Critical Loads of Atmospheric Deposition to Adirondack Lake Watersheds:

A Guide for Policymakers

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Critical Loads of Atmospheric Deposition to Adirondack Lake Watersheds: A Guide for Policymakers

Prepared for:

New York State Energy Research and Development Authority

Albany, NY

Gregory Lampman
Senior Project Manager

Prepared by:

Douglas A. Burns
U.S. Geological Survey
Troy, NY
daburns@usgs.gov

Timothy J. Sullivan,
E&S Environmental Chemistry Inc.
Corvallis, OR
tim.sullivan@esenvironmental.com

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Fishing Brook Pond
Photograph by Douglas Burns

Purpose and Scope

Good environmental policy reflects a balance of competing visions of how and to what extent human activities are impacting ecosystems with the costs and benefits of protecting these ecosystems.

Environmental policies can prevent the degradation of ecosystem services, but can conflict with attitudes about economic growth, governmental intervention, and costs to the general public. Governmental agencies that are responsible for regulation must sometimes serve as arbiters in this process, making decisions based in part on the best, albeit often incomplete or competing scientific information. Uncertainty of scientific data and the results of computer simulations of the environment can further complicate this process. If costs, benefits, and scientific uncertainty can be well-quantified, then this information may help reduce the level of conflict surrounding a policy decision. The broad goal of this report is to provide a scientific perspective on the environmental effects of atmospheric pollutant deposition and highlight key considerations that will help inform decision-makers and ecosystem managers who are responsible for environmental policy.

This guide offers considerations for policymakers and ecosystem managers regarding the interpretation and use of scientific data developed through critical load (CL) investigations. A load is the mass of a pollutant that is deposited from the atmosphere to the surface of a watershed. These considerations are illustrated through the example of a recently completed study of CLs of atmospheric sulfur and nitrogen, which are collectively termed acid deposition, for lake watersheds in the Adirondack region of New York State (NYSERDA 2014a and 2014b). This guide discusses salient aspects of this CL investigation with an aim of informing policymakers, ecosystem managers, and nonscientists who are required to make decisions related to the effects of acid deposition on natural ecosystems. With this audience in mind, the guide aims to minimize use of technical language. Although some terms and concepts that are applied in CL investigations are used in this guide, these terms are accompanied by a definition and reference for more detailed discussion. Five publications derived from the CL investigations are available to readers seeking a greater level of detail (Sullivan et al. 2011, Sullivan et al. 2012, Sullivan and Jenkins 2014, NYSERDA 2014a, NYSERDA 2014b).

Introduction and Background

Acid deposition is sometimes referred to as "acid rain," although part of the acid load reaches the surface by means other than rainfall. In the eastern U.S., acid deposition consists of several forms of sulfur and nitrogen that largely originate as emissions to the atmosphere from sources such as electricity-generating facilities (coal, oil, and natural gas), diesel- and gasoline-burning vehicles, some agricultural activities, and smokestack industries. Acid deposition is known to cause deleterious effects to sensitive ecosystems of which the Adirondack region of New York State provides several well-known and well-studied examples. This largely forested region includes abundant lakes, streams, and wetlands and possesses several landscape features that result in high ecosystem sensitivity to acid deposition. These features include bedrock that weathers slowly, steep slopes, and thin, naturally acidic soils. An ecosystem is described as sensitive to, or affected by, acid deposition if prolonged exposure to acid deposition has resulted in detrimental ecosystem effects. Soils, streams, and lakes that are less sensitive are better able to buffer acid deposition. A principal reason that acidification is a concern for resource managers is because of the changes induced in native biota and their habitat on land and in water. As the chemistry of soils and surface waters in sensitive landscapes changes in response to prolonged exposure to acid deposition, organisms that cannot tolerate high acidity, such as sugar maple trees and many species of fish and aquatic insects, may be gradually eliminated from the ecosystem. Other biota such as red spruce may experience increased stress and reduced growth rates as a result of acidification, exposing these species to increased susceptibility to disease and other natural stressors and perhaps increased mortality. The ecological effects of acid deposition have been documented by extensive research that began in the U.S. in the 1970s and continues today. This report does not provide a detailed discussion of these ecological effects, but interested readers can refer to four publications that provide good summaries of current scientific knowledge of these effects, including extensive reference to previous research in the Adirondacks (Driscoll et al. 2001, Jenkins et al. 2007, Burns et al. 2011, Sullivan 2015).

