TOTAL MAXIMUM DAILY LOADS

Waterbodies: 2 Acid Impaired Lakes

VT11-18L03	Lily (Londonderry)
VT13-16L01	Lily (Vernon)

Pollutant: Acid

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Introduction

Acid deposition is rain, snow, fog or dust that is polluted by acid in the atmosphere and damages aquatic and terrestrial systems. Two common air pollutants acidify the water or dust particles: sulphur dioxide (SO_2) and nitrogen oxides (NO_X). When these substances are released into the atmosphere, they can be carried over long distances by prevailing winds before returning to earth as acidic rain, snow, fog or dust. When the environment cannot neutralize the acid being deposited, damage occurs. One of the most apparent features in the natural environment affected by acid precipitation is lakes and ponds.

The Vermont Department of Environmental Conservation (VTDEC) has been monitoring the chemistry of low ionic strength lakes in Vermont since the winter of 1980. In 1983, the United States Environmental Protection Agency's (USEPA) Long-Term Monitoring (LTM) Project was initiated within the National Acid Precipitation Assessment Program (NAPAP) organizational framework. Since 1983, the VTDEC project has been conducted in cooperation with the USEPA. The cooperative LTM Project is managed by the USEPA's Environmental Research Laboratory in Corvallis, OR (ERL-C) and consists of federal agencies, state agencies and universities. Vermont's LTM Project (VLTM) currently samples 12 acid sensitive lakes on a seasonal basis. Eleven of these lakes are considered impaired. Numerous other acid impacted lakes and streams are monitored throughout Vermont by the VTDEC but on a less intensive schedule.

Based on data collected through these monitoring programs, a number of lakes were identified on previous years' 303(d) Lists. The VTDEC prepared and submitted to the USEPA Region 1 Total Maximum Daily Loads (TMDLs) for 30 acid impaired lakes in 2003 and another 7 in 2004. These 37 TMDLs were subsequently approved by EPA. Because the source and type of the problematic acid loading is similar for all these lakes, these TMDLs employed a single analytical approach to determine each lake's acid loading capacity, or critical load. Critical loads were calculated using the Steady State Water Chemistry Model (SSWC).

Since the previously developed TMDLs were approved, two additional acid impaired lakes were identified and listed on the 303(d) List in 2010. The necessary water chemistry data sets have since been compiled and the SSWC model was applied to develop TMDLs for the two acid-impaired lakes addressed here. Table 1 identifies these acid-impaired lakes and identifies some of their physical characteristics. The explicit derivation of the critical loading estimates for these 2 lakes is detailed in Appendix A, *"2012 Update: Calculating critical loads of acidity and exceedances for acid-impaired lakes in Vermont using the Steady State Water Chemistry (SSWC) model"*.

Table 1. Identification and physical characteristics of the 2 acid-impaired lakes.

Lake	Waterbody ID	Town	WQ Class	Drainage Area (ha)	Surface Area (ha)	Maximum Depth (m)	Elevation (m)
Lily	VT11-18L03	Londonderry	B	113.73	10.1	3.3	454
Lily	VT13-16L01	Vernon	B	350.51	15.2	3.8	112

Lily pond in Londonderry has a long history of low alkalinity values dating back to the early 1980s. Regular VLTM sampling for this pond ceased in 1992; however, the pond has since been sampled in 2004 as part of the TMDL Acid Lake Monitoring Program and sampled again in 2008 and 2009. Due to the combination of historical data and the three most recent data points, Lily Pond in Londonderry was listed on the 303(d) List in 2010.

Lily Pond in Vernon was sampled in 2008 and 2009 and exhibited Gran alkalinities of 1.48 and 1.84 mg/L respectively. These values were well below the listing threshold for impairment determination and the pond was 303(d) listed in 2010.

This TMDL has been developed for the overall acidic inputs to the waters. The methodology used for determining the critical loads incorporates acidic inputs of the two largest contributors of acidity to these lakes, sulfur and nitrogen compounds. However, since the ratios of these strong mineral acid components vary among lakes, the combined overall acid critical load was used.

According to the Vermont 2012 303(d) List of Impaired Surface Waters (Part A), the waterbodies addressed in this TMDL are identified as a high priority for TMDL development. This indicates that TMDLs are scheduled for completion over the next 1-3 years.

The establishment of critical loads of acidity for these lakes provides one of the three important components to fully document the acid depositional process. The critical loads establish the maximum levels of acidic deposition each watershed can receive to facilitate recovery; however, more needs to be known about distant sources and transport in order to initiate proper controls. The critical loads provide a framework from which to "backtrack" and trace the origin and magnitude of the acidity sources to the atmosphere and their transport to Vermont. Combined with atmospheric transport and deposition modeling, they will provide a basis for evaluating the environmental effectiveness of alternative national or regional emissions control programs, or of quantifying the adverse contributions from specific emission sources if effective national legislation is not forthcoming. They also provide an environmental "benchmark" from which the effects of future changes in emissions and deposition can be quantitatively evaluated.

The critical loads established in this TMDL, coupled with previous acid-impaired lakes TMDLs, will facilitate better understanding of the status and magnitude of acidic atmospheric deposition on surface waters in Vermont and help lead to the control of significant acid sources.

Water Quality Standards

The 2 lakes identified in this TMDL have been listed as impaired, consistent with the Vermont Surface Water Assessment and Listing Methodology (2011) and the Vermont Water Quality Standards (VTWQS), as shown by in-lake water chemistry monitoring data. Based on the two lakes' Class B water quality classification, the applicable management objectives and designated uses are identified below.

Designated Uses
For these Class B designated lakes, the VTWQS Management Objectives in §3-04(A) state that:

- *"Class B waters shall be managed to achieve and maintain a level of quality that fully supports the following designated uses:*

including:

- *1. Aquatic Biota, Wildlife, and Aquatic Habitat - aquatic biota and wildlife sustained by high quality aquatic habitat with additional protection in those waters where these uses are sustainable at a higher level based on Water Management Type designation."*

Water Quality Criteria
The VTWQS (2011) have established general and specific criteria for a number of water quality parameters for all Vermont surface waters regardless of classification. With regard to the acid-impaired waters addressed by this TMDL, the parameters of interest are pH and alkalinity. Section 3-01(B)(9), which has both a numeric and narrative component, states that:

- *"pH values shall be maintained within the range of 6.5 and 8.5. Both the change and the rate of change in pH values shall be controlled to ensure the full support of the aquatic biota, wildlife, and aquatic habitat uses."*

Section 3-01(B)(8), a narrative standard, states that with regard to alkalinity, there shall be:

- *"No change from reference conditions that would prevent the full support of the aquatic biota, wildlife, and aquatic habitat uses."*

These are general criteria for all classes and types of water. There are no more specific criteria for these parameters for Class B waters.

The narrative nature of the alkalinity criterion requires a numeric threshold be established as a surrogate to assure that acidic inputs do not prevent the full support of aquatic biota, wildlife and aquatic habitat uses. As discussed below, an acid neutralizing capacity (ANC) target value of 2.5 mg/l $CaCO_3$ was established by the VTDEC to identify waters not in compliance with this narrative standard of the VTWQS.

Some of the lakes addressed in the previous acid lake TMDLs are unlikely to have pH values consistently in the 6.5-8.5 range even under completely natural conditions due to their position in the landscape. This is one reason why alkalinity was used as the main indicator of impairment. If the pH of waters outside the range of 6.5-8.5 occurs naturally, the VTWQS state that these waters remain in compliance as stated in §3-01(A):

- *"Waters in which one or more applicable water quality criteria are not met due to natural influences shall not be considered to be in noncompliance with respect to such criteria."*

Antidegradation Policy
In addition to the above standards, the VTWQS contain, in part, the following General Antidegradation Policy in § 1-03(A):

- *"All waters shall be managed in accordance with these rules to protect, maintain, and improve water quality."*

Pollutant Sources

It has long been understood that the deposition of strong mineral acids and acid-forming compounds from the atmosphere is the primary source of the acidification of hundreds of lakes throughout the northeast United States as well as other regions across the country. As noted previously, the overwhelming source of acidity to these lake watersheds is from atmospheric deposition through rain, snow, water vapor and dust. While the specific sources of these acidifying pollutants are not identified here, national atmospheric emission inventories and decades of atmospheric modeling results have implicated Midwestern coal-fired electric generating utilities as a predominant historical and continuing source of wet, dry and occult sulfate deposition, sulfate aerosol concentrations, regional haze and particulate matter in New England (and elsewhere throughout the Eastern US and Canada). Nitric acid deposition is heavily contributed to by coal-fired utilities but also results from a broader range of emissions source types (including motor vehicles and industrial sources). From a water quality perspective, it is not the atmospheric concentrations but rather the atmospheric cleansing or deposition of these pollutants that matters.

In 2002, VTDEC contracted with Ecosystems Research Group, Ltd. of Norwich, Vermont to apply the High-Resolution Deposition Model (HRDM) to provide high-resolution estimates of total atmospheric deposition of sulfur and nitrogen to 34 lake watersheds. One of the driving factors to have this work completed was the lack of comprehensive atmospheric depositional data, the primary source of acidic inputs to these lake watersheds. Existing loading estimates of sulfur and nitrogen were available for wet and dry deposition but little if any was available for cloud water (vapor) deposition. Cloud water deposition was believed to be a significant portion of the overall load to many of these watersheds, especially those at higher altitude. The results of the HRDM application to these acid impaired watersheds and the modeling methodology are given in Appendix B.

