New York State Energy Research and Development Authority

Critical Loads of Sulfur and Nitrogen to Protect Acid-Sensitive Resources in the Adirondack Mountains

Summary

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Summary

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1 Background

Research was recently undertaken to determine the critical load (CL) values that will promote resource recovery in previously acidified aquatic and terrestrial ecosystems in New York State, with focus on the Adirondack Ecoregion. Ambient levels of atmospheric sulfur (S) and nitrogen (N) deposition are declining in response to emissions control legislation. However, full chemical, and hopefully also biological, recovery of both surface waters and soils, may require additional emissions reductions and/or remediation. As a first step, researchers have to quantify how low acidic deposition levels must be for recovery to occur. The CL approach can provide such quantification. The CL is sometimes calculated under steady state conditions which may not occur for many decades or longer into the future. In this work, CLs are calculated that are specific to a particular point in time. These dynamic CLs are often called target loads (TLs).

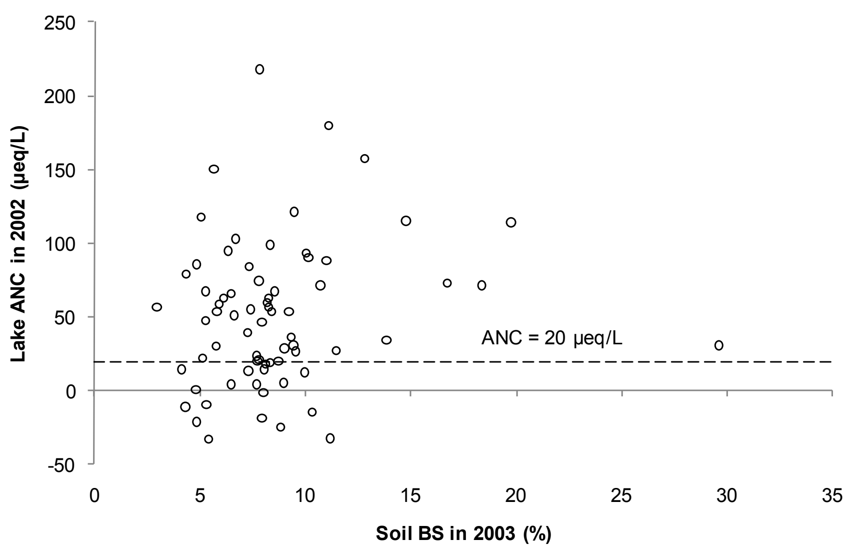
2 What is a critical load?

A CL is an amount of atmospheric deposition of S, N or acidity, below which significant ecological harm is not expected to occur to sensitive natural resources. The CL defines a tipping point; it separates ecosystems that have been or will be harmed by a given level of pollutant input from ecosystems that have not and will not be harmed. The CL can be calculated to protect aquatic resources such as fish or aquatic insects or terrestrial resources such as trees, herbaceous plants, or lichens. Most of the focus in this study was on CLs for protecting and restoring Adirondack lakes. Nevertheless, these aquatic and terrestrial CLs are linked. For example, Adirondack lakes only have acid-neutralizing capacity (ANC[1]) below about 20 microequivalents per liter (µeq/L), which is a level known to harm brook trout, if those lakes occur in watersheds having upper mineral soil base saturation (BS[2]) below about 12% (Figure 1).

Figure 1. Relationship between simulated lake ANC in 2002 and watershed averaged soil BS measured in the field in 2003 for 70 Adirondack lakes modeled using MAGIC[3]

A reference line is added at ANC = 20 µeq/L, illustrating that lake ANC below 20 µeq/L is only found in Adirondack watersheds that have average BS below about 12%.

Source: Modified from Sullivan et al. (2011). Target loads of atmospheric sulfur deposition protect terrestrial resources in the Adirondack Mountains, New York against biological impacts caused by soil acidification. J. Environ. Stud. Sci. 1(4):301-314. Copyright © 2011, Springer. Reprinted with permission.



