Using the Critical Load Concept to Protect Ecosystems from Acidification

Deborah Ulinski Potter
Air Resource Program, Southwestern Region, USDA Forest Service (retired)

Cindy Mitchell Huber
George Washington & Jefferson National Forests, Roanoke, Virginia

Sulfur and nitrogen in the atmosphere are major components of acid deposition, and the anthropogenic contribution to these pollutants comes primarily from burning fossil fuel. A *critical load* is a threshold for the loading rate of an air pollutant, such as sulfur or nitrogen, above which a specific deleterious effect may occur. When critical loads are exceeded, loss of acid neutralizing capacity, stream and soil acidification, nitrogen enrichment and direct toxicity can result. Thus, elevated levels of sulfur and nitrogen can have a cascading effect on aquatic and terrestrial resources. Scientific information on ecosystem response to pollutant loading is the basis for calculating a critical load. However, policy decisions must be made to identify the levels of protection desired for selected resources within specified timeframes, and these levels are called *target loads*. Once these policy decisions have been made and the critical and target loads have been calculated, land managers are able to clearly communicate the effect of air pollution on the resources they manage. In this manuscript we present examples showing how Forest Service land managers can use the critical load concept as a communication tool and to protect natural resources from air pollution effects.

Keywords: *air pollution, acid deposition, critical load, atmospheric deposition, ecosystem thresholds*

Introduction

Overviews about acid deposition in the United States have been published by the Ecological Society of America (1999), the United States Environmental Protection Agency [USEPA] (2001), and Hubbard Brook Research Foundation (Driscoll et al. 2001a). While sulfur (S) emissions have declined in the eastern United States, especially in the northeast, nitrogen (N) deposition has continued to increase in the west. Furthermore, ecosystems have been slow to respond to declining emissions. This discussion concerns critical loads for sulfur and nitrogen; however, critical loads are also being calculated for ozone and other compounds.

Air pollutants can travel hundreds to thousands of kilometers before deposition and ecosystem degradation occurs. Therefore, the concerns for acid deposition are local, regional, national and international. Lessons applicable to the United States are being learned from approaches adopted by the European Union, i.e., the International Cooperative Programme on Modelling and Mapping of Critical Loads and Levels and their Air Pollution Effects, Risks and Trends (ICP Modelling and Mapping). In recent years, U.S. partnerships have been expanded to include joint monitoring programs with Canada (Committee on the Environment of the Conference of New England Governors and Eastern Canadian Premiers 2001).

USDA Forest Service Program Responsibility

The Air Resource Management Program of the Forest Service has the responsibility to evaluate resource conditions and to advise decision-makers about the existing and potential effects of air pollution on natural resources. This includes effects on flora, fauna, soils, cultural resources such as petroglyphs and pictographs, geochemistry, water, and visibility. Impacts are predicted for individual ecosystem components and whole ecosystems, often using mathematical models. The Air Resource Management Program also recommends goals and objectives for resource management, and ensures that monitoring programs are designed and implemented.

The program often focuses on specific wildernesses, known as Class I areas, because the Clean Air Act provided special protection for these lands. Class I areas include all international parks, national wilderness areas that exceed 5,000 acres (2023 ha) in size, national memorial parks that exceed 5,000 acres (2023 ha) in size, and national parks that exceed 6,000 acres (2428 ha) in size, and

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that were in existence on 7 August 1977. Federal Land Managers (FLMs) have received Congressional direction to "err on the side of protecting the environment" when implementing the Clean Air Act requirements (Senate Report #95-127, 95th Congress, 1st Session, 1977). Critical loads can assist in this effort by helping us clearly communicate the effects of air pollution on resources.

Federal Land Managers have developed consistent methods for protecting resources from air pollution that include developing critical loads. These interagency methods were published as the Air Quality Related Values Workgroup (FLAG) Phase I Report (National Park Service 2000). Accordingly, the FLMs have agreed to:

- Protect the most sensitive resources;
- Ensure no unacceptable change to the resource;
- Use the best science available;
- Develop methods for establishing critical loads;
- Calculate critical loads for areas with adequate information;
- Review and update critical loads; and
- Develop strategies to obtain needed information for other areas.