Numeric Water Quality Target

The VTWQS do not set forth an explicit numeric water quality target regarding acidic inputs to water. Since no numeric value for alkalinity is given, an ANC value of 2.5 mg/l $CaCO_3$ is used as a cutoff in determining impairment. This value has been used historically based on literature information describing minimal impacts on fish and macroinvertebrate communities and is considered by VTDEC to be an adequate measure of potential acid stress on aquatic organisms in Vermont's lake systems. Values above 2.5 mg/l $CaCO_3$ are considered to provide an adequate level of buffering against acid inputs to protect resident aquatic life. Additionally, the level of 2.5 mg/l $CaCO_3$ is considered effective to prevent violations of the pH criteria in the VTWQS. Although some lakes may naturally fall below a pH of 6.5, these lakes are not considered impaired for pH because §3-01(A) of the VTWQS, which states that waters where criteria are not met due to natural influences shall not be considered in noncompliance with the criteria. In addition, the full support of the naturally occurring aquatic biota would still be protected with a buffering level of 2.5 mg/l $CaCO_3$.

However, the measure of in-lake ANC does not provide any link to how acidic loading may affect a lake's ANC. It is the purpose of the TMDL to identify this linkage and quantify the maximum amount of acidity the watershed can receive to maintain the appropriate ANC to protect aquatic communities. For this TMDL, the Steady State Water Chemistry model (SSWC) was utilized to make this connection between maximum acidity loading and the maintenance of a protective 2.5 mg/l $CaCO_3$ ANC. A description of the SSWC model is outlined below. For a more detailed description of its application for this TMDL, refer to Appendix A *"2012 Update: Calculating critical loads of acidity and exceedances for acid-impaired lakes in Vermont using the Steady State Water Chemistry (SSWC) model"*.

Critical Loads

The SSWC model estimates the critical load of acidity to a watershed where the critical load is defined as the level below which significant harmful effects to specified elements of the environment do not occur. The underlying concept of the model is that excess base cations in a catchment should be equal to or greater than the acid anion inputs. This balance maintains the lake's ANC in order to support aquatic communities. The SSWC model has been used widely for critical load determinations across sections of the world where acid deposition is problematic, namely northern Europe and Canada.

The SSWC model calculates critical loads based on in-lake water chemistry and also accounts for annual surface runoff amounts and a user specified ANC limit. The ability to set a predefined ANC limit forces the model to output a critical load based directly on VTDEC's water quality target of 2.5 mg/l $CaCO_3$. The critical load for the two impaired waterbodies is given in Table 2.

Table 2. Critical load of acidity for 2 acid impaired waters.

Waterbody	Critical Load ($meq/m^2/yr$)
Lily (Londonderry)	31.24
Lily (Vernon)	36.11

Positive critical load values indicate that the waterbody has some tolerance for acidic inputs while still maintaining a minimum ANC level of 2.5 mg/l $CaCO_3$. The greater the critical load value, the greater tolerance the waterbody has to acidification. On the other hand, negative critical loads represent situations where the selected ANC target of 2.5 mg/l $CaCO_3$ is higher than the original, pre-acidification, base cation concentrations would naturally allow. Neither of the two lakes have a negative critical load.

The use of the SSWC model for critical load determination has many benefits. First, the model has a successful track record in northern Europe and Canada supporting establishment of source reduction targets. Second, the inputs for the model are readily available. Third, the model has the flexibility to adapt to the user-specific ANC target. This flexibility allows the direct output of the necessary critical loads without additional extrapolation.

The primary weakness of the model is not in its ability to calculate critical loads, but rather in its ability to predict responses to reduced deposition. For example, a reduction in acid loading to the watershed may alter current weathering rates, soil base cation depletion or mineralization rates. Any of these changes may affect the future critical load. Under the steady state conditions required of the SSWC model, the critical loading limits in this TMDL are the best estimates available with current data.

Exceedances

In addition to the critical loads, exceedances of the critical load can be determined by comparing the critical load to recent loading estimates of acidic nitrogen and sulfur compounds. While the calculation of exceedances (Table 3) is not critical for the TMDL, it does provide a means to gauge the extent of the impairment and the level of reductions needed. Exceedances also demonstrate the range of sensitivity of Vermont's acid impaired lakes. While some lakes may improve with modest reduction of acidic inputs, others require far greater reductions to achieve recovery. A compilation of all critical loads and exceedances for Vermont lakes calculated to date can be found in Appendix A (Appendix B, Table 1).

Table 3. Critical load exceedances.

Waterbody	Critical Load Exceedance ($meq/m^2/yr$)
Lily (Londonderry)	27.85
Lily (Vernon)	24.04

Positive excess load values indicate that a lake's critical load has been exceeded based on the SSWC model output compared to depositional data. A negative value indicates that the critical load is not being exceeded.

TMDL Allocations

The proximate source of acidity to these lakes is from wet and dry atmospheric deposition. As previously noted, the ultimate source of atmospheric acidity is primarily individual out-of-state smokestacks and out-of-state mobile sources of air pollution. However, smokestack-related atmospheric acid has not traditionally been regulated under the Clean Water Act. Therefore, for the purposes of this TMDL the total pollutant load, minus an explicit margin of safety, is allocated to nonpoint sources in the Load Allocation. Because the determination of specific air contaminant sources polluting Vermont's waters is outside the scope of the TMDL, no attempt has been made to sub-allocate the load allocation among either different geographic areas or types of atmospheric acid sources.

Rather than expressing the TMDL for these lakes as a daily loading term, it is more appropriate for it to be expressed as an annual load. Due to the variable nature of acidic deposition, both wet and dry, and the internal lake processes that occur over long periods such as seasons and years, a daily loading limit would be difficult to determine and of little use. It's the overall annual acid loading that ultimately affects the lake ANC and thus the biological communities. Also, the springtime in-lake water chemistry, used to calculate a protective critical load, is the result of the annual acidity load that peaks during the springtime snowmelt runoff events.

TMDL Allocation Summary

Table 4 summarizes the acid allocations for the acid impaired waters covered under this TMDL.

Table 4. Summary of acidity allocations.

Lake	Waste Load Allocation ($meq/m^2/yr$)	Load Allocation ($meq/m^2/yr$)	Margin of Safety ($meq/m^2/yr$)	TMDL (Critical Load) ($meq/m^2/yr$)
Lily (Londonderry)	0	29.68	1.56	31.24
Lily (Vernon)	0	34.30	1.81	36.11

Nonpoint Source Load Allocation

The most significant source of acidity to these lake watersheds is from atmospheric deposition. Therefore, the critical load value, minus an explicit 5% allocation for a margin of safety, is allocated to the nonpoint source Load Allocation.

Point Source Wasteload Allocation

There are no point sources of significant acidity loading in these watersheds now or expected in the future. Therefore, a wasteload allocation of zero is allotted to point sources.

Margin of Safety

The TMDL regulations require that a TMDL include a margin of safety to account for any lack of knowledge concerning the relationship between loading and attainment of water quality standards. This TMDL has incorporated an explicit 5% allocation to account for any uncertainty in critical load determination. This safety margin is considered appropriate in this instance since the majority of the input data for the SSWC model was current and site specific (loading and water chemistry).

Seasonal Variation

Critical loads were calculated based on water chemistry data collected during the spring. The spring is when the lakes exhibit their lowest base cation concentrations associated with high runoff from snowmelt. When the lowest measured base cation concentrations for the lakes are used in the critical load calculation, the most conservative critical load is returned. Therefore, the calculated critical loads are protective for all seasons.

Monitoring and Assessment Plan

The VTDEC intends to continue monitoring the chemical status of all acid impaired waters and ideally to initiate biological monitoring. As national efforts to control acid deposition to the northeast United States progress, VTDEC anticipates the ability to identify resultant changes to the waterbodies. The four-part monitoring plan below outlines the major steps to achieve that goal.

1. Continue chemical monitoring of the current 11 Vermont Long-Term Monitoring (VLTM) lakes that are assessed as impaired. These lakes are sampled seasonally during the open water period. Most outlets will be sampled six times during the spring thaw to assess the critical period when the waters are prone to episodic acidification.

2. Since 2004, the VTDEC has used a rotational sampling approach to monitor the 36 impaired waters at least once over each five-year period. This has resulted in 7 to 8 lakes sampled during the spring index period each year. This rotational approach will continue as it is important to have current information to document potential chemical recovery.

Additional information regarding the source and transport of the acidifying pollutants is also important to Vermont's understanding of the necessary source controls. Since the most sophisticated regional, national and international scale atmospheric transport, transformation and deposition models (RADM, CMAQ, REMSAD) and the emissions and meteorology data needed to run them are extremely resource-intensive, and since EPA has substantial expertise and experience in running these models (for example to evaluate alternative national emissions control strategies), Vermont requests EPA assistance to:

1. Develop quantitative estimates of total sulfate and nitrate deposition at locations representative of Vermont's 36 acid impaired lakes for the various future emissions growth and control strategies that are being evaluated. If possible these estimates would be most useful if the deposition calculations were broken down into separate wet, dry and cloud water subcomponents, and if they also included calculations of ambient air concentrations of sulfur and nitrogen oxides, gaseous nitric acid and aerosol sulfate and nitrate concentrations.

2. Apply the Model of Acidification of Groundwater in Catchments (MAGIC) to Vermont's 11 LTM acid impaired lakes.

Implementation Plan

Because of Vermont's low population and absence of industrial and utility fossil fuel sources, in-state emissions of sulfur and nitrogen oxides are already among the lowest in the nation. The bulk of the acidifying pollutants contributing to the acid impairments identified in this TMDL are from sources well beyond Vermont's borders. Vermont has little direct control over these sources and is forced to rely on national enforcement efforts spearheaded by the USEPA. Substantial reductions in upwind emissions of acidifying pollutants are likely needed to reduce the critical load exceedances in Vermont's acid-impaired lakes.

Public Participation

A comment period, July 13, 2012 through August 10, 2012, was established to allow the public to inspect and to comment on the final draft of the TMDL document. Notice of the comment period and availability of the document was provided on the Watershed Management Division website. At the end of the established comment period no comments were received.

