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.

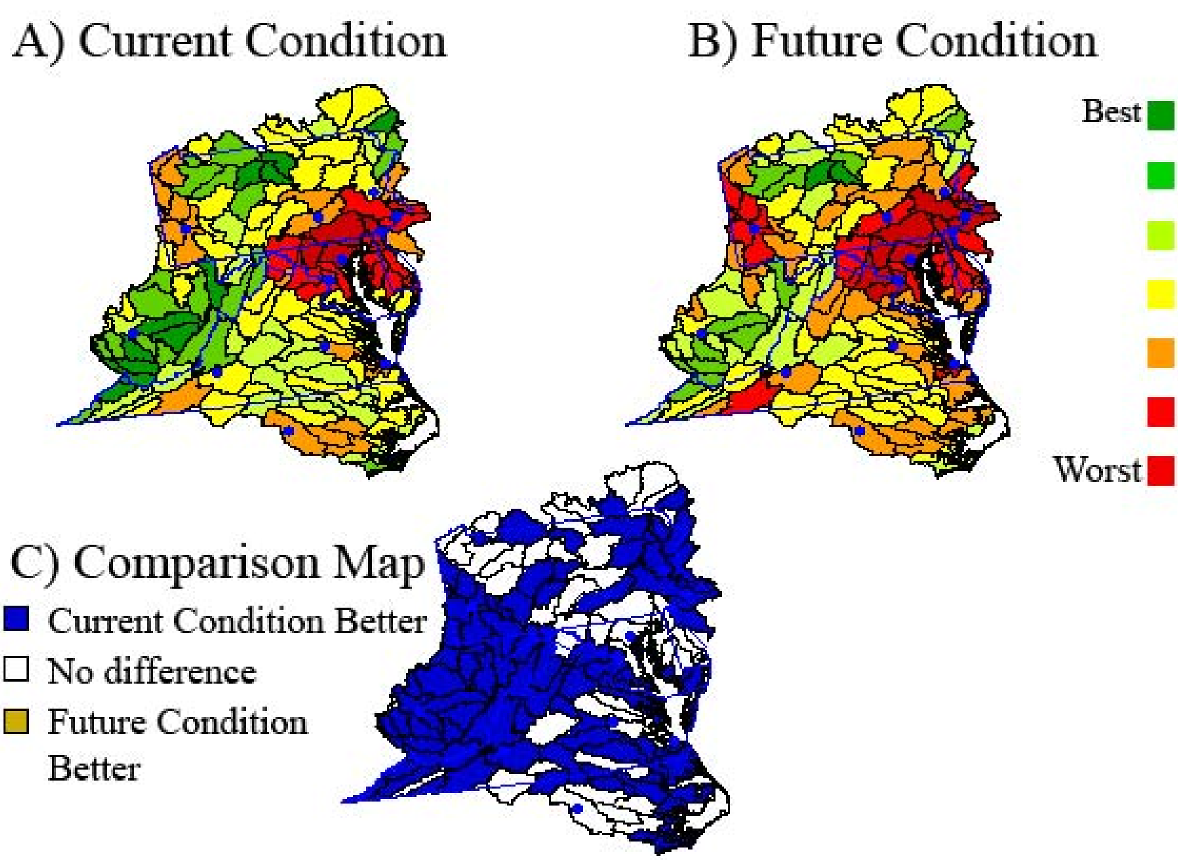

Figure 4. Map of current (A) and future (B) environmental condition in the Mid-Atlantic integrated using the Simple Sum method. Map C shows a comparison of current and future conditions.

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.

