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# Regional Vulnerability Assessment for the Mid-Atlantic Region: Forecasts to 2020 and Changes in Relative Condition and Vulnerability



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# Regional Vulnerability Assessment for the Mid-Atlantic Region: Forecasts to 2020 and Changes in Relative Condition and Vulnerability

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# Executive Summary

The EPA's Regional Vulnerability Assessment (ReVA) Program develops and demonstrates approaches to 1) integrating spatial data and model results, 2) forecasting future scenarios, and 3) applying these methods towards regional priority setting and decision making. This report demonstrates the projection of multiple drivers of ecological change at a broad scale to the year 2020 followed by the application of different integration methods that synthesize results to address a suite of assessment questions to guide proactive decision making.

Identified drivers of change for the Mid-Atlantic region include land use change and population growth, non-indigenous species, pollution, and resource extraction (Smith *et al*. 2001). Making use of available data and models, projections were made for land use/land cover, population and demographics, non-point source pollutants in surface water, nitrogen in groundwater, and spread of non-indigenous species for the year 2020. These were then compared to a similar set of variables available for the current time period to assess changes in condition and vulnerability for the Mid-Atlantic region.

Selecting the appropriate integration method(s) to address specific assessment questions was an important objective of this project and the process followed results of earlier work evaluating a suite of integration methods for their sensitivity to different data issues and how well they addressed different assessment questions (Smith *et al.* 2003). To address questions associated with changes in pattern and condition, three integration methods were used: the Simple Sum, Principal Components, and State Space. Simple Sum and Principal Components have been shown to be complementary in their results as they are sensitive to different properties of the data. Together, they provide a good overview of regional conditions. State Space, used in this example to quantify the distance between each individual watershed and the most vulnerable watershed, is useful for quantifying how much change has occurred in that it highlights both where degradation is small and where major changes might occur.

To address questions related to identifying the most important stressors and resources now and in the future, the matrix method was used. While this method has been used for many years in a qualitative manner, correlation coefficients were used to quantify the relationship between stressors and resources based on the large amount of data available for the Mid-Atlantic region to rank among stressors and resources for both current and future periods.

Vulnerability questions were addressed using the Stressor-Resource Overlay method and the Criticality method. The Stressor-Resource method highlights areas where valued resources coincide with stressors that threaten them and where there are either no resources left or where there are only a few stressors threatening them. The Criticality method is based on the theory that as an ecosystem is moved further from its natural state it moves towards a state of being irreversibly damaged. Application of the Criticality method requires setting the suite of variables to values that are near "natural" which was done in this application using fuzzy numbers to reflect our imperfect knowledge.

Assessment results are necessarily the sum of the full set of analyses as each integration method provides different information and insights into the pattern of condition and vulnerability and how it may change for this region. Current patterns generally showed that the best conditions were in the Mid-Atlantic Highlands and the worst were in the urban areas of Baltimore, Washington, Pittsburgh and Raleigh. For future conditions, the Principal Components Analysis (PCA) showed less degradation of the urban areas as it adjusts for covariance among the stressor variables, which may underestimate the possibility of synergistic effects. The Simple Sum may thus be a more conservative predictor of environmental condition and better predictor of the probability of where cumulative effects can be expected. The State Space method indicated the least change in watersheds in the highlands and the most in watersheds in suburban areas around urban centers with intermediate changes projected for the coastal plain and piedmont. The State Space method maintains full dimensionality but minimizes the effect of covarying stressors so the pattern can be interpreted as the minimum change expected.

The matrix method identified land conversion by humans, nitrogen and phosphorus loading to streams, forest fragmentation, and soil erosion as the most damaging stressors to present environmental conditions. The most damaging stressors identified for the year 2020 were predicted to be the same with the exception of fragmentation, which was replaced by road density. The most vulnerable resources both now and in the future were small intact forest patches and forest cover in general.

The overlay analysis identified several watersheds in the highlands and several in the piedmont and coastal plains as vulnerable currently. Vulnerability to irreversible change as identified by the Criticality method was shown to be associated with more intense human activity particularly around Baltimore, Washington, north of Pittsburgh and east of Raleigh. Another 20 vulnerable watersheds were concentrated around urban centers. An additional five watersheds in eastern suburban areas entered this category of vulnerable to irreversible change with the 2020 projections.

# Table of Contents

# List of Tables

# List of Figures

# Introduction

## Background

The U.S. EPA's Regional Vulnerability Assessment (ReVA) program develops and demonstrates approaches to assessing broad-scale environmental vulnerabilities through the analysis of spatial data and models (Smith *et al.* 2001). A necessary component of such ecological vulnerability assessment is a characterization of ecological condition and identification of stressors that can degrade condition in the future. ReVA was designed recognizing that regional assessments are primarily the responsibility of regional decision-makers (Moss 2002) who need concise measures of condition and vulnerability and the ability to use projections or forecasts to make proactive decisions. Therefore, two of ReVA's objectives are (1) to develop and evaluate techniques to integrate information on exposure (stressors and resources) and effects so that ecological risk due to multiple stressors can be assessed, compared, and management actions prioritized; and (2) to project consequences of potential environmental changes under alternative future scenarios (Smith *et al.* 2001). ReVA scientists have researched, developed, and published methods and guidance for integrating exposure information into vulnerability assessments (objective 1) in a previous EPA report *Regional Vulnerability Assessment for the Mid-Atlantic Region Evaluation of Integration Methods and Assessment (EPA/600/R-03/082)*. In that study, ReVA tested how well data integration methods performed. This current report describes the application of these methods to a future scenario (objective 2). The goal is to show how ReVA's approach, including integration methods, can be used to identify current stressors and resources and how those stressors and resources can change across the landscape under some future scenario. The scenario described here is not a prediction of what will happen, but is an evaluation of what could happen under a plausible future scenario.

Vulnerability has multiple elements in its definition, but is most simply represented by the likelihood that future condition will change in a negative direction. Thus, the vulnerability of an ecological system increases as the number, intensity, and frequency of stressors increase. In this report, ReVA uses vulnerability to refer to the relative amount and number of resources and stresses present in a watershed. While reading this document, it is important to remember that the vulnerability of a watershed is a relative rather then absolute measure. In fact, an absolute measure of vulnerability in a probabilistic sense would be difficult to derive for any watershed with confidence, let alone for all the watersheds in a region. Although ReVA's analyses do not provide estimates of the probability of change, they do provide a set of powerful screening tools for identifying the most and least vulnerable watersheds in a region. This can enable decision makers to focus resources and prioritize planning for multiple types of questions.

## Purpose of this Report

This report presents analyses supportive of our strategic priority to assess condition and develop methods to examine scenarios and alternative futures in support of assessment and management. Arguably, management prioritization involves balancing many different factors that can be addressed through a series of assessment questions. Taking that approach, the report focuses on methods that can be used to address the following assessment questions:

1. What is the current spatial pattern of environmental condition?
2. How will the spatial pattern of condition change in the future?
3. How much will environmental condition change in the future?
4. What are the most important stressors in a region?
5. Which watersheds will become the most stressed in the future?

6. What are the most stressed resources in the region?
7. How will future change affect the least stressed watersheds in the region?
8. What watersheds are currently vulnerable to further impacts?
9. What watersheds may become vulnerable in the future?
10. Which watersheds are most vulnerable to irreversible change?
11. Which watersheds may be vulnerable to irreversible change in the future?

## Study Area, Temporal Extent, and Reporting Units

ReVA's pilot area was the Mid-Atlantic region used as part of the Mid-Atlantic Integrated Assessment (MAIA; Bradley and Landy 2000). The Mid-Atlantic encompasses portions of eight states and several ecoregions (Figure 1). Current conditions described here were derived from 1992 National Land Cover Data (NLCD) and all current conditions described here are for 1992; future projections are for the year 2020. Data is summarized and reported by hydrologic units (8 digit HUCs).

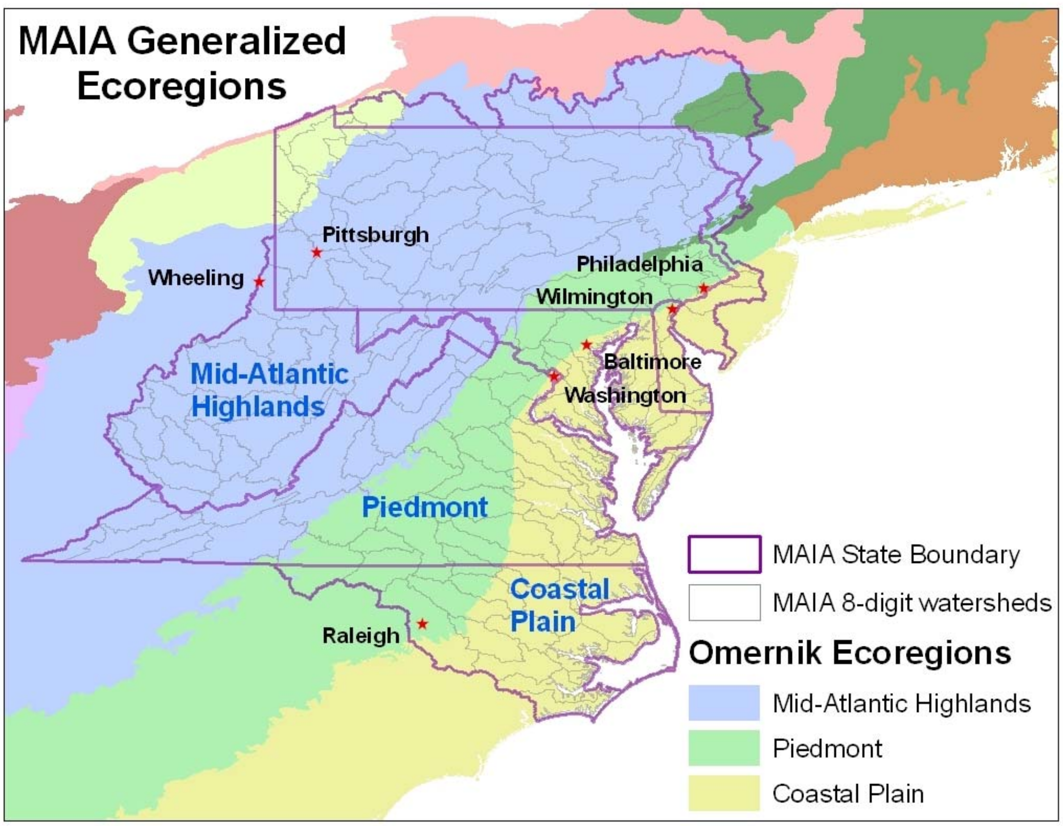


**Figure 1. Study area.**

Regionally, temperate forest is the dominant Mid-Atlantic land cover (Figure 2), despite the long history of human presence. Urban development dominates the coastal plain and most of the large cities in the region lie along the geologic boundary between the coastal plain and the piedmont. The piedmont includes most of the region's agricultural lands, with smaller cities and forestland scattered throughout.