Acid deposition refers to the sum of all rain, snow/ice, fine particles, fog, and gases that are deposited from the atmosphere to the earth's surface and that are more acidic than expected under natural conditions unaffected by human activities.

Critical Load Concepts

Ecosystems show considerable variation in sensitivity to the effects of acid deposition. Even in the sensitive Adirondack region, one stream or lake may have become acidified in response to acid deposition, whereas a nearby stream or lake may show few effects.

These varied responses are related to factors such as the presence or lack of calcium carbonate (limestone) in soils and bedrock. This mineral breaks down rapidly and buffers or neutralizes acidity. The result is that a given level of acid deposition may have deleterious ecological effects on only part of the landscape, determined by how rapidly minerals break down among other factors, in combination with the load of acidity in atmospheric deposition.

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Time is another important factor to consider when evaluating the ecological effects of acid deposition. Ecosystems can become gradually more acidic with time when exposed to acid deposition. Conversely, when exposed to deposition that is becoming less acidic over time, ecosystems may become gradually less acidic. This process is sometimes referred to as ecosystem recovery. Acidification and recovery over time is important because Adirondack ecosystems have been exposed to acid deposition since at least the early 20th century, but deposition has become less acidic since the late 1970s. As a result, the evidence generally indicates that ecosystem recovery is now occurring.

The CL approach accounts for the spatial and temporal elements of acidification and recovery. A CL is the amount of acid deposition (usually on an annual basis) below which there is no ecological harm based on current scientific knowledge. Although the concept may sound simple, many details about the application of CL information that are important to policymakers and ecosystem managers can be confusing to nonscientists. These details are outlined in this guide as a series of issues following a logical progression that managers or policymakers could consider as part of the process of using information from CL studies. Specific examples of how and where to find answers to these issues are illustrated by reference to the Adirondack study of Sullivan and coauthors (Sullivan et al. 2011 and 2012; NYSERDA 2014a; NYSERDA 2014b), but a similar approach could be taken in any geographic setting.

Policy Management Considerations

Although a CL assessment is based on a synthesis of scientific data, often accompanied by simulations of the environment through application of computer models, the manager or policymaker plays an important role in interpreting this information.

Indeed, CL studies only have value when applied in a policy or management context. Sullivan and Jenkins (2014) indicate that ecosystem managers and policymakers can apply a CL approach either diagnostically or prescriptively. Nonscientists have several issues to consider when interpreting and using the results of CL information derived from scientific investigations.

The following list of these considerations can aid in interpreting CL studies for the policy and ecosystem management communities:

1. Defining the issue to be addressed. A CL approach can be applied to any pollutant that has known environmental effects. Therefore, the first step is to identify the problem and the pollutant of concern. This guide focuses mainly on acidification, a well-recognized and documented issue in the Adirondack region. However, another related issue is nutrient over-enrichment and associated biological changes caused by atmospheric nitrogen deposition in excess of the amount that organisms can take up before the nutrient is transported to drainage waters. This issue is referred to as eutrophication, and can also be addressed through a CL approach. However, the indicators of harm will be different.

2. Terrestrial, aquatic, or both environments. A CL approach can be applied to either the land (terrestrial environment) or the water (aquatic environment). In the case of the Adirondack study, CLs were developed for both the terrestrial environment (Sullivan et al. 2011) and the aquatic environment (Sullivan et al. 2012). Although CLs are calculated differently for land and water, they tend to be broadly related to each other. For example, the amount of available (exchangeable) calcium in the soil might determine a CL for sugar maple health. Soils with low levels of available calcium may limit sugar maple regeneration. Surface waters that drain soils with low calcium concentrations also typically have high levels of acidity and are more likely to show impairment of fish or other organisms. Therefore, lowering levels of acid deposition to protect aquatic ecosystems will likely also improve protection of terrestrial ecosystems and vice versa. However, the deposition levels at which aquatic organisms experience harm may not be the same as those at which terrestrial organisms experience harm. Clearly, CL information for both environments is valuable when assessing ecosystem effects.