Appendix A

SSWC Model Application:

2012 Update: Calculating critical loads of acidity and exceedances for acid-impaired lakes in Vermont using the Steady State Water Chemistry (SSWC) model.

2012 Update: Calculating critical loads of acidity and exceedances for acid-impaired lakes in Vermont using the Steady State Water Chemistry (SSWC) model.

by
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Abstract

In 2003-2004, a critical load model was applied to Vermont's 37 acid-impaired lakes to estimate the excess loading of sulfur and nitrogen these lakes receive from atmospheric deposition (Pembrook, 2003 and Pembrook, 2004). Critical loads of acidity were calculated using the Steady State Water Chemistry (SSWC) model (Henriksen and Posch 2001). Three ponds have been removed from the list due to increased alkalinity (Round Pond) and the loss of impoundment (Lye Brook (North) and Lye Brook (South). This report addresses the 2 acid-impaired lakes which were added to the 303(d) impaired waters list in 2010 and sampled in the spring of 2009 to provide current data for calculating critical load and excess load estimates. Estimates were based on springtime, open lake water chemistry and annual average deposition data. Both lakes exceeded their critical load when a 2.5 mg/L (50 ueq/L) acid neutralizing capacity limit was selected.

Background

The Vermont Department of Environmental Conservation (VT DEC) has been monitoring the chemistry of low ionic strength lakes in Vermont since the winter of 1980. In 1983, the United States Environmental Protection Agency (US EPA) Long-Term Monitoring (LTM) Project was initiated within the National Acid Precipitation Assessment Program (NAPAP) organizational framework. Since 1983, the VT DEC LTM (VLTM) Project has been conducted in cooperation with the US EPA. The cooperative LTM Project is managed by the US EPA's Office of Air and Radiation, Clean Markets Division in Washington, D.C. (OAR-CAMD) and consists of federal agencies, state agencies and universities. The VLTM currently samples 12 acid-sensitive lakes on a seasonal basis. Eleven of these lakes are considered impaired.

The acid rain workgroup of the Conference of the New England Governors and Eastern Canadian Premiers (NEG/ECP) initiated a critical load project in order to assess waterbody sensitivity in the region using the SSWC model (Dupont et al. 2002). VT DEC participated in the NEG/ECP project and chose to use the SSWC model to analyze its acid-impaired lakes because the model relates present day water chemistry to current deposition estimates. Further, the model allows the user to select a target acid neutralizing capacity (ANC), below which harmful effects occur to selected biota. The NEG/ECP approach was refined for Vermont using lake-specific sulfate loading and runoff estimates.

Introduction

Critical loads have been used widely in Europe and Canada to characterize regional and transboundary air pollution (Henriksen, Dillon and Aherne 2002; Henriksen and Posch 2001; Hindar and Henriksen 1998). VT DEC selected the SSWC model to define the critical loads of acidity for its 303(d) listed acid-impaired waterbodies because it links present day water chemistry data to acid loading estimates. This makes the model particularly useful in developing Total Maximum Daily Loads (TMDLs) for these impaired lakes. Lakes were considered acid-impaired if the gran alkalinity, or ANC, value was measured below 2.5 mg/L (50 ueq/L). While pH is the typical measurement of acidity, ANC was chosen as an indicator of acidification because toxicity in waterbodies is linked not only to pH, but also to the presence of inorganic aluminum (Hindar and Henriksen 1998). The toxicity of inorganic aluminum is offset by the presence of organic acids, present in low pH colored waters. ANC has been shown to be a better indicator of harmful biological effects due to the influence of CO_2 and organic acids on pH (Wilander 2001).

SSWC Model Concepts and Definitions

The Steady State Water Chemistry (SSWC) model calculates critical loads of acidity based on in-lake water chemistry. It also calculates exceedances of the critical load based on sulfate and nitrate contributions. Sulfate and nitrate are the major contributors to waterbody acidification in the northeast United States.

Two concepts important to understanding and applying the SSWC model are the critical load and the exceedance of the critical load. A critical load is defined as “a quantitative estimate of an exposure of one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (Nilsson and Grennfelt 1988). An exceedance of the critical load is the amount of excess acid above the critical load.

Henriksen and Posch (2001) state the usefulness of the SSWC model by saying that “critical loads can be directly compared to deposition estimates; which makes them usable and useful in integrated assessment models, linking emission abatement strategies to the capacity of ecosystems to withstand and buffer the effects of acid deposition.”

Study Area

Figure 1 presents the distribution of Vermont’s acid-impaired lakes. Most of Vermont’s acid-impaired lakes are concentrated in the southern half of the state where buffering capacity is minimal and proximity to pollution sources is greatest. Acid-impaired lakes tend to be scattered up the spine of the Green Mountains, typically located at high elevation, in small watersheds, and underlain by poorly buffered bedrock and soils. The remaining lakes are located in the northeast portion of the state which is underlain with granitic plutons. **Table 1** provides a summary of physical characteristics for the 2 lakes addressed in this document. All physical information is from the VT DEC Lakes and Pond Inventory database unless otherwise noted. Henriksen and Posch (2001) state that “the SSWC-model is particularly applicable to dilute oligotrophic water located on granitic and gnessic bedrock and with thin overburden.” The lakes located in the northeast corner of Vermont fit this description. This model was used successfully by Henriksen et al (2002) in Ontario and by Dupont et al (2002) for the eastern Canadian provinces and the New England states, including Vermont. As a result, we have assumed that the SSWC model adequately represents the lakes located along the spine of the Green Mountains which are underlain by bedrock with low buffering capacity.

Figure 1. Map of Vermont acid-impaired lakes. The two lakes being addressed in this report are boxed in the figure below. May 2012.

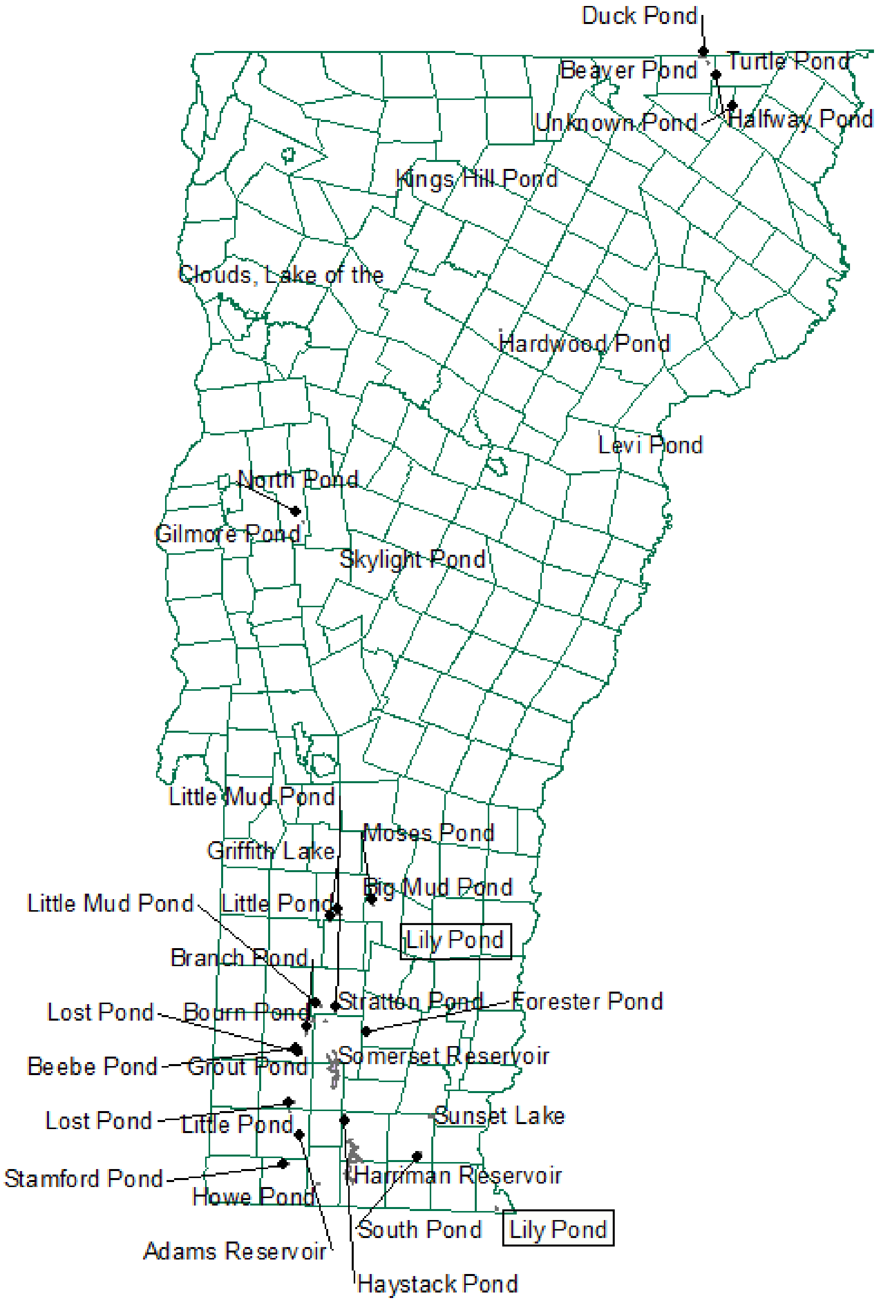

Table 1. Physical characteristics for 2 of Vermont's 303(d) list of acid-impaired lakes.