1 A measure of the ability of water to buffer or neutralize acidic inputs from the atmosphere.

2 A measure of the relative amount of basic cations (such as calcium [Ca] or magnesium [Mg]) versus acidic cations (such as hydrogen [H] or aluminum [Al]) adsorbed to the soil.

3 Model of Acidification of Groundwater in Catchments, a commonly used dynamic model of watershed acidification.

3 How can a critical load be calculated?

CLs can be calculated in various ways. They can be based on field measurements, experimentation, simple steady-state mass balance models, or process-based dynamic models. Pollutant loads below the CL are assumed to cause no damage at the point in time specified in the analysis. This pollutant load can be at an assumed future steady state condition or at a designated time in the future. One step in the CL process is to determine how much pollutant produces how much impact. This determination can be done by adding pollutants experimentally or by comparing otherwise similar communities that receive different pollutant loads. Critical loads determined this way are called empirical CLs. They are determined by observation and can be used as screening tools.

In many cases, modeling is required. We may want to know, for example, the CLs of a thousand Adirondack Mountain lakes, or the load that will keep a forest healthy for the next hundred years. In these cases, a mathematical model is applied that simulates the behavior of the community. Typically, these models simulate the chemistry of a community rather than its biology. For this simulation, researchers need to find a chemical variable that has been found to be a good indicator of the amount of biological change interpreted by land managers or policymakers as significant ecological harm. These variables are called indicators or proxies.

When CLs are determined using a model, the model can be long-term, steady-state, or tied to a particular point in time. The CL can be intended to protect against harm caused by S, N, both, or some other pollutant or stressor. The harm under investigation can be caused by excess nutrient supply, acidification, or toxicity. The focus can be on the protection of a single species deemed to be important to humans (such as brook trout or sugar maple trees) or an entire biological community. Resources can be protected to varying levels using multiple indicators of harm. Therefore, for a given biological community there is a matrix of CLs. All of these can vary from one watershed to another.

4 What are the CL values for Adirondack lakes and their watersheds?

Researchers recently reported modeled dynamic CLs for Adirondack lakes and their watersheds.[4] Model simulations were constructed using the MAGIC model based on two acidic deposition drivers (S and N), three sensitive receptors (lake water, soil, and soil solution), one or more chemical indicators for each, two to three critical threshold levels for each indicator, and three to four endpoint years or periods (Table 1). Selection of these various CL parameters influenced the results of the CL calculations. The report presented a large matrix of CL results, some of which are summarized in this document. The calculated CL values must be interpreted in the context of these modeling choices. For modeling the CL to protect or restore Adirondack lakes, the indicator ANC was used with critical threshold criteria values equal to 0, 20, and 50 µeq/L. For protection of terrestrial resources, the CL was modeled to attain soil % base saturation (BS) values of 5, 10, and 15%, plus various parameters and values for soil solution.

Table 1. Indicators, critical levels, and timeframes investigated during a recent study of critical loads modeling

Pollutants	Ecosystem Stress	Sensitive Receptor	Indicator	Critical Level	Timeframe
S, N	Acidification	Lake Water	Lake ANC	0, 20, 50 µeq/L	2020, 2050, 2100, steady-state
	Eutrophication	Lake Water	Lake NO_3^-	10, 20 µeq/L	2020, 2050, 2100
	Acidification	Soil	B-horizon BS	5, 10, 15%	2020, 2050, 2100
	Acidification	Soil Solution	B-horizon Ca:Al	1, 10	2020, 2050, 2100
	Acidification	Soil Solution	B-horizon Bc:Al	1, 10	2020, 2050, 2100

Lower aquatic S CL values (indicating a more limited ability to tolerate acidic deposition) were found for lakes that currently have low ANC. Furthermore, CL values tended to be lower if the objective was to protect lake water to a higher level (i.e., ANC = 50 µeq/L) as compared with a lower level of protection, such as only protecting to ANC = 20 µeq/L. For a given watershed and set of CL criteria, the CLs for N were much higher than those for S. This difference is largely because Adirondack watersheds modeled for this study currently retain most of the N that is atmospherically deposited. It is possible, however, that N retention in some watersheds will decrease in the future under continued N loading. Such a change would decrease the N CLs for lakes in these watersheds.