3. Chemical indicators as surrogates for biological response. CL assessments do not typically include mechanistic studies or computer simulation modeling of how specific organisms respond to the stress of acidification. In other words, most CL assessments are not true biological assessments. Rather, previous studies have found that certain chemical indicator measurements provide a good generalization of the presence or absence of a specific organism, the initiation of stress, or an increased likelihood of observing deleterious effects in a particular population. For example, acid-neutralizing capacity (ANC) generally provides a good index measurement of the acid buffering capacity of water and indicates the likely effects of acidification on biota in lakes and streams (Henriksen and Posch 2001). Acidification effects include those related to high concentrations of biologically available aluminum (which can be toxic), low pH (a measure of water acidity), and low concentrations of base cations (calcium, magnesium, and others) that act as plant nutrients and buffer acidity. In waters that are highly colored due to the presence of natural dissolved organic matter such as in some Adirondack lakes, a measure termed the base cation surplus seems to be a more effective indicator of acid buffer capacity than ANC (Lawrence et al. 2007). In the terrestrial environment, a measure of soil chemistry such as the base saturation is often used as a CL indicator. The base saturation provides an index of the balance of nutrient base cations such as calcium that are readily available to vegetation in the soil compared with acid cations such as hydrogen and aluminum that can contribute to biological harm. The ratio of exchangeable calcium to aluminum in soil or soil water is another commonly applied CL indicator for terrestrial ecosystems.

4. Each ecosystem has many CLs. Organisms vary greatly in their sensitivity to acid deposition. For example, brook trout, a species of great interest and concern in the Adirondacks, is less sensitive to acid deposition than are other fish species such as sculpin and sucker. Each species in a biological community often has a unique CL, which can result in a need to manage a range of CLs for various species. Therefore, a manager must decide which species are being targeted for protection or recovery before proceeding with a CL assessment.

5. Importance of timeframe. The environmental effects of acid deposition occur gradually as the result of complex biogeochemical processes that occur in soils and waters. Specific organisms and whole communities respond differently to the stress of acidification. Similarly, the process of recovery as acidification eases and reverses is a slow and complex process. Therefore, the element of time is paramount in any policy or management assessment that uses CL information. Some evaluations are based on steady-state assumptions or models that indicate the level of recovery that the ecosystem may reach over many (unspecified) years, decades, or longer. A steady-state CL assessment simply evaluates the rate of acid deposition relative to a rate that is known to cause ecological harm. Time is not considered in such an assessment. In contrast, a dynamic CL (often called a target load) assessment attempts to simulate the effects over time and the speed with which key processes occur. For example, a dynamic assessment might simulate the ANC of a water body as acid deposition declines over time to a level that is considered to cause no ecosystem harm. Dynamic assessments are often more useful than steady-state assessments because time is nearly always an issue of concern in ecosystem management and in policy development and evaluation. In other words, the CL that will provide protection or recovery within the time frame of a management goal is likely to be more informative than the CL that will provide protection at an unknown future time when a steady-state condition is achieved.

6. Determining the end point, tipping point, or target value. A CL is usually established relative to a particular value of an index measurement that is applied in the assessment. For example, an ANC value of less than 50 microequivalents per liter (µeq/L) has commonly been used to indicate impairment of surface waters. Figure 1 shows a sharp decrease in fish species richness in Adirondack lakes at ANC values less than 50 µeq/L, providing support for the use of 50 µeq/L as a threshold value in this region. However, computer model simulations indicate that the pre-industrial ANC in some surface waters in regions like the Adirondacks was likely never as high as 50 µeq/L. Consequently, a target value of 50 µeq/L is unlikely to be reached in such a water body, even if acid deposition were to completely cease. When making a CL assessment of surface waters in a region, those that are not expected to reach the target value, often termed “can’t get there from here” (Sullivan et al. 2011), should be considered in the assessment. A second related consideration is the use of a single target value for the index measurement of concern. In the case of ANC for example, 50 µeq/L may represent an average or a low flow value for a surface water body. Studies have shown that ANC varies during the year, and the lowest values are typically observed during spring snowmelt when strong acids are flushed from soils into surface waters (Wigington et al. 1992). Many organisms are sensitive to these temporary ANC conditions, when values may be 50 µeq/L to 100 µeq/L less than average or low flow values in a lake or stream. Figure 2 supports the previous statement by illustrating a long-term inverse relation between streamflow and ANC at Buck Creek in the Adirondacks. A manager or policymaker would be well served by determining whether the results of a CL study were based on an average value of the indicator, and may want to consider whether the particular indicator is prone to shift seasonally or during high flow conditions. If the organism of concern is sensitive to these temporary shifts in the indicator measurement, then a pertinent concern is whether an additional protective margin should be added to the indicator value to reduce the risk of harm to an acceptable level.

