6.0 CONCLUSIONS

This report summarizes recent efforts to quantitatively project the environmental effects of acidic deposition on aquatic resources within the Southern Appalachian Mountains. A number of conclusions can be drawn from this assessment. These conclusions relate to an array of issues and potential environmental effects ranging from atmospheric deposition to streamwater chemistry, forest health, and effects on fisheries. Model projections, in response to the three Emissions Control Strategies developed for this study, yielded a range of responses. These modeled responses varied within and among strategies and showed distinct geographical patterns, especially with respect to north-south gradients and across physiographic provinces. The primary conclusions of this study are summarized below.

Deposition

There is high spatial variability within the SAMI study area in the current atmospheric deposition of sulfur and nitrogen. Highest levels of deposition of both elements have been observed in the high elevation portions of the Great Smoky Mountains, where cloud deposition contributes heavily to the total deposition loads, and in West Virginia.

Atmospheric modeling of the three Emissions Control Strategies developed for this study by SAMI resulted in estimated large reductions in projected sulfur deposition for all three strategies. The mean percent changes in sulfur deposition at the modeled sites from 1995 to 2040 were -57%, -67%, and -73% for the OTW, BWC, and BYB strategies, respectively. Estimated changes in total (oxidized plus reduced) nitrogen deposition for these strategies were much smaller. Mean percent changes in nitrogen deposition indicated an increase of 10% for OTW and decreases of 14% and 34% for BWC and BYB. Estimated future changes in sulfur and nitrogen deposition were not uniformly distributed across the SAMI region. Changes were in many cases estimated to be largest in West Virginia.

The principal conclusions with respect to deposition are as follows:

- High spatial variability was observed in current deposition of sulfur and nitrogen, with highest quantities observed at high-elevation sites in western North Carolina and eastern Tennessee and in the Appalachian Plateau physiographic province of West Virginia.
- High spatial variability was observed in modeled changes in sulfur and nitrogen deposition in response to the three Emissions Control Strategies
- Generalized strategy results for deposition were as follows:

- All strategies showed decreased sulfur and oxidized nitrogen deposition at all sites, with largest decreases in the BYB Strategy.

- Reduced nitrogen deposition increased at all sites under the OTW Strategy, at most sites under the BWC Strategy, and at about half of the sites under the BYB Strategy.

- Projected changes in total (oxidized plus reduced) nitrogen were variable across sites and strategies, with largest decreases in West Virginia,

Watershed Sensitivity to Acidification

Watersheds within the SAMI study area are highly variable spatially with respect to their sensitivity to acidification. This sensitivity is reflected in variations in base cation concentration and ANC of streamwaters, soil base saturation, sulfur adsorption on soils, and watershed retention of atmospheric nitrogen inputs. To some extent, elements of watershed sensitivity are predictable, based on such features as geology, elevation, and physiographic province.

Lithologic coverages developed by the USGS were classified into five geologic sensitivity classes, ranging from primarily siliceous rock types (most acid-sensitive) to carbonate types (least acid-sensitive). Although lithology proved to be the best single predictor of acid sensitivity, as reflected by negative or low values of ANC, lithology was an inconsistent predictor of site-specific ANC. Acidic and low-ANC streams were almost always found in areas covered by lithologies classified in the most sensitive geologic classes. However, other less acid-sensitive watersheds were also found within areas covered by these classes. This finding is a logical reflection of the coarse scale of available lithologic maps used as the basis for geologic sensitivity classification and the common presence of pockets of highly weatherable geologic materials within areas generally classified as acid sensitive.

The extent to which watersheds currently retain sulfur and nitrogen inputs has an important effect on simulated responses to changing levels of sulfur and nitrogen deposition. Sulfur retention was noted to vary spatially and this variation was related to location, both relative to physiographic province and latitude.

Sulfur retention was projected to decline at many sites, especially in the southern portion of the Ridge and Valley Province and throughout the Blue Ridge Province. This projected decline in sulfur adsorption on soils contributes to model projections of delayed acidification at many of these sites.