The Critical Load Concept

A critical load is the amount of pollution delivered to an ecosystem that will not cause harmful changes to physical, chemical, or biological factors (Nilsson and Grennfelt 1988). It is often expressed as kilograms of pollutant per hectare per year (kg ha^{-1} yr^{-1}). The critical load quantifies a cumulative effect to an ecosystem receptor, rather than the effect of single sources of pollution. Loading rates for S and N that are greater than the critical load result in acidification or nutrient enrichment, and are not sustainable.

Critical loads are scientifically determined, and are usually calculated using steady-state or dynamic mathematical models. Examples of steady-state (mass balance) models for acidification are the first order acidity balance (FAB) model (Henriksen et al. 2002) and the Steady-State Water Chemistry (SSWC) model (Aherne et al. 2004). Dynamic models for acidification include Model of Acidification of Groundwater in Catchments, MAGIC (Cosby et al. 1985; Wright 2001) and PnET-BGC, a biogeochemistry model that simulates nutrient cycling, including soil processes such as weathering, cation exchange, adsorption and solution chemistry (Groffman et al. 2004).

The Forest Service, National Park Service and Fish and Wildlife Service have begun calculating critical loads for terrestrial and aquatic ecosystems. These calculations are site-specific (i.e., designed for individual terrestrial and aquatic ecosystems rather than large geographic areas) and apply to the most sensitive resources. Critical loads can also be empirically determined based on field observations showing ecosystem changes or experimental studies that define a dose-response relationship for resource conditions under background or "natural" loading rates compared to conditions under current and predicted (future) loading rates.

A target load is selected to incorporate agency policy, and is similar in concept to a desired future condition. Target loads could be higher or lower than critical loads based on political, economic, social, geographic, or temporal considerations. Intermediate target loads above critical loads could be applied where deposition levels far exceed critical loads (often in the east). Target loads that are more protective than critical loads can prevent degradation in more pristine environments (often in the west), or provide a safety margin for wilderness protection.

Critical and target loads are being used to communicate how pollution is currently affecting natural resources. They are also used to convey what is needed to protect resources that can be affected by air pollution in the future, and to restore resources that have been degraded. These needs can include goals for emission reductions, specific control technologies and mitigation measures.

Discussion

The Forest Service Air Program is concerned about the deposition of nitrogen, sulfur, metals and other toxic substances to both aquatic and terrestrial ecosystems. This concern is due to current conditions and increases in population, energy development and air quality permit activity (and thus subsequent emissions). Acid deposition has contributed to or caused chronic stream acidification from New England into the southern Appalachian Mountains (Driscoll et al. 2001b). It contributes to soil nutrient changes such as calcium and magnesium leaching, or aluminum mobilization, and causes stream acidification (Herlihy et al. 1993). Acid deposition has also affected tree growth in spruce-fir forests. Examples of how acid deposition affects forest resources in the eastern and western United States are presented below.

Case Studies: Eastern U.S. – Chronic Acidification

Historically high deposition, combined with watersheds having low buffering capacity, has resulted in stream acidification and likely changes in soil nutrient status in parts of the eastern United States, including the mountains of Virginia and West Virginia. In some cases of chronic stream acidification, limestone sand (calcium carbonate) is being added to the water as a temporary way to neutralize

the acids so that aquatic life won't be precluded, but it does not solve the problem of high sulfur loading rates. Liming is a common occurrence in West Virginia, and the Forest Service has limed headwater streams in St. Mary's Wilderness in Virginia. Liming, especially in a wilderness area, could be controversial, but the decision is generally made based on a desire to maintain the aquatic biota until sulfur loading is reduced through air regulations.

As a result of acidification, soil chemistry is also degraded and aluminum is mobilized in soil solutions. Nutrient cycling is affected by the leaching of nutrients such as calcium and magnesium, and there is interference with calcium uptake and other root functions. Soil nutrient change may lead to changes in vegetation growth and reproduction (Shortle and Smith 1988; Shortle et al. 1997; Lawrence et al. 2005).