7. Considering uncertainty. Information derived from a CL assessment or study is often a compilation or synthesis of data that represents the state of scientific knowledge regarding the ecological effects of acid deposition in a region. This information is commonly developed using a computer model that simulates the chemical reactions that occur in the environment and are believed to most greatly affect the metric of interest such as ANC. A nonscientist using this information would benefit from considering the inherent uncertainty in CL modeling relative to the level of ecosystem protection that is desired. There are many sources of uncertainty in CL data. These sources include the precision and accuracy of the measurements on which the assessment is based, and the uncertainty of the parameter values (typically environmental measurements that must be estimated because they are not directly measured)

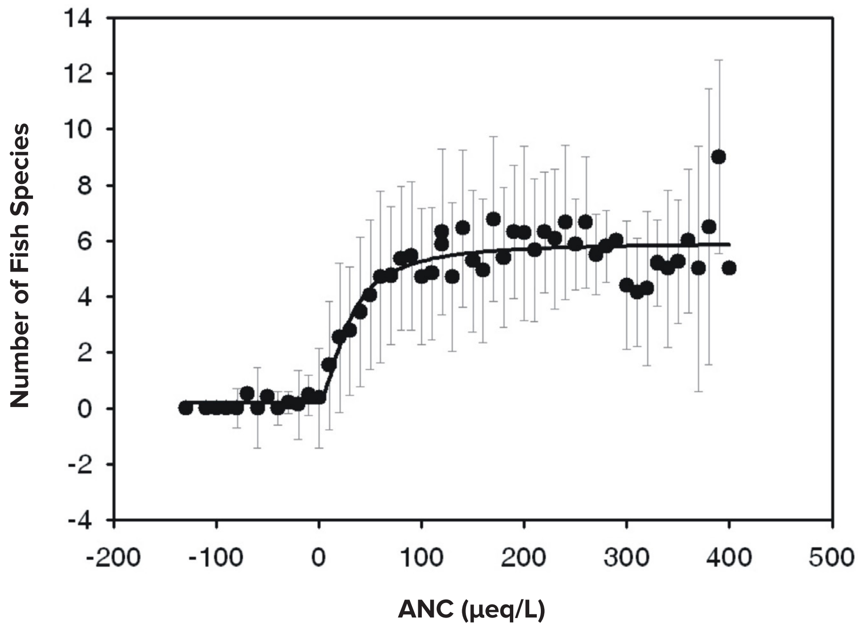

Figure 1.
Fish species richness as a function of ANC in 1,469 lakes that were sampled during 1984–1987 by the Adirondack Lakes Survey Corporation

Each filled symbol represents the mean of data that span a 10 µeq/L range and error bars represent the standard deviation of the mean.

Source: NYSERDA 2006

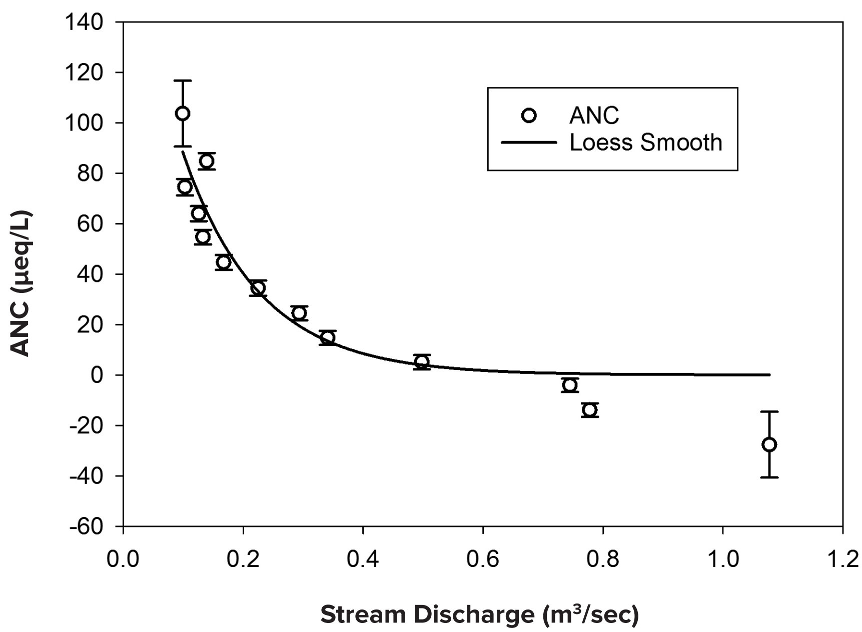

Figure 2.
Mean ANC and mean discharge at Buck Creek, Hamilton County, New York, for 1,104 samples collected during 1995–2013

Each symbol represents the mean of data that span a 10 µeq/L range and error bars represent the standard deviation of the mean. The line described in the legend as a Loess smooth represents a broad fit to the data designed to inform the reader of the general pattern of change in ANC as stream discharge changes.