The Mid-Atlantic Highlands retains the world's largest remaining contiguous temperate forest (Riitters *et al.* 2000), interspersed with small- to medium-sized cities, some agriculture, and numerous mines. In essence, there is a gradient from the coastal plain (urban/agricultural matrix) to the piedmont (agriculture/forest matrix) to the Mountains (forest matrix).

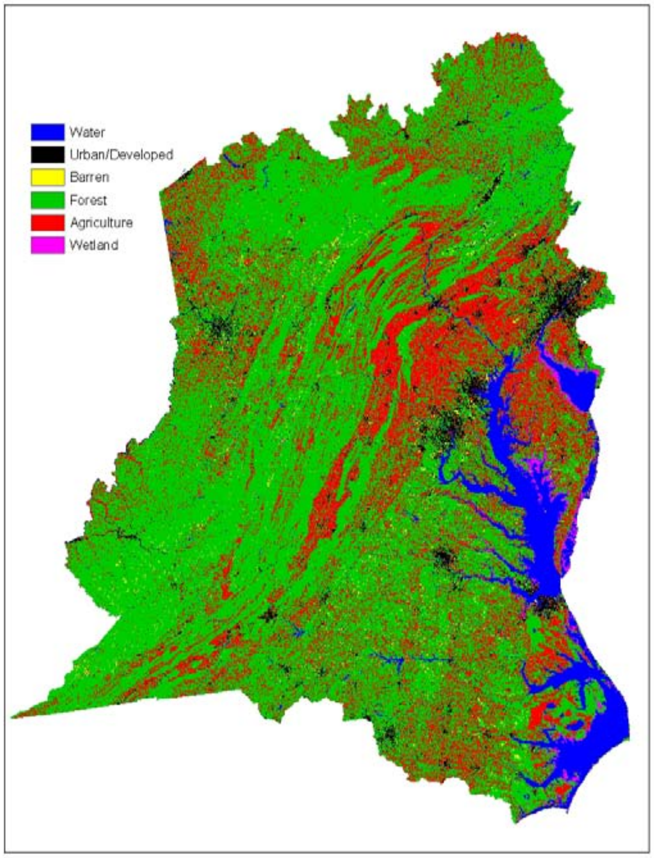


**Figure 2. National Land Cover Data (NLCD) land-cover map of the Mid-Atlantic region (1992).**

## Projecting the Drivers of Change in the Mid-Atlantic Region

Projections of the major drivers of change were used to develop a future scenario for the Mid-Atlantic. Changes in land use were projected using a combination of planned new roads and road improvements along with a model of future development (SLEUTH - Slope, Land use, Exclusion, Urban, Transportation, Hillshading; Clarke *et al*. 1997) that projects changes based on projected population changes from the Woods & Poole Complete Economic and Demographic Data Source (CEDDS) (2002). Changes in the spread of non-indigenous species were made for major problem species using a niche model (Genetic Algorithm for Rule-set Prediction - GARP; Stockwell and Peters 1999) to predict probability of a species becoming established across the region (see Appendix 1). Resource extractions were projected using existing areas permitted for future mining obtained from individual states. Changes in human population distributions were also included to evaluate impacts to human health and well being.

# Data and Variables

Data were chosen that provided the best available regionally consistent spatial coverage for both current and future scenarios. In some cases, better local data were available, but not used because it was not consistently available across the region and an acceptable regional data set was used in its place (e.g., TIGER road data, NLCD land cover). These data represented the important known stressors and resources in the region. All data were reported by 8-digit hydrologic unit codes (HUCs) as they were the only regionally consistent watershed delineation available at the time of this study (Figure 1).

A total of 24 variables was used to relate various environmental, social, and economic dimensions over the 147 8-digit HUCs (Table 1). All variables analyzed were normalized and inverted if necessary to make all indicators range from 0 to 1, where zero and one represent environmentally desirable (low stressor coverage, extensive resource coverage) and undesirable (extensive stressor coverage, low resource coverage) conditions, respectively. Normalization provides a transformation that preserves the ranking and correlation structure of the variables, and allows for variables with different scales to be used together (Pielou 1984).

## Landscape Metrics

Land cover and land use variables (percent forest, road density, roads crossing streams, human use and wetland) were generated using the Analytical Tools Interface for Landscape Assessments (ATtILA), version 3.0, an ArcView 3.x extension written by the U.S. EPA (2004). Metrics were based on 1992 National Land Cover Data (NLCD) (projected to 2020 for future scenario), TIGER roads, and National Hydrology Data (NHD) streams to calculate the density, counts, or proportions per HUC. The proportions were determined by summing the variable area and dividing by the total area inside the HUC minus water. Density was calculated as total length divided by area of HUC and counts were summed per HUC. Roads were not weighted for width or lane number.

Forest edge (EDGE2 and EDGE65) and interior (INT2 and INT65) were calculated by moving a fixed sized window across the NLCD land cover at two scales, fine (5 by 5 pixel window covering 2 ha) and coarse (27 by 27 pixel window covering 65 ha) (see Riitters *et al.* 2002). When the center pixel was forest, the number of forest pixels in the window was summed. If the amount of forest in the window was greater than 60%, but less than 100%, the center cell was labeled edge; when all pixels in the window were forest, the center cell was labeled interior.

Forest defoliation was determined using a geographic information system (GIS), to assemble, collate, and analyze gypsy moth defoliation data (Eastman 1989). A 2 x 2 km grid cell size was selected as standard for all map layers in the GIS. The grid size was selected because it represented the minimum dependable spatial resolution of the defoliation data available from state agencies. Data from the suitable habitat combined with forest density, and adjusted for preferred tree species basal area and the predicted geographic pattern of defoliation, were used to predict future potential for gypsy moth defoliation.

## Native and Nonnative Species

Data from NatureServe were aggregated by native and nonnative taxa to 8-digit HUCs (see metadata for details). Terrestrial and aquatic species data were based on museum records, literature, expert opinion, and digital databases. A species was considered to be introduced if it did not historically occur in the

**Table 1. List of variables ($^{S}$ Stressors and $^{R}$ Resources) used in scenario analysis.**

| Abbreviation | Description |
|---|---|
| AGSL$^{S}$ | Proportion of watershed with agriculture land cover on slopes >9% |
| AQUAEXOTIC$^{S}$ | Counts of exotic fish and mussel species from heritage data |
| DISSOLVEDP$^{S}$ | Estimated dissolved phosphorous in streams modeled using land-cover metrics reported as kg/ha/yr |
| EDGE2$^{S}$ | Percentage of watershed area with forest edge habitat (2 ha scale) |
| EDGE65$^{S}$ | Percentage of watershed area with forest edge habitat (65 ha scale) |
| FORCOVDEFOL$^{S}$ | Percent of forest cover defoliated and with mortality as proportion of existing forest |
| FORPCT$^{R}$ | Percentage of forest coverage |
| NITRATEGW$^{S}$ | Nitrate in groundwater; probability of exceeding threshold of 3 mg/L |
| INT2$^{R}$ | Percentage of watershed with interior forest habitat (2 ha scale) |
| INT65$^{R}$ | Percentage of watershed with interior forest habitat (65 ha scale) |
| MIGSCENARIO$^{R}$ | Migratory scenarios for long-distance forest migrants |
| POPDENS$^{S}$ | Population density |
| POPGROWTH$^{S}$ | Population growth rate from 1990-1995; 2015-2020 |
| PRAGFM$^{S}$ | Percentage of population in agricultural farming |
| PRMINE$^{S}$ | Percentage of population in mining industry |
| PSOIL$^{S}$ | Proportion of watershed with potential soil loss greater than one ton per acre per year |
| RDDENS$^{S}$ | The road density expressed as meters of road per square hectare |
| RIPAG$^{S}$ | Proportion of total stream length with adjacent agriculture land cover |
| STRFOR$^{R}$ | Proportion of total stream length with adjacent forest land cover |
| STRD$^{S}$ | Number of road crossings per total stream length |
| TERREXOTIC$^{S}$ | Count of exotic birds, mammals, butterflies, amphibians, and reptiles |
| TOTALN$^{S}$ | Estimated total nitrogen in streams modeled using land-cover metrics |
| UINDEX$^{S}$ | Human use index (proportion of watershed area with agriculture or urban land cover) |
| WETLNDSPCT$^{R}$ | Percent of area classified as wetlands |

target HUC. The data were compiled on a species-by-species basis. Migratory bird stopover habitats were quantified in 10-km radius hexagons (Tankersley 2004) for the entire study area, modeled on forest density, percent agriculture, and road density (based on NLCD). Details of non-indigenous species spread and migratory bird projections are discussed in the Methods section.

## Water

U.S. Geological Survey National Water-Quality Assessment Program groundwater data from studies conducted in the Mid-Atlantic region were used in association with geographic data (land cover, geology, soils, and others) to develop logistic-regression equations that use explanatory variables to predict the likelihood of exceeding nitrate concentration thresholds in shallow aquifers (Greene *et al.* 2005).

Excess export of nitrogen and phosphorus to streams was calculated using a statistical model developed by Reckhow *et al.* (1980) which uses the amounts of land cover to estimate loadings. Weightings for each land cover type were measured in kg per hectare per year. For example, each hectare of urban land cover contributes 1.2 kg of phosphorus and 5.5 kg of nitrogen to a watershed. Final loading values were the sum of contribution by all land cover and uses within a HUC. The loadings model was available in ATtILA (USEPA 2004).

## Demographics

Population data were drawn from the Woods and Poole county database (Woods and Poole 2002). Percent change in population from 1990-2000 was then calculated by subtracting the 1990 population from the 2000 population and dividing by the 1990 population. Population density was calculated by dividing projected total population in 2020 by county area. The proportion of the population employed in mining and agricultural farming was calculated by dividing selected employment by total employment. Population data were then apportioned to HUCs using a population-weighted method.

# Methods

## Future Scenario Analysis

### *2020 Land Cover Change Projection*

Population growth can result in conversion of land to residential or agricultural uses (Wheeler *et al.* 1998), but these two land uses result in different stressors. Thus, distributing these changes spatially was critical to projecting changes in stresses such as aquatic non-point source pollution (e.g., percent impervious surface or agriculture on steep slopes) and forest productivity. Land use changes can also directly alter estimates of resource condition or abundance (e.g., wildlife habitat; Browder *et al.* 1989).