Case Studies: Western U.S. – Episodic acidification, N enrichmen

Episodic acidification is defined as "the short-term decrease of acid neutralizing capacity from a lake or stream. This process has a time scale of hours to weeks and is usually associated with hydrological events" (Irving 1991). Thus, it refers to pulses of acidic input that generally are infrequent, but may cause severe damage. In watersheds where snowmelt is the dominant source of water, episodic acidification most likely would occur during early snowmelt, perhaps before ice-free conditions. This can adversely affect the most acid-sensitive aquatic biota, especially early life stages or reproducing individuals. Some phytoplankton and diatom species are very sensitive to pH and water chemistry, and occur only within a small range of pH or ionic concentrations (Mason 1992). Also, snowmelt can flush aquatic systems rapidly, causing an abrupt change in water chemistry or aquatic biota. Episodic acidification can result in an increase in inorganic-monomeric aluminum concentration, which can be toxic to aquatic life. Headwater streams, vernal pools, and high-elevation lakes with low buffering capacity are particularly susceptible to episodic acidification (Baron et al. 2000).

Fenn at al. (2003) provide an overview of the effects of eutrophication and nitrogen saturation in the western United States. Increases in nitrogen deposition and resultant changes in the nitrogen cycle can affect forest growth, health, and carbon sequestration. Since many aquatic ecosystems in the west are nitrogen limited or co-limited, small additions of nitrogen can increase primary production, especially in high elevation lakes. Lichens, diatoms and nitrate concentrations in water are especially sensitive to nitrogen enrichment. Nitrogen saturation means that ammonium and nitrate concentrations exceed demand, and this affects soil and plant calcium to aluminum ratios, aluminum toxicity, and leaching of base cations. Calcium depletion may affect the ability of trees to withstand stress, decrease the rates of decomposition and other microbial processes (Fenn et al. 1998).

Case Studies: Western US – Rocky Mountains

In 1993 the Rocky Mountain Region of the Forest Service certified impairment of visibility and aquatic ecosystems of Mt. Zirkel Wilderness, Colorado, due to emissions from local power plants. This led to a reasonable attribution study of visibility impairment in 1996-1997. This type of study is designed to identify the sources of air pollution that are affecting a particular site or area. The results of the reasonable attribution study led to revision to the long-term strategy portion of Colorado's State Implementation Plan (SIP) for Class I Visibility Protection, and most importantly, to new control strategies and emission reductions. Although the critical load had not been calculated, direct observations of aquatic chemistry supported the certification of impairment (Turk and Campbell 1987). The background information for certification noted the following conditions:

1. High elevation location along the Continental Divide - elevations of the Mt. Zirkel Wilderness range from 2,256 to 3,712 m and include alpine and subalpine lakes;
2. Watersheds composed of non-reactive bedrock with slow weathering rates;
3. A minimum of 18 lakes in the Mt. Zirkel Wilderness with observed alkalinity < 50 μeq/L, and some lakes with < 10 μeq/L;
4. Precipitation chemistry with higher concentrations of sulfur and nitrogen than background-- evaluation of sulfur isotopes indicate that local sources contribute to this condition;
5. Presence of acid-sensitive amphibians, salmonids and other biota;
6. Conceptual modeling that indicated a loss of buffering capacity had probably occurred in some lakes within the Mt. Zirkel Wilderness;
7. Potential for episodic acidification during snowmelt;
8. Potential response of aquatic ecosystems to increases in acid deposition; and
9. Proximity to sources of nitrogen and sulfur that can be transported to the wilderness by prevailing winds. This included the electric-generating stations in Hayden and Craig, CO, located west and upwind of the wilderness, and sources located at greater distances.

If critical loads were established for Mt. Zirkel Wilderness, then comparisons could be made to deposition loading rates that result from emission reductions. This would facilitate tracking progress toward the desired future condition.

Rocky Mountain National Park has also suffered impacts of atmospheric deposition. The effects of nitrogen deposition on terrestrial and aquatic systems have been subtle, yet critical loads may currently be exceeded (Williams and Tonneson 2000; Wolfe et al. 2003). High elevation watersheds have nitrogen saturation and therefore high nitrate concentrations in surface waters and soils. Changes in hydrogen ion concentration over time and an excess of nutrients during the growing season have occurred. Changes that have been observed in alpine lakes in the park include a shift in phytoplankton species and productivity and a shift in diatom community species compared to 50 years ago (Wolfe et al. 2002). The increase in nitrogen emissions can be attributed to population growth and the associated emissions (transportation, industrial, power generation and agricultural) east of the Colorado Front Range.