4 NYSERDA. 2014. "Critical Loads of Sulfur and Nitrogen for Protection of Acid Sensitive Aquatic and Terrestrial Resources in the Adirondack Mountains." Report 14-10.

5 What can be learned by extrapolating modeled CL values to the broader region?

Extrapolation of model-simulated CL values at specific locations for this project focused in part on estimating numbers and percentages of Adirondack lake watersheds predicted to exhibit various CL values. This analysis was based on the statistical design of the U.S. Environmental Protection Agency's (EPA) Environmental Monitoring and Assessment Program (EMAP). It yielded estimates of numbers and percentages of lakes and watersheds in various CL classes, without any information regarding where within the Adirondack Ecoregion those watersheds are located. To satisfy the need to discern where these acid-sensitive lakes are located, model results for aquatic CLs were also spatially extrapolated to 1,136 lakes included in the Adirondack Lake Survey (ALS) that was conducted in the 1980s and mapped throughout the study region. As an example, results are compared in Table 2 among various groups of Adirondack lake watersheds based on one suite of CL specifications and assumptions. The percentage of lakes found to be within the various CL classes, where each class represents a range of CL values in meq/m^2/yr, varied substantially based on the group of lakes modeled or represented by the estimate. In extrapolating CL results obtained by modeling individual lake watersheds to the broader population of Adirondack lakes and their associated watersheds, it is therefore important to specify the lake population or statistical frame to which the results are being applied.

Table 2. Estimated percentage of Adirondack lake watersheds having various critical load of sulfur deposition values to protect against sulfur-driven lake acidification to ANC = 50 µeq/L in the year 2100, using different approaches and population frames

Source: Sullivan et al. (2012)

		Percentage of Lakes in Critical Load Class					
Approach	**Number of Watersheds**	**CL (S)**	**≤25**	**25-50**	**50-75**	**75-100**	**> 100 (meq/m^2/yr)**
MAGIC model simulations for all modeled lake watersheds	97		28.9	26.8	17.5	15.5	11.3
Numeric extrapolation of MAGIC model simulation results to the EMAP frame of Adirondack lakes that are larger than 1 ha, deeper than 1 m, and that have ANC ≤ 200 µeq/L	1,320		19.5	21.8	22.2	10.1	26.4
Same as above, except assuming a high CL for all EMAP lakes that were not modeled using MAGIC because they had ANC > 200 µeq/L	1,829		14.1	15.7	16.0	7.3	46.8
Spatial extrapolation of MAGIC model simulation results to all lakes surveyed by the ALS that are larger than 1 ha	1,136		25.8	13.1	10.4	8.9	41.8

MAGIC model simulations of the CL of S deposition needed to protect lake ANC from falling below designated critical criteria values could successfully be predicted across the landscape using only lake water ANC as a predictor variable. The most robust predictions were obtained for estimating the CL to protect lake ANC from going below 50 µeq/L in the year 2100 ($r^2 = 0.92$). For reasons of simplicity, the final equations applied here only used ANC and a constant to predict each CL. Inclusion of other aspects of water chemistry or watershed features such as elevation, slope, watershed area, and/or soil characteristics (pH, percent clay, depth) that correlate with acid sensitivity did not appreciably improve CL predictions beyond what was achieved based only on measurements of lake ANC.