The SLEUTH (Slope, Land use, Exclusion, Urban extent, Transportation, Hillshade) model (formerly known as the Urban Growth Model; Clarke *et al.* 1997) was used to determine the likelihood of urbanization. Briefly, the SLEUTH model applies growth rules to geographic data on a cell-by-cell basis. The model produces raster land-cover maps for the projected period, and cumulative probability maps that show the likelihood of urbanization for each 1-km square cell during the selected time period. For more details and case studies of SLEUTH, see *Project Gigalopolis: Urban and Land Cover Modeling* (http://www.ncgia.ucsb.edu/projects/gig/); *Methods and techniques for rigorous calibration of a cellular automaton model of urban growth* (Clarke *et al.* 1996); and *A Self-Modifying Cellular Automaton Model of Historical Urbanization in the San Francisco Bay Area* (Clarke *et al.* 1997).

To create the 2020 land cover map (Figure 3), areas of the 1992 NLCD coverage predicted by SLEUTH to have a 50% or higher probability of being developed were modified. Planned roads and road expansions and areas where new mining permits had been granted were also added. Projected future roads were obtained by state from Departments of Transportation (DOT). Mining permits were obtained from Pennsylvania (Anthracite coal only), West Virginia, and Virginia. All permitted areas were assumed to be mined by 2020. Locations where mines and urban were coincident were left as mines. Areas that didn't coincide with new urban, roads, or mining retained their 1992 land cover.

### *Projection of Migratory Bird Flights*

Forest-dwelling Neotropical migratory birds require intact forested stopovers during migration. The greater the number of paths that pass through a given HUCs, the more important that HUC is in the migratory system. Modeled migratory flights were based on flight distance and direction to examine how nightly flights link stopovers into flyways (Tankersley 2004). Stopover habitats were quantified in 10-km radius hexagons for the entire study area, modeled on forest density, percent agriculture, and road density. All models were developed using the ReVA future land-use projection. Field observations made in 1999 were used to determine high-quality stopovers and as points for movement models created in Arc/Info using the Eucdirection function. Each scenario represents a unique combination of distance and compass direction, with a maximum of 32 scenarios supported by any one HUC. Importance of a HUC to the migratory systems was based on the number of scenarios supported by a HUC. The resulting output highlighted portions of the landscape that are important for the continued success of migratory birds. Areas where many different migration scenarios overlap are particularly important, as these areas will support a diverse collection of migratory strategies and populations.

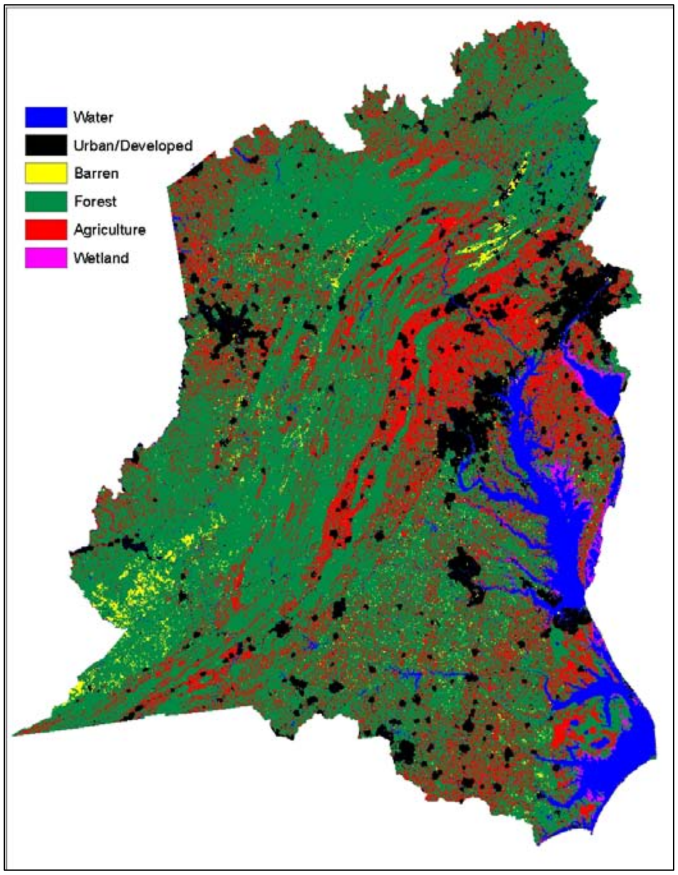


**Figure 3. Map of predicted land cover for the Mid-Atlantic region in 2020.**

### *Projection of Non-Indigenous Species*

The Genetic Algorithm for Rule-set Prediction (GARP) model was used to create spatial maps of invasive species distributions. Briefly, GARP uses native species distributions to explore nonrandom relationships between point localities and the environmental conditions (niche modeling) surrounding the site (Grinnell 1917). Basic inputs include species records, temperature, precipitation, solar radiation, snow cover and frost-free days (Appendix 1). GARP uses multiple rule types including BIOCLIM, logistic regressions, and a genetic algorithm (artificial intelligence application) to generate a set of IF…THEN rule statements to describe the relationships between species and environmental conditions. The output from GARP can then be projected onto a landscape to visualize the species potential distribution. The distribution can also be projected onto areas of actual or potential invasion/introduction under different land cover and climatic conditions (Peterson *et al.* 2003). Current geographic distributions were used to project potential distributions onto a spatially explicit scenario for 2020. Detailed documentation can be found in Stockwell and Noble (1991) and Stockwell and Peters (1999).

Gypsy Moth was considered a special case of non-indigenous species because of the seriousness of the risk it poses and because of the availability of risk information available from the U.S. Forest Service (USFS). Forested areas with repeated annual defoliation by gypsy moth become more stressed and are at increased risk of permanent damage if further defoliation occurs in the future. A GIS was employed by the USFS to assemble, collate, and analyze locations of gypsy moth defoliation data (Eastman 1989).

When combined, data on suitable habitat, forest density, and geographic pattern of defoliation can be used to predict future potential for gypsy moth defoliation (Morin *et al.* 2005). The grid of future defoliation risk was provided by the United States Forest Service as a 2 x 2 km spatial map. The data were then summarized to add up all the grid cell values within each 8-digit HUC watershed.

Sources for aquatic species data include:

1. Nonindigenous Aquatic Species Web site (http://nas.er.usgs.gov/) (Hydrilla, Eurasian watermilfoil, giant salvinia)
2. Queensland Herbarium specimen data, Jardim Botanico do Rio de Janeiro specimen data (giant salvinia)
3. Auckland Museum specimen data, Te Papa Museum specimen data (New Zealand mud snail).

Sources for the terrestrial species included:

1. National Agricultural Pest Information System (NAPIS; http://www.ceris.purdue.edu/napis/) (hemlock woolly adelgid, greater pine shoot beetle)
2. Smithsonian Institution, National Museum of Natural History specimen data (greater pine shoot beetle)
3. Eduard Jendek, Institute of Zoology, Slovak Academy of Sciences (emerald ash borer)
4. OakMapper Web application (http://kellylab.berkeley.edu/SODmonitoring/OakMapper.htm) (Sudden oak death)
5. Literature (Peterson *et al*. 2003, garlic mustard; and Lingafelter and Hoebeke 2002, Asian long-horned beetle)

Predicted future distributions of aquatic and terrestrial species data were calculated as a weighted proportion of appropriate habitat overlapped by the potential distribution of a given species. These predictive models were built in the GARP (Stockwell and Noble 1991) and used a Hadley Centre climate model (CM2 GSdX20) (http://www.metoffice.com/research/hadleycentre/).

### *Projection of Nitrogen and Phosphorus in Surface Water*

Excess export of nitrogen and phosphorus to streams was calculated using a statistical model developed by Reckhow *et al.* (1980) which uses the amounts of land cover to estimate loadings. Furthermore, the loadings model was available in ATtILA (USEPA 2004). The projection of nitrogen and phosphorus loadings in surface water by the year of 2020 was obtained with the use of ATtILA on the 2020 land-cover projection.

### *Projection of Nitrate in Groundwater*

Available water-quality well data obtained from U.S. Geological Survey National Water-Quality Assessment Program studies were used in association with geographic data to develop logistic-regression equations to predict the probability of nitrate exceeding a specified threshold (Greene *et al.* 2005). Independent variables include geographic data such as land cover, soil permeability, soil organic matter, depth of soil layer, depth to water table, clay content of the soil, silt content of the soil, and hydrologic groups within a specified area. To project groundwater vulnerability for the 2020 scenario, the projected land cover was used as input; all other variables were held at their current values.

### *Combining Various Projections in Future Scenario Analysis*

Each projection was reflected via changes in one or several specific variables used in the analysis. For example, projection on land-cover change was accounted for via changes in AGSL, EDGE2, EDGE65, FORCOVDEFOL, FORPCT, INT2, INT65, PSOIL, RDDENS, RIPAG, STRFOR, STRD, UINDEX, and WETLNDSPCT. Demographic change was reflected in POPDENS, POPGROWTH, PRAGFM, and PRMINE. Projected changes in water quality due to land-cover change and other factors were estimated in DISSOLVED, NITRATEGW, and TOTALN. Projection of non-indigenous species was represented in AQUAEXOTIC and TERREXOTIC. Finally, projection of migratory bird flights was seen in MIGSCENARIO. The future scenario analysis for the Mid-Atlantic region was carried out via addressing a set of assessment questions with the use of multiple integration methods on the set of available variables for both current values and projected ones for the year 2020. The integration methods used in the analysis are presented in the next section.

## Integration Methods Used in Scenario Analysis

The methods section below is intended to provide a brief description of the integration methods used in this reports; methods are fully explained and documented elsewhere. For a detailed discussion of methods, see EPA*/600/R-03/082 Regional Vulnerability Assessment for the Mid-Atlantic Region Evaluation of Integration Methods and Assessment* (Smith *et al.* 2003). Error analysis is presented in Smith *et al.* (2006). Additional information and list of related publications are available at http://www.epa.gov/reva/products.htm.

### *Simple Sum*

Normalized values of environmental variables are summed into a single index to produce the Simple Sum where values can range from 0 (best) to 1 (worst). An advantage of the Simple Sum method is that it is easily understood and communicated. Furthermore, it is not sensitive to discontinuities or non-normal distributions and does not depend on meeting assumptions about the statistical distribution of the data. The Simple Sum method can, however, lead to occlusion and this method cannot account for covariance in the data set.

