIS data sets maintained by Penn State's Office of Remote-Sensing of Earth Resources and the Pennsylvania Spatial Data Analysis facility. Dr. O'Connell and G. Rocco will acquire and compile selected vertebrate and invertebrate data sets. They will work with Dr. Patil's team to link biological and geographic data. The CVI-sponsored graduate student, K. Hychka, will also work to interface biological and geographic data. T. DeMoss, R. Pomponio, and J. French (CVI) will coordinate contacts with managers and seek reactions to interim products. A focus will be state and regional water managers responsible for assessment and TMDLs. Our products will be compatible with Water Quality Standards that drive TMDLs.

Senior Personnel

Robert P. Brooks - PI and Project Co-Director - has 25 years of research and administrative experience. As Professor of Wildlife and Wetlands at Penn State, he has developed a widely recognized wetland research and education program. Current projects include: wetlands restoration on altered landscapes; cumulative impacts in riparia; hydrogeomorphic models; and ecological indicator models using macroinvertebrates, amphibians, and birds. He founded the Cooperative Wetlands Center in 1993, and supervises a technical staff of 8, supports 6 graduate students, and administers a budget of \$1-2 million/yr. Since 1978, he has published over 120 technical papers, books, and book chapters, and presented over 125 oral papers at conferences. Dr. Brooks specializes in designing and managing geographically dispersed projects, such as monitoring 200 reference wetlands in Pennsylvania; developing a Regional Index of Biological Integrity for Forested Riparian Ecosystems with a consortium of three institutions; and managing the Atlantic Slope Consortium, a six-institution team that received a \$6 million USEPA grant to develop indicators that link aquatic ecosystems in the Mid-Atlantic Region.

George D. Constantz - PI and Project Co-Director - has 25 years of experience in research, teaching, and administration. He has published 30 research papers and chapters in edited symposia, and one book. Basic research studies have addressed the life history patterns and social behavior of stream fishes. Applied environmental projects have included quantifying the effects of a nuclear electric plant on the Savannah River's fish community, assembling the

ecological baselines of two Appalachian rivers, preparing and implementing a strategic plan for managing West Virginia's watersheds, and helping grassroots watershed associations build scientific and organizational capacities. During 1993-95, while at the WVDNR, he coordinated the EPA-funded Watershed Conservation and Management Program, and during 1995-98, he helped launch the WV DEP's Watershed Assessment Program. Thus, he is experienced in indicator development, study design, baseline and monitoring studies, watershed ecology and assessment, data management; as well as in identifying stakeholders, building consensus, and other forms of public involvement. Lastly, through his work in state agencies, he is familiar with the needs of water quality regulators.

G. P. Patil – PI and Director of Analysis. Distinguished Professor of Mathematical Statistics at Penn State, and Director, Penn State Center for Statistical Ecology and Environmental Statistics. Over the past thirty year period, Dr. Patil has been in the forefront of research and outreach in mathematical statistics and stochastics, statistical ecology and environmental statistics, multiscale regional policy research, multiscale advanced raster map analysis (MARMAP) for sustainable environment and development. From time to time, he has served on advisory committees of several federal and state agencies and environmental research institutes. For simultaneous integration and transfer of knowledge: (1) Director, First Advanced Institute on Statistical Ecology, 1972, Penn State, NSF; (2) Director, Satellite Program in Statistical Ecology, 1977-1978, Berkeley, College Station, Parma, and Jerusalem, Multi-Agency; (3) Principal Lecturer, NSF-CBMS Regional Conference on Diversity Measurement and Comparison, 1986, Oklahoma; (4) Director, Ninth Lukacs Symposium on Synergistic Directions for Statistics, Ecology, Environment, and Society; (5) Science Advisory Board, Spatial Accuracy Symposia; (6) lead author of 300 disciplinary and cross disciplinary research papers, and lead author and lead editor of twenty five monographs; (7) has trained and interned 100 graduate students and visiting scholars. For creation of knowledge: (1) PI, USAFOSR and USFS on signal detection and statistical distributions in scientific work, 1960-1980; (2) PI, NMFS on recruitment distributions in fisheries, 1976-1986; (3) PI, NOAA on crystal cube for coastal and estuarine degradation, 1980-1984; (4) PI, EPA on environmental sampling and observational economy, 1986-1996; (5) PI, NSF on multiscale assessment, 1995-1999; and several others, inclusive of publications in JASA, Annals of Mathematical Statistics, Biometrics, Annals of Statistical Mathematics, Communications in Statistics etc.; (6) Chair and Editor, MARMAP System for Ecosystem Health Assessment and Management, International Congress for Ecosystem Health, Sacramento, CA 1999; (7) Chair, MARMAP System Partnership, 2000-; (8) Chair, Plenary Forum on Environmental Indicators and Their Integration for Quality of Life, Index 2001 Congress, Rome, Italy 2001; (9) Plenary Lecture, MARMAP System: Definition, Design and Development, Brazilian Ecological Congress, Porto Allegre, Brazil, 2001; (10) Plenary Lecture, MARMAP System: Definition, Design, and Development, International Environmetrics Society, Portland, OR, 2001; (11) Chair, Joint Statistical Meetings Invited Session on MARMAP System: Definition, Design, and Development, New York City, 2002.(12) Member, Three Nobel Laureate Panel, UNEP Science Advisory Board, 2000.