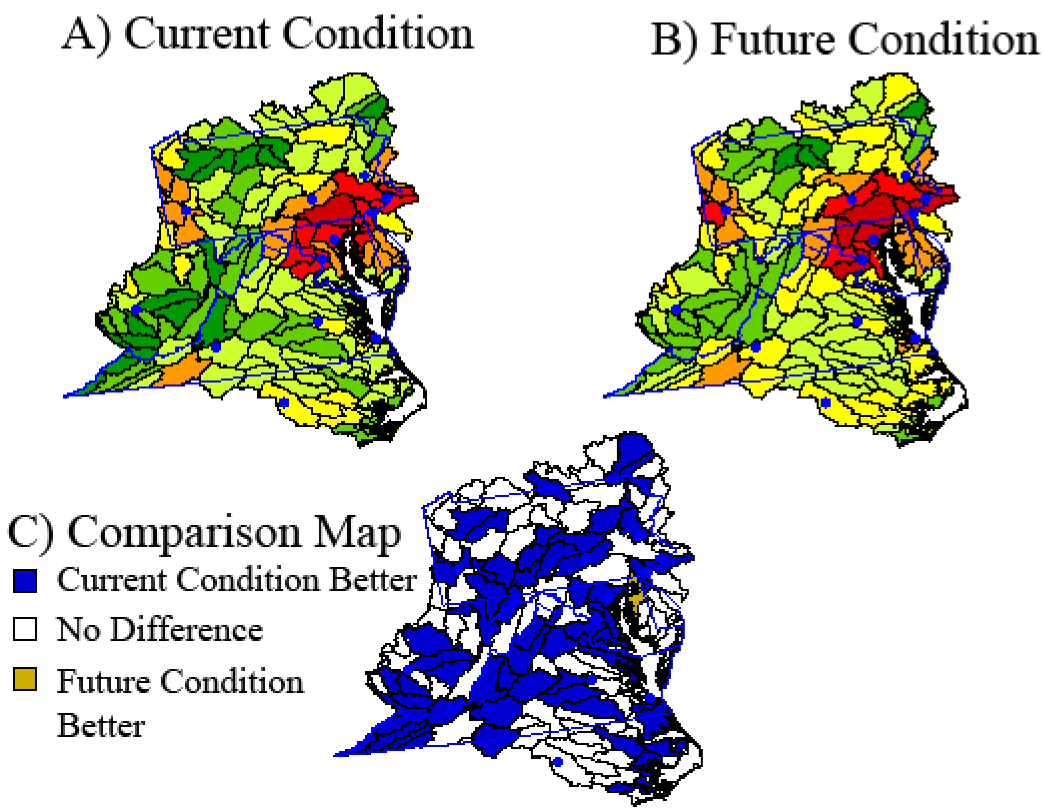

Figure 5. Map of current (A), future (B), and comparative (C) environmental stress in the Mid-Atlantic integrated using the PCA Sum method.

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.

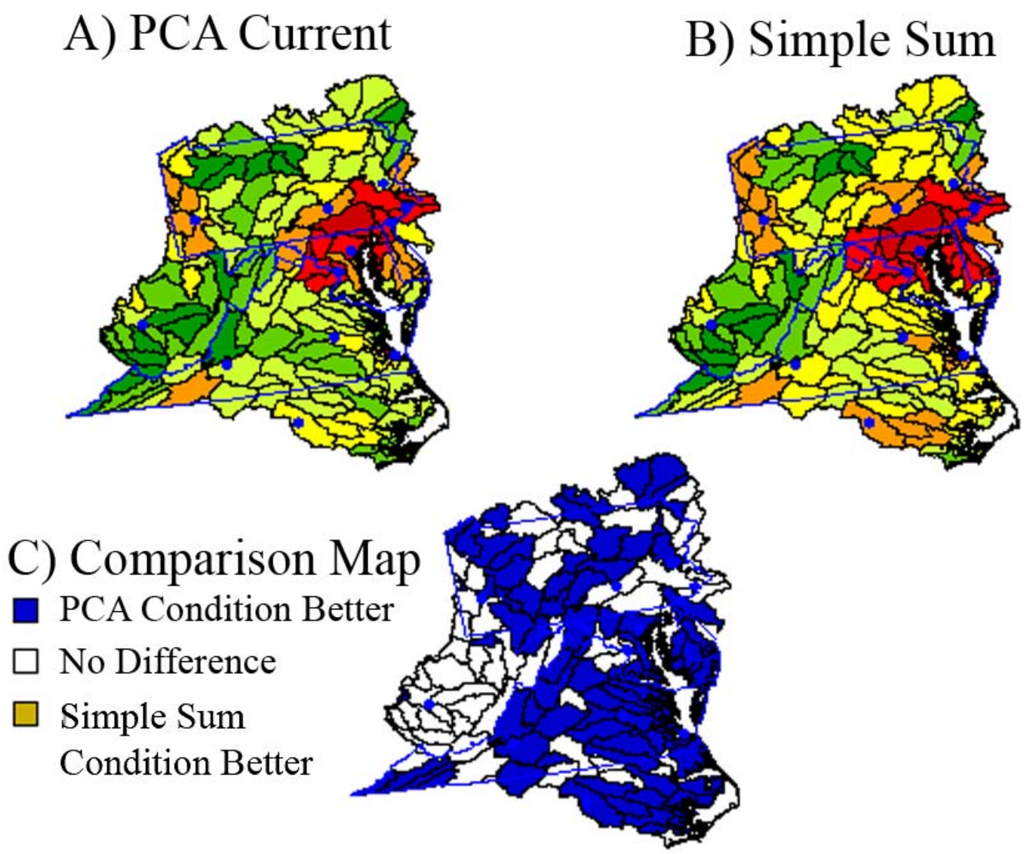

Figure 6. Map of current environmental condition in the Mid-Atlantic using PCA (A) and Simple Sum (B) methods. Map C shows where results differ.