### *Principal Components Analysis*

Principal Components Analysis (PCA) is a statistical technique used to reduce a set of complex multivariate data into a simpler set of uncorrelated variables, each of which is a linear combination of the original variables. Varimax rotation was used to minimize the number of variables having high loadings on each factor, simplifying the interpretation of the factors. The eigenvectors (loadings) derived from the PCA were then used to compute the principal component (PC)-based indices. The PC-based indices were weighted sums of the environmental indicators where the weights were the loadings' absolute values. The averages of the PC-based indices were then used as an integrated index for ranking and clustering. The primary advantage of the PCA method is the replacement of a set of multivariate data with a new set of uncorrelated variables. However, it is sometimes difficult to interpret environmental meanings of the new set of uncorrelated variables and PCA can be strongly influenced by data abnormalities (e.g., non-normal distribution, discontinuities).

### *State Space Analysis*

State Space analysis was used to determine the distance (Mahalanobis 1936) of each watershed from the most vulnerable watershed in the region. Theoretically, the most vulnerable watershed in the region has relatively large amounts of intact valued resources, but these resources are comparatively more threatened by degradation from stress. The primary advantage of the State Space method is that it maintains the full dimensionality of the data set while modifying the calculation of distance to account for data covariance. The primary disadvantage of the State Space approach is not any mathematical property of its calculation, but that the method requires a choice be made to identify the "most vulnerable" watershed. At the moment, there is no entirely objective definition for identifying the most vulnerable watershed.

### *Matrix Method*

The matrix method was used to identify the most important stressors and resources in the Mid-Atlantic. This method is not novel and is used elsewhere to characterize risks from multiple stressors (Foran and Ferenc 1999, Ferenc and Foran 2000). The matrix method was originally proposed by Leopold *et al.* (1971) and a number of variations were reviewed by Canter (1977). In more recent applications, the emphasis has been on identifying important stressors (Cormier *et al.* 2000). The matrix represents stressors as rows and resources as columns and this has been used to organize complex assessment information for several decades (Phillips *et al.* 1978; Lumb 1982a, 1982b; Witmer *et al.* 1985; Clark 1986; Emery 1986; Risser 1988). In most applications, quantitative information is not available and a panel of experts is typically asked to assess the individual impacts and supply a qualitative value (e.g., 1 for a minor impact, 2 for a moderate impact, and 3 for a major impact). This value is then inserted into the appropriate cell of the matrix and when the matrix is complete; the values in each row were summed and taken as the total effect of each stressor across all resources. The row sums can then be ranked to indicate which stressors represent the greatest threat and, in a decision-making context, were in greatest need of control.

For ReVA's analyses, the data were available for stressors and resources presenting a unique opportunity to apply the matrix approach quantitatively by using the correlation matrix (which measures the relationship between each stressor and resource pairing) (Smith *et al.* 2003). The correlation data were reduced to a matrix with the stressors as rows and resources as columns. The row sums represent the relationship between each stressor and all of the resources. The stressors with the largest row sums were then taken as the most important stressors as they were expected to have the greatest effect across all resources. A column sum of coefficients was done for each resource. The largest column sums were associated with resources that were the most stressed because they show the closest relationship with the stressors (considered across all stressors). Earlier testing of this approach (Smith *et al.* 2003) indicated that the row sums were reliable and stable, particularly when only the largest 2 or 3 row and column sums were considered. Therefore, while the range of row and column sums was divided into seven equal intervals our attention was restricted to only the top and bottom three septiles. To determine which watersheds may shift out of the top three or into the bottom three septiles, the septile ranges from the current condition were used to assess the 2020 data. It is possible that statistically insignificant coefficients represent spurious relationships and results were presented for both the total row sum and also the sum of the statistically significant correlation coefficients in each row.

### *Criticality Analysis*

Criticality analysis calculates the distance between the vector of variable values representing current conditions on each watershed and a vector representing a hypothetical "natural" state. The distance is calculated using a fuzzy distance measure and attempts to reconstruct the set of conditions under which the components of the ecological system evolved. This approach assumes that systems in the natural state retain the feedback networks that permitted stable response to disturbances over the long period of evolutionary history. As humans add stressors (e.g., chemical pollutants), extract resources (e.g., lumber), and change landscape patterns (e.g., fragmentation), the natural feedbacks are disrupted and the system becomes more vulnerable to radical and potentially irreversible change. To deal with the uncertainties involved in defining the natural state, the Criticality analysis is based on "fuzzy" values.

The greatest strength of the Criticality approach is that it provides a unique perspective on regional watersheds. The phenomenon of catastrophic change in complex adaptive systems is a potentially important concept in large-scale assessment. Another strength of the Criticality approach is its relative insensitivity to the assumptions involved in defining a "natural" state. The greatest weakness of the Criticality approach is our inability to predict where the critical threshold lies. Although it appears reasonable to estimate relative vulnerability, it is not possible to pinpoint exactly which watersheds will undergo radical change given a natural disturbance or further development. For a detailed discussion of this method, see Tran and Duckstein (2002).

### *Stressor-Resource Overlay*

The Stressor-Resource Overlay method was used to try to locate watersheds in which high amounts of valued resources occur together with high levels of stressors. For this analysis, stressor and resource variables were divided into quintiles and watersheds were scored on the number of stressor variables that fell into the worst two quintiles and also on the number of resource variables that fell into the best two quintiles. The advantage of the Stressor-Resource Overlay is in its ease of interpretation and it is the only method that directly addresses the geographic distribution of vulnerability. The primary disadvantage of the Stressor-Resource Overlay method is that it does not account for correlation between variables. However, the Stressor-Resource Overlay is not influenced by the correlation structure of the data as long as each resource is valued and stressors can interact to cause synergistic effects.

# Results

The Mid-Atlantic region has a history of human inhabitation and disturbance that spans some 300 years for Europeans and much longer for Native Americans and has resulted in widespread changes. Some of these changes, such as the buildup of large urban areas, were obvious and easily interpreted; others were subtle, with synergistic effects that can only be examined by looking at groups of environmental measures.

## Pattern and Condition

One of the advantages of ReVA's approach is that it can provide an overview of current and future environmental condition across an entire region. This helps put individual small-scale problems into a larger context. The complementary methods of Simple Sum and PCA-Sum were used to examine current and future overall spatial patterns of environmental quality (Smith *et al.* 2003). The State Space approach was used to estimate how far each watershed moves or changes in multivariate space from present conditions. These methods make it possible to determine where degradation was likely to be small or trivial and where major changes might occur. The types of questions that can be addressed using these three methods include:

1. What is the current spatial pattern of environmental condition?
2. How will the spatial pattern of condition change in the future?
3. How much will environmental condition change in the future?

### *About the Analysis*

The Simple Sum method sums the 24 variables for each watershed and serves as a composite indicator of condition (see Data section, above). Smaller sums represent better environmental quality. The range of the sums was divided into seven equal intervals and each watershed assigned to one of the septiles. For the second method, the PCA-Sum method, the data were first analyzed using a Principal Components Analysis and the first five principal components were used to weight the variables before they were summed. The result of this approach accounts for covariance among the variables.

The two methods are complementary because they were sensitive to different properties of the data. The Simple Sum is not affected by skewed distributions in the variables, but is sensitive to covariance and tends to weight excessively a watershed where several stressors co-occur. The PCA-Sum method accounts for covariance but is sensitive to skewed distributions because the PCA step assumes normal distributions. The two methods produced similar, but not identical spatial distributions. The range of sums differs between the PCA-Sum and Simple Sum and therefore, the resultant septile intervals also differ. For both methods the values of the sums cannot be compared directly, but the relative rankings (i.e., which septile a given watershed was in) can be compared.

Accurately assessing change in environmental condition and vulnerability often requires full use of available information. Environmental variables are, however, often correlated and the correlation structure of environmental data should be addressed and often warrants exclusion of some data. The third method (State Space method, Johnson 1988), however, preserves data dimensionality by correcting the calculation to account for covariance using a multivariate approach (Mahalanobis 1936). Mahalanobis distance was used to measure how far the environmental condition might move between the present and the year 2020. Distances were calculated for each watershed using the covariance structure of the current data to correct for correlations. The range of calculated distances was then divided into seven equal intervals or septiles and mapped.

### *Maps*

The results from the Simple Sum method show a distinct regional pattern for current condition (Figure 4). Best condition watersheds were in the Mid-Atlantic Highlands and those in the worst environmental condition were in and around Baltimore and Washington, Pittsburgh, and Raleigh. Watersheds of intermediate quality were in areas scattered throughout the piedmont, coastal plains, and the Mid-Atlantic Highlands. The relative condition of watersheds in 2020 derived using the Simple Sum method shows a similar pattern to present conditions with poorest conditions in urban areas around Washington, DC-Baltimore and also around Pittsburgh, and the best conditions in the Mid-Atlantic Highlands. The comparison map shows, however, widespread environmental degradation in the future in all of West Virginia and much of the Virginia Mid-Atlantic Highlands.

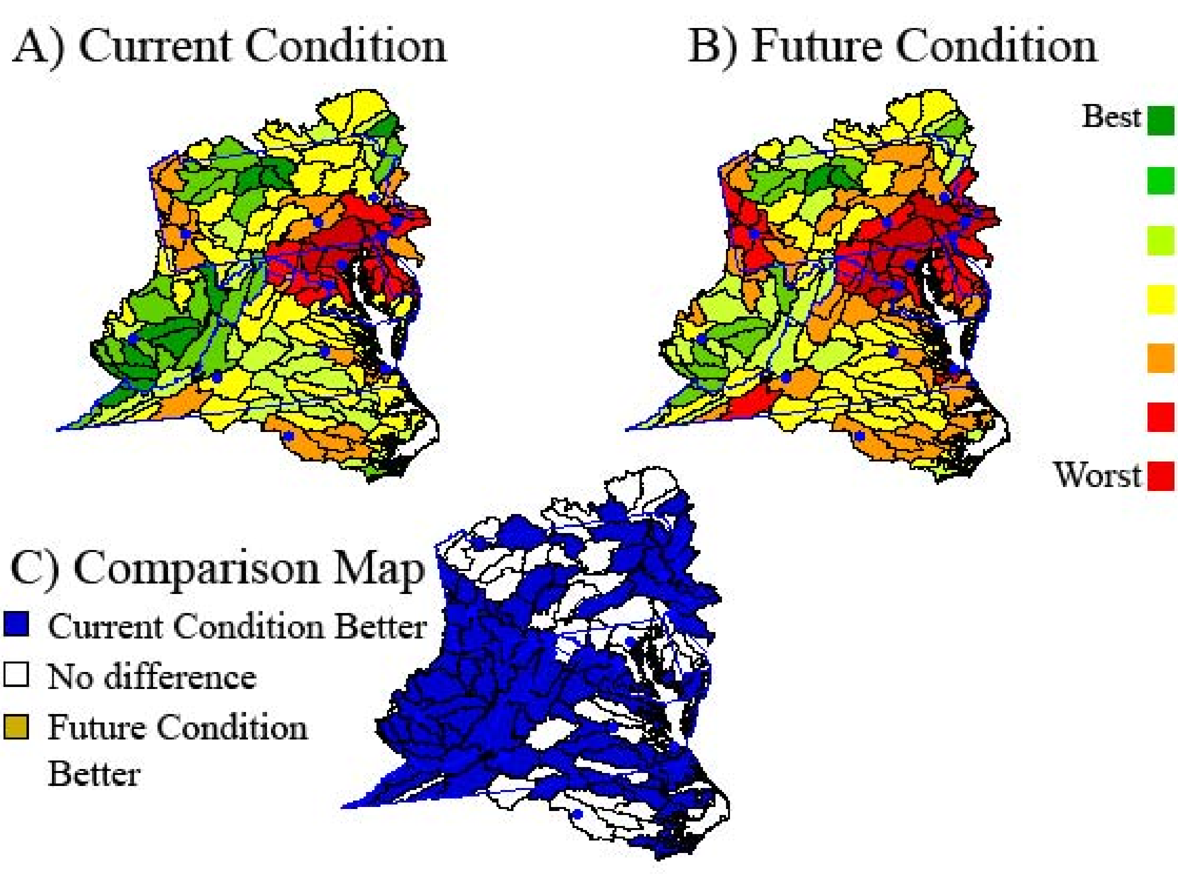


**Figure 4. Map of current (A) and future (B) environmental condition in the Mid-Atlantic integrated using the Simple Sum method. Map C shows a comparison of current and future conditions.**