Institutional Assets

Pennsylvania State University – As a major public, land-grant university, Penn State has all of the capabilities required to conduct their portion of this research project. Most of the work will

be conducted collaboratively between two centers, the Penn State Cooperative Wetlands Center (CWC and the Center for Statistical Ecology and Environmental Statistics. Each center supports an accomplished and productive staff and has adequate office and computer facilities. In addition, the CWC has direct links to the GIS capabilities at Penn State through ORSER and PASDA. Dr. Myers is Co-Director of ORSER and will be assisted by J. Bishop in helping the CVI GIS team to compile and analyze the data layers used for characterizing watersheds. ORSER's mission is to provide a focal point within the University for research and other activities related to remote sensing and geographic information processing. ORSER has participated in projects involving the use of remotely sensed data and other types of spatially referenced data since 1970. Since its inception, ORSER has completed more than 200 projects involving the application of GIS and/or remote sensing to environmental and ecological analyses. ORSER serves as a GIS support center for the Pennsylvania Department of Environmental Protection (DEP) under an open-ended contract. Should there be a need to distribute the GIS data layers publicly, this will be accomplished through PASDA. PASDA (www.pasda.psu.edu) maintains and manages a geospatial clearinghouse for metadata and databases, accessible to the public and is the official spatial data clearinghouse for the Commonwealth of Pennsylvania, and is compliant with the Federal Geographic Data Committee (FGDC) metadata standards. PASDA is a repository for many of the watershed-based databases of interest for this project, such as the Delaware and Susquehanna River Basin Commissions, and the Chesapeake Bay Program, and they can easily expand their databases to include information for other regions.

The Center for Statistical Ecology and Environmental Statistics is well known for its unique initiatives in statistical ecology, environmental statistics, and quantitative risk analysis. For the past ten years, it has had its focus on multiscale regional assessments and methodologies at landscape and watershed scales, multiscale advanced raster map analysis system, and prioritizations without having to composite multiple indicators. This experience and expertise is particularly relevant and timely for the proposed project. Details are on website <http://www.stat.psu.edu/~gpp> together with thirty-five related publications, describing the methods, tools, case studies, and outcomes.

Canaan Valley Institute--The GeoSpatial Team offers expertise in landscape ecology, watershed modeling, ecological restoration, cumulative impact assessment, GIS application development, Internet map servers, image processing and classification, and global positioning systems (GPS). The Team uses a fully functional LAN/WAN, T1 Internet Connectivity, and Clustered Dell Servers. Five Dell 610/620 NT 4.0 GIS workstations are each equipped with ESRI ArcView, ArcInfo, ArcIMS, ArcSDE, and ERDAS Imagine 8.4. Ongoing projects include:

- Development of NRCS-sponsored 14-digit HUCs for West Virginia
- Development of ecoregion-specific Landscape Assessment Approach for the Mid-Atlantic Highlands
- Landscape assessment of cumulative impacts of mountaintop mining
- FGDC Framework Demonstration to enhance NHD through spatial and attribute conflation for Upper Monongahela River Watershed WV
- Creation of multi-tiered decision-tree for image classification within MAH

- Development of the Landscape Analyst Extension to ArcView GIS.

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