Lake	Town	Latitude	Longitude	Drainage Area (ha)	Surface Area (ha)	Maximum Depth (m)	Elevation (m)
Lily	Londonderry	43.2345129	72.7506406	113.73	10.1	3.3	454
Lily	Vernon	42.7398563	72.5050596	350.51	15.2	3.8	112

Methods

Calculating Critical Loads

The SSWC model is based on the concept that excess base cations in a catchment should be equal to or greater than the acid anion inputs. This balance would maintain a lake's ANC above a pre-selected level (Reynolds and Norris 2001). The equation for calculating critical loads has been described in many journal articles (Henriksen et al. 2002; Henriksen and Posch 2001; Hindar and Henriksen 1998). The SSWC model estimates critical loads based on the following variables: in-lake water chemistry data, ANC limit, and annual surface runoff.

Equation 1 presents the primary critical load calculation:

$$Cl(Ac) = ([BC^*]_o - [ANC]_{limit}) \times Q \quad (1)$$

where:

$Cl(Ac)$ = critical load of acidity (S+N).
$[BC^*]_o$ = pre-acidification non-marine flux of base cations from the lake.
$[ANC]_{limit}$ = ANC criteria. VT DEC selected a 2.5 mg/L (50 ueq/L) threshold.
Q = annual surface runoff (m/yr).

In-lake water chemistry: BC, USO_4, UNO_3

The SSWC model uses in-lake water chemistry concentrations for the following inputs: sum of the base cations (BC), in-lake sulfate concentration (USO_4), and in-lake nitrate concentrations (UNO_3). Water chemistry concentrations were provided by VLTM (See **Appendix A**, **Tables 1** and **2**). Critical load calculations for these lakes were completed using epilimnion data collected above the deepest portion of the lakes. In order to reflect the potential episodic acidification in lakes, a springtime index period was used. This captures the minimum annual values for ANC, pH, and cations and thus provides a more protective approach for calculating critical loads (Wilander 2001).

Sea-salt correction

The SSWC model applies a sea salt correction to water chemistry concentrations. This correction was applied to Quebec lakes and was assumed appropriate for Vermont lakes because they are within 200 km of the Atlantic Ocean, close enough to be affected by marine salt (Baker et al. 1990). The following calculations correct for sea salt and convert concentrations from mg/L to ueq/L for purposes of the model. An asterix (*) indicates the value has been corrected for sea salt (i.e. represents non-marine inputs only).

USO_4^* = $(SO_4 - (Cl \times 0.14) \times 20.82)$
UCa^* = $(Ca - (Cl \times 0.0213) \times 49.9)$
UMg^* = $(Mg - (Cl \times 0.0669) \times 82.26)$
UNa^* = $(Na - (Cl \times 0.557) \times 43.5)$
UK^* = $(K - (Cl \times 0.0206) \times 25.57)$
UNO_3 = $(NO_3\text{-}N \times 71.4)$
UCl = $(Cl \times 28.21)$

Pre-acidification non-marine flux of base cations: $[BC^*]_O$

The pre-acidification non-marine flux of base cations from a catchment to a lake is difficult to approximate. Instead, water quality data is used in the SSWC model to represent pre-acidification non-marine flux. **Equation 2** presents the calculation of the pre-acidification non-marine flux of base cations where the subscripts o and t refer to original (background) and present concentrations:

(2) $BC^*_o = BC - \text{F-factor} \times (USO^*_{4\,t} - USO^*_{4\,o})$

where:

BC^*_o = sum of the present day non-marine base cations ($UCa^* + UMg^* + UNa^* + UK^*$)

F-factor = annual base cation flux accounting for high and low runoff in a catchment = $\sin\{[(\pi/2)*Q*BC]/S\}$
S = base cation flux at which F-factor =1. S = 400 meq/m^2/yr was considered appropriate for Ontario lakes (Henriksen et al. 2002).

$USO^*_{4\,t}$ = current non-marine, in-lake sulfate concentration

$USO^*_{4\,o}$ = pre-acidification non-marine sulfate concentration. Several estimates are available for non-anthropogenic sulfate concentration, mostly from the Scandinavian countries (Norway, Finland and Sweden). These concentrations consist of an atmospheric and geologic contribution in relation to the base cation concentration. Henriksen et al. (2002) estimates for Ontario lakes were used for the NEG/ECP project and were assumed to be adequate for Vermont lakes. While other estimates do vary greatly, they have not been shown to significantly affect the calculation of critical loads or exceedances (Henriksen and Posch 2001).

ANC Limit: $[\mathrm{ANC}]_{\mathrm{limit}}$

$[\mathrm{ANC}]_{\mathrm{limit}}$ is the lowest ANC concentration that does not damage selected biota (Henriksen and Posch 2001). The model allows for an $[\mathrm{ANC}]_{\mathrm{limit}}$ to be pre-selected depending on the geographic area. Vermont chose an $[\mathrm{ANC}]_{\mathrm{limit}}$ of 2.5 mg/L (50 ueq/L) in order to protect the most sensitive aquatic biota. Other studies in North America have chosen ANC values in the range of 40-50 ueq/L (Hindar and Henriksen 1998; Dupont, J. et al. 2002). "At an ANC = 50 ueq/L, there was no recorded damage to invertebrates and only slight or no declines in fish populations" (Lien at al. 1996). While some lakes have pre-acidification ANC values lower than 2.5 mg/L, this criterion protects communities with slightly higher ANC values that are the most susceptible to biological damage.

Annual Surface Runoff estimates: Q

Annual estimates of surface runoff (Q) were extrapolated from William Krug et al. (1990). These values represent the mean annual runoff for the period of 1951-1980. Runoff estimates for the 2 acid-impaired lakes addressed here are provided in **Appendix A, Table 2**.

Calculating Excess Loads

Excess loads of acidity are calculated by subtracting the critical load from the sum of current pollutant loads. Calculation of the current pollutant load includes the sum of current sulfate deposition loading and in-lake nitrate concentrations.

Equation 3 presents the Critical Load Exceedance [Ex(Ac)] calculation:

(3) $\mathrm{Ex(Ac)} = \mathrm{SO_4{}^*}_{dep} + \mathrm{N}_{leach} - \mathrm{CL(Ac)}$

where:

$\mathrm{SO_4{}^*}_{dep}$ = current non-marine sulfate deposition
N_{leach} = current nitrogen leaching flux from the catchment.
= non-marine nitrate concentration ($\mathrm{UNO_3{}^*}$) multiplied by the runoff (Q)
CL(Ac) = critical load of acidity with fixed ANC_{limit}

Current non-marine sulfur deposition: $[\mathrm{SO_4{}^*}_{dep}]$

The Ecosystem Research Group Ltd. (ERG) applied the High-Resolution Deposition Model (HDRM) to estimate total (wet, dry and cloud) sulfur deposition for 34 acid-impaired Vermont lakes (Miller, 2002). The ERG data represents 1996-1999 average deposition data for S+N. Total sulfur deposition data was used to calculate current non-marine sulfate deposition. Sulfur and sulfate deposition estimates for the 2 lakes addressed here are provided in **Appendix A, Table 2**.

Lily Pond in Londonderry and Lily Pond in Vernon lacked specific sulfur loading estimates. Data from Forester Pond in Jamaica was used as a surrogate for Lily in

Londonderry and Sunset Lake in Marlboro was used as a surrogate for Lily Pond in Vernon due to their relative proximity and similarity in elevation; Forester in within 19.2 linear kilometers and 78 meters higher in elevation and Sunset is 306 meters higher and 24.1 km away.

Current nitrate leaching flux: N_{leach}

Unlike sulfur, which is assumed to be a mobile anion, nitrogen is retained in catchments through various biological and chemical processes (forest uptake, immobilization, denitrification and in-lake retention) (Hindar and Henriksen 1998). In lieu of modeling nitrogen processes for each catchment, in-lake nitrate levels are assumed equal to nitrate concentration in runoff (Reuss and Johnson 1986). Nitrate concentrations are converted to a flux by multiplying the in-lake nitrate concentration (UNO_3^*) by the runoff value (Q) (Reynolds and Norris 2001; Curtis et al. 2001).

Results and Discussion

Critical Load and Exceedances

Critical load and exceedance values were calculated using 2009 lake monitoring data and are presented in **Table 2**. Both lakes exceeded their critical load which is reflected in their having gran alkalinity values below the 2.5 mg/L ANC threshold.

Table 2. Critical load and exceedance values

Lake name	Date	Critical Load meq/m^2/yr	Excess loads meq/m^2/yr
Lily (Londonderry)	04/23/2009	31.24	27.85
Lily (Vernon)	04/22/2009	36.11	24.04

Critical load values range from 31.24 meq/m^2/yr to 36.11 meq/m^2/yr. The average critical load is 33.68 meq/m^2/yr. Excess loads range from 24.04 meq/m^2/yr to 27.85meq/m^2/yr. **Appendix B** provides all Vermont acid-impaired lakes with their critical loads and exceedance values.

Interpreting Critical Load Values

Positive Critical Load Values

Positive critical loads indicate that the waterbody has some tolerance for acid inputs. The greater the critical load value, the greater the tolerance to acidification. "Very high values indicate acceptable water quality for sensitive organisms regardless of deposition scenarios, whereas low values indicate sensitivity to acidification" (Hindar and Henriksen 1998).

Negative Critical Load Values

Negative critical loads occur "when the selected ANC_{limit} is higher than the calculated original base-cation concentration. Such results implied that we demanded better conditions in the lakes than nature provides: the original conditions were such that the original ANC-concentration was lower than that required for protection of biota. Thus for such lakes the critical load will be zero" (Henriksen et al 1992). As a result, under prior acid lake TMDLs, Vermont lakes with negative critical load values were adjusted to zero in order to calculate exceedances. Both lakes addressed in this document had positive critical load values.

Interpreting Excess Load values

Positive Excess Load Values

Positive excess loads indicate that a lake's critical load of acidity has been exceeded by acid inputs. These lakes have been impaired by the acid inputs and the lack of buffering capacity in the catchment. The ANC on these lakes is too low to prevent damage to the most sensitive biota. Both lakes exceeded their critical loads, resulting in positive excess loads.

Negative Excess Loads Values

Negative excess loads indicate that the critical load of acidity had not been exceeded by the acid inputs. The ANC on these lakes exceeds the amount necessary to protect sensitive biota. Neither of lakes addressed in this updated application of the SSWC yielded negative excess loads.

Sensitivity of the Model

The SSWC model is highly sensitive to two parameters: the ANC_{limit} and the F-factor. The ANC_{limit} was established based on a study conducted by Lien et al. (1996) which relates fish and macroinvertebrate tolerance to ANC limits. VT DEC chose to use the most protective ANC limit of 50 ueq/L (2.5 mg/L) as outlined in the study. A less protective ANC_{limit} would increase the critical load values and reduce the excess load values.

The F-factor accounts for the rate of base cation leaching from a catchment. This study and others (Henriksen et al 2002; Hindar and Henriksen 1998) used an F-factor based on a Norwegian estimate which takes into account high and low runoff from a catchment. This estimate was considered appropriate for Ontario lakes (Henrikesen et al 2002), for the NEG/ECP project on critical loads (Dupont et al 2002) and was assumed adequate for Vermont lakes.

Achieving the Critical Load

Reducing sulfur and nitrogen deposition will undoubtedly reduce the excess loads of acidity to Vermont lakes. An Ontario study has shown a significant relationship between recent reductions in sulfur loading from the U.S. and Canada and declines in the number of lakes with excess loads from the 1980 to the 1990s (Henriksen et al 2002).

The New England Governors and Eastern Canadian Premier's workgroup on acid rain recommended a target wet sulfate deposition rate of 20 kg/ha/yr (41.64 meq/m^2/yr) as an interim goal to protect moderately sensitive surface waters in 1985. The concept of a target load was set aside in the 1990s by the NEG/ECP because acidification continued to occur with significant deposition reductions. The critical load concept was embraced by NEG/ECP because it protects the most sensitive of organisms and can be calculated for individual lakes.

Acid-impaired lakes fall into two categories: organically stained [high in dissolved organic compounds (DOC)] and clear water mineral lakes (low DOC). Organic acids, present in the high DOC lakes, offset the toxic effects of aluminum. The biota on these lakes may be capable of recovering before eliminating their excess loads of acidity. With a reduction in acid loading, clear water, low DOC lakes are also expected to improve biologically, even if the lakes continue to experience excess loads. Organically stained acid-impaired lakes may have had a pre-acidification ANC concentration of less than 50 ueq/L and may respond more quickly to improvements than clear water lakes. It is important to note that the SSWC model does not consider organic acids in the calculation.

In 1998, the proposed NEG/ECP Acid Rain Control Plan called for additional national emissions reductions of at least 50% SO_2 and 25% NO_x below current levels. Between 1985-1996, sulfur deposition declined by 29%. This has resulted in no further acidification of lakes in Vermont. However, the anticipated chemical recovery of ANC and pH has been delayed due to reductions in base cation concentrations. These reductions have been attributed to a depletion of base cations in the watershed soils (Stoddard et al. 1999). In addition, while sulfate deposition has shown a marked decline in the northeastern United States, there have been no detectable trends in nitrate deposition. Nitrate is a stronger acid than sulfate and is now nearly equivalent to sulfate in deposition. Further reductions in sulfur and nitrogen loading to these catchments will be necessary to increase pH and alkalinity.

The SSWC model is based on steady state conditions and it does not allow evaluation of when this state will be reached. It cannot model climate-based changes such as weathering rates, soil base cation depletion, increased mineralization, and increased runoff (Hindar and Henriksen 1998) which are in flux. As a result, while we feel confident that reductions in sulfur and nitrogen loading will eventually result in chemical recovery, we cannot predict when.

Conclusions

The Steady State Water Chemistry Model has been used to calculate critical loads and their exceedances for all 39 acid-impaired lakes in Vermont; thirty lakes were addressed in 2003 (Pembrook, 2003), 7 more in 2004 (Pembrook, 2004) and two included with this update. Several lakes have been removed from the impaired waters list including Round Pond in Holland due to reduced acidity, Lye Brook Meadows (North) and Lye Brook Meadows (South) due to a beaver dam breaking, and North Pond in Chittenden which was mistakenly added to the original 303(d) list. Both Lily in Londonderry and Lily in Vernon currently exceed their critical load. Thirty six lakes are now considered acid impaired.

It is important to acknowledge the limitations of the critical load calculations. That is, an exceedance to a lake's critical load serves as only an indicator of the potential for harmful effects to aquatic biota. By reducing the acid loading to these lakes and diminishing the likelihood of episodic acidification, a biological community albeit simplified is expected to return to these lakes.

Future work

Since 2003, VT DEC has chemically monitored all acid-impaired lakes on a five-year rotational basis. Results of these monitoring efforts which track the chemical status of these waterbodies are available from the State of Vermont's Watershed Management Division.

Acknowledgements

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Appendix A.

Table 1. Critical load and excess loads for 2 of Vermont acid-impaired lakes.

Lake name	Date	PH unit	ALK (mg/L)	Q m/yr	UCl ueq/L	UCa* ueq/L	UMg* ueq/L	UNa* ueq/L	UK* ueq/L	UNO_3* ueq/L	USO_4* ueq/L	BC ueq/L	F	USO_4o ueq/L	BCo ueq/L	CL(Ac) meq/m^2/yr	Excess Loads meq/m^2/yr
Lily (Londonderry)	2009/04/23	6.24	2.42	0.6096	23.41	54.01	26.69	16.43	10.30	0	56.50	107.43	0.25	32.19	101.25	31.24	27.85
Lily (Vernon)	2009/04/22	6.12	1.84	0.5080	19.18	79.12	28.34	28.33	3.73	0	104.41	139.52	0.27	37.32	121.09	36.11	24.04

Table 2. Sulfate deposition and runoff estimates.

Lake	runoff estimate[1] (in/yr)	runoff estimate[2] (m/yr)	sulfur deposition average[3] (kg/ha/yr)	sulfate deposition average [4] (meq/m^2/yr)
Lily (Londonderry)	24	0.6096	9.46	59.09[5]
Lily (Vernon)	20	0.5080	9.63	60.15[5]

[1] Runoff estimates based on maps produced by Krug et al. (1990).

[2] Runoff estimates converted from in/yr to m/yr.

[3] Sulfur estimates provided by ERG (2002).

[4] Sulfur estimates converted from kg/ha/yr to meq/m^2/yr of sulfate.

[5] A specific sulfur loading deposition was not available. Data from Forester and Sunset Pond were used as surrogates for Lily in Londonderry and Lily in Vernon, respectively.

Appendix B.

Table 1. Critical Loads and excess loads for Vermont's acid impaired lakes

	Lake name	Date(s)	Average CL(Ac) meq/m^2/yr	Average Excess loads meq/m^2/yr
1.	Adams Reservoir	2003	38.01	37.21
2.	Beebe (Sunderland)	05/07/2004	42.91	38.97
3.	Big Mud	1998-2002	24.65	47.05
4.	Bourn	1998-2002	18.39	50.83
5.	Branch	1998-2002	12.28	62.58
6.	Duck	2001	20.68	22.82
7.	Forester	1998-2002	24.50	35.30
8.	Gilmore	2001	51.18	0.87
9.	Griffith	2001	39.12	29.91
10.	Grout	1998-2002	42.96	25.40
11.	Halfway	2001	38.34	10.29
12.	Hardwood	1998-2002	49.39	2.98
13.	Harriman	05/27/2004	74.70	7.03
14.	Haystack	1998-2002	-3.72	89.38
15.	Howe	1998-2002	41.51	25.71
16.	Kings Hill	2001	26.18	22.91
17.	Lake-of-the-Clouds	1999	-0.20	135.35
18.	Levi	05/10/2004	24.47	28.13
19.	Lily (Londonderry)	04/23/2009	31.24	27.85
20.	Lily (Vernon)	04/22/2009	36.11	24.04
21.	Little (Winhall)	05/27/2004	27.71	45.66
22.	Little (Woodford)	1998-2002	18.90	66.88
23.	Little Mud (Mt. Tabor)	2002	32.70	50.21
24.	Little Mud (Winhall)	05/11/2004	38.29	24.01
25.	Long Hole	2001	56.73	23.24
26.	Lost (Glastenbury)	05/21/2004	23.06	83.47
27.	Moses	2001	11.29	50.88
28.	North (Bristol)	2001	2.51	50.99
29.	Skylight	05/19/2004	55.92	55.26
30.	Somerset	1996, 2002	37.42	36.10
31.	South	1998	49.85	11.30
32.	Stamford	1998-2002	39.09	44.80
33.	Stratton	1995,1998, 2001	38.49	30.37
34.	Sunset	1998-2002	26.25	36.06
35.	Turtle	1996	26.63	23.15
36.	Unknown	1995, 2001	49.52	8.64

Note: Three ponds which were originally on the 303(d) list have been removed: Round Pond because its alkalinity improved above the 2.5 mg/l criteria; and Lye Brook (North) and Lye Brook (South) because they no longer were impounded by beaver dams.

Appendix B

HRDM Results and Methodology

Table 1. Results of HRDM. Nitrogen and sulfur deposition data for 34 of Vermont's acid impaired lakes.

VT TMDL LAKE WATERSHEDS			Watershed	precip	precip	N	N	N	N	N	N	S	S	S	S	S	S
			Area	avg	total	Average	Total	Dry	Dry	Cloud	Cloud	Average	Total	Dry	Dry	Cloud	Cloud
WATERBODY	NAME	#	Albers(ha)	cm/y	m3/y	kg/ha/y	kg/y	kg/y	%	kg/y	%	kg/ha/y	kg/y	kg/y	%	kg/y	%
VT17-02L06	DUCK (HOLLND)	1	47.52	117.6	7486.4	11.03	524	276	52.8%	0	0.0%	6.93	330	86	26.2%	0	0.0%
VT17-02L02	TURTLE	2	354.33	126.4	60032.6	11.59	4107	2107	51.3%	39	1.0%	7.55	2674	675	25.2%	37	1.4%
VT17-02L03	ROUND POND (HOLLND)	3	16.92	118.4	2684.3	9.39	159	70	44.0%	0	0.1%	6.89	117	29	24.9%	0	0.2%
VT17-03L04	HALFWAY POND	4	89.01	129.7	15471.7	11.32	1007	492	48.8%	12	1.2%	7.75	690	171	24.8%	12	1.7%
VT16-11L01	UNKNOWN (AVYGOR)	5	119.79	134.3	21556.4	12.73	1525	678	44.4%	152	9.9%	9.12	1092	248	22.7%	134	12.3%
VT06-06L01	KINGS HILL POND	6	58.86	127.5	10054.7	11.88	699	369	52.7%	4	0.6%	7.82	460	124	26.8%	4	0.8%
VT07-13L02	LAKE OF THE CLOUDS	7	0.45	140.1	84.5	29.05	13	4	32.2%	6	47.2%	21.06	9	1	14.5%	5	55.6%
VT08-13L01	HARDWOOD POND	8	74.7	124.9	12501.8	10.83	809	393	48.6%	9	1.1%	7.89	590	165	28.0%	8	1.4%
VT14-07L01	LEVI POND	9	61.56	118.8	9797.9	11.73	722	391	54.1%	8	1.1%	7.86	484	147	30.3%	7	1.5%
VT03-11L01	NORTH POND (BRISTL)	10	13.5	123.1	2226.4	12.42	168	89	52.8%	5	3.1%	8.53	115	34	29.6%	5	4.3%
VT03-11L02	GILMORE POND	11	128.61	123.2	21238.1	12.81	1647	901	54.7%	42	2.5%	8.3	1067	299	28.1%	42	3.9%
VT09-07L01	SKYLIGHT	12	7.02	132.5	1246.3	23.8	167	62	37.4%	64	38.2%	17.25	121	24	19.5%	55	45.2%
VT11-18L06	MOSES POND	13	42.3	130.6	7403.6	14.84	628	347	55.3%	32	5.2%	9.91	419	130	30.9%	31	7.5%
VT03-18L03	BIG MUD POND	14	107.91	134.6	19469.4	15.74	1698	873	51.4%	179	10.5%	11.11	1199	351	29.3%	167	13.9%
VT03-18L02	GRIFFITH LAKE	15	42.03	134.2	7560.7	15.28	642	317	49.3%	74	11.5%	11.01	463	127	27.5%	71	15.3%
VT11-15L02	LITTLE POND (WINHLL)	16	53.82	128	9234.8	14.62	787	429	54.5%	45	5.7%	9.93	534	165	30.8%	45	8.4%
VT11-16L01	STRATTON POND	17	106.92	129.6	18573.1	14.49	1549	815	52.6%	107	6.9%	10.17	1088	328	30.2%	106	9.7%
VT01-05L01	BOURN	18	113.31	129.4	19649.9	14.43	1635	842	51.5%	130	8.0%	10.43	1181	366	31.0%	123	10.4%
VT11-15L01	FORESTER POND	19	83.88	125.8	14141.5	14.89	1249	744	59.6%	24	1.9%	9.46	794	274	34.5%	23	2.9%
VT01-06L01	BRANCH POND	20	127.53	130.4	22284.9	15.35	1958	997	50.9%	210	10.7%	10.94	1396	413	29.6%	197	14.1%
VT01-06L02	BEEBE POND (SUNDLD)	21	65.16	129.2	11278.4	15.15	987	535	54.2%	71	7.2%	10.38	677	214	31.6%	66	9.8%
VT12-03L01	GROUT POND	22	166.32	129.1	28769.2	14.25	2369	1287	54.3%	110	4.6%	10.05	1671	557	33.3%	103	6.2%
VT12-04L02	LOST (GLASBY)	23	26.19	132.4	4646.3	20.36	533	257	48.1%	120	22.6%	14.1	369	87	23.6%	118	31.8%
VT12-04L04	LITTLE POND (WOODFD)	24	130.59	130.7	22876.8	16.56	2163	1127	52.1%	263	12.2%	11.28	1473	395	26.8%	268	18.2%
VT11-08L01	SUNSET LAKE	25	205.11	123.9	34053.1	14.22	2917	1724	59.1%	28	0.9%	9.63	1975	753	38.1%	25	1.3%
VT12-04L01	ADAMS RESERVOIR	26	332.46	130.7	58223	15.55	5170	2909	56.3%	295	5.7%	10.23	3400	1058	31.1%	290	8.5%
VT12-07L01	SOUTH POND (MARLBR)	27	138.33	124.6	23099.9	14.27	1973	1154	58.5%	30	1.5%	9.75	1349	507	37.6%	27	2.0%
VT12-02L03	STAMFORD POND	28	103.14	129.7	17927.4	15.08	1556	837	53.8%	111	7.2%	10.24	1056	311	29.5%	110	10.4%
VT12-02L02	HOWE POND	29	666.45	127.8	114090	15.8	10528	6195	58.8%	456	4.3%	10.15	6766	2273	33.6%	451	6.7%
VT12-05L01	HAYSTACK	30	53.46	136.2	9760.3	16.26	869	393	45.2%	151	17.4%	12.48	667	187	28.0%	137	20.5%
VT12-01L01	HARRIMAN (WHITHM)	31	47285.19	129.6	8210149.3	15.5	732710	415099	56.7%	40001	5.5%	10.24	484306	157192	32.5%	38350	7.9%
VT12-03L03	SOMERSET	32	6602.04	130	1150192.4	15.35	101351	55237	54.5%	7296	7.2%	10.45	69010	21595	31.3%	6971	10.1%
VT03-18L06	LONG HOLE	33	736.83	135.6	133848.1	18.04	13293	6381	48.0%	2471	18.6%	12.76	9405	2385	25.4%	2327	24.7%
VT03-18L07	LITTLE MUD (MT TABOR)	34	133.74	134.5	24108.6	15.61	2088	1076	51.5%	211	10.1%	11.01	1472	432	29.3%	197	13.4%

Atmospheric Deposition to Complex Landscapes: HRDM - A Strategy for Coupling Deposition Models to a High-Resolution GIS

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Summary

A spatially distributed modeling environment was developed that couples detailed physical models of atmosphere-surface heat, mass and momentum transfer processes to a high-resolution geographic information system and regional climatology for the northeastern United States (ME, NH, VT, MA, RI, NY, NJ, PA). The high-resolution distributed model (HRDM) was developed for a series of applications which include: providing high-resolution estimates of total atmospheric deposition to lake-watershed ecosystems, regional studies of pollutant accumulation in soils, and regional studies of air pollution effects on ecosystem health, productivity and carbon sequestration. The distributed model can produce estimates of atmospheric deposition at seasonal and annual time steps with 30-meter ground resolution subject to the constraints of positional and characterization accuracy of underlying land surface and atmospheric descriptive data. The modeling environment is designed to be flexible enough to accommodate alternative approaches to estimating meteorological and atmospheric chemistry fields.

Project Rational and Objectives

HRDM provides high-resolution (30x30 meter ground area) estimates of total atmospheric deposition (wet + dry + cloud water) in complex terrain.

High spatial resolution atmospheric deposition estimates are useful for:
- Estimates of total atmospheric loading to watersheds
- Assessment of land-cover effects on regional deposition rates
- Identification of sensitive landscape segments and ecoregions
- Ranking of landscape regions with respect to historic and current deposition loads
- Characterization of deposition at locations remote from NADP or CASTNet stations

HRDM improves upon existing approaches for regionally consistent estimates of local atmospheric deposition rates. Most existing spatial models of deposition were developed to operate at much coarser spatial and temporal scales than would be desired for addressing many important questions in ecosystem science.

Existing estimates of atmospheric deposition fields for the northeastern US have one or more of the following limitations for application to local and regional ecological problems:
- Incomplete estimates of total atmospheric deposition (models may be wet-only or wet+dry, but all lack estimates of cloud water deposition).
- Limited temporal resolution (a few months to a few years represented)
- Low spatial resolution (80km to 1km)
- Omission of terrain and land cover effects on deposition rate (direct spatial interpolations of network observations)
- Weak interpolations of dry-deposition fields from a sparse observation network
- Oversimplification of terrain effects (due to terrain averaging at low spatial resolutions)
- Oversimplification of receptor surface effects (surface type averaging at low resolutions)
- Oversimplification of receptor surface/terrain interactions

Applications of the high-resolution total deposition model include:
- Estimation of current and historical total nitrogen and sulfur deposition to watersheds in support of a study of terrestrial ecosystem influences on N and P supply to aquatic ecosystems in the Northeast (USEPA - http://es.epa.gov/ncerqa_abstracts/grants/98/ecological/stemberger.html)
- Comparison of historical total nitrogen and sulfur deposition to total ecosystem pools of N and S at a series of forest sites throughout the Northeast. (USDA)
- Estimation of current and historical total nitrogen and sulfur deposition to New England in support of the Forest Mapping Initiative Program of the NEG/ECP Acid Rain Action Plan (NESCAUM, USDA-FS)
- Characterization of N and S deposition for Vermont Acid Impaired Lakes (VTDEC).
- Characterization of wet and dry mercury deposition to the watersheds of the VT/NH REMAP Lakes (VTDEC)

Overview of the Spatially Distributed Modeling Environment

The complexity in patterns of rainfall, vegetation (dry and cloud deposition receptor surface) and deposition at sub-kilometer scales in the mountainous northeastern US states (Figure 1) requires a high spatial-resolution approach to atmospheric deposition estimates. Miller (2000) developed a spatially-distributed modeling environment which couples detailed physical models of atmosphere-land surface heat, mass and momentum transfer processes (Miller et al. 1993a,b) to a high-resolution geographic information system and regional climatology for the northeastern US. The model provides estimates of wet, dry and cloud water deposition at 30-meter resolution. Key features of the HRDM include:

1. Wet, dry and cloud-water deposition processes are represented – providing a true "total deposition" regional model for mountainous landscapes.
2. Statistical modeling of regional spatial gradients is combined with surface interpolation of residual fields to obtain 10-km grid resolution estimates of atmospheric chemistry with a high degree of fidelity to network observations.
3. Wet deposition is calculated as a combination of the 10-km resolved precipitation chemistry, 1-km resolved regional precipitation field, and 30-m (90-m in older versions) resolved terrain corrected precipitation amount.
4. Either point observational records or gridded meteorological model output can be spatially interpolated to 30-m resolution, corrected for local topographic and landscape positional effects and monthly regional climatology to drive the dry and cloud water deposition models.
5. The receptor surface for dry and cloud water deposition is represented at 30-m resolution. The biophysical characteristics of the receptor surface (leaf area, aerodynamic properties, stomatal response to light, temperature and humidity) are estimated in terms of the proportion of leaf area expected to be attributable to specific plant species. Species proportions are estimated by a forest species distribution submodel with guidance from the USGS/EPA NLCD data set.
6. Deposition estimates are generated on a seasonal basis using sub-season time steps including representations of diurnal fluctuations employed in the dry deposition process model.
7. Depositing species represented in the model include: aqueous H^+, K^+, Na^+, NH_4^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, NO_3^-, Cl^-, $Hg_{(total)}$; dry particle phase H^+, K^+, Na^+, NH_4^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, NO_3, Cl^-, $Hg_{(total)}$; and vapor-phase HNO_3, NO_2, SO_2, O_3, $Hg_{(0)}$, RGM.

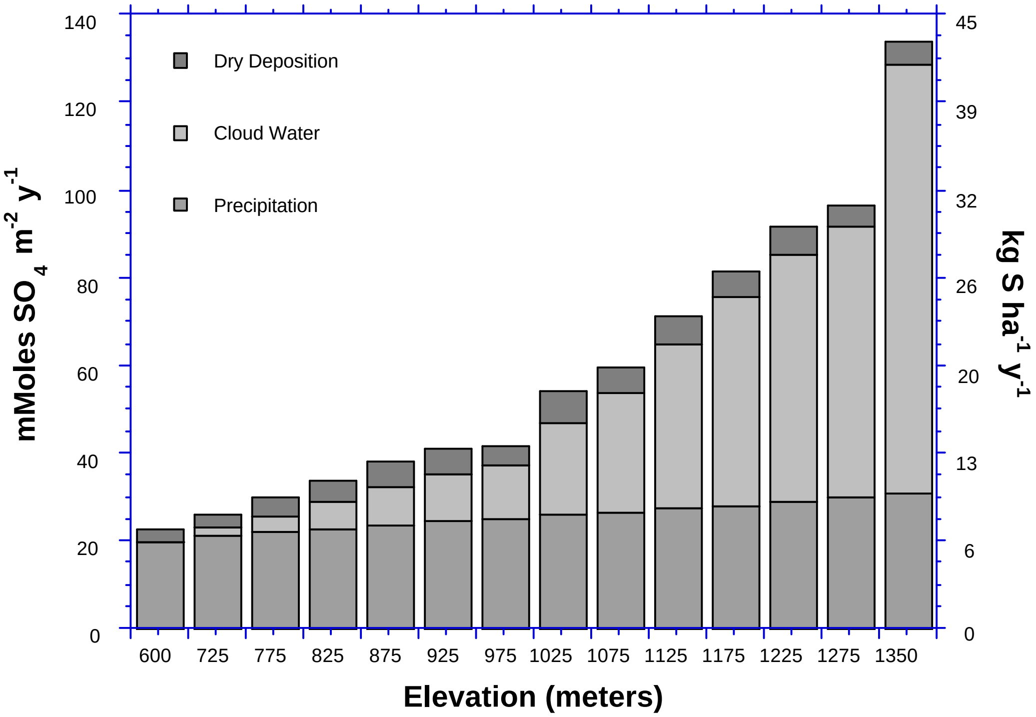

Figure 1. Variation in wet, dry, cloud, and total sulfur deposition over ~2km ground distance as a function of elevation on Whiteface Mt., NY, 1986-1989 (from Miller et al. 1993).

The relationships between the primary model components and data layers in the modeling environment are shown in Figure 2 and described briefly below.

Spatial Data Layers

Digital Elevation Model – USGS 3 arcsec (nominal resolution of 60x90m at 45^o latitude) – exisiting data sets produced by the HRDM are based on this DEM. All new data sets being generated with the HRDM are based on the USGS NED 30-m ground resolution DEM.

General Land Cover – USGS/EPA NLCD 30-m ground resolution, 23 general land-cover classes derived from LANDSAT TM+ (1992/1993)

Regional Climatology – regional temperature and precipitation fields interpolated from climate data at 619(ppt), 323(T) stations from the NOAA cooperative observation network

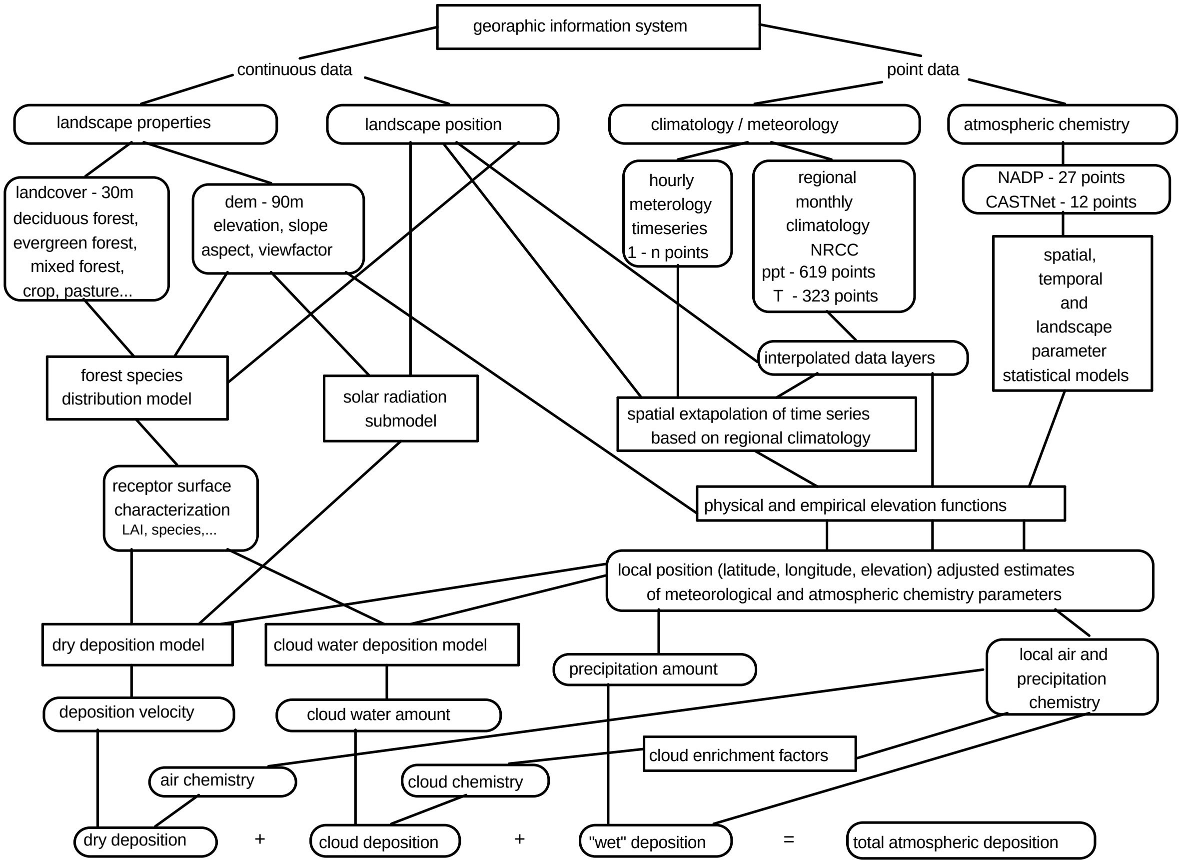

Figure 2. Relationships between model components and data layers in the high-resolution distributed modeling environment (HRDM).

Time Series

Regional Climatology is monthly, Meteorology (temperature, RH, wind speed, percent of possible solar radiation, cloud frequency) is hourly from multiple point records obtained as near as possible to the region of interest, extrapolated on the basis of terrain functions (for example see Miller et al. 1993b) and regional climatology fields. The model can also be driven with meteorology time series in the form of gridded output (any spatial resolution) from atmospheric models.

Precipitation Chemistry – monthly or seasonal – statistical models based on NADP observations at 27 sites are used to provide localized, terrain-corrected estimates (Miller, 2000).

Air Chemistry – monthly or seasonal – statistical models based on CASTNet observations (direct interpolation) or coupled CASTNet-NADP observations (scavenging ratio approach, Miller, 2000). Precipitation and Air Chemistry data can also be provided to the model in the form of gridded output from a regional transport model such as RADM (Chang et al. 1987)

Atmosphere-Surface Transfer Models

Dry Deposition Velocities for aerosol particles and gasses – big leaf model designed for complex terrain (Miller et al. 1993a,b). This model includes the appropriate physics to simulate deposition in a complex landscape. A big-leaf model is preferred over a multi-layer model for this application because of the limited information available to properly characterize the receptor surface at each 30-m pixel.

Cloud Water Deposition – due to both severe computational requirements and limitations of information on canopy structure, a multi-layer canopy model (Miller et al. 1993a,b) was parameterized with a representative canopy for the major surface types expected to receive cloud water deposition. Multiple sensitivity analyses were conducted with the multi-layer model in order characterized model response to a large set of possible canopy by meteorological condition interactions. We then statistically apportioned the multi-layer model response to key environmental parameters that can readily be obtained for each 30-m pixel.

“Wet” (rain and snow) Deposition – a statistical model of the effect of elevation on precipitation rate was derived using data from 619 observation stations for each season. Precipitation rate at each station was then corrected to sea level and regional precipitation fields were interpolated. Precipitation at each point in the model was then estimated from the regional sea level precipitation field and the statistical model of elevation effect on precipitation rate.

Submodels

Several submodels provide location-specific input to the atmosphere-landsurface transfer models.

Solar Radiation – simulates the effects of terrain on direct and diffuse solar radiation. An option is available to include local horizon blockage of direct beam radiation which is a significant factor in mountainous terrain.

Forest Species Distribution – estimates detailed biological character of receptor surface (tree species, LAI) as a function of landscape position using the NLCD as guidance on general surface type and data from the Eastwide FIA to characterize the probability of occurrence of different forest types at a given landscape position (for example see Iverson and Prasad 1998).

Meteorology – when gridded meteorological data are not used, this submodel is used to extrapolate observed point-location records of meteorological time series to the full model domain. Extrapolation methods include both empirical and physically-based representations of the effect of landscape position on monthly climatology (see Miller et al. 1993a, Miller and Friedland 1999).

Example Model Output

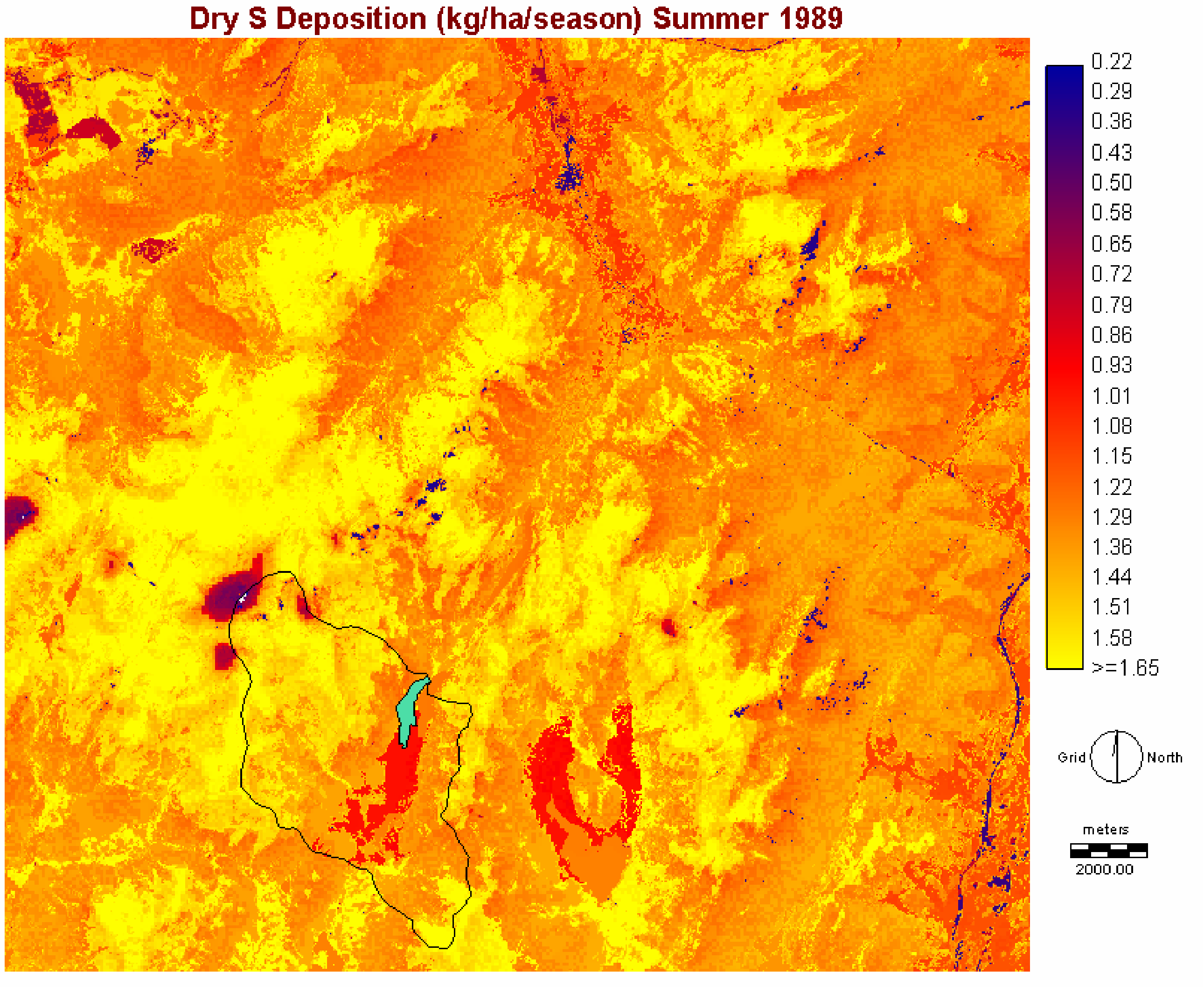

Figure 3. High-Resolution Deposition Model (HDRM) estimated summer dry sulfur deposition (SO_2 plus particle SO_4) for a portion of the High-Peaks region of the Adirondack Mountains, NY, USA. Mount Marcy is on the left side of the image. Keene Valley is near the top center of the image. The black line delineates the watershed of the Upper Ausable Lake (shown in light blue). The image represents an approximately 27x28 km ground area. Dry deposition to this region would be represented by a single value when using dry/wet ratios and the 40-km resolution NatChem or NADP wet deposition grid as a basis for the estimate.

A Brief Discussion of How the HRDM Differs from Previous Approaches to Spatially Distributed Estimates of Atmospheric Deposition

The high-resolution deposition model (HRDM) described in this document was developed to address the need for spatially explicit and spatially distributed estimates of atmospheric deposition in the complex mountainous landscape of the northeastern US. Many ecological applications of atmospheric deposition estimates in the northeastern US require appropriate representation at spatial scales of less than 100 meters. High spatial resolution simulations are necessary because it is recognized that tremendous variation in meteorological conditions such as temperature, wind speed and cloud immersion may occur within 1 km due to the topography of the region. The biophysical characteristics of receptor surfaces also vary substantially at scales less than 1 km, in part due the influence of the climate variation discussed above on vegetation distribution. Such small-scale variation in meteorology and surface type can result in very large (4-5X) and ecologically significant variations in atmospheric deposition rates over the same distances (see Figures 4 and 5 in Miller et al. 1993b). If atmospheric deposition estimates are required for small watersheds (1–20 km^2) or for identification of acid or nitrogen sensitive ecoregions, then sub-kilometer resolution approaches will be required to adequately represent what is currently understood about atmospheric deposition regimes in the Northeast.

Examples of Several Approaches to Spatially Distributed Estimates of Atmospheric Deposition

Chang et al. 1987 – (RADM) Reactive transport model for acid deposition

- Wet and dry deposition
- Meteorological data provided by a mesoscale model
- Very low horizontal spatial resolution (80 km) masks important topographic and landcover related variance
- Simplistic formulation of dry deposition and surface type due to coarse spatial scale
- Statistical aggregation of model scenarios representative of observed climatology to produce seasonal and annual totals

Ollinger et al. 1993 – Hybrid statistical – GIS-aided interpolation of NADP and NDDN observations

- Wet and dry deposition
- Published estimates represent average deposition over a variable 4 to 11-y time period in the 1980s and early 1990s
- Weak interpolations of dry air concentrations due to sparse observational network
- One surface type and one constant dry deposition velocity applied to the whole region

Brook et al. 1999 – (RDM) Hybrid mesoscale meteorology coupled to a dry deposition velocity model

- Dry deposition velocities only, but could be coupled with other sources of wet deposition and air concentrations to produce deposition estimates
- Meteorology averaged at 35 km horizontal resolution masks important topographic related variance
- Land cover input to deposition velocity model at 1 km resolution grossly simplifies biological characteristics of receptor surface. For example, forest surface types are simplified to broadleaf and needleleaf, evergreen and deciduous.
- While this model provides estimates of dry deposition velocities at 1 km resolution the 35 km resolution of input meteorological data suggests that the deposition velocities would be more appropriately interpreted at a much coarser scale in complex terrain.
- Unfortunately this model is not coupled in any way to landscape estimates of the air concentration field. At this point in time the authors intend for the model deposition velocities to be used with the sparse point observations of the CAPMoN, NAPS and CASTNet dry deposition networks.

Miller 2000 – (HRDM) Hybrid statistical – GIS – mixed resolution physical process model

- Combines the strengths of the Ollinger et al. 1993 and Brook et al. 1999 approaches with significant further improvements.
- Wet, dry and cloud-water deposition. Only true "total deposition" regional model for mountainous landscapes.
- Allows either point observational records or gridded meteorological model output to be spatially interpolated to 30-m resolution, corrected for local topographic and landscape positional effects based on monthly regional climatology.
- Receptor surface is represented at 30-m resolution. The biophysical characteristics of the receptor surface are estimated in terms of the proportion of leaf area expected to be attributable to specific plant species. Species proportions are estimated by the forest species distribution submodel with guidance from the USGS/EPA MRLC data set.
- Deposition estimates are generated on a seasonal basis using sub-season time steps including representations of diurnal fluctuations employed in the deposition process models
- Deposition can be calculated for each year of the period 1980 to the present

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