The current and future spatial pattern derived using the PCA Sum method (Figure 5) was similar to the pattern derived using the Simple Sum, with the Mid-Atlantic Highlands in the best condition, the piedmont in intermediate condition, and metropolitan areas around Washington, DC-Baltimore and Pittsburgh in the worst condition. The PCA-Sum method again shows better conditions in some watersheds where multiple stressors coincide because the method accounts for the spatial co-occurrence of stressors. The current versus future scenarios integrated using the PCA Sum method shows widespread future degradation, but less widespread than did the Simple Sum comparison, particularly in the southern part of the piedmont and coastal plains.

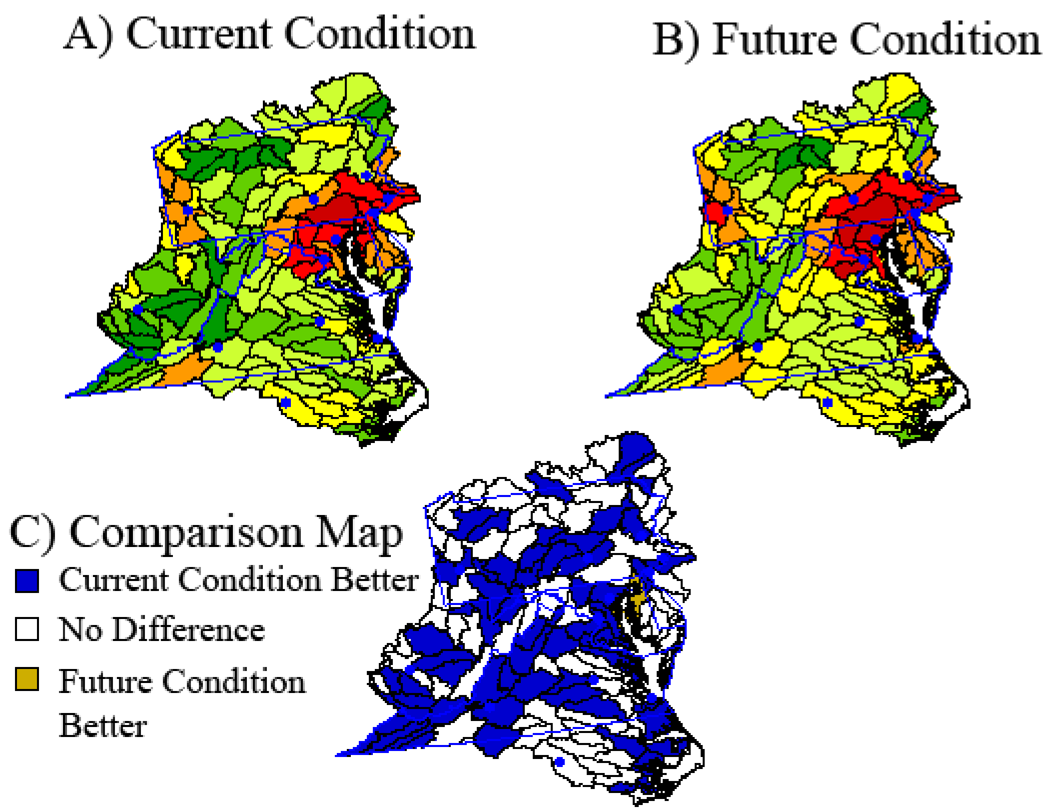


**Figure 5. Map of current (A), future (B), and comparative (C) environmental stress in the Mid-Atlantic integrated using the PCA Sum method.**

Results from the PCA Sum method show a similar, but not identical current condition pattern as the Simple Sum (Figure 6). The PCA Sum method corrects for covariance of multiple correlated stressors, and therefore, the urban and suburban watersheds appear less degraded, showing better relative environmental condition than in the Simple Sum.

An important advantage of the State Space method is that it maintains the full dimensionality of the regional data base while modifying the calculation of distance to account for the covariance substructure of the data set. This makes it possible to depict the pattern of change across the entire region. However, there is a cautionary note; methods that minimize the effect of covarying stressors (e.g., PCA Sum) might also underestimate the synergistic effects of multiple stressors. Therefore, the pattern shown in Figure 7 should be interpreted as the minimum change that can be expected. Synergistic and cumulative effects would probably be greater.

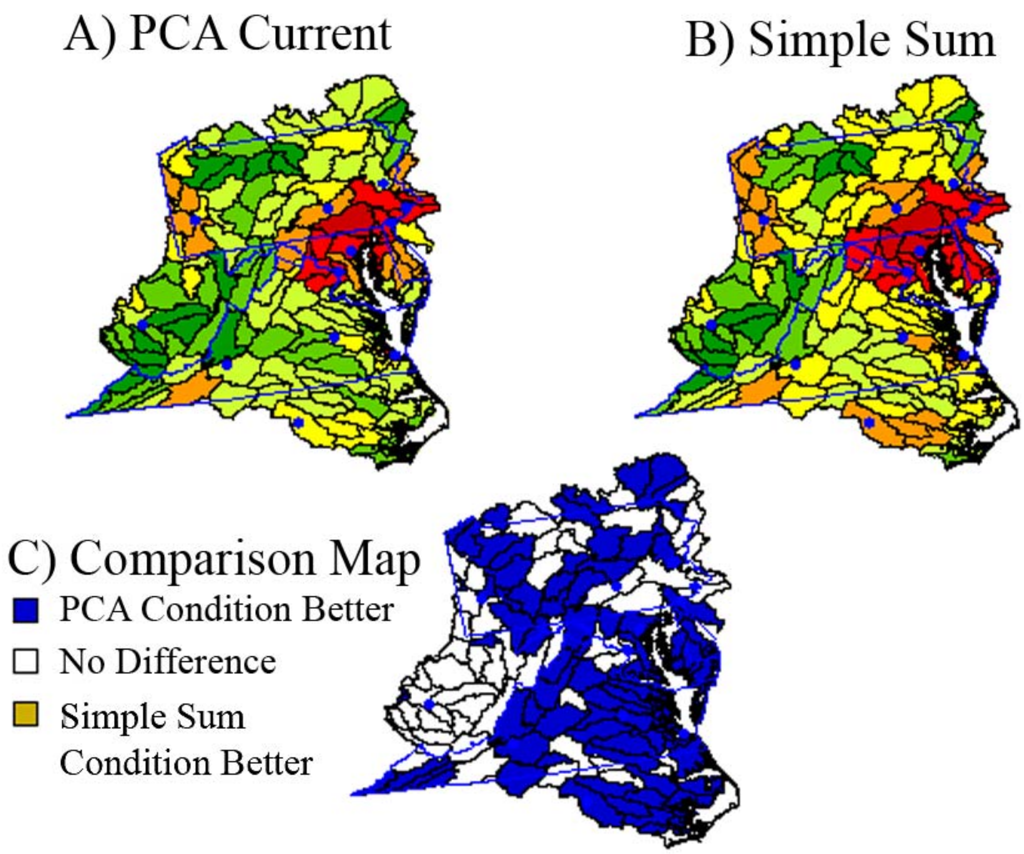


**Figure 6. Map of current environmental condition in the Mid-Atlantic using PCA (A) and Simple Sum (B) methods. Map C shows where results differ.**

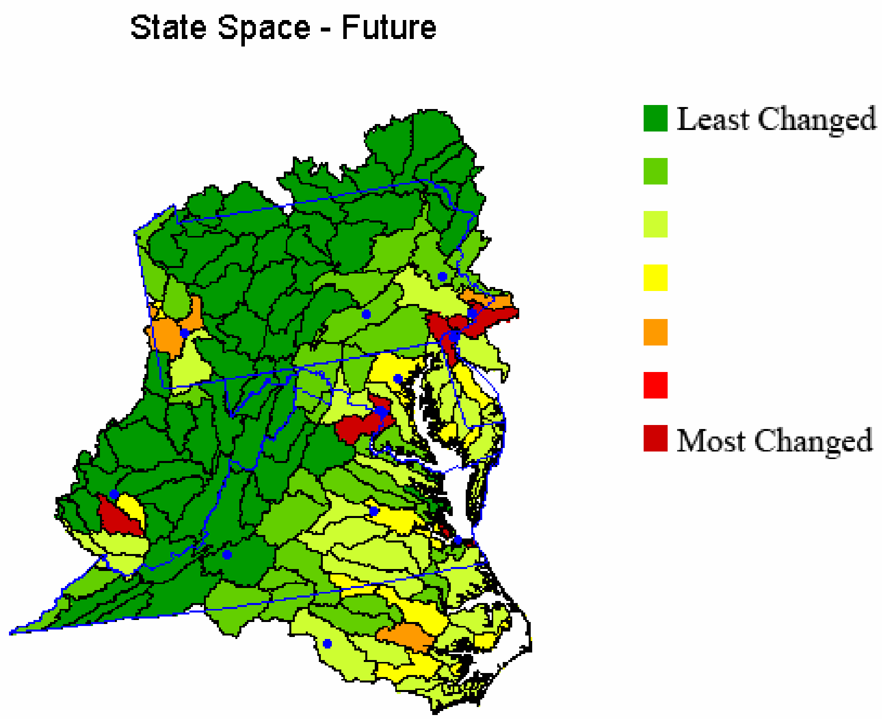


**Figure 7. State Space analysis.**

## Stressors and Resources

Using the matrix method approach, it was possible to identify the most important stressors and resources across a region and where watersheds had changed the most (Figure 7). Identifying these stressors and resources can facilitate an understanding of current spatial patterns as well as predicting future impacts. In planning for future regional land-use change, it is important to identify watersheds currently in the best environmental condition and watersheds most likely to be degraded in the future. Watersheds in the best environmental condition could be important sources for maintaining wildlife populations in surrounding watersheds. These watersheds also contribute ecosystem services important to society both at a regional and local scale. Identifying degraded watersheds or those that were likely to degrade in the future could help guide restrictions to development or mitigation and restoration strategies for maintaining environmental quality.