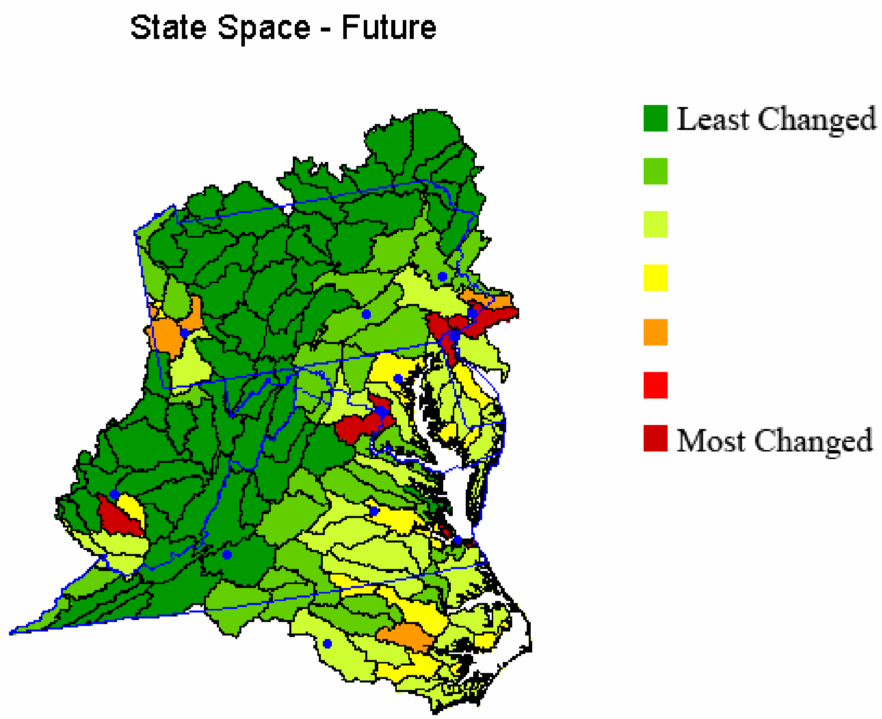

Figure 7. State Space analysis.

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

<u>Stressors</u>

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

Stressor-Resource Overlay

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.

Criticality

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).