Source: G.B. Lawrence, personal communication

that are input to the computer model simulating the behavior of the environment. Other sources of uncertainty that are related to processes in the environment that may be important, but are not included in the simulation model. The uncertainty resulting from these missing processes is not readily quantifiable, and therefore the manager or policymaker generally does not consider them.

Some CL assessments include a formal evaluation of uncertainty with results for the target value presented with appropriate error bounds. One approach to testing the accuracy of a computer model is to check it against available measurements to see how well current and past environmental behavior is simulated. Future forecasts of environmental conditions are likely to be no better than the accuracy with which ambient and past conditions were modeled.

East Copperas Pond
Photograph by Karen Roy

Another source of uncertainty is related to how strongly a chemical measure is related to the biological effects of interest. For example, is there a precise value of ANC in lakes that can indicate harm as inferred from the presence or absence of a fish species? Typically the answer to this question is derived from some combination of: 1) lab experiments in which chemistry is varied and the response in an organism is measured, and 2) field observations that relate surface water ANC to the presence or absence of the organism of interest. Often, a species can be present over a range of ANC values as reflected by the error bars in Figure 1. The error bars indicate a realistic range of uncertainty that commonly exists for the threshold of harm to a given species or biological community.

8. Importance of CL exceedance. A key CL concept that can inform management and policy assessments is the exceedance, or the extent to which current levels of acid deposition exceed the level expected to cause ecological harm (the CL). Exceedance can be viewed in both a spatial and temporal context. Several different approaches to evaluating CL exceedance can be helpful in informing management and policy decisions related to acid deposition. These approaches are embodied in the following questions:

1. How much of the landscape is in exceedance?
2. What are the relative exceedance levels?
3. How will the answers to questions 1 and 2 change in the future under different levels of pollutant emissions controls?

9. CLs are moving targets. Acid deposition has been declining in the Adirondack region and throughout much of the eastern United States since the mid-1970s to early-1980s. Recent decreases in the acidity of deposition during the 21st century have been especially pronounced. Previous scientific studies may have been based on deposition levels that differed substantially from levels observed today. Thus, the acid deposition levels that were the basis of CL studies and exceedance calculations completed in the past (even relatively recently) are likely to be different than those measured today. This is relevant to the Adirondack CL study that is discussed in the next section of this document in which the deposition levels used in the computer simulations were from the year 2005 (Sullivan et al. 2012). Those in the ecosystem management and policymaker communities who apply the results of CL studies would benefit from considering that discussions of exceedance or decreases in atmospheric deposition are likely referring to deposition loads from the past, which may be much higher than current deposition loads. Note that recent data on atmospheric loads of sulfur and nitrogen are readily available to the public through the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/). Several deposition monitoring stations in the Adirondack region have been operating for more than 25 years. A comparison of current deposition loads with those referred to in CL studies may be warranted to provide appropriate perspective for interpreting past results.

Adirondack Mountains Region: A Case Study Application of Critical Loads

Sullivan et al. (2011 and 2012) discussed CLs for terrestrial and aquatic ecosystems using a representative sample of Adirondack lake watersheds that allowed extrapolation to a population of 1,320 lakes with depths greater than 1 meter, surface areas greater than 1 hectare, and ANC values less than 200 µeq/L. They chose some generally recognized tipping point levels (that coincide with increased risk of biological harm) of key chemical measures of soil, soil solution, and lake water. Then they simulated environmental responses to acid deposition over time for the years 2050 and 2100 using the Model of Acidification of Groundwater in Catchments (MAGIC). The results showed a wide range of relative protection of Adirondack lakes and watershed soils depending on the chemical measures chosen (Sullivan et al. 2011). At sulfur deposition rates designed to promote soil recovery (25 meq/m^2/yr), about 94% of modeled lake watersheds could achieve a base saturation (a measure of readily available base cations in the soil) of 5% by the year 2050, whereas only 34% could achieve a base saturation of 10% by the same year (Figure 3). However, 58% of the modeled lake watersheds had pre-industrial base saturation of less than 10%, suggesting that this target value is not a realistic management objective for Adirondack lake watersheds. Other measures showed a wide range of responses in the number of watersheds that could reach a level of deposition below the exceedance level by the mid-21st century.