As with the other analyses, the effects, represented by these data, were not direct but represent spatial, cumulative, and synergistic effects. The stressor and resource matrix analyses presented here can be used on both regional and terrestrial systems within a region to answer the following types of questions:

1. What are the most important stressors in the region?
2. What are the most stressed resources in the region?
3. How do stressors and resources change in the future?

*Tables*

Stressors

Overall, the most significant stressors were human land use (UINDEX; Table 2) and the loadings of nitrogen (TOTALN) and phosphorus (TOTALP) to aquatic systems in the region. These three stressors were important under current land use and remained so in 2020. Results were considered reliable because the top stressors remain the same, both in the future and when summing only the significant coefficients.

Considering only the terrestrial systems across the region, the most important current stressors were human land use (UINDEX), small-scale fragmentation of forests (EDGE2), and potential soil erosion (PSOIL). These remain the top current stressors when only the significant coefficients were considered. In 2020, human land use and potential erosion remain important and fragmentation was replaced by road density (RDENS). However, there were no statistically significant coefficients in the road density summation, making us less confident of these results.

The results in Table 2 were largely consistent whether they were based on all correlation coefficients or only on the significant correlation coefficients. This consistency results primarily because the row sums were dominated by statistically significant coefficients. It is important, however, to recognize that statistically insignificant correlations were not necessarily spurious. Given the complexity of the region, indirect and cumulative effects remain important even though they may be reflected in smaller correlations. The important point was that the correlations represent the results of past and present stressors, and synergistic and cumulative effects. The results of the correlation analysis should not be construed to mean that the stressors identified in the analysis were the only important stressors in the region. Furthermore, the top-ranked stressors should not be assumed to be those in most need of immediate mitigation as the coefficients do not necessarily represent direct impacts. Mitigating or eliminating the top stressors identified in the matrix might only result in small, or long-delayed, responses.

**Table 2. The most important stressors from matrix analysis. Values are the sum of all correlation coefficients; numbers in parentheses are the sums of the statistically significant coefficients (alpha = 0.05). An asterisk indicates that there are no statistically significant coefficients in the summation. See Table 1 for stressor definitions.**

| STRESSOR | CURRENT | FUTURE |
|---|---|---|
| **Overall** | | |
| UINDEX | 3.87 (3.04) | 4.12 (3.04) |
| TOTALN | 3.63 (2.16) | 3.98 (2.86) |
| TOTALP | 3.57 (3.13) | 4.18 (3.35) |
| | | |
| **Terrestrial** | | |
| EDGE2 | 2.90 (2.31) | |
| UINDEX | 2.88 (2.39) | 2.88 (2.32) |
| PSOIL | 2.22 (0.67) | 2.32 (1.30) |
| RDDENS | | 1.91 (*) |

Resources

Table 3 shows the results of matrix analysis of regional resources. Summations using only significant coefficients are shown in parentheses. Overall, the most stressed resources were small intact forest patches (INT2) and forest cover (FORPCT). The same resources were indicated for the present and for 2020.

The results for the most important terrestrial resources in the region were virtually identical to the overall resources. Small forest patches (INT2) and forest cover (FORPCT) were, again, the most stressed. The results appear reasonable because fragmentation and loss of habitat are well-established causes of environmental degradation in the region. The results were also supported because they were consistent between the present and future and were insensitive to using only the significant correlation coefficients. The results in Table 3 show surprising consistency. Nowhere was there a change between the present and 2020. The top two resources do not change when only the statistically significant coefficients were summed. The results indicate that the underlying correlation structure of the region was unaltered by the future scenario examined in this study. The most stressed resources remain the same in 2020.

**Table 3. The most important resources from matrix analysis. Values are the sum of all correlation coefficients; numbers in parentheses are the sums of the statistically significant coefficients. See Table 1 for resource definitions.**

| RESOURCES | CURRENT | FUTURE |
|---|---|---|
| **Overall** | | |
| INT2 | 5.02 (3.89) | 3.09 (1.60) |
| FORPCT | 4.74 (3.17) | 3.33 (2.27) |
| | | |
| **Terrestrial** | | |
| INT2 | 3.29 (2.36) | 1.51 (-0.05) |
| FORPCT | 2.98 (1.5) | 1.48 (0.56) |

## Vulnerability

The Stressor-Resource Overlay and Criticality methods were used to identify areas particularly vulnerable to continued degradation. Vulnerable in this case refers to those watersheds that currently support valued resources and that were subjected to some level of stress. Additional stress to these watersheds could result in the loss of the remaining resources. Additional stress to these watersheds could result in the loss of the remaining resources. It was of particular interest to evaluate how the class of vulnerable watersheds will change by 2020. Under the future scenario, stressor distribution and intensity changed and some forest resources were lost. It was important to know if the additional stressors changed the spatial pattern of vulnerability. Identifying the most vulnerable watersheds could help drive urban planning actions to prevent the degradation. These watersheds could be candidates for mitigation, restoration, or protection of some type, and knowing the sources of vulnerability would provide guidance to planners.

The vulnerability analyses presented in this section could be used to answer the following types of questions:

1. What watersheds are currently vulnerable to further impacts?
2. What watersheds may become vulnerable in the future?
3. Which watersheds are most vulnerable to irreversible change?
4. Which watersheds may be vulnerable to irreversible change in the future?

### *About the Analysis*

The Stressor-Resource Overlay method was used to identify watersheds with high levels of valued resources and high levels of stressors. For this analysis, variables were first divided into stressors and resources and then each stressor and resource variable was divided into quintiles. Watersheds were scored on the number of stressors that fell into the worst two quintiles and also on the number of resources that fell into the best two quintiles. The results were mapped to show where high amounts of resources coincide with high levels of stressors (Smith *et al.* 2003). The method used to determine changes in vulnerability by 2020 was the same Stressor-Resource Overlay method used to identify current vulnerabilities.

Criticality calculates the distance the current state is from a hypothetical natural state. During the long period of natural selection, prior to human disturbance, biological populations in the linked terrestrial/aquatic system evolved complex feedbacks that permitted recovery from natural disturbances and maintained a relatively stable system. The farther the systems were forced away from this natural state, the greater the probability that the systems will be unable to respond to natural disturbances and normal variations in environmental conditions (O'Neill 1999). Although it was not possible to predict the critical threshold beyond which the ecological system will move to a new and undesired state, it was possible to estimate how far the watersheds have already moved from their natural state. As human activities add stressors (e.g., chemical pollutants), extract resources (e.g., timber), and change land cover (e.g., fragmentation), the natural feedbacks are disrupted and the system becomes more vulnerable to radical and potentially irreversible change.

The first step in the Criticality analysis was to define the hypothetical "natural" state. The task was simple for some variables, e.g., human population and pollutants, which can be assumed to have been zero, but was more arbitrary for other variables such as biodiversity. In addition, it cannot be assumed that biotic variables can be characterized by a single value. The watersheds in the Mid-Atlantic region range from highland forests in the Appalachians, through the Ridge and Valley Province to the Coastal Plains. Even under pre-human conditions, it cannot be assumed that this diversity of systems was characterized by a single set of biotic variables. Criticality analysis was based on "fuzzy" values to deal with the uncertainties involved in defining the natural state. A fuzzy value was expressed not as a single number but as a range of possible values plus an assumed distribution. The range of values was selected as the lowest and highest values that can be reasonably expected to have existed in the natural state. A triangular distribution was assumed if the most reasonable value would be expected to lie toward the center of this range. A flat or rectangular distribution was assumed if our ignorance only permits us to say that the value lies somewhere within the range. For the present study, the natural state for each variable was defined as given in Table 4. Once the definition of the "natural state" was established, it was possible to calculate a "fuzzy" distance between each watershed and the natural state.

Future criticality was evaluated using the same methods as the current, but using the data from the future scenario. The fuzzy distance was calculated according to Tran and Duckstein (2002). The reference state was the same as used in the previous analysis and the fuzzy distance was calculated from the reference state to the future scenario used in this study.

**Table 4. Definition of "natural state" of the 24 indicators used in the analysis. See Table 1 for indicator definitions.**

| Indicators | Natural States | Rationale |
|---|---|---|
| UINDEX$^{S}$ | 0 | All variables associated with humans are set equal to 0.0 |
| RDDENS$^{S}$ | 0 | All variables associated with humans are set equal to 0.0 |
| AGSL$^{S}$ | 0 | Variables associated with humans are set equal to 0.0 |
| RIPAG$^{S}$ | 0 | Variables associated with humans are set equal to 0.0 |
| STRD$^{S}$ | 0 | Variables associated with humans are set equal to 0.0 |
| POPDENS$^{S}$ | 0 | Variables associated with humans are set equal to 0.0 |
| POPGROWTH$^{S}$ | 0 | Variables associated with humans are set equal to 0.0 |
| PRAGFM$^{S}$ | 0 | Variables associated with humans are set equal to 0.0 |
| PRMINE$^{S}$ | 0 | Variables associated with humans are set equal to 0.0 |
| TERREXOTIC$^{S}$ | 0 | Without human interference, natural communities are extremely difficult to invade |
| AQUAEXOTIC$^{S}$ | 0 | Without human interference, natural communities are extremely difficult to invade |
| FORCOVDEFOL$^{S}$ | 0 | No gypsy moths or introduced defoliators |
| EDGE65$^{S}$ | smallest quintile = least fragmentation | In the natural state, some fragmentation is expected |
| EDGE2$^{S}$ | smallest quintile = least fragmentation | In the natural state, some fragmentation is expected |
| INT2$^{R}$ | largest quintile = most forest | In the natural state, some fragmentation is expected |
| INT65$^{R}$ | largest quintile = most forest | In the natural state, some fragmentation is expected |
| WETLNDSPCT$^{R}$ | largest quintile = most wetlands | |
| STRFOR$^{R}$ | largest quintile = most forest | |
| FORPCT$^{R}$ | largest quintile = most forest | |
| TOTALN$^{S}$ | smallest quintile = least pollution | We assume some small amount of N and P existed in the natural state |
| TOTALP$^{S}$ | smallest quintile = least pollution | We assume some small amount of N and P existed in the natural state |
| NITRATEGW$^{S}$ | smallest quintile = least pollution | We assume some small amount of N and P existed in the natural state |
| PSOIL$^{S}$ | same as current | |
| MIGSCENARIO$^{R}$ | largest quintile | |

*Maps*

<u>Stressor-Resource Overlay</u>

Results were displayed based on a matrix (see Figure 8 legend) with stress increasing from left to right and resource abundance increasing top to bottom (Figure 8). For the current scenario, the most highly stressed watersheds would be in dark red, but none are mapped because no watersheds with that much stress still have valued resources. The map does show 19 watersheds with more than two resources in the upper quintiles in stressor categories A and B. These watersheds were primarily in the Mid-Atlantic Highlands (an area of relatively high resource abundance) although there were a few in the piedmont and coastal plain (areas where many resources typically have been lost). In the futures analysis, no watersheds fell into the red, indicating again that watersheds with the highest number of stressors had few or no valued resources remaining. In the 2020 scenario, however, nine additional watersheds were categorized as vulnerable. The comparison of present and future scenarios shows a clear spatial pattern of possible future vulnerability; many watersheds in the Mid-Atlantic Highlands and several in the southern Piedmont and coastal plains become increasingly vulnerable in 2020 under the future scenario.