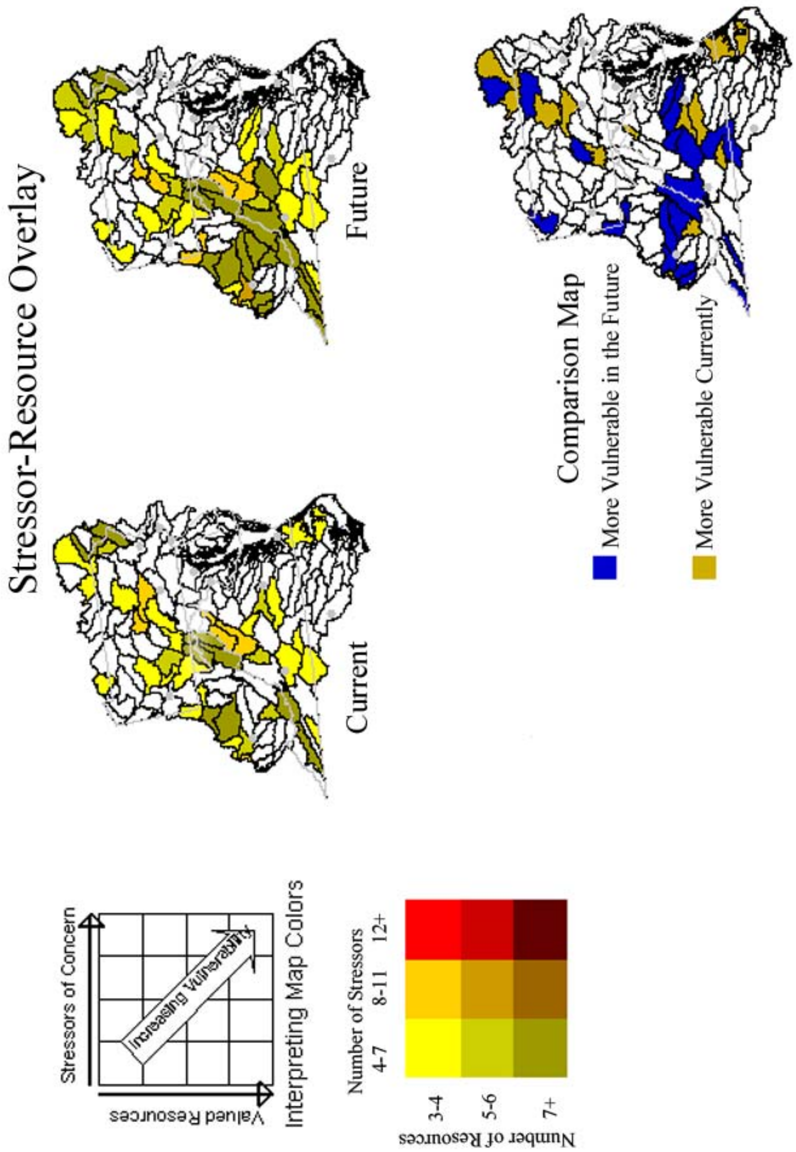

Figure 8. Stressor-Resource Overlay showing the most vulnerable watersheds. Vulnerability here is characterized by the number of valued resources that are exposed to stressors of concern in each watershed (for resource and stressor definitions see Table 1). The comparison map shows where watersheds are 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.

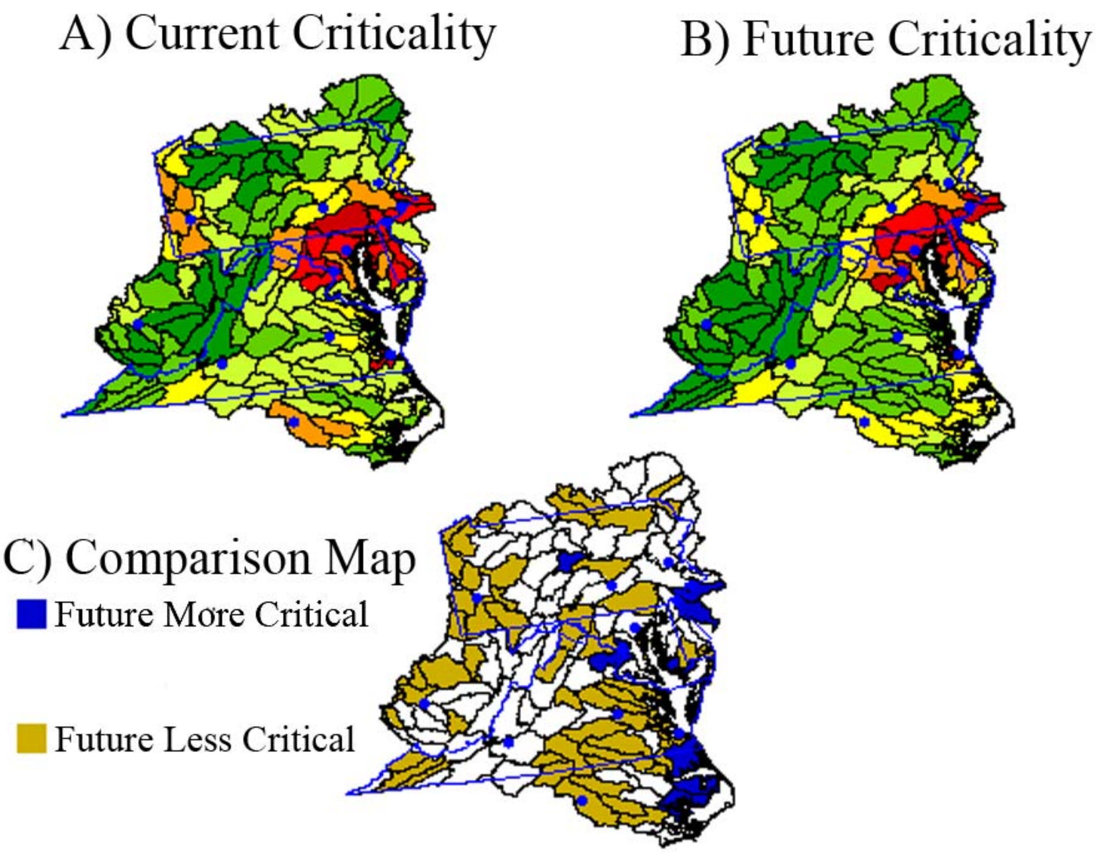

Figure 9. Watersheds currently most vulnerable to irreversible change (A), most vulnerable to irreversible change by 2020 (B), and comparison map (C).

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