How Forest Service Managers Can Use Critical Loads and Target Loads

Critical loads are a way to quantify current resource conditions in terms that many audiences can understand. Some people may understand the concept of exceeding a threshold better than they can understand changes in ecosystem function due to anthropogenic pollution. The target audiences for communication about critical loads include our own decision makers, the regulatory community that sets the rules for controlling air pollution, the regulated entities, and the public whose support is needed for positive change to occur.

A primary use for the critical load concept is in the Clean Air Act's New Source Review process for evaluating permit applications to modify or build sources of air pollution. Critical loads can be used to determine how wilderness conditions would be affected by the new emissions, and to make recommendations to permitting authorities, including states, EPA and tribal governments. Another potential application for the critical load concept is land management planning. Critical loads could be incorporated into goals or objectives in Forest Plans or amendments. Progress toward meeting critical loads could be reported in assessments of resource conditions. For example, the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) requires the Secretary of Agriculture to conduct an assessment of the Nation's renewable resources every 10 years. Critical loads could also be used to evaluate project impacts, including cumulative effects, in the National Environmental Policy Act (NEPA) process.

Since critical loads are important tools for evaluating potential impacts from new sources of air pollution, states could adopt them in their State Implementation Plans that describe how clean air will either be achieved or maintained according to national and state standards. Regional Planning Organizations (RPOs) for air pollution control could use critical loads to help measure the rate of progress toward more natural visibility conditions. Current RPOs include the Western Regional Air Partnership (WRAP), Central States Regional Air Planning Association (CENRAP), Midwest Regional Planning Organization, Mid-Atlantic/Northeast Visibility Union (MANE-VU), and the Visibility Improvement State and Tribal Association of the Southeast (VISTAS).

Aquatic Critical Loads

Various regions of the Forest Service have been using the Model of Groundwater Acidification in Catchments (MAGIC) in their efforts to protect ecosystems from air pollution. For example, the MAGIC model was used to evaluate the effects of increasing sulfur deposition on lakes in the Absaroka-Beartooth Wilderness and the Selway-Bitterroot Wilderness of Montana, and to develop critical and target load relationships for Class I areas in North Carolina and West Virginia.

The MAGIC model simulates chemistry of soil solution and surface water to predict average ion concentrations per month and year. It is also being used to help managers establish target loads (Table 1). For example, assume that an acid neutralizing capacity (ANC) of 50 μeq/L indicates no harmful effects occurring to the aquatic ecosystem, and that current sulfur deposition rate is at 10 kg S ha^{-1} yr^{-1}. Site A has current stream chemistry that is well below the pre-1900 condition, indicating that degradation has occurred. A future stream ANC of 50 μeq/L would not restore this system to "natural" conditions, but would allow most aquatic biota to live in the stream. The target load for Site A varies from 1-6 kg ha^{-1} yr^{-1} depending on how quickly recovery is desired. To improve from a current ANC of 7 μeq/L to 50 μeq/L (on the way toward the baseline ANC of 91 μeq/L) by the year 2040, would require deposition to be reduced from the current loading rate of 10 kg S ha^{-1} yr^{-1} to 4 kg S ha^{-1} yr^{-1}.

For site B, stream ANC is less than "natural," but still above 50 μeq/L, indicating that aquatic biota can survive. In this situation more deposition can be tolerated and the ANC will still remain above 50 μeq/L. In both Sites A and

Table 1. Sample target loads, in kg sulfur (S) ha^{-1} yr^{-1}, to meet desired future conditions of stream Acid Neutralizing Capacity (ANC). In this example, the current loading rate is 10 kg S ha^{-1} yr-1 and target ANC is either 20 or 50 μeq/L. Note that for Site A to improve from a current ANC of 7 μeq/L to 50 μeq/L (on the way toward the baseline ANC of 91 μeq /L) by the year 2040, would require deposition to be reduced from the current loading rate of 10 kg S ha^{-1} yr^{-1} to 4 kg S ha^{-1} yr^{-1}.

Stream ANC (μeq/L)			Target Load for Sulfur (kg S ha^{-1} yr^{-1}) for ANC = 20 μeq/L			Target Load for Sulfur (kg S ha^{-1} yr^{-1}) for ANC = 50 μeq/L		
Site	Pre-1900	Current	Year 2020	Year 2040	Year 2100	Year 2020	Year 2040	Year 2100
A	91	7	5	8	9	1	4	6
B	82	60	43	26	13	15	10	7
C	60	21	2	3	3	6	9	13

B if the desired future condition of ANC is less than 50 μeq/L, then more deposition could be tolerated.

For the stream at Site C, ANC is only slightly above 50 μeq/L in a natural state, and the current ANC has deteriorated to 21 μeq/L. Depending on how long we are willing to wait for recovery, deposition would have to be reduced from 10 kg S ha^{-1} yr^{-1} to between 2 and 9 kg S ha^{-1} yr^{-1}.

The Pacific Northwest Region of the Forest Service has initiated a five year study, the Cascade Wilderness Lakes Project, to calculate critical loads for aquatic ecosystems. The CE-QUAL-W2 model will be modified for biological processes and dilute lakes to calculate the critical loads of ammonia, nitrate and hydrogen ion. CE-QUAL-W2 is a hydrodynamic model developed by the US Army Corps of Engineers (Wells 1997). It is a two-dimensional model for various temporal and spatial scales. The revised model will characterize hydrologic, biologic and chemical variables of the lakes. First the water budget will be calculated. Then the conservative ions such as chloride and the reactive ions such as nitrate, ammonia and phosphate will be incorporated. The major biological components that affect the reactive ions include phytoplankton, zooplankton, benthos, and fisheries. CE-QUAL-W2 incorporates hydrodynamic factors that most acid-rain related models do not, and also includes critical biological processes. Thus, both acidification and eutrophication will be modeled.

The Pacific Southwest Region of the Forest Service is developing a screening procedure for identifying acid-sensitive lakes based on catchment characteristics. This project includes predicting ANC for high-elevation lakes in California's Sierra Nevada mountains using conceptual and general linear models (Berg et al. 2005). The catchment characteristics being studied are: catchment-to-lake area ratio, lake perimeter-to-area ratio, carbonate lithology, lake headwater location, and geochemistry.

Terrestrial Critical Loads, Cooperation with Research Scientists

Air Program Managers from National Forest Systems are cooperating with scientists from Forest Service Research to better quantify critical loads. One project is developing a protocol for estimating terrestrial critical loads in Class I areas and collecting essential data at an eastern and western demonstration site. The purpose of this project is to summarize the methods available for calculating terrestrial critical loads and to form a strategy for estimating critical loads in all Class I areas. The eastern demonstration site is at Fernow Experimental Forest, West Virginia, in the Monongahela National Forest. This site contains high elevation spruce-hardwood forest, and receives loading rates of approximately 8 kg N $ha^{-1}yr^{-1}$ and 18 kg S $ha^{-1}yr^{-1}$. The western site is Kings River located in the Sierra National Forest of California. The effects of nitrogen deposition from San Joaquin Valley sources on ponderosa pine (*Pinus ponderosa*), Sierran mixed conifer, fir, and alpine meadows are a concern. We hope that this collaboration will result in a broader network of air pollution study sites that is linked to the Forest Health Monitoring Program. Once the critical loads are calculated and entered into a spatial database, a map of critical loads for federal lands could be generated.

Conclusion

Critical loads are exceeded when episodic or chronic acidification has been documented or nutrient enrichment is occurring. Where critical loads are not exceeded, antidegradation is a concern, especially since the Wilderness Act states that wilderness is to be "protected and managed so as to preserve its natural conditions." It is possible that unacceptable effects may occur when critical loads are approached, if uncertainties have not been quantified or a

safety margin has not been incorporated.

Three things are needed to enable federal land managers to move forward with the critical load concept. First, we need to acquire site-specific data for soil chemistry, water chemistry and deposition rates. Second, decisions have to be made regarding the empirical data or models used to calculate critical loads. Finally, we need to complete the demonstration projects that are currently underway to collect data to populate a variety of models that can be used to calculate critical loads. Although the Air Resource Management Program is currently funding collaborative projects with Forest Service Research and Development to implement the critical loads concept, additional cooperation with researchers will be required to establish critical loads for all Class I areas.

Scientific information on ecosystem response to pollutant loading is the basis for calculating a critical load. However, policy decisions must be made to identify the levels of protection desired for selected resources within specified timeframes, the target load. Once critical and target loads have been calculated, land managers will be able to clearly communicate the effect of air pollution on the resources they manage.

Critical and target loads can be used to better communicate how pollution is affecting natural resources and what is needed to protect and restore them. The audiences for this communication are:

- Our own decisionmakers;
- The regulatory community that sets the rules for controlling air pollution; and
- The public whose support is needed for positive change to occur.

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LITERATURE CITED

Aherne J, M Posh, PJ Dillon, and A Henricksen. 2004. Critical loads of acidity for surface waters in south-central Ontario: regional application of the First-order acidity balance model (FAB). Trent University, Peterborough, Ontario. URL *http://bink.trentu.ca/biogeochemistry/posters/ahernefab.pdf*

Baron, JS, HM Rueth, AM Wolfe, KR Nydick, EJ Allstott, JT Miear, B Moraska. 2000. Ecosystem responses to nitrogen deposition in the Colorado Front Range. *Ecosystems* 3:352-368. URL *http://www.springerlink.com/content/gl5n1at671ykrjbn/fulltext.pdf*

Berg, NH, A Gallegos, T Dell, J Frazier, T Procter, J Sickman, S Grant, T Blett and M Arbaugh. 2005. A screening procedure for identifying acid-sensitive lakes from catchment characteristics. *Envionmental Monitoring and Assessment* 105:285-307. URL http://www2.nature.nps.gov/air/Pubs/pdf/2005ScreeningProcedureAcidSensitiveLakes.pdf

Committee on the Environment of the Conference of New England Governors and Eastern Canadian Premiers. 2001. Acid Rain Partnership. Available online at URL *http://www.cap-cpma.ca/images/pdf/eng/ en-datawoborders.pdf*

Cosby BJ, GM Hornbeger, JN Galloway and RF Wright. 1985. Modeling the effects of acid deposition: assessment of a lumped parameter model of soil water and streamwater chemistry. *Water Resources Research* 21: 51-63.

Driscoll CT, GB Lawrence, AJ Bulger, TJ Butler, CS Cronan, C Eagar, KF Lambert, GE Likens, JL Stoddard, and KC Weathers. 2001a. Acid rain revisited: advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments. The Hubbard Brook Research Foundation, Hanover, NH, Vol. 1, no 1. 24 pp. Available online at URL *http://www.hubbardbrook.org/education/Glossary/AcidRain.pdf*

Driscoll CT, GB Lawrence, AJ Bulger, TJ Butler, CS Cronan, C Eagar, KF Lambert, GE Likens, JL Stoddard, and KC Weathers. 2001b. Acidic deposition in the northeastern United States: Sources, and inputs, ecosystem effects, and management strategies. *BioScience* 51:180-198.URL *http://www.esf.edu/efb/mitchell/Class%20Readings%5CBioSci.51.180.198.pdf*

Ecological Society of America. 1999. Acid rain revisited. Washington, DC: The Ecological Society of America, Available online at URL http://www.esa.org/education/edupdfs/acidrainrevisited.pdf

Fenn, ME, MA Poth, JD Aber, JS Baron, BT Bormann, DW Johnson, AD Lemly, SG McNutly, DF Ryan and R Stottlemyer. 1998. Nitrogen excess in North American ecosystems: Predisposing factors, ecosystem responses, and management strategies. *Ecological Applications* 8(3):706-733. URL *http://www.fs.fed.us/psw/publications/fenn/psw_ 1998_fenn006.pdf*

Fenn ME, Baron JS, Allen EB, Rueth HM, Nydick KR, Geiser L, Bowman WD, Sickman JO, Meixner T, Johnson DW, and Neitlich P. 2003. Ecological effects of nitrogen deposition in the western United States. *BioScience* 53: 404-420. Available online at URL *http://www.nrel.colostate.edu/projects/lvws/pages/publications/publinks/Fenn_ecol_biosci.pdf*

Groffman, PM, CT Driscoll, GE Likens, TJ Fahey, RT Holmes, C Eagar and JD Aber. 2004. Nor gloom of night: A new conceptual model for the Hubbard Brook ecosystem study. *BioScience* 54:139-148. Available online at URL *http://www.bioone.org/bioone/archive/0006-3568/54/2/pdf/i0006-3568-54-2-139.pdf*

Henriksen A, PJ Dillon, and J Aherne. 2002. Critical loads of acidity for surface water in south-central Ontario, Canada: Regional application of Steady-State Water Chemistry (SSWC) Model. *Canadian Journal of Fisheries Aquatic Sciences* 59: 1287-1295.

Herlihy, AT, PR Kaufmann, MR Church, PJ Wiggington Jr., JR Webb, MJ Sale. 1993. The effects of acid deposition on streams in the Appalachian Mountains and Piedmont Region of the mid-Atlantic United States. *Water Resources Research*: 29:2687-2703.

Irving PM, ed. 1991. Acidic deposition: State of science and technology. Volume II–Aquatic processes and effects. US National Acid Precipitation Assessment Program, Washington, DC.

Lawrence, GB; Lapenis, AG; Berggren, D; Aparin, BF; Smith, KT; Shortle, WC; Bailey, SW; Varlyguin, D; Babakov, B. 2005. Climate dependency of tree growth suppressed by acid deposition effects on soils in northwest Russia. *Environmental Science and Technology.* 39(7): 2004-2010.

Mason BJ. 1992. Acid rain: its causes and its effects on inland waters. Science, Technology and Society Series, New York: Clarendon Press, 126 p.

National Park Service. 2000. Air Quality Related Values Workgroup (FLAG) Phase I Report. United States Department of Interior National Park Service, Air Resources Division, Lakewood, Colorado. Available at: *http://www2.nature.nps.gov/air/Permits/flag/index.cfm*

Nilsson J. and Grennfelt P., eds. 1988. Critical Loads for Sulphur and Nitrogen. Copenhagen (Denmark): Nordic Council of Ministers.

Shortle, WC, and KT Smith. 1988. Aluminum-induced calcium deficiency syndrome in declining red spruce trees: *Science* 240: 1017-1018.

Shortle, W.C.; Smith, K.T.; Minocha, R.; Lawrence, G.B., David, M.B. 1997. Acidic deposition, cation mobilization, and biochemical indicators of stress in healthy red spruce. *Journal of Environmental Quality* 26:871-876.

Turk, JT, and DC Campbell. 1987. Estimates of acidification of lakes in the Mt. Zirkel Wilderness Area, CO. *Water Resources Research* 23:1757-1761.

United States Environmental Protection Agency [USEPA]. 2001. Frequently asked questions about atmospheric deposition: A handbook for watershed managers. EPA-453/R-01-009. Triangle Park, NC: Office of Air Quality Planning and Standards, Research. Available online at URL *http://www.epa.gov/oar/oaqps/gr8water/handbook/*

Wells, S. A., 1997: Theoretical Basis for the CE-QUAL-W2 River Basin Model," Dept. of Civil Engr., Tech. Rpt. EWR-6-97, Portland St. Univ., Portland, OR, 1997. The model can be downloaded at the following website, which also contains additional information on applications. *http://www.wiz.uni-kassel.de/model_db/mdb/ce-qual-w2.html*

Williams, MW and KA Tonneson. 2000. Critical loads for inorganic nitrogen deposition in the Colorado Front Range, USA. *Ecological Applications* 10:1648-1665.

Wolfe, AP, SS Kaushal, JR Fulton and DM McKnight. 2002. Spectrofluorescence of sediment humic substances and historical changes of lacustrine organic mater provenance in response to atmospheric nutrient enrichment. *Environmental Science and Technology* 36(15): 3217-3223. Available online at URL *http://www.nrel.colostate.edu/projects/lvws/pages/ publications/publinks/Wolfe_sediment_spectro.pdf*

Wolfe, AP, C Van Gorg and JS Baron. 2003. Recent ecological and biogeochemical changes in alpine lakes of Rocky Mountain National Park: A response to anthropogenic nitrogen deposition. *Geobiology* 1:153-168. URL *http://www.ualberta.ca/~ersc/water/publications /rocky.pdf*

Wright RF. 2001. Use of the dynamic model "MAGIC" to predict recovery following implementation of the Gothenburg Protocol. *Water, Soil and Air Pollution. Focus 1*: 455-482.