<u>Criticality</u>

The assumption of "natural state" given in Table 4 produces the maps shown below. The current map shows the 20 watersheds most vulnerable to moving to a new and potentially irreversible condition (Figure 9). The greatest current vulnerability is associated with more intense human activity, particularly around Baltimore and Washington, north of Pittsburgh, and east of Raleigh, North Carolina. The 20 watersheds most vulnerable to irreversible change in 2020 were concentrated around urban centers; of these watersheds, those shown in red have ecological systems dominated by anthropogenic controls and are unlikely to change spontaneously.

Comparisons of watersheds most vulnerable to irreversible change currently and in the future (Figure 9C) indicate that the watersheds adjacent to Pittsburgh and Raleigh dropped out of the most vulnerable category in 2020. However, five other watersheds (shown in dark blue) become more vulnerable to irreversible change by 2020. The watersheds were in eastern suburban areas. Three of these watersheds, however, were among the 20 most vulnerable in the current conditions analysis.

The two watersheds newly in the most vulnerable to irreversible change category were the Lower Susquehanna-Swatara and Shenandoah. Environmental degradation in these two watersheds resulted from the loss of multiple resources rather than just a single resource. Total forest cover changes by 2-5% of current values and stream-side forest shows a 2-8% change (Table 5). The greatest change, however, was in interior forest habitat (INT65 and INT2), which ranged from 10 to 37% of the current interior forest lost in both watersheds by 2020. There was a small increase in nutrient inputs (TOTALN, TOTALP, GRDWN) to the aquatic systems, but a much more substantial increase in terrestrial exotic species (~50% over current values) and in aquatic exotics (~20% over current values).

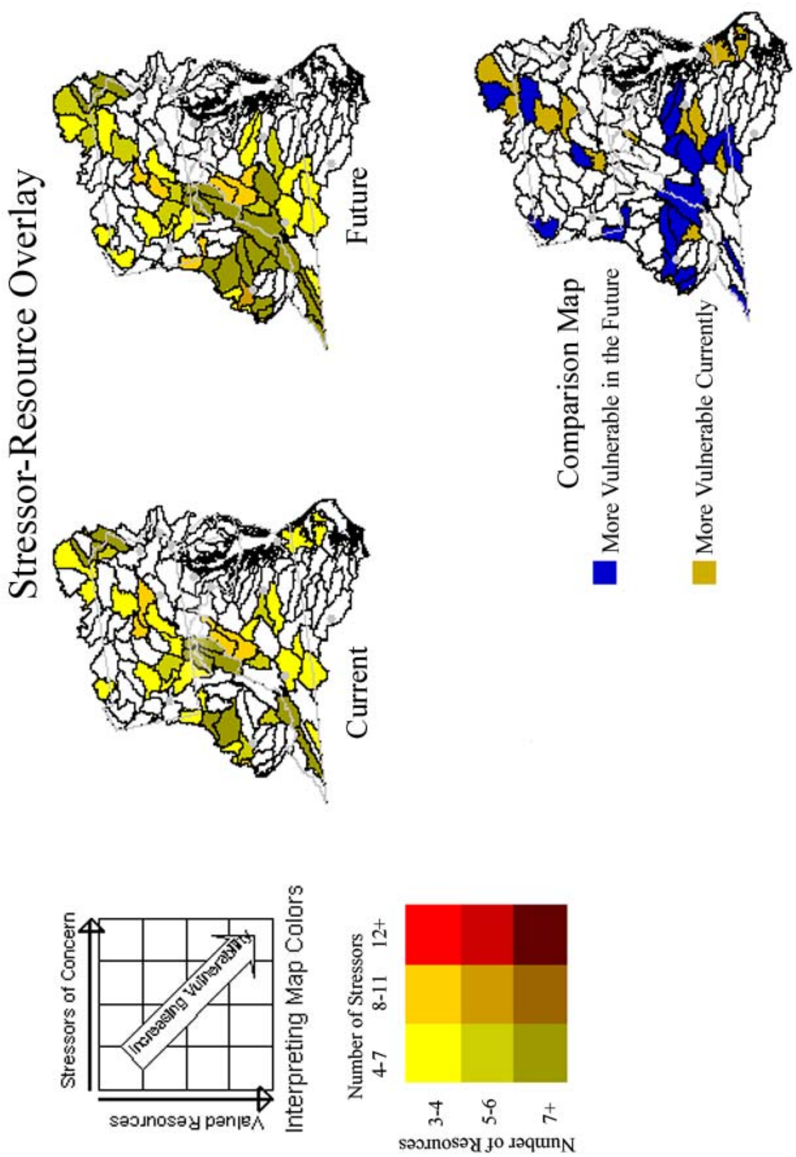


**Figure 8. Stressor-Resource Overlay showing the most vulnerable watersheds. Vulnerability here is characterized by the number of valued resources that are exposed to stressors of concern in each watershed (for resource and stressor definitions see Table 1). The comparison map shows where watersheds are more vulnerable under the future scenario (blue) and where watersheds are more vulnerable under current conditions (yellow-brown). Vulnerability of watersheds in white does not differ between the two scenarios.**

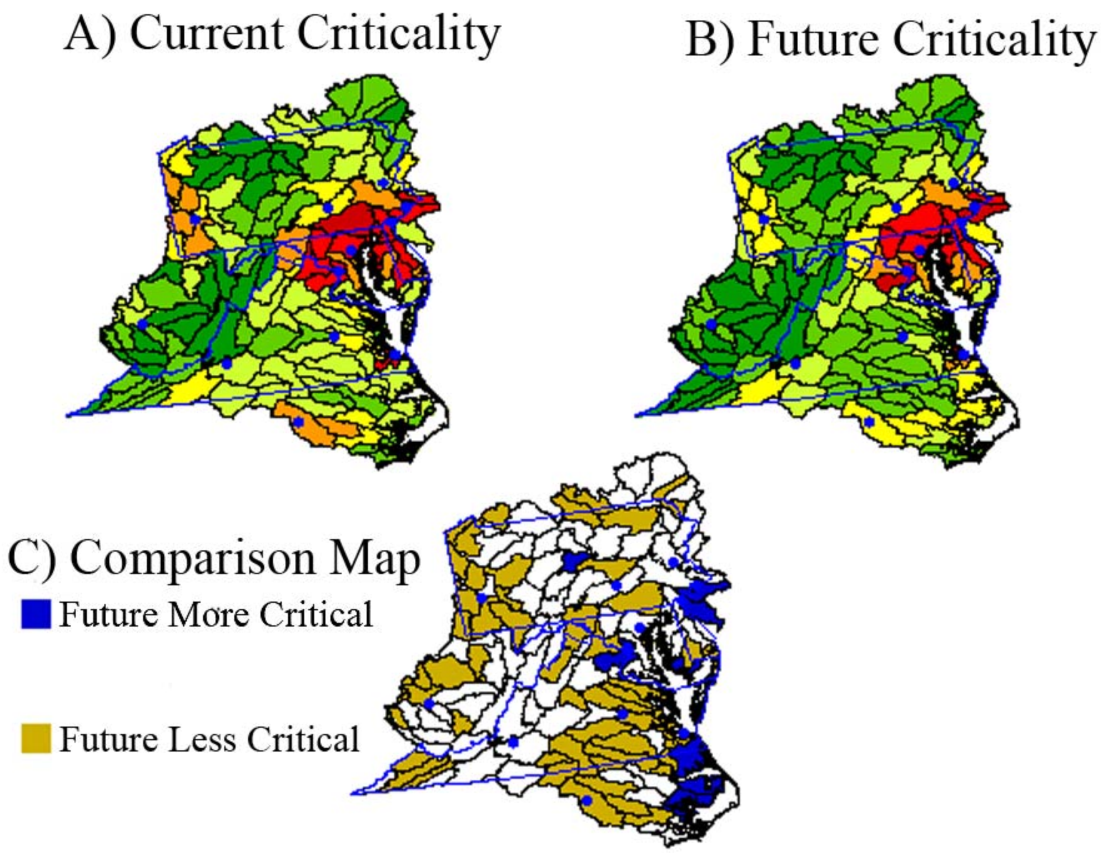


**Figure 9. Watersheds currently most vulnerable to irreversible change (A), most vulnerable to irreversible change by 2020 (B), and comparison map (C).**

**Table 5. Stressor and resource change in two of the top 20 watersheds most vulnerable to irreversible change.**

| | LOWER SUSQUEHANNA-SWATARA | SHENANDOAH |
|---|---|---|
| Variable | Change (%) | |
| STRFOR | -8.3235 | -2.1119 |
| FORPCT | -4.4646 | -2.1329 |
| TOTALP | 0.0290 | 0.0215 |
| TOTALN | 0.0517 | 0.0524 |
| NITRATEGW | 0.0849 | 0.0690 |
| INT65 | -12.2334 | -10.9325 |
| INT2 | -36.5848 | -34.7877 |
| TERREXOTIC | 46.0000 | 50.0000 |
| AQUAEXOTIC | 22.0000 | 17.0000 |

# Discussion

## Current Conditions and the Future Scenario: Analysis of the Mid-Atlantic Region

A series of assessment questions was developed for use in examining current and future conditions in the Mid-Atlantic. ReVA began this study by developing the following assessment questions.