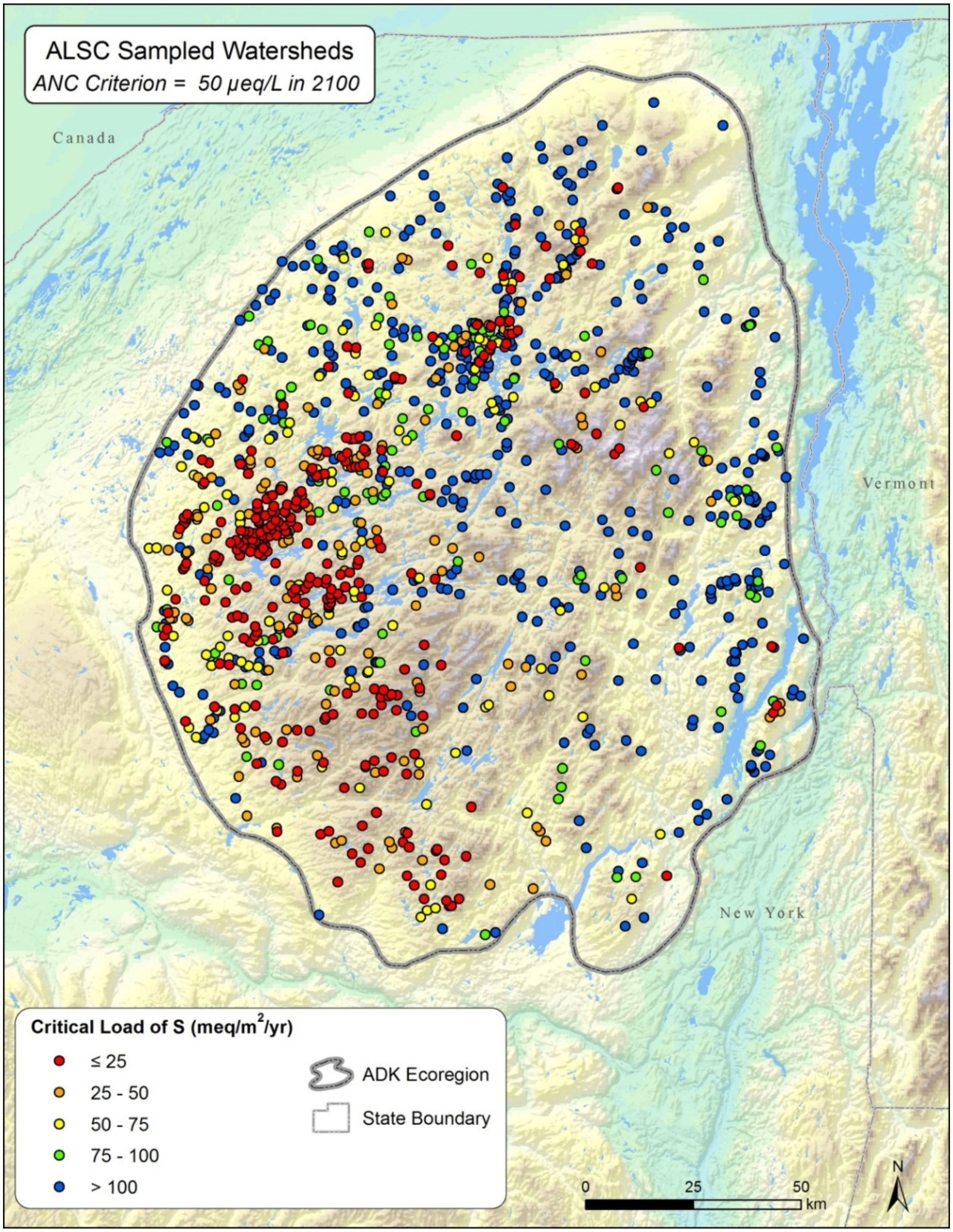
The spatial patterns in acid sensitivity are readily apparent in map depictions of S CLs extrapolated to the population of ALS lakes. One example is shown in Map 1, based on protecting the lakes to ANC = 50 µeq/L in the year 2100. For these simulations, the vast majority of the ALS lakes in the southwestern third of the Adirondack Ecoregion have S CL less than 50 meq/m^2/yr, as do many lakes in the high peaks area to the north.

The population distributions of the S CLs for the low-ANC EMAP population of lakes and for the ALS surveyed lakes were generally similar. Median and quartile CL values were slightly lower for the ALS lake population than for the EMAP population, although the differences were small (Table 2).

Map 1. Estimated critical load of sulfur deposition based on extrapolation of MAGIC modeling results to the population of lakes surveyed by the Adirondack Lakes Survey (ALS)

Exceedances were calculated for the year 2100 using a critical threshold ANC value of 50 µeq/L.