Model results suggested that nitrogen retention may be influenced by latitude, elevation, and physiographic province. In general, the areas with the lowest nitrogen retention, as indicated by high nitrogen leaching as streamwater nitrate, were located mostly at high elevation in the Blue Ridge Province and in northern portions of the Appalachian Plateau Province.

Conclusions regarding watershed sensitivity to acidification and the observed relationships between acid-base chemistry of streams and watershed characteristics include the following:

- Base cation concentration and ANC of streamwaters vary spatially.
- Lithology, by itself, is not an entirely reliable predictor of streamwater ANC. However, lithology can be grouped into generalized sensitivity classes, and the most acid-sensitive watersheds are almost always found within areas covered by lithologies classified as most sensitive. In addition, other less acid-sensitive watersheds are also located within areas covered by the most sensitive geologic classes.
- The ability of watersheds to retain (versus leach to streamwaters) incoming sulfur and nitrogen varies spatially, and this retention ability has a large impact on modeled responses of streamwater chemistry to changes in deposition of sulfur or nitrogen.
- Some watersheds currently retain a high percentage of sulfur deposition through sulfur adsorption on soils, but that adsorption was projected to decrease with continued sulfur deposition loading.
- A classification scheme was developed for the SAMI region based on lithologic sensitivity class and stream site elevation. The acid-sensitive area delimited in this manner only covered 26% of the SAMI domain, but included 95% of the stream sites presently known to be acidic and 88% of the sites exhibiting an ANC $\leq$ 20 µeq/L. It also included 86% of the stream sites that were projected to be both acidic in 1995 and to increase to positive ANC by 2040 in the BYB Strategy.

Streamwater Chemistry

Streams exhibited a broad range of response to the cumulative sulfur deposition loadings received to date and the large simulated decreases in sulfur deposition in the future. Some streams showed modeled streamwater sulfate concentrations increasing in the future, even while sulfur deposition in two strategies was reduced by more than two-thirds. These were mostly sites that had relatively low sulfate concentrations ($\leq$ about 50 µeq/L) in 1995. They generally showed simulated future acidification, which was most pronounced for the OTW strategy. Other streams were simulated to show relatively large decreases in future streamwater sulfate concentrations and concurrent increases in ANC in response to the strategies, with progressively larger changes from the OTW to the BYB strategies. These tended to be streams that had relatively high concentrations of sulfate (> 50 µeq/L) in 1995, suggesting that these watersheds were likely closer to equilibrium with respect to inputs and outputs of sulfur. Some streams were projected to decrease in both sulfate and nitrate concentrations but nevertheless to continue to acidify. This response can be attributed to large simulated decreases in base cation concentrations at these sites.

Most simulated changes in streamwater ANC from years 1995 to 2040 were relatively small compared to the very large estimates of decreased sulfur deposition represented by the strategies. Few modeled streams showed projected change in ANC more than about 20 µeq/L. Some of the largest changes were simulated for some of the streams that were most acidic in 1995. For such streams, however, even relatively large increases in ANC would still result in negative ANC streamwater, and therefore little biological benefit would be expected from the simulated improvement in chemistry. The model suggested, however, that benefits would continue to accrue well beyond 2040 for all strategies, even if deposition was held constant at 2040 levels into the future.

None of the strategies resulted in projections of large improvements in the percent of modeled streams within the various ANC classes. Although the BWC strategy and more substantially the BYB strategy resulted in fewer acidic and low-ANC streams than did the OTW strategy, these differences were relatively small (< 10% of the modeled streams). In all cases, however, strategy projections of improvement, based on changes in the percent of the modeled group estimated to be acidic in 2040, were pronounced (16% to 26% lower) in comparison with results of the scenario that was based on continued future deposition at 1995 levels. The model results suggest that current efforts to reduce emissions from 1995 levels, as represented by the OTW Emissions Control Strategy, will prevent substantial future deterioration in streamwater acid-base chemistry. However, additional reductions in emissions, as represented by the BWC and BYB Emissions Control Strategies, will probably not have a large additional impact on streamwater chemistry to the year 2040.