1. What is the current spatial pattern of environmental condition?
2. How will the spatial pattern of condition change in the future?
3. How much will environmental condition change in the future?
4. What are the most important stressors in a region?
5. Which watersheds will become the most stressed in the future?
6. What are the most stressed resources in the region?
7. How will future change affect the least stressed watersheds in the region?
8. What watersheds are currently vulnerable to further impacts?
9. What watersheds may become vulnerable in the future?
10. Which watersheds are most vulnerable to irreversible change?
11. Which watersheds may be vulnerable to irreversible change in the future?

The Simple Sum and PCA Sum methods were used to address questions 1-3 and showed similar spatial patterns of environmental condition; highly urbanized areas were in poorest condition and watersheds that were not near urban centers were in the best condition (particularly those in the Highlands). The future scenario used for this study showed degraded environmental condition scattered across the Mid-Atlantic region with possible synergistic effects from multiple stressors impacting many of the Mid-Atlantic Highlands watersheds. The changes were not necessarily large, often involving only a shift of a single septile, but the degradation was widespread across the region.

The PCA Sum method accounts for the co-occurrence of stressors resulting in slightly better environmental condition than the Simple Sum on several watersheds. The better current and future condition predicted by the PCA Sum approach may be the result of underestimating the effect of multiple correlated stressors which act synergistically causing greater environmental damage than what was depicted. Therefore, the Simple Sum method might be a more conservative estimate of environmental condition and perhaps a better prediction of where cumulative effects can be expected.

The results of the matrix analysis were used to answer question 4 and indicated that the most threatening current stressors (urbanization and nutrient runoff) will also be the most threatening stressors in 2020. No changes in the ranking of the top stressors occur in the overall evaluation, although minor changes occur when individual sub-groupings were considered. In no case did more than one of the three most important stressors change and none of the new top stressors that appear in the 2020 analysis were based on significant coefficients. Therefore, changes were possible rather than probable and likely include cumulative and indirect effects rather than solely direct effects.

State Space analysis was used to answer question 5 and indicated that the least change between current and future condition was concentrated in watersheds along the Mid-Atlantic Highlands. Watersheds that changed the most were concentrated in suburban areas that surround the major urban centers:

Wilmington, Philadelphia, Baltimore, Washington, Pittsburgh, and Wheeling. Intermediate change was projected for parts of the coastal plain and piedmont. The observed pattern of environmental degradation was expected because the model used to project land cover change in the future scenario was primarily an urban sprawl model and concentrates land cover changes in the areas surrounding the major urban centers.

The Stressor-Resource Overlay method (questions 6-9) illustrates how a watershed can have many valued resources, but still not be vulnerable now or in the future because of the absence of stressors. Many watersheds in the highlands had high levels of resources, but were isolated from many of the land-cover changes that degraded other areas. On the other hand, a highly stressed watershed might not be considered vulnerable because its valued resources have been destroyed. For example, the watershed containing Baltimore was highly stressed, but was not among the most vulnerable because few valued resources remain. The most vulnerable watersheds often were those with intermediate to high levels of stressors together with intermediate to high levels of resources. The watersheds identified as vulnerable in the Stressor-Resource analyses were in rural areas that retain natural resources because they were not yet covered by urban sprawl and other development. Thus, vulnerable watersheds have valued resources in amounts intermediate to the best and worst areas and these resources might only be protected by careful planning.

The watersheds most vulnerable to irreversible change (questions 10-11) according to current and future Criticality analyses were concentrated in and around the Baltimore-Washington, DC, metropolitan area. These watersheds were so highly altered that they were unlikely to return to their pre-human natural state if human controls were removed. The important resources and stressors in the highly altered watersheds were similar to those indicated by the best and worst quintile methods, including measures of habitat condition, nutrient inputs, and invasive species. A few shifts occurred in the top 20 most vulnerable watersheds between the current and future scenarios; however, the majority of the watersheds remained in the same rank between time periods. The "fuzzy" definitions of the natural state used in the Criticality analyses give the appearance of bias toward false negatives (i.e., possibly underestimating the risk of catastrophic change) and this bias can be interpreted in either of two ways. First, it makes a strong case that the watersheds shown were indeed vulnerable and, second, the results should not be interpreted as meaning that other watersheds were "safe" from further degradation.

The general pattern for the future scenario used here shows that forests will continue to dominate the landscape, but human disturbances will increase around existing metropolitan centers and will also spread in the Mid-Atlantic Highlands, especially in West Virginia. The coastal plain, which was dominated by urbanization, was forecasted to receive even more pressure from urban development. The other likely large-scale land-cover change was in mining, which increased most in the Mid-Atlantic Highlands. The spread of mining as presented is the worst case scenario, however, because all permitted areas were assumed to be mined by 2020, all mining was assumed to cause surface disturbance, and no reclamation was included.

Using ReVA's approach, decision makers in the Mid-Atlantic and in other regions can identify current stressors and resources and how those stressors and resources can change across the landscape under some future scenario. Conventional ecological vulnerability assessment is mainly based on "source-based" approach (single stressor on single resource) where the concept of probability is dominant. However, it is almost impossible to derive a probabilistic vulnerability in a "place-based" and/or regional method as in ReVA where data are multiple stressors and resources collected from various sources with different types of uncertainty (or no information of uncertainty at all). In that context, future scenario analysis in ReVA portrays the vulnerability concept in a "qualitative" and "relative" context. The concept is based on relative comparison and spatial relationships among watersheds. The use of various simple methods (e.g., Simple Sum, Principal Components Analysis, State Space analysis, Criticality analysis, and Stressor-Resource Overlay) to address a set of vulnerability assessment questions demonstrates successfully the concept of relative vulnerability. It also shows that different methods can facilitate different tasks of environmental planning, in general, and future scenario analysis, in particular, to different extents.

The following are recommendations for the use of the integration methods described in this report:

- Address a set of assessment questions at the same time: as management prioritization involves balancing many different factors, future scenario analysis should be addressed through a series of assessment questions to cover the various aspects of the system under study.

- Use a suite of integration methods: there is no single integration method that can fully address future scenario analysis. Each method has advantages and disadvantages. The use of multiple methods in a complementary manner will help the user look at the problem from different angles/perspectives.

- Pay attention to your data: how data are coded or transformed can have substantial influence on the integration results. Try to keep a balance between data transformation and data interpretation.

## Other Uses of ReVA Assessments

### *Environmental Conservation*

Ecological conservation is often carried out at small scales, and, combining approaches from both conservation biology and landscape ecology provides a suitable approach to examine problems and questions at a regional scale. The analyses in this report provide powerful insights for such integrated approaches. By examining those analyses collectively and comparatively, scientists and policymakers can identify not only the best watersheds for conservation at the local level but also identify the critical ecological linkages that can facilitate regional conservation efforts. Such insights cannot be found in a single analysis of a single question with a single method or tool.

Results presented in this report are potentially useful in numerous ways. First, the questions and the methods used to answer them help depict a comprehensive assessment of a region's current and possible future environmental condition. Second, the information can be used to target risk reduction actions and prioritize use of resources at the regional and sub-regional level. Third, it illustrates how different integration techniques developed and presented in the first report (Smith *et al.* 2003) can be used in a complementary manner to examine various issues of environmental planning and management, especially on environmental risk reduction, restoration, and mitigation.

### *Ecological Restoration*

Arguably, many of the principal keys to the restoration of aquatic systems (USEPA 2000) are applicable to terrestrial ecosystems. Our report highlights and augments many of these principles. The analyses in our report suggest ways to locate ecosystems in the best condition for conservation. By identifying these most intact ecosystems, the biodiversity needed for recovery is preserved. Many of the analyses used for this report, in particular State Space and Criticality analyses, depend on comparison to some reference watershed(s) in best ecological condition with similar structure and function. The watersheds in the best quintiles may be used as models for restoration projects, as well as a reference for measuring the progress of the project.

Restoration is most appropriately done at a watershed-wide scale and not simply done at a single most degraded point within a watershed. By conducting an assessment on a regional scale, the relationships of watersheds to each other as well as their ecological settings, resources, stressors, and changes that occur within individual watersheds can be examined. Ecological integrity refers to the overall condition of an ecosystem in terms of its structure, composition, and natural processes of the biotic communities and physical environment. The indicators and integration techniques used in this report aid in the analysis of the ecosystem's structure, composition, and its dynamics. We provide through our Criticality analyses a method for understanding the natural potential of a watershed and an evaluation of irreversible changes that may affect the ability of a watershed to be restored. Addressing ongoing causes of degradation within a watershed is vital for restoration planning and avoiding irreversible changes. Our Stressor-Resource Overlay analyses are one method of identifying the important stressors that should be remediated wherever possible. Furthermore, by including spatial and temporal dynamics in all our analyses we provide planners a way to anticipate foreseeable ecological and societal changes.

A final principle often stated for restoration is the need to develop clear, achievable, and measurable goals that are set at levels achievable ecologically, financially, and with the support of the community. In our analyses, the criteria for choosing candidates for conservation can be modified and relaxed to some extent to achieve realistic conservation goals and objectives.

# Appendix

**Appendix 1. National Land Cover Data (NLCD) classes used for GARP modeling of invasive species. N is the number of geographic occurrence points used to develop predicted distributions.**

| Species | Scientific name | NLCD class | N | Occurrence data sources |
|---|---|---|---|---|
| Asian long-horned beetle | *Anoplophora glabripennis* | 21, 22, 41, 43, 61, 91 | 80 | Lingafelter & Hoebeke 2002 |
| Hemlock woolly adelgid | *Adelges tsugae* | 21, 42, 43, 91 | 177 | NAPIS, online sources |
| Hydrilla | *Hydrilla verticillata* | 11, 92 | 190 | Peterson *et al.*, NAS Web site, online sources, other pubs, www.ramsar.org |
| Eurasian watermilfoil | *Myriophyllum spicatum* | 11, 92 | 263 | NAS Web site, online sources, other pubs, www.ramsar.org |
| Greater pine shoot beetle | *Tomicus piniperda* | 21, 42, 43, 61 | 122 | NAPIS, online sources, other pubs, NMNH |
| Emerald ash borer | *Agrilus planipennis* | 21, 41, 43, 91 | 39 | Jendek Pers. Comm., St. Petersburg Academy, Michigan DNR |
| Garlic mustard | *Alliaria petiolata* | 41, 43, 91, 92 | 143 | Peterson *et al.* |
| Sudden oak death | *Phytophthora ramorum* | 21, 22, 41, 43, 51, 91 | 116 | OakMapper |
| Giant salvinia | *Salvinia molesta* | 11, 92 | 47 | NAS Web site, Queensland Herbarium, Jardim Botanico do Rio de Janeiro |
| New Zealand mud snail | *Potamopyrgus antipodarum* | 11, 92 | 253 | Auckland Museum, Te Papa Museum |

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