Source: Modified from Sullivan et al. (2012). Target loads of atmospheric sulfur and nitrogen deposition for protection of acid sensitive aquatic resources in the Adirondack Mountains, New York. Water Resour. Res. 48 doi:10.1029/2011WR011171. Copyright © 2012, American Geophysical Union. Reprinted with permission of John Wiley and Sons, Inc



6 How does ambient atmospheric sulfur deposition compare with the modeled CL values in Adirondack lakes?

The extent to which ambient acidic deposition exceeds the CL for resource protection/recovery is called the exceedance. If deposition is higher than the CL, the receptor (lake or forest soil) is said to be "in exceedance" of the CL. Some Adirondack lakes and their watersheds receive ambient S deposition that is more than double the respective CL (Map 2). Depending on the critical threshold value of the sensitive criterion and the endpoint year selected for a particular CL analysis, some lakes and watershed soils are unable to attain the critical threshold value by the specified endpoint year even if S or N deposition is reduced to zero and maintained at zero throughout the duration of the simulation (to the endpoint year). These lakes, soils, or soil solution receptors are sometimes called "can't get there from here" receptors.

All of the EMAP lakes were simulated to be able to achieve ANC = 0 µeq/L, regardless of endpoint year. Most EMAP lakes (93%) could achieve ANC = 20 µeq/L by the year 2050 or 2100. Somewhat fewer (84%) could attain ANC = 50 µeq/L by either of these endpoint years. For the lakes that were judged to be unable to achieve the specified ANC threshold, that inability to achieve the target was attributed primarily to low ANC during pre-industrial time (that is, in the absence of acidic deposition), and secondarily to delayed recovery response due to effects of acidic deposition on watershed soils.

Regional estimates of ambient (average centered on the year 2002) total wet plus dry S and N deposition were highest in the southwestern portion of the Adirondack Ecoregion and lowest to the northeast. These deposition estimates were used to calculate CL exceedance by comparing ambient deposition with CL estimates. The number and percentage of Adirondack lakes that receive ambient S deposition above their respective CL are reported. For protecting lake water ANC in the year 2100, the percent of 1,320 low-ANC EMAP lakes projected to be in exceedance ranged from 15.5% for protecting to ANC = 0 µeq/L to 46.3% for protecting to ANC = 50 µeq/L; the estimate for protection to ANC = 20 µeq/L was intermediate (22.7%). Comparable calculations for the year 2050 yielded slightly lower estimates of the numbers and percentages of lakes in exceedance.

Only 13.5% (for the year 2100) of these low-ANC EMAP Adirondack lake watersheds were simulated to be in exceedance of the S CL to protect soil BS to 5%. If a more protective critical threshold value for BS is assumed (BS = 10% or 15%), many additional watersheds are estimated to be in exceedance for protecting soil condition. Results of a recent field study conducted for NYSERDA suggest that sugar maple trees are failing to regenerate at locations in the Adirondacks where soil BS is less than about 12%.

Map 2. Exceedance classes for 1,136 Adirondack lakes based on extrapolation of MAGIC model results of sulfur CLs to the ALS-surveyed lakes

Exceedances were calculated for the year 2100 using a critical threshold ANC value of 50 µeq/L.

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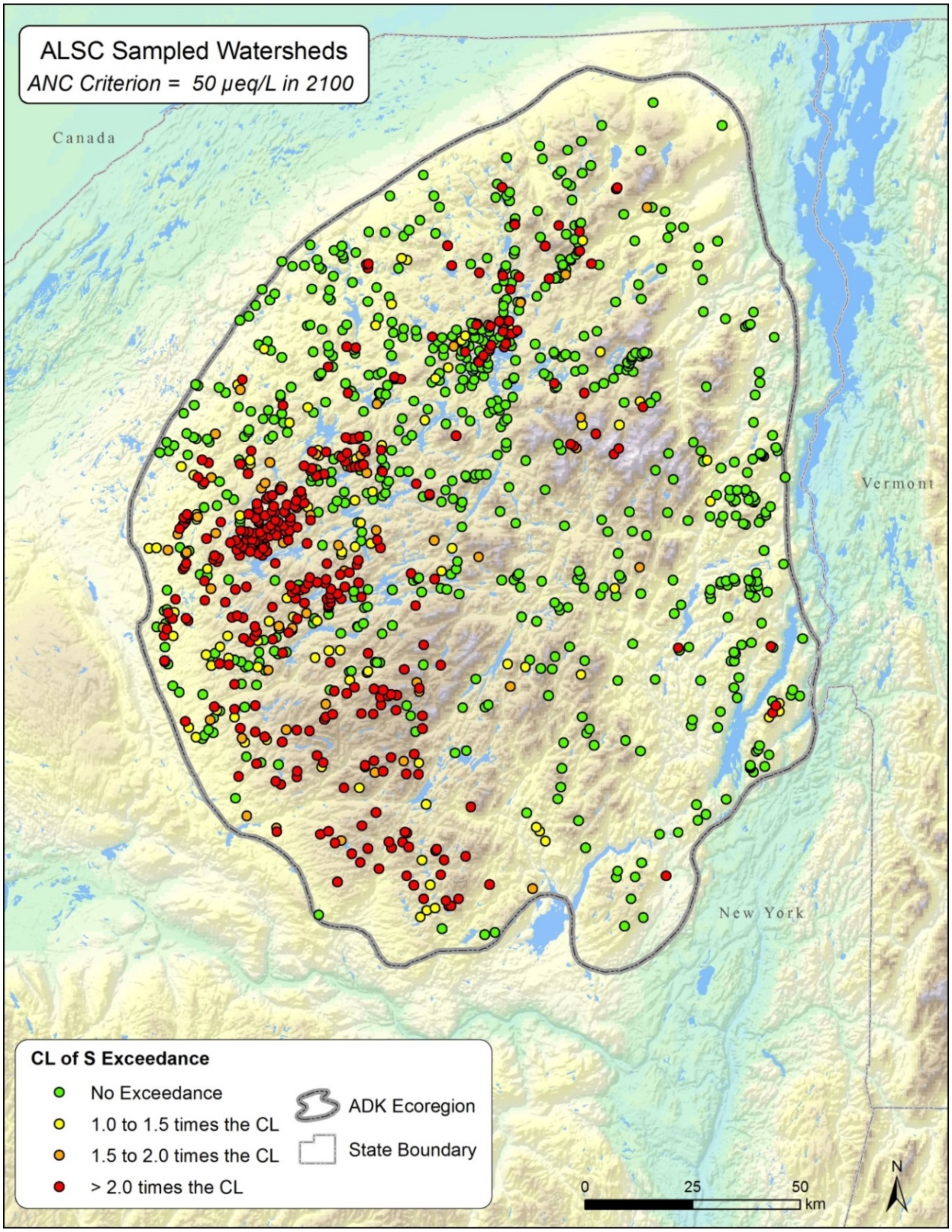

7 What do these critical load estimates tell us?

These research results are important for managing ecosystems across New York State that have been impacted by acidic deposition. Model simulations quantify the CLs of atmospheric deposition needed to achieve resource recovery to a range of chemical indicator tipping point values. In addition, the estimated aquatic CLs at discrete dynamic modeling sites were extrapolated to 1,136 lake locations in the region that have been surveyed for lake chemistry. This research identified locations in the Adirondacks where acidified lakes and forest soils receive ambient acidic deposition in exceedance of their CL, where acidified ecosystems are most likely to recover, and the long-term sustained deposition loads that would be required to allow such recovery.

8 References

Sullivan, T.J., B.J. Cosby, C.T. Driscoll, T.C. McDonnell, and A.T. Herlihy. 2011. Target loads of atmospheric sulfur deposition protect terrestrial resources in the Adirondack Mountains, New York against biological impacts caused by soil acidification. J. Environ. Stud. Sci. 1(4):301-314.

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