Watersheds that had relatively high nitrate concentrations in 1995 (> about 20 µeq/L) were most sensitive to estimated changes in future nitrogen deposition. However, projected acidification was not consistently associated with particular patterns in starting point nitrate concentrations or projected changes in nitrate concentrations. Sizeable (e.g., > 5 µeq/L) projected changes in streamwater nitrate concentration were mostly restricted to the Appalachian Plateau.

Modeled changes in streamwater ANC in the SAMI strategies were driven primarily by changes in sulfur deposition, rather than changes in nitrogen deposition. This was because simulated changes in nitrogen deposition were smaller than simulated changes in sulfur deposition and because simulated changes in nitrogen deposition were projected to have substantial impacts on streamwater nitrate concentration only in a limited geographical area.

Watersheds found to be most sensitive to modeled changes in nitrogen deposition were located primarily in the northern section of the Appalachian Plateau province in West Virginia and at high elevation in the Blue Ridge Province in North Carolina and Tennessee.

Of the 130 watersheds included in the regional modeling effort, 18% were acidic in 1995. Model results suggested that this percentage should be expected to increase by the year 2040 to 25%, 19%, and 15% under the OTW, BWC, and BYB strategies, respectively. Estimates of change in the number of streams within this group having low ANC ($\leq$ 20 μeq/L) under the three strategies were 50%, 41%, and 38%, respectively, as compared with 40% in 1995. The model estimated that more streams would likely shift downward from the "0 to 20 μeq/L" class to the "less than 0 μeq/L" class than would shift between the classes < 20 μeq/L and those > 20 μeq/L. These changes that were simulated for the group of 130 regional watersheds are expected to be generally representative of the types of potentially acid-sensitive streams (defined as those having ANC $\leq$ 150 μeq/L) found within the SAMI region.

Modeling results were extended to the statistical frame of the NSS by applying the median model output from among all modeling sites within a given modeling bin to all NSS sites within the ANC class and physiographic province represented by that bin. There were 12 bins, stratified by 3 physiographic provinces and 4 ANC classes. Based on the NSS statistical design, approximately 3% of the lower node streams within the study area were acidic and chronically unsuitable for supporting brook trout in 1995. That percentage was projected to decline by 2040 to 2% (BWC) and 1% (BYB), but to remain at 3% under the OTW strategy. Similarly, an estimated 7% of the upper node streams were acidic in 1995, and that percentage was projected to increase to 10% under OTW but to remain at 7% under the other two strategies.

The percent of streams represented by the NSS statistical design within the SAMI domain that were projected to be suitable for brook trout (ANC > 50 μeq/L) in 2040 was estimated to range from 77% (OTW Strategy) to 78% (BYB Strategy) for upper node streams (compared with 78% in 1995) and would remain stable at 90% for lower node streams in 1995 and under the three strategies. The percent of chronically and/or episodically acidic lower node streams within the study area was projected to be similar in 2040, regardless of strategy (7% for all strategies). For upper node streams, those projected percentages would vary from 15% (OTW) to 12% (BWC) and 11% (BYB). The latter strategy yielded an estimated percent of chronically and/or episodically acidic upper node streams in 2040 equal to the estimated percent in 1995.

Important conclusions regarding streamwater chemistry include the following:

- Many watersheds showed modeled streamwater sulfate concentration increasing, even while sulfur deposition was projected to decline.

- Some watersheds that currently show low sulfur retention and high streamwater sulfate concentration were projected to decrease in sulfate concentration and increase in ANC in response to lower sulfur deposition.

- Watersheds that currently show relatively low nitrogen retention and high streamwater nitrate concentration are projected to further acidify in response to the increased nitrogen deposition of some strategies.

- The median projected changes in streamwater ANC from 1995 to 2040 for the 130 regional modeling sites ranged from -1.3 (BYB Strategy) to -6.7 (OTW Strategy). All strategies indicated continued acidification of the median stream site, despite large decreases in sulfur, and in some cases nitrogen, deposition. These projected changes were highly variable across the study area, however.

- Streamwater acid-base chemistry was generally projected to deteriorate under the OTW and to a lesser extent the BWC Strategy from 1995 to 2040. Under the BYB Strategy, streamwater chemistry in 2040 was projected to be similar to chemistry in 1995. These projected differences among strategies were small ($\leq$ 4% of the SAMI stream population).

- Projected continued acidification was largest for sites in the southern portion of the SAMI region, mainly due to model projections of future decreases in sulfur adsorption on soils. Projected future increases in streamwater ANC, where they occurred, were largest in the north, especially in the BYB Strategy.

- Modeled changes in streamwater ANC in the SAMI strategies were driven primarily by changes in sulfur deposition, rather than changes in nitrogen deposition. This was because simulated changes in nitrogen deposition were smaller than simulated changes in sulfur deposition and because simulated changes in nitrogen deposition were projected to have substantial impacts on streamwater nitrate concentration only in a limited geographical area.

- Watersheds found to be most sensitive to modeled changes in nitrogen deposition were located primarily in the northern section of the Appalachian Plateau province in West Virginia and at high elevation in the Blue Ridge Province in North Carolina and Tennessee.

- Base cation depletion caused some streams to be projected to continue to acidify in the future despite projected decreases in streamwater sulfate and nitrate concentrations.

- The Emissions Control Strategies resulted in very small projected differences in the percentages of streams or length of stream segments within the various ANC classes.

- Although the model projections of future change in streamwater ANC in response to the Emissions Control Strategies suggested only modest changes and little improvement as compared with baseline conditions, the projections represent pronounced improvements in acid-base chemistry as compared with projections based on continued deposition at 1995 levels.

- Model projections beyond 2040 suggested that the sites that were projected to increase in ANC from 1995 to 2040, and also many of the sites that showed projected slight additional acidification from 1995 to 2040, would show considerable additional improvement in ANC beyond 2040, even if future deposition was held constant at 2040 levels.

- Almost all streams that were projected to have ANC below 20 μeq/L in 2040, in all of the strategies, were located in the northern Appalachian Plateau subregion.

Biological Effects

Conclusions regarding biological effects have greater uncertainty than conclusions regarding changes in the chemistry of streamwater. This is because of the complexity of the factors that govern biological systems response. For example, fish habitat suitability is determined by a host of variables, of which acid-base status is only one. For that reason, biological inferences derived from the modeling results presented in this report should be treated with caution.

There is no doubt that acidification of surface waters lowers species diversity for both fish and invertebrates. Since species differ in acid sensitivity, there is a predictable sequence of species loss as acidification progresses. The elevated concentrations of hydrogen ion and aluminum, which occur as pH and ANC falls, act as poisons which attack the gill structures responsible for body salt and water balance. This produces a cascade of negative physiological effects culminating in death of the organism.

These processes are well understood and appear to occur wherever fish and invertebrates are affected by the acidification of aquatic habitats. Adequate habitat structure is a necessary, but not sufficient, requirement for healthy fish populations; water acid-base chemistry must be suitable as well.

Results from the modeled group of regional watersheds suggested that the percent of the potentially acid-sensitive streams having chemistry unsuitable for brook trout would increase slightly during the period 1995 to 2040 under the OTW, but not the BYB strategy. Other species of fish, and also other species of aquatic biota other than fish, would also be expected to respond to the simulated changes in streamwater ANC. Fish species richness and aquatic species diversity, both within and among taxonomic groups, would be expected to decline with simulated acidification and increase with simulated chemical improvement.

Important conclusions regarding biological effects include the following:

- The number of acid-sensitive streams having chemistry either chronically or episodically unsuitable for brook trout was projected to increase under the OTW and BWC Strategies, but decrease slightly under the BYB Strategy.

- Forest soil conditions were projected to deteriorate at most of the modeled forest sites under all strategies. The calcium to aluminum molar ratio in soil solution was projected to decline well below the generally accepted threshold for protection of forest health and growth at many sites, especially spruce-fir sites.