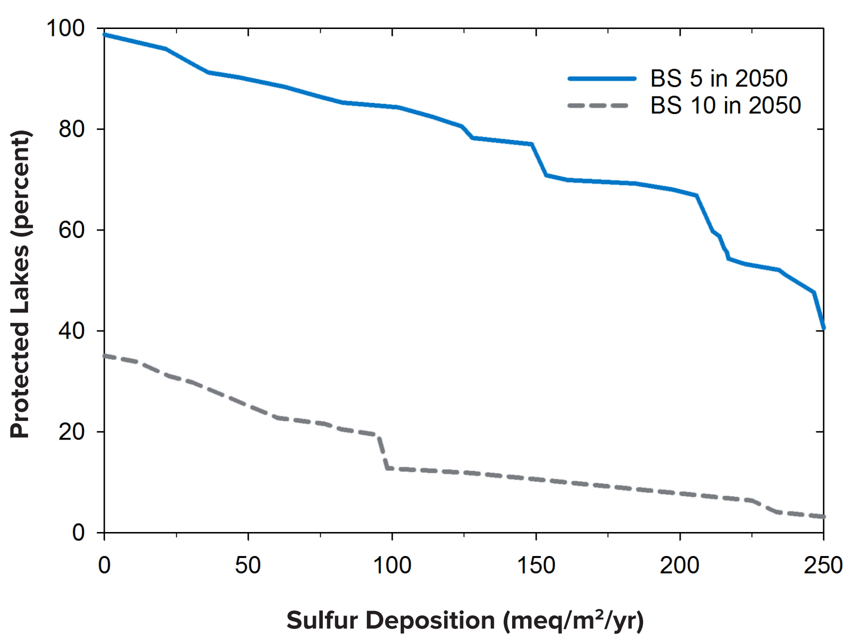

Figure 3.
Percent of Adirondack lake watershed soils expected to recover to base saturation values of 5% and 10% by the year 2050 for different levels of sulfur deposition according to simulations with the MAGIC model

These lakes are representative of a population of 1,320 that have ANC values of less than 200 µeq/L.

Source: Sullivan et al., 2011

Adirondack High Peaks from the summit of Goodnow Mountain with Rich Lake in foreground

Photograph by Douglas Burns

The dose-response levels for ecological harm to terrestrial ecosystems are not as well known as those of aquatic ecosystems. This poses a challenge to managers and policymakers who want to apply the terrestrial CLs calculated by Sullivan et al. (2011) to the decision-making process. Because the results were very sensitive to the chemical tipping point selected and the uncertainty is great regarding an appropriate level to select, this study suggests that a terrestrial CL approach is scientifically less defensible than an aquatic CL approach in seeking protection of Adirondack watersheds from the effects of acid deposition.

Sullivan et al. (2012) examined a range of values for the ANC indicator in the Adirondack aquatic CL assessment and provided projections for the years 2050 and 2100 using the MAGIC model. Their results showed that 46.3% of a regionally representative set of lakes will be in exceedance of the CL required to reach an ANC of 50 µeq/L in the year 2100, if year 2002 atmospheric sulfur loads are extended throughout the time range of the simulation. If the desired ANC value is a less protective 20 µeq/L, only 22.7% of the lakes would be in exceedance in 2100. Sullivan et al. (2012) also showed that Adirondack lakes were not very sensitive to excess nitrate from atmospheric nitrogen deposition, so the analysis focused mainly on effects from acidity resulting from sulfur deposition.

Several considerations are worth noting when interpreting the work of Sullivan et al. (2012) in a policy or management context. First, ANC values were likely never as high as 50 µeq/L in about 15% of the Adirondack lakes. Even at a lower threshold ANC value of 20 µeq/L, about 7% of lakes likely never had a historical value this high. This finding is consistent with recent work using a different model indicating that 27% of the most acidic lakes in the Adirondacks never had an ANC as high as 11 µeq/L (NYS DEC 2014, Fakhraei et al. 2014). These findings demonstrate that decreasing sulfur deposition even to a value of zero would not allow lake recovery to a targeted ANC that is greater than the historical value, the so-called "can't get there from here" problem described by Sullivan et al. (2012).

A final consideration when translating the results of Sullivan et al. (2012) into a policy context is that their conclusions are based on calculations of atmospheric deposition levels in 2002. A recently published study indicates that atmospheric sulfur deposition declined by 40% across the northeastern U.S. from the early 2000s through 2010, and recent evidence shows this rate of decline has continued at least through 2012 (NYS DEC 2014). Mean sulfur deposition values across the most sensitive southwestern part of the Adirondacks are now in the range of 20 – 25 meq/m^2/yr (NYS DEC 2014, Fakhraei et al. 2014), which should foster eventual recovery to an ANC of at least 50 µeq/L in most acidified Adirondack lakes except for lakes that never had that level of ANC. An unresolved challenge is the rate of that recovery and the year by which an ANC of 50 µeq/L can be reached. The work of Sullivan and colleagues indicates that this level of recovery can be realized by the year 2100, and that more than 90% of the year 2100 recovery results can be achieved by 2050 (NYSERDA 2014b). But even the year 2050 is a long time frame for assessing the benefits of many management and policy actions. For this reason, continued monitoring of the chemistry of lakes and their surrounding watersheds is needed to inform managers and policymakers as well as to provide feedback to test the results and assumptions of computer model simulations such as those described by Sullivan et al. (2011, 2012, NYSERDA 2014a and 2014b).

Continued monitoring of the chemistry of lakes and their surrounding watersheds is needed to inform managers and policymakers as well as to provide feedback to test the results and assumptions of computer model simulations.

The results of Fakhraei et al. (2014) can be compared with those of Sullivan et al. (2011, 2012, NYSERDA 2014a and 2014b). The Fakhraei et al. study (2014) evaluated a set of 128 of the most sensitive and acidic lakes in the Adirondack region in contrast to the lakes evaluated by Sullivan, which were meant to broadly represent the entire Adirondack region. Fakhraei et al. (2014) also used a lower (and therefore, less difficult to achieve) target ANC of 20 µeq/L. They concluded that 62.5% of these lakes would reach the target ANC by 2100 in response to a 60% reduction (from the year 2010) in sulfur deposition to a mean regional value of 7.9 meq/m^2/yr. Less than half of the 128 lakes would reach this target ANC by 2050. About 40% of the lakes would have an ANC of less than 20 µeq/L in 2050, even if sulfur deposition was reduced to zero. This work shows that recovery of these sensitive lakes becomes progressively more rapid as sulfur deposition is further lowered, emphasizing the benefit of additional emissions controls. The Fakhraei et al. (2014) study shows lower percentages of lake recovery and suggests lower CL values than those of Sullivan et al. (2011 and 2012, NYSERDA 2014a and 2014b). These differences are driven by the different populations of lakes that were modeled, the starting year of reductions in sulfur deposition, and the different ANC target values that were selected. These differences provide the policymaker or manager with a suite of results to examine, determined by the goals of policy decisions as to which population of surface waters to protect, and the desired level of protection.

A final cautionary note is that recovery of surface water chemistry to a specified level of an index measurement such as ANC, does not guarantee the expected biological recovery. The species of interest must have a means of dispersal to reach a previously acidified habitat that is now suitable for reproduction and survival. For example, fish may not be able to easily reach a lake with improved water quality because of physical barriers such as dams or sharp drops like waterfalls in connecting waters that may limit their migration. Furthermore, the environmental conditions of today may be quite different than those that existed at an earlier time when a given species was present in a water body. The climate in the Adirondacks has changed substantially from that of 50 – 100 years ago (Stager et al. 2009), and additional climatic changes are expected in the 21st century. These climate-driven changes such as warmer water temperatures are likely to favor some species over others, and could prove especially challenging to cold water species such as brook trout. Additionally, any species that may return to a habitat where it has previously been eradicated will have to compete with a different mix of species than were present historically. For example, invasive species of plants, mollusks, and fish are present in many Adirondack lakes that were not evident 50 years ago (Strayer 2010). This renewed competition alone may prevent or limit the re-establishment of a species in its former habitat.

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New York State
Energy Research and
Development Authority

17 Columbia Circle
Albany, NY 12203-6399

toll free: 866-NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov