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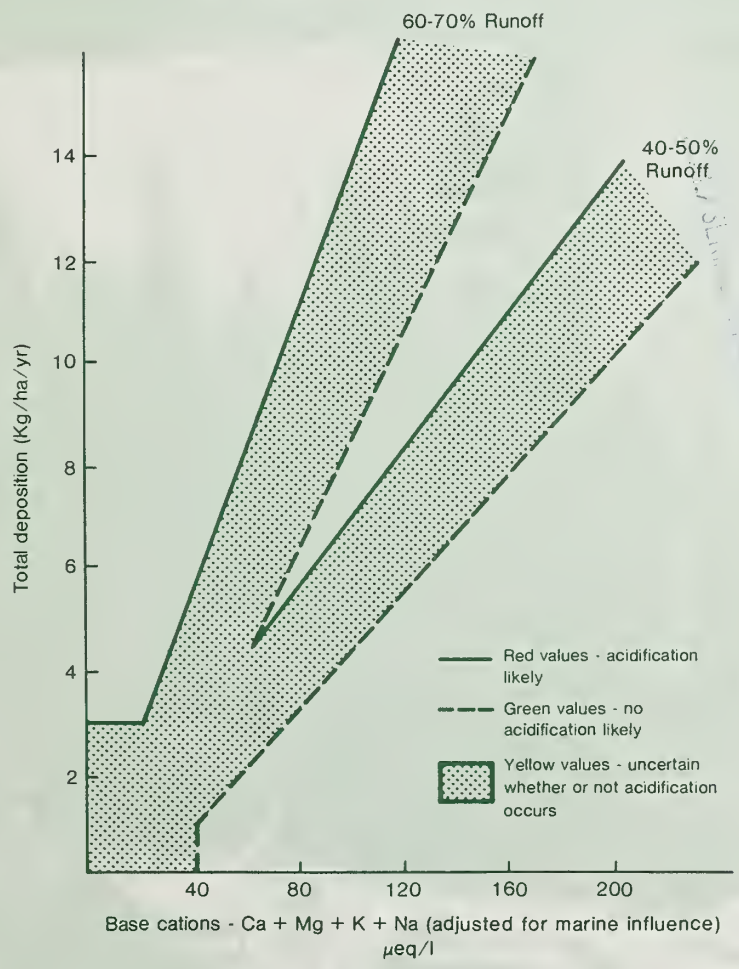
Fort Collins,
Colorado 80526

General Technical
Report RM-168



A Screening Procedure to Evaluate Air Pollution Effects on Class I Wilderness Areas

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68.61 1998
12/11/98
12/11/98

Fox, Douglas G.; Bartuska, Ann M.; Byrne, James G.; and others. 1989. A screening procedure to evaluate air pollution effects on Class I wilderness areas. Gen. Tech. Rep. RM-168. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 36 p.

This screening procedure is intended to help wilderness managers conduct "adverse impact determinations" as part of Prevention of Significant Deterioration (PSD) applications for sources that emit air pollutants that might impact Class I wildernesses. The process provides an initial estimate of susceptibility to critical loadings for sulfur, nitrogen, and ozone. It also provides a basis for requesting necessary additional information where potential adverse impacts are identified.

Keywords: Prevention of Significant Deterioration, air pollution

On the Cover:

Foreground: The screening graph for determining effects of atmospheric deposition on aquatic ecosystems (fig. 1, page 6). Background: West Glacier Lake, part of the Glacier Lakes Ecosystem Experiments Site (GLEES), a high-elevation area that, while not a designated wilderness, is being used for research to quantify atmospheric effects on wilderness. GLEES is instrumented for meteorological, aerometric, deposition, snowmelt, and streamflow measurements as part of a holistic ecosystem monitoring program conducted by the air pollution research unit at the Rocky Mountain Station. GLEES is located on the Medicine Bow National Forest, approximately 15 km west of Centennial, Wyoming, in the Snowy Range Mountains.

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PREFACE

A group of scientists and land managers held a cooperative workshop to help the Forest Service develop a screening process for evaluating Prevention of Significant Deterioration (PSD) applications for sources that might impact Class I area wildernesses. The process described in this document provides an initial estimate of the susceptibility of different Class I areas to critical loadings for sulfur, nitrogen, and ozone. Results should help Forest Service land managers when conducting "adverse impact determinations" of PSD permit applications and provide a ready basis for requesting necessary additional information where potential adverse impacts are identified.

This document was prepared by the authors and participants at the Workshop on Air Pollution Effects on Wilderness, held May 2-5, 1988, at the Institute of Ecosystem Studies, Millbrook, New York.

ACKNOWLEDGMENTS

Dr. Gene Likens and his co-workers at the Institute of Ecosystems Studies, New York Botanical Gardens, hosted the workshop at the Mary Flagler Cary Arboretum in Millbrook, NY. The participants at the May 1988 meeting in Millbrook developed the concept of this document, and the authors wrote the first draft. All the participants reviewed a second draft. A final step involved the review of 8 scientific peers who were not at the meeting, but by virtue of both their research and their positions with government, industry, and interested groups, were able to substantially improve the document. Finally, scientists at the Rocky Mountain Station conducting research on effects of atmospheric deposition on natural ecosystems, particularly Frank Vertucci, Robert Musselman, and Anna Schoettle added significantly to the final report by evaluating and incorporating reviewers' comments, correcting references, and providing the benefit of their substantial knowledge and experience to the final report.

USER NOTES

When implementing the PSD review process, line officers and staff must understand the assumptions and variables used to construct the screening model. The model will help in PSD review only if the assumptions and logic involved are fully understood. It is critical that the user recognize the development methodologies and limitations. For instance, participating scientists and managers agreed on similar numerical loadings for a pollutant in seemingly different Class I areas. This agreement resulted because similarly sensitive ecosystems occur in many different Class I areas, although not to the same extent. For example, alpine is the dominant ecosystem in Alpine Lakes Wilderness in northern Washington, but a minor portion of the San Geronio Wilderness in southern California. However, the loading values for these two

wildernesses are the same because the alpine ecosystem was considered most sensitive, and the loadings were established to protect the most sensitive ecosystems.

It should also be recognized that the loadings suggested by this screening technique are likely to overestimate potential impacts. As such, they may be applicable for PSD permit review of effects on designated Class I air quality areas, but are not intended to suggest target loadings on ecosystems in general.

Users should recognize that this document represents the state of understanding in Spring 1988. Science is very productive in this field, and it is anticipated that this document will be upgraded periodically.

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INTRODUCTION

Forest Service land managers need information about the effects of air pollution on wilderness areas that have been formally designated as Class I by the Clean Air Act (Public Law 95-95). Managers of Class I areas are responsible for the review of preconstruction applications termed "Prevention of Significant Deterioration" (PSD) permits. Forest Service managers must review PSD permits for major new emission sources (more than 100 tons of a pollutant per year) or the modification of an existing source that may cause possible effects on Class I areas.

This introductory section describes a workshop of Forest Service management leaders and prominent scientists studying the biological effects of air pollution and acid deposition. They worked together to identify how best to merge the current state of science with needs of Class I area managers. (Work group participants are also identified.) It then briefly describes Forest Service responsibilities under the Clean Air Act and the Wilderness Act.

The second section summarizes the major results of the workshop. Results are stated as proposed maximum acceptable pollutant loadings on specific ecosystems. These maximum loadings are intended for use by federal land managers screening PSD permits. The proposed screening process suggests one of three decisions: recommend permit approval (new pollutants will lead to loadings below Green Line), recommend permit denial (new pollutants will lead to loadings above Red line), and an intermediate zone (Yellow Zone), where more data are needed before deciding on a course of action.

The screening concept uses numerical values of sulfur and nitrogen deposition and ozone concentrations in nine different wildernesses considered representative of the diversity of wilderness ecosystems.

The third and fourth sections provide detailed explanations, justifications, and cautions regarding the screening approach as applicable to aquatic and terrestrial ecosystems in wilderness landscapes.

Workshop Organization and Participants

A partnership between scientists and managers is needed to protect air-quality-related values in Class I area wildernesses. The form of such a partnership was developed and approved by some 70 distinguished scientists at the 1987 Cary Conference,² which focused on long-term studies of ecosystems:

"Ecological understanding is required to develop environmental policies and to manage resources for the benefit of humankind. Sustained ecological research is one of the essential approaches for developing this understanding, and for predicting the effects of human activities on ecological processes. Sustained research is especially important for understanding ecological processes that vary over long periods of time. However, to fulfill its promise, sustained ecological research requires a new commitment on the part of both management agencies and research institutions. This new commitment should include longer funding cycles, new sources of funding, and increased emphasis and support from academic and research institutions. Because they have common long-term goals, we propose a new partnership between scientists and resource managers. Elements of this partnership include:

1. Agreement by scientists to answer the questions asked by managers, while making clear the level of uncertainty that exists and what additional research needs to be done.

²Statement adopted at the Cary Conference in Millbrook, New York, on May 13, 1987; revised July 4, 1987 (Likens in press).

2. Agreement by managers to give serious consideration to these answers and to support the continuing research toward better answers. Sustained ecological research supported by this new partnership can contribute significantly to the resolution of critical environmental problems."

Such partnerships are essential to use scientific information in an orderly and efficient manner for the management of complex natural resources.

Organizers of this workshop invited a group of prominent scientists, knowledgeable in the areas of effects of air pollution (sulfur and nitrogen deposition and ozone exposure) on ecosystems, to interact with a group of Forest Service managers who have air resource management responsibilities. The objectives of this workshop were to establish communication between these two groups of individuals, and to develop a screening process for evaluating PSD applications. This relationship was fostered by a 3-day workshop at the Institute of Ecosystem Studies of the New York Botanical Garden in Millbrook, New York.

The May 1988 workshop was to develop an air pollution screening process for managers of Class I areas. The participants decided that a screening process that considered only the impacts of the deposition of sulfur and nitrogen and ozone concentration on specific ecosystems would be appropriate. Other pollutants can adversely affect ecosystems, but the chosen pollutants are those most commonly of concern. Pollutant loadings are determined by using air dispersion models and estimates of deposition velocity to project the worst case deposition of S and N from proposed industrial emissions.

Four teams of scientists and managers (see table 1) were formed to determine independently the sulfur, nitrogen, and ozone values to be used in answering the following questions:

1. Below what magnitude of sulfur and nitrogen deposition and ozone concentration, resulting from proposed air pollution emissions, for each of the nine Class I area wildernesses, can a land manager have a high degree of confidence that no air-quality-related values (AQRV's) would be adversely affected?

2. Above what magnitude of sulfur and nitrogen deposition and ozone concentration for each of the nine Class I area wildernesses can a land manager have a high degree of confidence that at least one of the selected air-quality-related values would be adversely affected by the proposed air pollution emissions?

The Forest Service managers present at the Workshop picked tentative AQRV's (or reported those already developed in Forest Plans) for the selected wildernesses in their Regions. These AQRV's were then used by the teams and working groups in the

development of their loading estimates. Also, each Class I area wilderness was described. Appropriate site data and first-hand knowledge were used to estimate numerical loadings and identify problems in applying these numbers to specific areas. Values were chosen to protect the current condition of the selected AQRV's in each Class I area.

Visibility is the only AQRV specifically mentioned in the Clean Air Act, and it has been determined to be an important AQRV in all class I areas except Bardwell Bay (FL) and Rainbow Lake (WI). However, this workshop did not address visibility. The scientists, known for their expertise in air pollution effects on biotic systems, were invited to this workshop to develop screening guidelines for only the terrestrial and aquatic components of the ecosystem. The absence of comments on visibility should not be construed as a judgment of its relative value compared to biotic systems. In fact, in some areas, visibility might be considered adversely affected by air pollution concentrations that were not considered adverse to the biotic systems. For more discussion of visibility, the Forest Service Air Resource Management Manual (USDA 1987) should be consulted.

Federal Land Managers' Responsibilities Concerning Protection of Class I Area Wildernesses

Wilderness Act

The Wilderness Act of 1964 (Public Law 88-557) established the National Wilderness Preservation System "to secure for the American people an enduring resource of wilderness." The Act states:

"A wilderness... is an area where the earth and community of life are untrammelled by man, where man himself is a visitor who does not remain... Wilderness is...undeveloped Federal land retaining its primeval character and influence, without permanent improvements or human habitation, which is protected and managed so as to preserve its natural conditions and which generally appears to have been affected primarily by the forces of nature, with the imprint of man's work substantially unnoticeable..."

Wilderness is a distinct resource with inseparable parts. When possible, natural processes are allowed to operate within wilderness; for example, lightning-caused fires are allowed to burn under prescribed conditions. Wilderness is managed to make it as wild and natural as possible, including closing old roads, restoring damaged trails and campsites, and removing most structures. Managers use primitive tools to do the

Table 1.--Work group assignments for participants.¹

Team 1 Aquatic Ecosystems

Gene E. Likens (*Chairperson*)
Peter Dillon (*Combined group chair*)
Thomas Frost
Dale W. Johnson
Dale Nichols
Ed Brannon
Tom Thompson
Bill Carothers
Dave Unger
Jay Messer (*Note Taker*)

Team 2 Aquatic Ecosystems

Rick A. Linthurst (*Chairperson*)
Mike Pace
Richard Wright
Steve Mealey
Mike Edrington
Gray Reynolds
Anne Fege

Richard Fisher (*Note Taker*)

Team 3 Terrestrial Ecosystems

Ann M. Bartuska (*Chairperson*)
Jan Nilsson
John Reuss
Bill Mattson
Steve Lindberg (*Combined group chair*)
David F. Karnosky
Chuck Wildes
John Butruille
Clif Benoit
Bob Loomis
Douglas G. Fox (*Note Taker*)

Team 4 Terrestrial Ecosystems

Ellis Cowling (*Chairperson*)
Gary M. Lovett
Dave Peterson
J. R. N. Jeffers
Peter B. Reich
Dave Radloff
Dick Stauber
Steve Harper

James G. Byrne (*Note Taker*)

¹Affiliations of participants are given in appendix D.

job. As with other National Forest resource management efforts, public involvement is sought in planning for wilderness management and use.

Many management activities and uses are prohibited in wilderness: roads, motorized equipment and mechanical transport, landing of aircraft, most commercial enterprises, and permanent structures and installations. The Wilderness Act allows certain activities within wilderness, as long as the wilderness character is preserved. These uses include livestock grazing, hunting, fishing, exercising water rights, and existing mineral claims. Special exceptions are made in some wilderness legislation that permit mineral exploration and exploitation, access to private land, maintenance and use of airstrips, and, in Alaska, native use for subsistence.

The scientific value of wilderness is recognized in the 1964 Act. A decade or a century in the future, wildernesses will serve as baseline or "control" areas, since they are managed to preserve natural conditions and generally will have been affected primarily by the forces of nature. Permission to conduct scientific studies is granted only if the studies require a wilderness environment, and cannot be accomplished outside the wilderness. Motorized equipment or mechanical transport cannot be justified on the basis of cost or efficiency, and are allowed only if a comprehensive analysis shows there are no alternatives.

Clean Air Act

The Clean Air Act (CAA) Amendments of 1977 included a program for prevention of significant deterioration of air quality, generally referred to as the "PSD" program. This PSD program is to prevent areas currently having clean air from becoming too polluted. Certain wilderness areas and National Parks established before August 1977 were designated as Class I areas. A Class I designation allows only very small increments of new pollution above already existing air pollution levels within the area. Wildernesses established since August 7, 1977, are Class II areas. Class II areas have a larger increment, which is about 25 percent of the national ambient air quality standard. Class I areas in the National Forest System are identified in figure A-1 in the appendix to this report.

The CAA charges the federal land manager (FLM) of Class I areas with an affirmative responsibility to protect the air-quality-related values (AQRV's) of these areas from adverse air pollution impacts. AQRV's are those values within the Class I area that could be affected by air pollution such that the purpose for which the area was established (biological diversity, water

quality, fish) would be adversely affected. Within the Forest Service, the Regional Forester has been delegated this affirmative responsibility. Managers must minimize the conflicting human impacts of air pollution, much as they manage other uses to limit their impacts on the wilderness resource.

The PSD program is a preconstruction review and permitting process for major new or expanding sources of pollution. Any major facility seeking a new source permit for location or expansion in a clean air area must meet several requirements: Class I and/or II increments, the AQRV impact analysis, and the Best Available Control Technology (BACT) evaluation. In the PSD permitting process, the FLM determines whether a proposed source's emissions will have an adverse impact on Class I area AQRV's.

New source permit applicants submit plans to the

permitting authority, who examines the proposed location of the facility, its general design, projected air pollution emissions, and potential impacts. When a proposed source's emissions may have an impact on a Class I area, the permitting authority (EPA, or the State, if EPA has delegated PSD authority to that State) alerts the FLM. The FLM then determines the impact of the projected pollution level increases on the Class I area AQRV's and recommends approval, denial, or modification of the preconstruction permit. When the air regulatory authority certifies that a permit application is complete, the FLM might have as little as 30 days to review the permit application and respond to the regulatory authority. The FLM's determination of adverse impact must be completed within this period. This reply is included in the required public participation phase of the PSD program.

WORKSHOP RESULTS

The Green-Yellow-Red Screening Model

A conceptual framework was developed to implement the partnership between scientists and managers to help evaluate the potential impact of proposed new air pollution sources on Class I areas. This framework includes the idea of acceptable (Green Line), unacceptable (Red Line), and intermediate (Yellow Zone) levels of pollution. It is very important to keep in mind that this framework represents a screening tool. As such, it is intended to simplify the decision process by providing guidelines for general use rather than formulas for specific application. In all circumstances, the magnitude of these screening values, both Red and Green, are subject to change based on better site specific information. In the absence of such data, use of screening values should advance the evaluation of PSD permits.

Pollutant doses less than the Green Line value might be judged permissible by managers, and the application recommended for approval without additional data. Conversely, doses above the Red Line value are likely to cause at least one AQRV to be adversely affected. Thus they would result in a recommendation for denial unless additional site-specific data are provided to prove that the identified AQRV of the Class I area would not be adversely affected. Doses falling between the Green and Red Lines (the Yellow Zone) would be evaluated on the basis of additional information provided or gathered by the applicant or the USDA Forest Service.

It is prudent for the Class I manager to have AQRV's clearly identified, their current status monitored, and specific limits of impact defined. To avoid challenges, such information must be based upon or include multiyear data, and scientific peer review. Use of these screening techniques is also based on the availability of accurate deposition and concentration data at or near the Class I areas. These data also should be quality assured. Suggestions from long-term sustained ecological research will be useful in this context.

Specifically, the Green Line denotes a total loading (current deposition plus predicted additional deposition from the new source) of sulfur and nitrogen and the total dose of ozone that predicts, with a very high degree of certainty, that no AQRV will be adversely affected. The Red Line denotes a total loading of sulfur and nitrogen and the total dose of ozone that predicts, with a very high degree of certainty, that at least one AQRV will be adversely affected. Sustained ecological research, part of the partnership between managers and scientists, will refine and modify these decision points with new or better data.

Participants agreed that Green and Red Line numbers need to be ecosystem-specific. The selected numbers reflect the effects of pollutants on the AQRV's identified within the nine example Class I areas. Terrestrial and aquatic systems were considered separately because the understanding of combined impacts is not sufficiently developed to set numerical levels. Ozone was considered only to affect terrestrial

ecosystems. Aquatic impacts were estimated by the sensitivity of surface waters as measured by the combined concentrations of calcium, magnesium, potassium, and sodium (corrected for marine influences) expressed in microequivalents per liter ($\mu\text{eq/l}$). Green and Red Line values for aquatic impacts are presented graphically.

Aquatic Green and Red Line Screening Graph

Green and Red Line screening values associated with effects on aquatic ecosystems are most appropriately displayed graphically. The sensitivity of aquatic ecosystems to S and N deposition is measured by their acid-neutralizing capacity (ANC). The ANC may already be reduced, however, in systems subjected to significant deposition loading. A good measure of sensitivity for fresh surface waters is the sum of the concentrations of base cations (calcium, magnesium, potassium and sodium ions) in the water. Since Class I areas contain a diversity of lakes and streams, the participants felt that Green and Red Line values should be presented as a function of the ion concentration. The manager will need loadings based on knowledge of the surface waters in the Class I area as well as the deposition environment.

Terrestrial Green and Red Line Screening Numbers

Participating scientists familiar (to varying degrees) with detailed data applicable to these Class I area wildernesses agreed to the values in table 2. The Green Line represents the total pollution loadings (current plus proposed new source contribution) pollution loadings *below* which a land manager can recommend a permit be issued for a new source unless data are available to indicate otherwise. The Red Line represents an estimate of the total pollutant loadings that each wilderness can tolerate. Total loadings *above* these values suggest the land manager recommend reduction of emissions from a new source unless data are available to indicate that no AQRV of the Class I area is likely to be adversely affected.

Pollutant loadings *between* these values require the gathering of enough valid data to determine whether or not a permit for a new source should be recommended. General ideas for dealing with loadings that fall between the values are described in the next section.

The graph for aquatic systems shows Green and Red Line values with total deposition loading (in kg of S/ha-yr) on the vertical axis and concentration of (nonmarine) Ca+Mg+K+Na (in $\mu\text{eq/l}$) on the horizontal axis. The significance of these concentrations is based on the relative amount of water that is exported from the watershed. Green and Red Line values are presented in figure 1 for runoff estimated to be about 60-70% of the precipitation, and for 40-50% runoff. Green and Red Line values for additional runoff percentages are presented in appendix C in figures C-1 and C-2.

Table 2.--Terrestrial Green and Red Line screening values.

Wilderness area ¹	Nitrogen deposition ²		Sulfur deposition		Ozone concentration ³	
	Green Ln	Red Line	Green Ln	Red Line	Green Ln	Red Ln
	----kg N/ha-y----		---kg S/ha-y---		-----ppb-----	
Alpine Lakes, WA	5-7	15	3-5	20	35/75	55/110
Hoover, CA	3-5	10	3-5	20	35/75	55/110
San Geronio, CA	5	15	3-5	20	35/75	55/110
Bob Marshall, MT	3-5	10-15	5	20	35/75	55/110
Bridger, WY	3-5	10	5	20	35/75	55/110
Superstition, AZ	3-5	15	5-7	20	35/75	55/110
Joyce Kilmer, NC/Slick Rock, TN	7-10	15	5-7	20	35/75	55/110
Otter Creek, WV	7	10-15	5	20	35/75	55/110
Boundary Waters Canoe Area, MN	3-5	10	5	20	35/75	55/110

¹ See appendix B for description of wildernesses.

² Nitrogen and sulfur deposition are total values including all forms, wet, dry, $\text{NH}_4\text{-N}$ and $\text{NO}_x\text{-N}$, $\text{SO}_4\text{-S}$, $\text{SO}_2\text{-S}$, etc.

³ Growing season average/second highest 1 hour average value in a year.

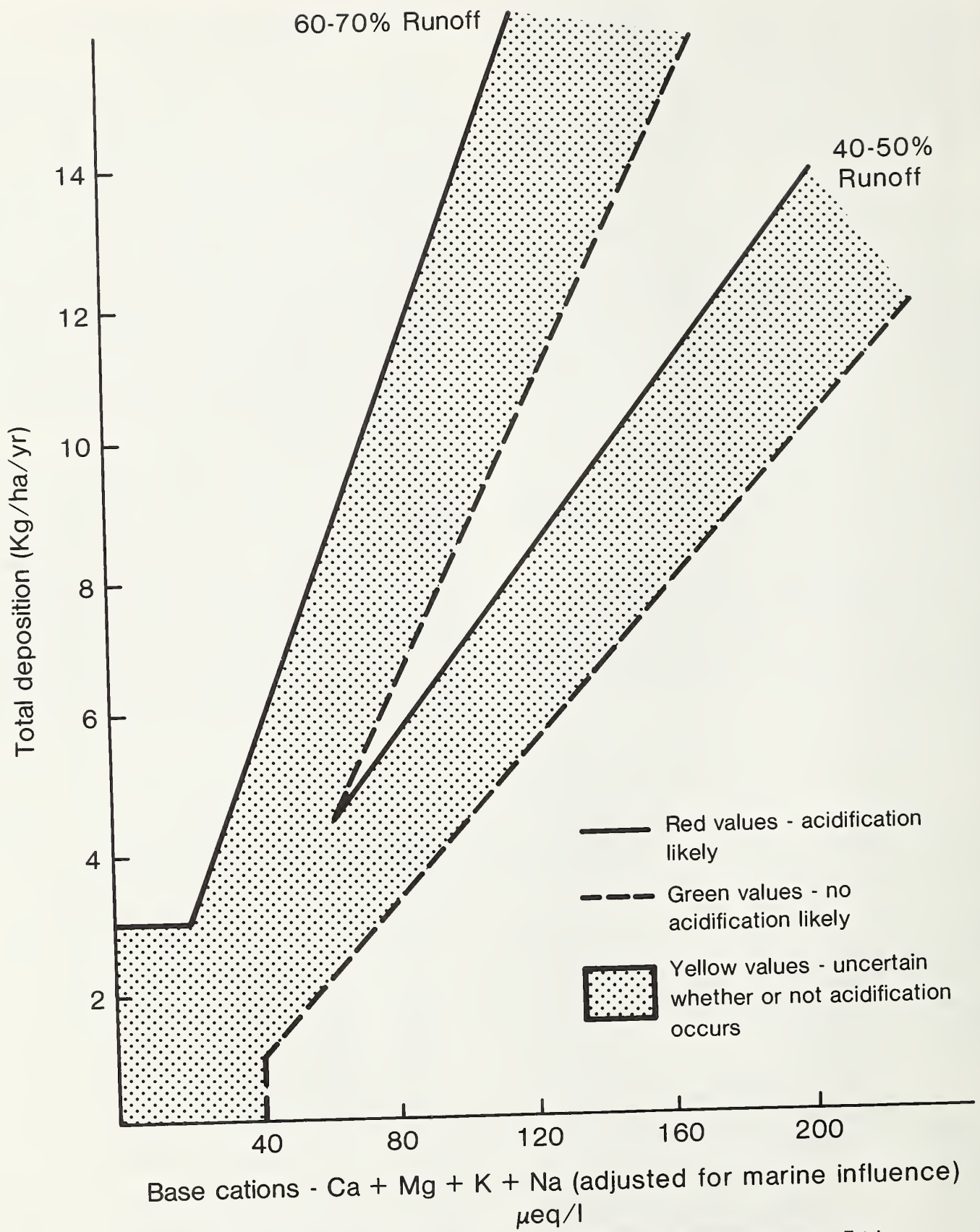


Figure 1.--Green and Red Line values for effects of deposition on freshwater systems. Total deposition is total sulfur deposition except for selected locations as noted in the text where 25% of total Nitrogen deposition should be included.

Part of the water that falls on a watershed as precipitation is lost as water vapor through evaporation or through transpiration by plants. Depending on geologic conditions, some may seep deep below surface and be lost from the immediate watershed as ground water. The rest leaves as surface runoff. High mountain areas with cool temperatures, large amounts of rain and snow, steep slopes, and thin soils have high runoff percentages. Warm temperatures, deep soils, level topography, and vigorous plant growth all favor evapotranspiration and reduce runoff.

Participants considered that, with a few complex exceptions, effects of N deposition on aquatic resources are not likely to be significant because the N is taken up by the watershed terrestrial and aquatic biota and does not contribute to acidification. Exceptions are very sensitive lakes and watersheds, primarily at high-elevation sites in the western United States, with base cation concentrations below 50 $\mu\text{eq/l}$. Such systems can be acidified by addition of N (Grennfelt and Hultberg 1986). For such circumstances, we recommend adding 25% of the total N deposition to the S deposition for use in the aquatic graph. Thus, if the total deposition projected for a western Class I area containing low base saturation waters is 2 kg S/ha-yr and 4 kg N/ha-yr, the value of $2 + .25 \times 4 = 3$ should be used in determining the Green and Red Line loadings on the Graph.

Below a total deposition of 3 kg S/ha-yr, there are no field data to develop the Green and Red lines. Particularly in Class I areas in the western United States, deposition levels are low and surface waters have low ionic concentrations (10-40 $\mu\text{eq/l}$). No evidence of chronic acidification has been reported. However, snow melt has the potential to seasonally acidify these surface waters. Another potential effect of episodic snowmelt loading in lakes in the west is eutrophication, a nutrient fertilization effect leading to increased organic productivity. This effect would also require additional study. Thus, these systems fall in the Yellow zone.

Implementing the Screening Technique

Information Needs

Listed below are six types of data helpful to managers for using the Green/Yellow/Red screening technique. These data can be obtained from published sources, or local scientists who may have access to additional sources of information. It is also prudent for managers to formulate recommendations for additional research or assessment efforts which should be undertaken by the permittee, Forest Service, state, or by other organizations before or as a condition to the permit.

Managers are encouraged to develop working relationships with local university, state, federal, and industrial research personnel to assist in identifying already existing sources of information or recommendations for further research. This workshop report should be useful in initiating such communication.

Data needed to responsibly evaluate a PSD permit include:

1. Deposition and air concentrations to estimate current loadings.--Current loading and exposure conditions at wilderness sites must be estimated to assess the impact of new deposition increments. Measurements should take into account expected higher fluxes at higher elevations. Some protocols for these measurements have been established (Fox et al. 1987).

Ozone. Determine maximum hourly average values and growing season average concentrations.

Sulfur. Determine total deposition by wet, dry, and cloudwater processes. For some forest systems it has been shown that measurements of throughfall plus stemflow fluxes provide a simple but accurate estimate of total deposition of the major S components.

Nitrogen. Determine total deposition from precipitation, cloudwater, and air chemistry measurements (including HNO_3 vapor and ammonium ion) and appropriate dry deposition models. Characterization of meteorologic and climatologic parameters should also be considered. These can be used to determine potential climatologic stresses and to evaluate dry deposition and cloudwater deposition.

2. Expected deposition and air concentrations due to proposed source.--Predicted loading and exposure at each site must be estimated to assess the change in current loading or air concentrations for comparison with Red and Green Line values. Estimates must account for elevational effects and for important nearby sources that contribute to background loading and concentration. The expected worst case ambient loading or concentration should be predicted. Modeling is generally conducted by the proponent and/or the regulatory agency. Managers should be aware that ozone is a secondary pollutant (generated in the atmosphere) and must be predicted with a model incorporating photo-chemical reactions. Sulfur modeling should include any increased loading due to all important sulfur species (SO_2 , particle sulfate, cloudwater sulfate). Nitrogen modeling should consider all species of N available for plant uptake (HNO_3 vapor, nitrate and ammonium ions in rain and cloudwater, NH_3).

3. Inventory of biological resources associated with the identified AQRV's of the Class I area.--A description of the vegetation communities (type, cover) is needed to assess the relative response of the ecosystem(s) to pollutants. Include in a general assessment the identification of unique communities (such as small bog in an otherwise forested system), and the percentage cover of major ecosystem types.

Periodic remeasurement of stand composition and integrity. Linkage to developing long-term monitoring programs (EPA, FS) will assist in an evaluation of change. A species list including relative frequencies of occurrence is needed. An estimate of the biomass increment for assessment of nitrogen demand and use (for instance Douglas-fir require more than alpine plants) must be made. Percent cover by major vegetation type is useful for this purpose.

A full inventory of aquatic resources, including water column and benthic sampling to determine phytoplankton, zooplankton, and macroinvertebrates as well as associated water chemistry is needed. A quantitative sampling procedure for macroinvertebrates and flowing waters should be followed. Fish abundance, condition, age class, and other aspects of community composition should be measured (Fox et al. 1987).

4. Species response/biological effects data.--Following the vegetation survey, the response of key species to pollution loading must be evaluated. The FLM should coordinate these needs with FS Research and other research activities in the area of air pollution, plant response, acid deposition, and aquatic resources. One outcome of this might be the development of bioindicators and key sensitive organisms in Class I areas.

5. Lake, stream, and soil survey/geological assessment.--Data needs for lake and stream water chemistry are identified above. Information is necessary to understand the relative ability of soil and bedrock to buffer pollutant inputs for all subsystems within the wilderness.

Lake and stream water. Care should be exercised to ensure that appropriate guidelines are followed (see Fox et al. 1987).

Soil survey. Identify major soil series, followed by more detailed chemical characterizations of the important series. (See for example the description and protocols in the recent EPA Soil Survey; Fox et al. 1987.)

Geological assessment. Parent material can be assigned to one of several weathering as described in the Swedish critical load document (Nilsson 1986). Ecosystem sensitivity to S inputs can then be related to the percentages of the various classes within the wilderness.

6. Snowpack chemistry and hydrologic characteristics of the area.--Snowpacks in high-elevation wilderness have large surface area to capture S and N compounds. Thus pollution may accumulate in the snowpack. Careful measurement of snowpack chemistry (Fox et al. 1987) can provide good deposition loading information. Snowmelt causes a significant pulse of water which initially can release concentrated chemicals to the ecosystem. Since pollutants are not soluble in ice, they reside on the surface of the ice. As the snowpack warms, these chemicals are removed by the initial meltwater. This may result in a chemical pulse more concentrated in the initial runoff than in the snowpack itself. Managers should assess the potential and the likely effects of this process of pollutant storage and delivery.

Monitoring Considerations

A major consideration for all ecosystems is the current condition of the atmospheric environment. This requires measurement of meteorology and air quality in sites representative of the wilderness.

Meteorology

Meteorological instrumentation can be operated with battery power using microprocessors to record and process the data. The details of these systems are available in Fox et al. (1987).

Ambient Air Concentration

Air quality measurement is more problematical. Ozone measurement requires a major investment in an air-conditioned instrument shelter. The shelter and the ozone monitor require line power, frequent calibration, and standardization. Such instrumentation cannot be put in a wilderness. Rather, the site selected for monitoring ozone must be carefully selected to be representative in exposure, elevation, and ground cover (canopy, etc.) of the wilderness being monitored (Fox et al. 1987).

Ambient air concentrations of SO₂, NO_x, and NH₄ can be measured using filter packs. These filter packs also collect aerosol SO₄ and NO₃. These instruments also require power, although they need not be sheltered. Again, siting must be representative of the ecosystems being monitored. These techniques are described in Fox et al. (1987).

Deposition

A major concern in assessing impacts is the measurement of deposition. Dry deposition cannot easily be measured except with research quality instruments. However, it can be approximated by measurements of surrogates, for example snowpack in alpine areas. The snowpack can be monitored by

carefully digging a snowpit and collecting snow samples along its depth (Fox et al. 1987). In a forest, throughfall and streamflow together have proven a useful measure of dry deposition of some chemical elements.

Wet deposition should be measured using NADP-type collectors and protocols for consistency and comparison within the large national network. Other data required should be collected using the guidelines for wilderness measurements (Fox et al. 1987).

Cloud and fog water interception in certain locations can add considerably to the total deposition. They should be considered in mountain locations where such events occur.

General Considerations for Data Collection

The land manager should be aware of the degree of uncertainty in the numbers obtained, including those used to establish Red and Green Line values. The FLM should accept that some uncertainty is unavoidable and does not negate use in decision making. The following points are relevant.

1. The variance of certain measurements can be quite high, increasing the uncertainty in estimates, and decreasing confidence in prediction.

2. The level of resolution can increase uncertainty. Finer temporal resolution of data (such as hourly ozone averages) may be quite variable and difficult to interpret, but when averaged over a longer period of time (weekly), values are more stable and, hence, certain.

3. Temporal patterns in water and soil chemistry may or may not be greater than the magnitude of differences among soil types in the same watershed. The focus of the monitoring is on the most sensitive component of the ecosystem, rather than any average or representative condition.

4. Most wildernesses are comprised of several ecosystems (such as alpine at high elevation; Douglas-fir at lower elevation). The manager needs to evaluate the sensitivity and the importance of identified AQRV's in each ecosystem.

5. There may be mismatches between data sets. For example, air quality data may be provided for a region or large parcel of land (especially if derived from a model); however, the soil chemistry or vegetation type may be specific to a location. Also, microclimatic effects might alter an air-quality and/or deposition effect locally, reducing the representativeness of a measurement.

Quality Assurance and Quality Control

The need for quality assurance and quality control is implicit in the need for data upon which decisions can be upheld in an appeal. The following items reflect this need:

1. Utilize standardized quality assurance/quality control guidelines where available; in particular, EPA procedures and the QA Methods Manuals of the Forest Response Program (Blair 1986).

2. Implement standard protocols across regions. For soils, coordination with the Soil Conservation Service is recommended.

3. For chemical analyses, evaluate laboratory capability and performance prior to selecting a laboratory. Evaluation is especially relevant for many state and university laboratories where procedures may be appropriate for agricultural but not forest soils, and for lake and stream water but not necessarily dilute surface waters and precipitation. Water chemistry is particularly expensive and demanding on laboratory resources. Laboratory procedures should be carefully evaluated and monitored both prior to receiving samples and during sample analysis.

SPECIFIC FACTORS AND CONSIDERATIONS IN DEVELOPING THE MODEL

Terrestrial Systems

Effects of direct air pollution on terrestrial resources have been the subject of considerable research over the past 50 years. Many plant species have been tested for direct phytotoxicity due to the so-called criteria pollutants (O_3 , SO_2 , NO_x) as well as other reactive hydrocarbons. Concentrations necessary to cause a noticeable impact are generally well above the current loadings in many Class I areas, although ozone routinely occurs at phytotoxic levels in California and the eastern United States. The major problems associated with ozone toxicity are: (1) plants respond

almost immediately to low concentrations of ozone, but their response is not likely to be significant until concentrations are somewhat higher than the response level (Reich 1987), and (2) generally only economically important plants have been studied. Other species may or may not respond in the same manner.

In the 1980's there has been a growing awareness of so called forest declines: large-scale reductions in the health and vigor of trees. Declines are likely associated with a host of interacting stress factors; direct causes are hard to pin-point. Research has been focused recently on determining the role of acidic deposition in forest decline. This program is rapidly

accumulating quantitative and qualitative information about the effects of addition of S, N, and associated pollutants on forest health. Considerable research is addressing the mechanisms of how S and N affects forests, including soil influences, foliar leaching, carbon allocation, winter injury, reproduction and regeneration, and insect and pathogen influences. Finally, direct dose-response relationships are being determined.

Workshop scientists considered the current state of this rapidly moving field in developing the numerical values in the Green and Red Line tables. In addressing ozone impacts they needed to address the critical question of what constitutes an ecosystem-level impact, given that most experiments have dealt with single species. An exception may be studies in California by Miller and his coworkers (Miller 1973).

When considering the levels of S and N deposition, the scientists focused on soil effects because soils were presumed to be a very sensitive ecosystem component, and clearly soil effects are an ecosystem-level impact. Dealing with N in this context was difficult, however, because most Class I area ecosystems are likely to be N limited. In this case any increment of N is likely to cause some effect. Scientists had to estimate the significance of anticipated effects at an ecosystem level in order to develop numerical values.

Rationale Used in Selecting Ozone Values

It has been well established that exposure of plant leaves to air containing ozone results in a number of quantifiable effects, including visible injury, reduced photosynthetic capacity, increased respiratory rate, briefer leaf retention time, and reduced growth (Barnes 1972, Hayes and Skelly 1977, Pye 1988). The magnitude of these effects depends on several factors, including the concentration of the pollutant, the duration of exposure, and other environmental factors (USEPA 1986). Sensitivity to ozone varies among and within species because of inherent differences in uptake rates (Reich 1987) and also because of other unknown genetic factors (Karnosky and Steiner 1981). Despite differences at the leaf level, responses of a wide variety of species types can be effectively characterized by taking into consideration exposure dynamics and uptake characteristics (Reich 1987).

The immediate effect of elevated ozone levels in wilderness areas would be decreased leaf longevity, reduced net carbon gain of foliage, reduced growth of individual plants, and foliar injury. Other adverse effects could include alteration of plant allocation of carbon; greater susceptibility to insects, pathogens, water stress, winter injury, or other stress agents; possible changes in species composition of plant communities; and possible loss of genetic resources of sensitive genotypes within a species.

The Green Line values for ozone for all wilderness terrestrial plant ecosystems are set at 75 ppb (peak 1-hour average) or 35 ppb (growing season average).³ We follow regulatory procedures established by the Environmental Protection Agency, which define a peak as the second-highest one hour average concentration in a year (EPA 1986). Estimates of average ozone concentrations in clean air range from 15 to 30 ppb. However, estimates of background ozone concentration are very difficult because measurements do not exist, and models show complex nonlinear interactions where ozone production depends on NO_x concentration, nonmethane hydrocarbon (NMHC) concentration, and seasonality (Liu et al. 1987). NO_x background concentrations range from less than 1 ppbv (remote locations in the western United States) to about 7 ppbv (remote locations in the eastern United States) and about twice that in Europe (Fehnsfeld et al. 1988). Modeling estimates (Liu et al. 1987) would then project background ozone concentrations of approximately 20 ppb in the western United States and 70 ppb in the eastern United States. Of course, NO_x and ozone concentrations in the vicinity of urban areas (such as Los Angeles, Phoenix, and Denver) are often higher than the eastern background.

The Green Line values were chosen to give reasonable certainty that no significant damage will occur to the ecosystem. Based on available information about plant response to ozone, we conclude that any increase in ozone levels above background (clean air) will have some adverse effect on individual leaves of at least some species. However, we believe that the integrity of the ecosystem can be maintained with the slight amount of stress on either sensitive individuals and/or sensitive species that might occur below Green Line levels.

The Red Line values for ozone are set at 110 ppb (peak 1-hour average) or 55 ppb (growing season average). Species from all plant types suffer reduced net photosynthesis and growth if exposed to 55 ppb for the daylight hours every day of the growing season. Although some of the data used in the development of this value are based on average concentration during daylight hours only (12 hours), the loading value seasonal averages use 24 hours per day. While it is an area of scientific controversy (Musselman et al. 1988) whether a 12-hour or a 24-hour based ozone season average is better correlated with effects, 12-hour data are not available from regulatory agencies. Thus, 24-hour data are recommended to calculate seasonal averages.

³Growing season average may not be available in many locations, and determination of growing season will be specific to each species. Thus, it is likely that the peak values will be more useful than the growing season average values (USEPA 1986, Musselman et al. 1988).

Ambient ozone levels in Class I areas should not exceed peak annual 1-hour average values of 110 ppb. Data from numerous ozone monitoring stations suggest that exceeding 110 ppb for the peak 1-hour period of the year would be accompanied by 15 to 50 (or more) hours of exposure to ozone levels greater than 80 ppb. Adverse effects are greater at higher ozone concentrations.

Ozone effects are cumulative for each individual plant, but the chemical itself is ephemeral and does not accumulate in the plant or ecosystem. Also, ozone does not enter the soil in sufficient quantities to be of any significance. Finally, we conclude that some individuals and species will be damaged in all wilderness ecosystems at ozone levels between the Red and Green Line values. In such Yellow Zones, predicted damage must be evaluated on a case by case basis. The PSD recommendation may depend on the relative value of the plant community as an AQRV within that particular wilderness area.

Rationale Used in Selecting Sulfur Values

Two criteria or effects have been considered to set the Green and Red Line levels of deposition for sulfur: (1) removal of base cation from soils in association with the SO_4^{2-} anion, a "capacity" effect, and (2) the "intensity" effects resulting from the changes in soil solution composition. This distinction becomes important in areas affected by marine air masses where natural SO_4^{2-} levels may be well above our proposed Green Line values. An approximate correction can be made by subtracting the marine component based on the $\text{SO}_4^{2-}/\text{Cl}$ ratio in seawater. Marine sulfate is generally not considered deleterious because it is normally accompanied by base cations, particularly Na and to some extent Mg, and thus does not contribute to acidification of the system. There may be episodic exceptions to this.

For our basic capacity comparisons, we have assumed a soil depth of 30 cm with a bulk density of 1.1 kg/liter. At a loading of 3 kg S/ha, it would require approximately 175 years to achieve a reduction of 1 meq of base cations per 100 g soil. This reduction would be at least partially offset by weathering of primary minerals. Somewhat higher deposition levels would be acceptable in areas where soils are deep or are well supplied with bases, and these considerations are reflected in the proposed values for some of the particular ecosystems.

Given these assumptions, the maximum allowable (Red Line) values of 20 kg/ha of S could achieve the reduction of 1 meq base cation within about 26 years. This base cation reduction would generally be unacceptable unless the system contains free CaCO_3 . However, with the possible exception of the Superstition Wilderness, all of the specific ecosystems

considered here contain considerable areas of non-calcareous soils.

For our evaluation of intensity effects, we have assumed 1 m precipitation in excess of evapotranspiration. The Green Line value of 3 kg/ha would increase solution concentrations by about 19 $\mu\text{eq/l}$, which is near the natural background for surface waters in areas that do not contain significant amounts of readily oxidizable sulfur-bearing minerals. Furthermore, this concentration would be unlikely to result in significant mobilization of soluble inorganic forms of aluminum. The corresponding increase for the maximum value of 20 kg/ha would increase solution concentrations by about 125 $\mu\text{eq/l}$. This concentration is in the range where Al mobilization might occur in acid soils, and with the possible exception of the Sonoran systems, would probably not be acceptable.

Rationale Used in Selecting Nitrogen Values

The basic features of N cycling in forest ecosystems are fairly well understood, and can provide a broad conceptual outline for arriving at deposition loadings to wilderness areas. The following is a brief summary of some of the important features of N cycles relevant to loading considerations.

Nitrogen is the only major plant nutrient that does not accumulate to any significant extent in inorganic forms in the soil. Although ammonium is strongly adsorbed to soil cation exchange sites, ammonium almost never significantly accumulates because of biological uptake by plants, grazers, decomposers, and nitrifying bacteria. Thus, forest ecosystems can accumulate atmospherically deposited N only by biological mechanisms; specifically through incorporation into plants, plant feeders (herbivores), and decomposers such as soil microorganisms and invertebrates. Because N is the nutrient most commonly limiting growth of forests in North America, forested ecosystems usually show a net accumulation of atmospherically deposited N.

Any increase in N deposition as nitrate or ammonium ion to N-limited wilderness areas will most probably result in some increase in growth, and may actually improve the health of the ecosystem. Species adapted to low N conditions might be replaced as a result of fertilization. It is also possible that chronic N enrichment may eventually predispose plants to outbreaks of plant-feeding insects and fungal pathogens because of changes in the plants' carbon allocation to growth and defensive processes.

N deposited in excess of biological need almost invariably leads to nitrification, microbially mediated nitrate and nitrite formation in the soil, and increased leaching of nitrate and associated cations. The nitrate so produced may lead to surface- or groundwater

degradation unless it encounters anaerobic conditions. Under these conditions, it may be microbially reduced to N₂O gas (denitrification), thus decreasing the potentially deleterious effects of excessive N deposition on water quality. These processes may still leave the potential increases in soil acidification to be considered.

The Green Line values (3-10 kg/ha-yr) for nitrogen, across all the ecosystems considered, were selected to give reasonable certainty that no significant change in the forest ecosystem will occur below this amount of nitrogen deposition.

The Red Line values (10-15 kg/ha-yr) for nitrogen, across all the ecosystems considered, were selected to give reasonable certainty that these amounts of nitrogen deposition will result in significant changes in the accumulation of nitrogen and in the species composition or other important features of the ecosystem.

While the fundamental elements of forest N cycles are reasonably well understood, quantitative data on N cycling in wilderness areas is quite scarce at best, and in many areas completely lacking. Therefore, the Red and Green Line loadings for N deposition in wilderness areas are judgments based on a very limited database. We strongly urge that relevant N cycling parameters be measured in those wilderness areas for which there is a potential concern about increased N deposition. It is also important to note that atmospheric deposition at the chosen target loadings may well have some effect upon wilderness areas in terms of stimulating growth; thus, there is no assertion that these levels will protect the wilderness areas from all effects. In our judgment, however, the Green Line levels are sufficiently low that perceptible deleterious effects upon plant health, changes in species composition, or degradation of water quality are unlikely.

Aquatic Systems

Aquatic resources are important Air Quality Related Values in most Class I areas. Determining how best to prevent significant deterioration by atmospheric pollutants, however, is not as straightforward as establishing their importance.

This section provides general guidelines for all surface waters relative to the amount of sulfur and nitrogen that can be deposited on an annual basis.

Green Line values indicate levels *below* which it is highly *unlikely* that the most sensitive aquatic resources will be significantly affected, while Red Line values indicate levels *above* which it is highly *likely* that the most sensitive aquatic resources will be significantly affected.

The guidelines use the concentrations of base

cations: calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na), as a measure of sensitivity. The sulfur and nitrogen loadings above which adverse change is likely and below which change is unlikely are based on the most sensitive waters.

Concept of Surface Water Sensitivity

Lakes and streams differ in their inherent sensitivity to inputs of acidifying compounds from the atmosphere. A number of factors affect lake sensitivity; bedrock geology, soil and vegetation type, hydrologic characteristics, lake chemistry and biology, and precipitation volume are among the important factors. Maps of bedrock geology are often used to indicate areas with sensitive lakes and streams. Seepage lakes, lakes which have no visible outlet, are likely to be dominated by precipitation, while drainage lakes are likely to be influenced by watershed base cation supply. Seepage lakes, all other things being equal, will be more sensitive to acidification. The lake or stream chemistry itself provides a convenient measure of sensitivity. The lake water integrates many watershed factors that may be difficult to measure or estimate in the field.

Any of several water chemistry parameters may be used to estimate sensitivity. In pristine areas receiving little or no acid deposition, acid neutralizing capacity (ANC) provides a useful measure--the lower the ANC, the more sensitive is the water body. In areas receiving acid deposition, however, ANC may have decreased. Since ANC changes with acid deposition, it cannot be used directly to assess sensitivity. Acid neutralizing capacity can be defined as the sum of the base cations minus the sum of the strong acid anions (SO₄⁻, NO₃⁻, Cl⁻) in a water sample if concentrations of organic acids and aluminum are insignificant. Because of the principle of electroneutrality, changes in base cations and/or acid anion concentrations must affect the ANC of the sample.

Calcium and magnesium concentrations have been used widely as a measure of inherent sensitivity. Henriksen's (1979) empirical nomograph for lake acidification uses Ca+Mg concentrations as a measure of sensitivity and SO₄ concentration (or alternatively pH of precipitation) as a measure of acid deposition to determine whether a given lake will be acidic (pH<4.7), transitional (4.7-5.3), or bicarbonate dominated (pH>5.3). This empirical approach developed on the basis of several hundred Norwegian lakes has been shown to be of general applicability to lakes in many regions of Europe and North America (Wright and Henriksen 1983, Henriksen and Brakke 1988, Wright 1988, Reuss et al. 1986).

While Ca and Mg are the major cations usually

associated with alkalinity, the weathering of minerals containing K and Na can also contribute significantly to ANC. Given the geological diversity of the Class I areas, we used the sum of the four major base cations (adjusted to subtract any marine influences) as the principal measure of inherent sensitivity.

The relationships between lake ANC, anions, base cations (Ca+Mg+K+Na), pH, and conductivity can be derived either empirically or from basic water chemistry theory. The figures used for our screening technique were constructed showing the relationships between non-marine base cations and total S or S+N deposition for sensitive lakes. Measured lake chemistry data from the 1984 Eastern Lake Survey (Linthurst et al. 1986) and the 1985 Western Lake Survey (Landers et al. 1987) were used. Total deposition for S and N were estimated for eastern lakes from analysis of wet deposition data done by Husar (1986) with 30 percent added to account for dry deposition. For the western lakes we averaged data from nearby high-elevation National Atmospheric Deposition Program (NADP) sites (NADP 1988) with data from high-elevation snow chemistry studies (Brown and Skau 1975, Melack et al. 1982, Laird et al. 1986, Loranger 1986, Loranger and Brakke 1988, Reddy and Classen 1985, Vertucci in press). No additional correction was made for dry deposition because not enough information is available to estimate the potential contribution (Young et al. 1988).

Acidification Response Levels

The effects of O₃, N, and S can be assessed directly for aquatic ecosystems. Ozone has no known direct effects on aquatic systems, and therefore does not warrant further consideration. For aquatic systems, pollutant loadings by N and S exert their influence on biotic communities primarily by changing pH conditions rather than by a direct influence due to the chemical species of N or S. Our focus, therefore, is on defining threshold levels for N and S loading based on their influence on pH. Again in very dilute, high-elevation N-limited lakes, the addition of N can initiate eutrophication.

Changes in lake or stream pH due to atmospheric inputs of N and S can have a variety of direct and indirect effects on aquatic communities and ecosystem processes. Increased hydrogen ion concentrations can have a direct, toxic effect on organisms. Such direct effects on one or a group of organisms may exert, subsequently, an indirect influence on the occurrence of other organisms, primarily through food web interactions. Changing pH may also influence the solubility of nutrients or toxic compounds and elements (such as aluminum) which in turn may affect the

occurrence of organisms either directly or indirectly. It is important to note that small-scale changes in chemical conditions are likely to affect physiological processes or a particular life stage of an organism prior to the disappearance of a taxon.

Information on the effects of a particular decrease in pH on a lake or stream can be derived from four types of sources (EPRI 1986): (1) laboratory bioassays, (2) synoptic surveys of the distribution of organisms across systems with a range of pH values (Eilers et al. 1984, Confer et al. 1983, Haines 1981), (3) manipulations of pH in mesocosms, and (4) whole-system experimental manipulations of pH (Schindler et al. 1985, Brezonik et al. 1986, Hall et al. 1980, Hall and Likens 1981). Each of these sources can provide useful information on the effects of changing pH conditions. However, whole-system experiments provide the best detailed information on the response of aquatic systems to acid stress because they involve a direct, controlled manipulation of pH conditions, and they are conducted at a scale that encompasses a full range of population and ecosystem processes (Schindler 1988, Hall and Likens 1984). Specifically, results from these studies indicate effects that *could not* have been discovered with other approaches.

In general, considering information drawn from all of the sources listed above, it is possible to conclude that pH changes of less than 0.5 units are capable of producing considerable change in the biotic communities of either lakes or streams. In many cases, fish populations would be expected to respond to a 0.5 unit pH change. Shifts of 1 pH unit can lead to major changes in the occurrence of other organisms, particularly sensitive ones such as mollusks. Workshop participants suggested a 0.5 pH unit change as a Red Line projection and a 0.1-0.2 unit projected change for the Green Line, in sensitive systems with pH of order 6 or very low ANC.

Because many wilderness areas contain a diversity of lakes and streams, it is important to target a subset of lakes and streams as primary AQRV's. Generally, lakes and streams with low base cation concentrations (BCC) or acid neutralizing capacity (ANC) are most likely to be affected by the lowest level of pollutant input. The federal land manager should therefore target the lowest BCC and ANC systems within a wilderness area for evaluation. An inventory of the BCC and ANC of aquatic resources in an area would provide extremely valuable and cost-effective baseline information. Among the low BCC lakes and streams, those with pH values of around 6.0 may be the most likely to change with an increased S or N loading, and should be given the most detailed attention. Typical symptoms of acidification for lakes and streams include the development of extensive mats of filamentous green algae, increased water clarity, and/or changes in

the proportional occurrence of macroinvertebrate species (Schindler et al. 1985, Hall et al. 1985, 1987). It is also important to note, however, that a shift in the pH of a lake or stream with a current value of 7.0 is also likely to cause changes in the biota.

In some wilderness areas, lakes or streams may already have pH < 6.0. In many cases these could be naturally acid rather than anthropogenically altered systems. Natural acidification is often the case where sphagnum bogs occur and runoff waters are yellow-brown stained. These waters can have high organic carbon concentrations, and therefore the natural contributions to acidity may be high. Although such naturally acid systems may contain assemblages of species that are adapted to low pH conditions, they may still be sensitive to the effects of increased N and S loading. These colored water systems require more detailed consideration.

Although the graphs presented are based on S deposition, N may, in some circumstances, also affect lake acidification. To account for the acidifying effect of N deposition, we again used an empirical approach. Generally, most N inputs are retained in the terrestrial ecosystem. The fraction that leaks out to surface water depends on a variety of site factors such as vegetation type, stage of ecosystem development, hydrology, and history of acid deposition. Large leaks of N often result from vegetation disturbance such as clearcutting, fire, and windthrow (Likens et al. 1970, Bormann and Likens 1979).

Henriksen and Brakke (1988) have shown from empirical data for surface waters in Norway that the percent of incoming N retained by the terrestrial system is generally 75-100%. Many of these lakes and streams are comparable chemically and biologically to mountainous areas in the United States. Some acidified areas have shown an increase in NO_3^- , while unacidified areas have very low concentrations of NO_3^- in runoff (Henriksen and Brakke 1988).

While there will be unusual situations where N can be released from ecosystems, a general exception is extremely sensitive high mountain lake watersheds. For such high elevation systems (BCC < 50 $\mu\text{eq/l}$), adding 25% N deposition to the S deposition is merely a guideline because the uptake will vary from site to site, and also over time at a given site. Our approach here is based on current situations measured at lakes and streams of varied sensitivity and receiving varied amounts of acid deposition both as N and S.

S and N Loadings

Current S and N loadings are necessary to locate the lake(s)/stream(s) on the nomograph (fig. 1). The S loading should be total S (wet SO_4 + dry particulate

SO_4 + SO_2 gas) and can probably be best estimated from the NADP wet deposition fields + measured SO_2 levels, combined with best estimates of deposition velocity. N loading (NO_3^- + NH_4^+) can be calculated in an analogous manner for cases (BCC < 50 $\mu\text{eq/l}$) where N is to be considered.

Illustration of Graph Use

For example, assume that lake water quality has been identified as an AQRV, and that pH was chosen as a measurement to be monitored. Lake pH, identified as an indicator of the health of the aquatic ecosystem, needs to be maintained above 5.8. This is equivalent to maintaining an ANC over 10 $\mu\text{eq/l}$ in water. Data have been collected that identify a particular lake whose base cation concentration is 80 $\mu\text{eq/l}$. The screening concept in the Aquatic Graph (fig. 1) is to be applied to this lake.

Since the lake in this example has a measured non-marine base cation sum of 80 $\mu\text{eq/l}$, the results are 3 kg S/ha/yr and 5.5 kg S/ha/yr for Green and Red Line deposition loading, respectively, if runoff is between 40-50% of precipitation. If runoff is 60-70% of precipitation, the Green Line deposition is 6 kg S/ha/yr and Red Line is 11 kg S/ha/yr. That is, if the low runoff lake would receive a total of < 3 kg S/ha including deposits from the new source, the pH of the lake would not likely drop below 5.8. The AQRV would not be adversely impacted, and the recommendation to the state regulatory agency would be for permit approval. If the low runoff lake would receive a total of \geq 5.5 kg S/ha/yr, including deposits from the new source, the pH of the lake would certainly drop below 5.8 and probably below 5.0. The AQRV would be adversely impacted, and the recommendation to the state regulatory agency would be for permit denial or permit modification, to reduce deposition from the new source to levels that would not adversely affect the lake.

Total deposition, including that from the proposed new source, between 3 and 5.5 kg S/ha-yr would have uncertain effects on the lake pH. The assessment would then require additional site-specific information indicating physical, chemical, and/or biological response to sulfur input.

Information Needs

To use the Aquatic Graph (fig. 1), the following information is needed:

- Distribution of cations, anions, ANC, and pH in wilderness lakes and streams, collected after spring runoff has receded.

- Estimates of annual runoff for watersheds containing low base cation (sensitive) systems.
- Estimates of background annual average (wet plus dry) sulfur and nitrogen deposition.
- Estimated total S and N deposition based on modeling of the proposed new source emissions.

Cautions

The aquatic Green/Red model developed at this workshop is based on an empirical relationship involving a large number of lakes and streams. These aquatic systems differ in watershed biogeochemistry and hydrology, and in their specific response to incremental additions of sulfur or nitrogen loading. The loadings themselves are based, in most cases, on estimated atmospheric values developed from models that use regional assumptions and "rules of thumb." Empirical models are best used as a screening technique to estimate the probability of a water body or group of water bodies responding to a given sulfur or nitrogen deposition rate in cases where minimal data are available. The terrestrial Green/Red Line model is equally approximate.

Empirical models are not able to predict exact results in any specific ecosystem. Because all of the assumptions in this report are conservative, a loading value below the Green Line has a low probability of causing negative effects on AQRV. However, there remain some sources of error that would cause an underestimate of the potential for wilderness acidification:

- Failure to include the most sensitive lakes or streams.
- Overestimation of average annual runoff.
- Underestimation of background S or N deposition.
- Underestimation of nitrogen assimilation and storage by watershed vegetation and litter.
- Episodic acidification due to acidic snowmelt or storm events (primarily in streams).
- Higher than normal initial concentrations of SO₄ in lakes from natural sources other than marine sources.
- Failure to correct lake cation values for marine influence or for other geological sources of Cl and associated anions.

The nitrogen loading data also do not consider possible effects of increased nitrogen on eutrophication (algal growth) and consequent low dissolved oxygen content in lakes.

If a loading appears above the Green Line, the graph indicates that the lake or stream may experience a pH below 5.8. The following factors lead to an overestimation of the effects of the predicted future loadings.

- Overestimation of background sulfur loadings due to:
 - a large component of alkaline sulfate dust.
 - overestimation of background dry deposition rates.
- Overestimation of background nitrogen loading due to:
 - overestimation of dry deposition rates.
 - underestimation of nitrogen assimilation by watershed vegetation.
- Delayed response to loadings because of:
 - high sulfate adsorption capacity of watershed soils.
 - higher than average background weathering rates.

If a loading falls above the Green Line criterion value, the manager should request data from a proponent as part of the PSD permit to determine if one or more of the above cases may apply. Determinations would involve deposition chemistry measurements (including dry deposition), watershed element budgets, analyses of watershed soils, and watershed simulation models. Such studies should be suggested or approved following consultation with scientists.

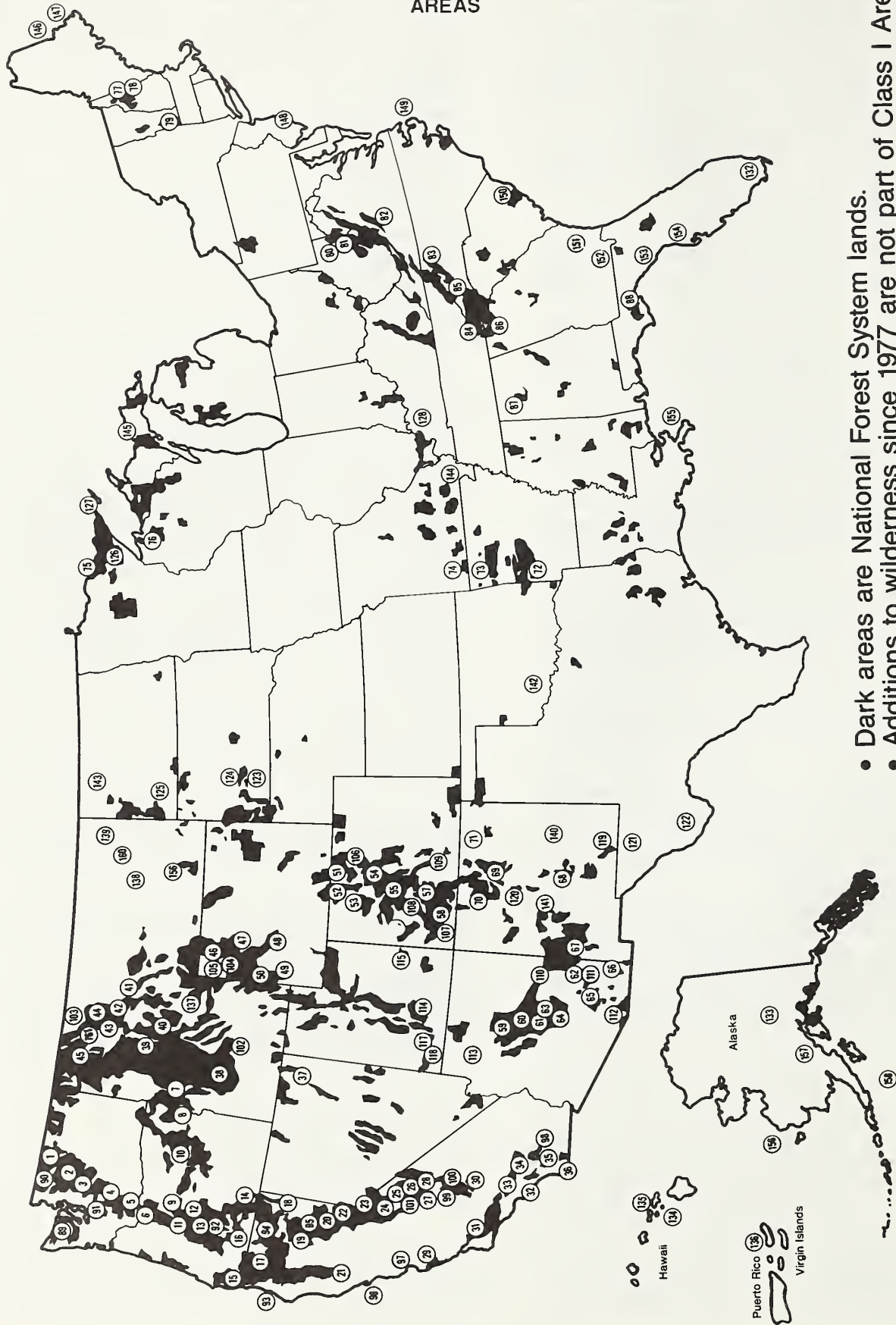
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APPENDIX A. MAP OF FOREST SERVICE CLASS I
AREAS



- Dark areas are National Forest System lands.
- Additions to wilderness since 1977 are not part of Class I areas.

Figure A-1.--USDA Forest Service wildernesses and acreages designated by Congress August 7, 1977 as Class I areas.

WASHINGTON					
1	Pasayten	505,524	53	Flat Tops	235,230
2	Glacier Peak	464,258	54	Eagles Nest	133,910
3	Alpine Lakes	303,508	55	Maroon Bells-Snowmass	71,060
4	Goat Rocks	82,680	56	West Elk	61,412
5	Mt. Adams	32,356	57	La Garita	48,486
			58	Weminuche	400,907
OREGON			ARIZONA		
6	Mt. Hood	14,160	59	Sycamore Canyon	47,757
7	Hells Canyon	See ID	60	Pine Mtn.	20,061
8	Eagle Cap	293,476	61	Mazatzal	205,137
9	Mt. Jefferson	100,208	62	Mt. Baldy	6,975
10	Strawberry Mtn.	33,003	63	Sierra Ancha	20,850
11	Mt. Washington	46,116	64	Superstition	124,117
12	Three Sisters	199,902	65	Galiuro	52,717
13	Diamond Peak	36,637	66	Chiricahua	18,000
14	Gearhart Mtn.	18,709			
15	Kalmiopsis	76,900	NEW MEXICO		
16	Mountain Lakes	23,071	67	Gila	433,690
CALIFORNIA			68	White Mtn.	31,171
17	Marble Mtn.	213,743	69	Pecos	167,416
18	South Warner	68,507	70	San Pedro Parks	41,132
19	Thousand Lakes	15,695	71	Wheeler Park	6,027
20	Caribou	19,080	ARKANSAS		
21	Yolla-Bolly-Middle Eel	109,091	72	Caney Creek	14,344
22	Desolation	63,469	73	Upper Buffalo	9,912
23	Mokelumne	50,400	MISSOURI		
24	Emigrant	104,311	74	Hercules-Glades	12,315
25	Hoover	47,916	MINNESOTA		
26	Minarets (Now Ansel Adams)	109,484	75	Boundary Waters Canoe Area	747,840
27	Kaiser	22,500	WISCONSIN		
28	John Muir	484,673	76	Rainbow Lake	6,388
29	Ventana	95,152	NEW HAMPSHIRE		
30	Dome Land	62,206	77	Great Gulf	5,552
31	San Rafael	142,722	78	Presidential Range-Dry River	20,000
32	Cucamonga	9,022	VERMONT		
33	San Gabriel	36,137	79	Lye Brook	12,430
34	San Gorgonio	34,644	W. VIRGINIA		
35	San Jacinto	20,564	80	Dolly Sods	10,215
36	Agua Tibia	15,934	81	Otter Creek	20,000
NEVADA			VIRGINIA		
37	Jarbridge	64,667	82	James River Face	8,703
IDAHO			N. CAROLINA		
7	Hells Canyon	193,840	83	Linville Gorge	7,575
38	Sawtooth	216,383	84	Joyce Kilmer-Slickrock	14,033
39	Selway-Bitterroot	1,240,618	85	Shining Rock	13,350
MONTANA			TENNESSEE		
39	Selway-Bitterroot	See ID	84	Joyce-Kilmer-Slickrock	See NC
40	Anaconda-Pintler	157,803	GEORGIA		
41	Gates-of-the Mtn.	28,562	86	Cohutta	33,776
42	Scapegoat	239,295	ALABAMA		
43	Mission Mountains	73,877	87	Sipsey	12,646
44	Bob Marshall	950,000	FLORIDA		
45	Cabinet Mountains	94,272	88	Bradwell Bay	23,432
WYOMING					
46	North Absaroka	351,104			
47	Washakie	686,584			
48	Teton	557,311			
49	Fitzpatrick	191,103			
50	Bridger	392,160			
COLORADO					
51	Rawah	26,674			
52	Mt. Zirkel	72,472			

APPENDIX B. BACKGROUND OF SAMPLE CLASS I AREAS

These descriptions were prepared jointly by scientists and managers at this workshop. The precision of these descriptions varies because the amount of information available to workshop participants was different. These Class I areas show the breadth of AQRV's considered and the diversity of approaches suggested by participants working together. Terrestrial values given each area may be the same because the different areas contain ecosystems with similar sensitivities, such as alpine areas. It is essential to consider the details of a specific Class I area being screened when applying information contained here.

Although visibility is an important AQRV in all these Class I areas, this workshop focused on the effects of air pollution on biotic systems and did not address physical impacts on visibility. In no way should the absence of visibility as an AQRV be construed as a judgment of its relative value compared to biological components.

Alpine Lakes and Glacier Peak Wildernesses - Washington

Brief Description

The Alpine Lakes and Glacier Peak Wildernesses are typical of the North Cascade mountains. The vegetation is fir, Douglas-fir, and hemlock, and precipitation is high. Soils are diverse in origin with modest fertility and moisture. This is a high mountain area with general elevation above 6,000 feet. Lakes and large perennial snow fields are common at the higher elevations. Streams peak during snowmelt runoff, but abundant year round stream flow persists.

Air Quality Related Values

Water flowing from the Cascade crest has significant value. The hydrologic system includes snowfields, glaciers, high mountain streams, small cirque lakes, cascading waterfalls, and larger streams and rivers in lower systems. The water and aquatic biota systems contribute greatly to these wildernesses. Maintaining these systems and their natural water clarity depends upon little chemical degradation or change.

These wildernesses include a wide variety of diverse plant communities and species typical of the northern Cascade range. Maintaining natural diversity

is a critical component of general health and balance of the ecosystem. Any significant change in plant communities due to the effects of air pollution would not only change the quality of wilderness experience, but also ecosystem interrelationships which contribute to wilderness values.

Much of the wilderness experience in the Cascades is influenced by sights, sounds, feelings, experiences, and even the smells the visitor encounters. In areas close to metropolitan areas, one of the significant changes for the city resident is the smell of the great out-of-doors. Whether it is a whiff of pine forest, an aroma of rain forest, or briskness of the clean, crisp high mountain air rising up and over the Cascade range, natural smell is a value only truly appreciated when it's replaced with the odor of civilization.

Hoover and Dome Land Wildernesses - California

Brief Description

Hoover. This Wilderness lies along the eastern slope of the Sierra Nevada Range in Mono County, California. It is bounded on the west by Yosemite National Park, which lies on the western slope of this Range. The area is characterized by recently glaciated canyons, composed of granitic and metavolcanic rocks. The vegetation is scattered among the rocky flats and ledges of the Sierra granite batholith.

Most soils are derived from granitic rock, are weakly developed, and are low in productivity. They are typically shallow over granitic parent material on the sloping areas, and are deeper in the canyon bottoms. They are sandy textured and low base saturation. Water quality is good to excellent, with low sediment loads in the streams. The many lakes in the high country act as natural sinks in absorbing sediments from the canyon uplands.

Scattered stands of timber grow on approximately 11 percent of the wilderness. Timber types generally are mixed conifer, with Jeffery pine and white fir dominating the lower elevations and lodgepole pine and limber pine dominating the higher elevations. Subalpine meadows occur throughout the area; riparian areas exist along the stream courses, springs, and other water influence zones. The higher elevations are dominated by subalpine and alpine shrubs and herbaceous vegetation, while elevations below the forest zones are dominated by sagebrush, bitterbrush, and mountainmahogany.

Air quality within the wilderness is excellent. Among potential threats is the possibility for NO_x, SO_x, and ozone to drift up the Toulumne valley, flow over the crest, and influence the AQRV of the area and acidify precipitation.

Dome Land: The Dome Land Wilderness is located on the southeastern slopes of the Sierra Nevada Range at the southern end of the Kern Plateau. Granite domes and unique geologic formations are the dominant features. Climatic conditions range from montane to semi-arid to desert with elevations from 3,000 to 9,700 feet above sea level. The South Fork of the Kern River flows through the wilderness.

Dome Land geography has been primarily influenced by the South Fork Kern River drainage. The wilderness is rimmed by high elevation peaks in a horseshoe configuration. Pollution may be transported up the Kern River drainage from the Bakersfield area of the San Joaquin Valley.

The Dome Land is covered mainly by mixed conifer forest. The higher elevations support primarily lodgepole and Jeffrey pine, red and white fir, and small amounts of oak and various shrubs. Small stands of limber and foxtail pine are also found at the higher elevations. A unique association of limber and foxtail pine at the southern most ends of their ranges has resulted in the establishment of a research natural area. The lower elevations support mainly pinyon, digger pine, oak, and shrubs.

Wildlife in the Dome Land is abundant. The wilderness provides summer range for the Monache and Kern River deer herds. A comprehensive species list is lacking, but other wildlife observed include quail, squirrels, chickaree, chipmunk, marten, marmot, black bear, mountain lion, and bobcat. In the 1970's California condors were sighted on several occasions.

There is light to moderate fishing within the wilderness. The heaviest fishing area is located on the South Fork of the Kern River. The rainbow trout found in the wilderness are introduced.

The Dome Land contains six major tributary streams of the South Fork of the Kern River. The general character of the wilderness is dry during the normal season of use, so these streams are very important to visitors, livestock, and wildlife. Below the wilderness, water from the South Fork is used for agriculture, recreation, electrical power, and domestic supplies. All of the Kern tributaries in the wilderness drop to a low level or become dry in late summer. Water becomes quite warm in creeks still flowing.

Soils within the Dome Land are derived from weathered granite. Most of the soil consists of coarse, sandy materials that have weathered from the barren, exposed rock that dominates the wilderness. These soils are very young, and lack the development characteristic of older soils. They are very infertile due

to coarseness, shallowness, and lack of capacity to store water. The soils are also susceptible to erosion.

Air Quality Related Values

Jeffery and ponderosa pines are prevalent above 5,000 feet. These sensitive tree species are subject to damage by ozone, and can be used as indicators of changes in plant communities. Needle retention and natural color are needed to maintain the aesthetics of these wildernesses. Limber, foxtail, and pinyon pine are also important vegetative species.

The buffering effect of meadows on water quality and quantity makes these areas very valuable for protecting the Class I areas' aquatic systems, especially the rainbow trout fisheries. Meadow condition and water quality should be maintained within current biological variability. Water quality needs to be maintained in the river and its tributaries.

The selected loadings for these wildernesses are lower than in some other wildernesses because of the presence of alpine ecosystems with limited ability to buffer additional S and N. The desire to maintain current ecosystem structure and function were primary considerations in the selection of threshold values.

The granitic domes characteristic in this wilderness should be protected.

San Gorgonio Wilderness - California

Brief Description

Geology of this wilderness is highly diverse and typical of southern California mountains. Climate is Mediterranean, and the soils are dry with base saturations about 50%. Water resources are scarce. Vegetation varies with elevation from chaparral through a pinyon-juniper and pine forest to alpine.

Air Quality Related Values

Ponderosa pine and Jeffrey pine are dominant species known to be susceptible to air pollutants, especially O₃. Symptoms of ozone injury (needle chlorosis and premature needle senescence) can be readily identified. The ponderosa pine forests in southern California often have high concentrations of pollutants present. West of the San Gorgonio Wilderness, ozone concentrations are high from May through September, with moderate concentrations at other times. Nitrogen deposition is very high, and although poorly quantified, may be an important component of the ecosystem (Riggan et al. 1985).

Water quality is important as it relates to pH, ANC, and productivity. The pH and ANC values are related to changes in acidity, which affect chemical processes and ultimately biological processes. Productivity is a general term that refers to the amount of carbon fixed on an annual basis; more N-rich systems are generally more productive. Productivity should be maintained.

Meadows are critical areas to maintain in subalpine and alpine ecosystems.

Bob Marshall Wilderness - Montana

Brief Description

The Bob Marshall Wilderness is nearly one million acres in size, located in northwest Montana in the Rocky Mountain Province. The bedrock is mostly precambrian meta-sedimentary argillites, quartzites, and limestones. Glaciation influenced the shape of the land and the composition of the soil. Soils are cool, moist, with base saturation of 25 to 50% with a volcanic ash surface ranging from 4 to 8 inches. The terrain has been influenced by glaciation, which formed high alpine basins and broad u-shaped valleys.

Precipitation ranges from 16 inches in the valley bottoms to more than 100 inches on the mountain peaks. Snow comprises over 80 percent of the precipitation at the higher elevations and 50 percent in the valley bottoms. Elevation within the area varies from 3,000 feet in the valleys to nearly 10,000 feet at the highest peaks.

Habitat types range from warm-dry ponderosa pine/bunchgrass to cool-moist whitebark pine. Subalpine fir is the dominant habitat type. The country is known for a mixture of big, open meadows and dense forest. Uncontrolled natural fire played a large part in producing a mosaic of different even-aged communities.

About 250 wildlife species and 22 fish species are found in the wilderness and surrounding national forest lands. Native fish species include bull trout, west slope cutthroat trout, mountain whitefish, and several non-game species. Big game species include elk, mule deer, white-tailed deer, moose, Rocky Mountain goat, grizzly bear, black bear, and cougar. Endangered species include the gray wolf, bald eagle, and peregrine falcon. Threatened species include the grizzly bear.

Lakes and streams are common and dependent on snowmelt. The Middle Fork and South Fork of the Flathead River flow out of the Bob Marshall. These rivers are designated Wild and Scenic and are important for rafting, fishing, photography, and domestic and other consumptive needs. Water quality is considered excellent, although water quality has not been extensively sampled.

Air Quality Related Values

Grizzly bear and west slope cutthroat trout are the key air quality related values in this wilderness. Effects of air pollutants on forage species and other critical grizzly habitat plant communities and on meadow vegetation that could change trout habitat must to be determined. This wilderness provides one of only two major grizzly bear population centers in the lower 48 states. The cutthroat is classified as a species of special concern in Montana because of declines in abundance and distribution. It is important to the wilderness visitor for both consumptive and non-consumptive uses.

Alpine and subalpine plant communities were thought to be the most sensitive to increases in N, because they are naturally stressed ecosystems and are likely to be naturally low N-consuming systems. The Bob Marshall Wilderness is in a very clean air region. Current deposition rates for N and S are probably 1 kg/ha-yr or less for each of these elements. Therefore, increases of N and S could represent large percentage increases in the quantity of these elements. This implies that tolerable increase levels are likely to be in the low end of the Yellow Zone.

Bridger Wilderness - Wyoming

Brief Description

The Bridger Wilderness is located on the west side of the continental divide in the Wind River Mountain Range. The elevation ranges from about 8,000 to over 13,000 feet on Gannet Peak, with most of wilderness above 9,000 feet. Almost all of the area is precambrian crystalline granite except for a small section of sedimentary rock in the northwest part. The area was glaciated in the past, and still contains the largest glaciers in the continental United States. Lakes are very common (roughly 1,300) and have been stocked since 1907 with all major species of trout found in North America. Since a large portion of the wilderness is above timberline, the vegetation is primarily alpine and subalpine in character. Precipitation is primarily snow, and the annual snow pack is deep. The soils are cold, wet, and shallow with base saturation below 25%. Granite or quartz rock outcrops and talus slopes are common. Perennial streams are fed by snowmelt. Groundwater flow is minimal.

Air Quality Related Values

This wilderness was originally designated as a Primitive Area in 1930 because of its unique alpine

ecosystem, with numerous cirque lakes. These lakes are the primary AQRV needing protection.

Because of the large amount of alpine vegetation, this area is potentially very sensitive to the effects of increased nitrogen deposition. The harsh climate, shallow soils, and presumed low nitrogen uptake rates of the alpine plants suggest significant changes in growth rates and species composition under conditions of even small atmospheric N deposition. The problem would be exacerbated because the exposed bedrock in the watersheds will focus large amounts of deposition into small areas of alpine meadow.

The effects of air pollution on alpine vegetation are not well known, and the interaction of pollutants with the other severe stresses acting on alpine vegetation make the problem especially complex. To improve the knowledge base, the response of species characteristic of this wilderness to ozone exposure and N and S loading should be determined. Such determinations should be performed in natural field settings which incorporate the rigor of the alpine environment. Plant communities of special concern are the primary successional plant communities near glacial margins. The chemistry and hydrology of the snowpack needs special attention because of its crucial role in maintaining the diverse plant communities.

Superstition Wilderness - Arizona

Brief Description

The Superstition Wilderness is located south of the Mazatzal Mountains about 65 miles east of Phoenix. Elevation is approximately 1,000 to 4,000 feet. The rugged, dissected landscape that rises spectacularly out of the desert has deep canyons with steep sonoran relief. Streams are ephemeral, and there are no lakes. Hydrographs are storm-dominated.

Climate is warm semi-arid and arid, with summer convection storms and occasional winter rain. Annual precipitation is 10 to 20 inches, but can vary as much as 40 percent annually. The growing season is about 280 days. Average annual temperature is 60 to 75°F.

Soils are deep, dry forest soils with base saturations above 50%. The geology includes highly diverse rock types and complex geological structures, including metamorphic, sedimentary, and intrusive and extrusive igneous rocks. The east half is proterozoic rocks that have been pervasively faulted. The west half is tertiary volcanic rocks of many different types.

Vegetation is typically open, with sonoran desert shrubs at lower elevations to interior chaparral and juniper woodland at higher elevations. Upland plants include grama grasses, creosote bush, yellow and blue

palo verde, saguaro cactus, cholla cacti, ocotillo, catclaw, beargrass, agave, yucca, mesquite, mountainmahogany, hopbush, turbinella and Emory oaks, pinyon pine, and junipers.

Air Quality Related Values

Water is scarce in the Superstitions and its availability and quality are critical to sustaining the diverse faunal populations, as well as providing water for recreationists.

Riparian species are important to the visual quality of this unique wilderness, as well as furnishing perhaps one of the most valuable wildlife habitats found in the Upper Sonoran Desert. The ability of the wilderness to support the diverse wildlife species found here would be greatly diminished without riparian areas. Riparian species include cottonwood, willow, sycamore, and numerous others.

Both the number and uniqueness of Upper Sonoran Desert plants give this wilderness its special character. To lose any of these species would be a serious loss to the wilderness. Vegetation in this type is thought to be quite resistant to environmental stress, except that vegetation growing in riparian areas may be more sensitive to O₃, SO₂, and other pollutant effects.

Joyce Kilmer - Slickrock Wilderness - North Carolina, Tennessee

Brief Description

Cove and upland hardwoods are the dominant forest types typical of this warm, humid climate that has abundant, uniform precipitation. Soils range from deep, moist, and well-developed to shallow, poorly developed, and with base saturation less than 25%. The low mountains underlain by sedimentary geology vary from 2,000 to 5,300 feet in elevation. Intermittent and perennial mountain streams are common.

Air Quality Related Values

Flora, water quality, and trout fisheries all had important roles in the designation of the Joyce Kilmer-Slickrock Wilderness, and continue to be important characteristics of the wilderness, and the experiences valued by visitors.

The floral diversity is great, with more than 60 species of trees. Most of the flora is of tertiary origin, and a number of plant species are close relatives to species in eastern Asia. Wildflowers are abundant throughout the wilderness. The Joyce Kilmer Memorial

Forest portion of the wilderness has many trees over 300 years old, some more than 20 feet in circumference and 100 feet tall. This part of the wilderness is a remnant virgin forest preserved by the Forest Service since 1935. Approximately 30% of the Slickrock portion of the wilderness is also representative of a forest in its primeval condition.

The high-quality mountain streams found in the wilderness, free of sediment with clean bottoms, cool and clear, with deep pools and numerous riffles, are rare in this part of the country. These streams have been rated by the State of North Carolina as type "C Trout" and have met State standards for use as a public water supply. Slickrock Creek is a highly productive trout stream yielding about twice as much poundage per acre as neighboring streams. "Native" (reproducing naturally in the stream) brook trout are abundant in the upper reaches of Slickrock Creek. Brown and rainbow trout are prominent in the lower reaches. Little Santeelah Creek and its tributaries are habitat for brown, brook, and rainbow trout. The trout fisheries in these streams represent a major recreation opportunity in the wilderness.

The location of the Slickrock area in the southern Appalachians and the locations of some portions of the area at elevations above 4,800 feet suggest that parts of this system currently receive relatively high loadings of S and N, as well as high concentrations of O₃ (NADP 1988). Any added loading due to new sources will move pollutant levels into the Yellow Zone or above the Red Line where granting of PSD Permits is not automatic. At the high-elevation sites, minor loadings may move pollutant levels into values above the Red Line.

Slickrock's diverse forest systems of high and low elevations require that the target loading values (Green Line values) cover a somewhat higher range than other wilderness areas. Over 90% of the area is characterized by a capacity to utilize higher loadings of N because of deep, well-developed soils of moderate sulfate absorption capacity that can tolerate higher S loadings. The remaining 10% of the area is boreal forest, which receives higher loadings due to elevational effects, and has soils, tree species, and age classes of trees sensitive to low loadings of S and N. The effect of the loss of the relatively small area of high-elevation boreal forest on downslope ecosystems is currently unknown, but hydrologic and chemical disturbances might result.

Otter Creek - West Virginia and Great Gulf - New Hampshire Wildernesses

Brief Description

Otter Creek: This 20,000 acre wilderness is located

in northeast West Virginia in an area with a cool, humid climate and abundant, uniform precipitation averaging 50 to 55 inches annually. It is located in the unglaciated Allegheny Plateau; mountainous, with elevations ranging between 1,800 feet near the mouth of Otter Creek, to 3,900 feet on McGowan Mountain. Otter Creek, a perennial stream, bisects the wilderness and a number of perennial tributaries occur throughout the area.

Waters are generally acid and low in productivity. There is a small native brook trout population in the upper reaches of Otter Creek, made possible by a demonstration project being conducted by the West Virginia Department of Natural Resources in which ground limestone is continuously added to Otter Creek just outside the wilderness boundary. Trout may also occur in the lower reaches of Otter Creek, below its confluence with Turkey Run, where limestone bedrock borders the stream. Otter Creek drains from a 6-acre open acid fen, and some tributaries (Yellow Creek and Moore Run) drain from open sphagnum/sedge/spruce swamps.

Soils are moderately deep to deep, with base saturation less than 35% (Ustisols), and 35 to 50% (Inceptosols). They are high in iron and aluminum. Forest vegetation is a mixture of northern hardwoods and Allegheny mixed hardwoods, including a component of yellow poplar, and with red spruce at the higher elevations. Rhododendron makes up understory vegetation over extensive areas. Ground and herbaceous vegetation is somewhat depauperate over most of the wilderness compared to other low-elevation mesic sites, with the exception of limited areas of limestone bedrock in which vegetation richness increases and spring wildflowers may be abundant. The area was logged between 1890 and 1915, and 200 acres of Norway spruce was later planted on the top of Green Mountain.

Great Gulf: This gulf and its tributary gulfs were hollowed out by the action of glaciers before the last ice age. One of the distinctive features of the eastern slopes of the Presidential Range, this glacial valley between Mount Washington and the Northern Peaks is from 1,100 to 1,600 feet deep. It extends easterly from Mount Washington some 3-1/2 miles as a narrow, steep-sided gulf before broadening gradually to more open terrain. It contains a number of remarkable cascades, and the views from the walls and from points on the floor are among the best in New England.

Many of the older trees have been damaged by hurricanes, but a few scattered stands of large virgin spruce remain. A small portion of the eastern part of the area, in the lower slope type, was cut over for large spruce late in the 19th century. Northern hardwoods are the typical forest at lower elevations. Alpine plants and lichens abound above treeline. Stunted spruce and

fir provide the transition between the alpine and forested areas.

A weather observatory on the 6,262-foot summit of Mount Washington, the highest point in the Northeast, just outside the southwest corner of the wilderness, has recorded the highest wind speed (231 mph) of any weather station world-wide. Wind speeds in excess of 100 mph are not uncommon. The weather is severe most of the year, and approximates conditions encountered at a much higher latitude. The summit of Mount Washington is in the clouds approximately 55 percent of the time. The effects and extent of acid cloud/fog water (pH generally less than 3.0) are currently being studied.

Air Quality Related Values

Otter Creek: Three isolated freshwater wetlands occur, with some sphagnum vegetation most commonly associated with more northern wetland areas. A 59-acre stand of virgin red spruce and hemlock remains on Shavers Mountain. Spring ephemerals, especially on the more productive sites, provide some very desirable diversity and richness. A large number of tree, shrub, and herbaceous species within the area have known sensitivity to various air pollutants (black cherry, yellow poplar, red spruce, etc.). Change in the native plant communities and associated fauna resulting from air pollution would be undesirable.

Water quality is important for drinking water by wilderness users, and for the limited cold water fishery in Otter Creek. However, water quality in Otter Creek is being artificially improved for fishery purposes by the continuous addition of ground limestone, raising the pH and alkalinity of the stream. Therefore, water quality measurements in Otter Creek are not representative of natural conditions. Without such limestone treatment, Otter Creek water in its natural condition is acid (pH 5.0) and very low in productivity (alkalinity much less than 2 milligrams per liter, and conductivity 25 μ S/cm) where it enters the wilderness. Water quality further deteriorates going downstream due to even poorer quality tributary inputs, until the neutralizing influence of limestone bedrock is encountered near the mouth of Otter Creek, where water quality improves somewhat for a fairly short reach of the stream (pH 5.8 to 6.0, alkalinity 3.1 mg/l and conductivity 31). Tributaries to Otter Creek have pH less than 4.0 and alkalinities less than 0.2 mg/l.

Great Gulf: Water quality is important for trout fisheries, and for hikers to drink and enjoy its scenic quality. Alpine flowers are rare in the Northeast and they exist in a harsh environment probably susceptible to damage from changes in soil chemistry.

Boundary Waters Canoe Area Wilderness - Minnesota

Brief Description

This second largest wilderness area (798,458 acres) under Forest Service administration sits astride the border between Minnesota and Ontario, Canada. The elevation averages 1,150 feet above sea level.

The climate is continental polar, with long cold winters and cool summers that provide only 95 frost-free days per year. Annual precipitation varies from 20 to 30 inches per year.

The bedrock underlying the Boundary Waters Canoe Wilderness is precambrian metamorphic and intrusive igneous rock, which has been glaciated only recently. The bedrock is overlaid with very thin, nutrient-poor spodosol soils of low cation exchange capacity, high in iron and aluminum, with moderately low acid neutralizing capacity, and are essentially neutral in pH.

This wilderness contains over 1,000 lakes larger than 10 acres. Three-fourths of these lakes are slightly to heavily stained a brown color from organic materials draining from the abundant peatlands in the wilderness. The pH of most of the lakes falls in the 6.6 to 8.3 range, with a mean of about 7.3. A few of the highly stained lakes have pH's as low as 5.6. Many of the lakes are sensitive, and could become acidified if acid deposition were to increase. About half have ANC's less than 130 μ eq/l and base cation concentrations below 215 μ eq/l. About 5% of the lakes in this wilderness have ANC's less than 50 and base cation concentrations below 140 μ eq/l.

Air quality at present is very good since the BWCA sits on the eastern fringe of the Canadian and United States Great Plains, which have so far sustained little industrial development. Also, the air quality standards of the State of Minnesota are substantially more stringent than the United States federal ambient air quality standards. As a result, in 1985 the Boundary Waters Canoe Wilderness sustained a measured wet deposition of only 1.4 to 2.3 kg of nitrate nitrogen, 0.2 to 0.3 kg of ammonium nitrogen, 2.3 to 3.5 kg of sulfate, and a hydrogen ion deposition of generally less than 0.1 kg per hectare per year. The annual average pH of precipitation was about 5.0. The average ozone concentration during the growing season is about 35 ppb.

Air Quality Related Values

- o High-quality waters that support a highly diverse fishery.

- o Coniferous and mixed coniferous forests that provide the critical habitat for one of the last remaining and viable eastern timber wolf populations in the continental United States.
- o Bird populations, especially bald eagles and loons.
- o Native American pictographs and buried sites.

The relatively lower than usual Green Line and Red Line values recommended for total sulfur and nitrogen deposition in this Wilderness are justified because of the substantial sensitivity of the shallow soils, the hard crystalline bedrock, and the low alkalinity of the surface waters.

Suggested factors to be considered in making a determination of Green Line (or better) conditions:

- o Based on current knowledge of species sensitivity, modelled increases in pollutant loads will, with a

high degree of certainty, result in no reduction in distribution of known pollutant sensitive tree or lesser vegetation species.

- o With a high degree of certainty, modelled increases in pollutant loads will have negligible or no impact on acid neutralizing capacity of any BWCA lake.

Suggested factors to be considered in making a determination of Red Line (or worse) conditions:

- o Based on current knowledge of species sensitivity, modelled increases in pollutant loads will result in either complete elimination or reduce distribution of at least one tree or lesser vegetation species.
- o Modelled increases in sulfate or nitrate deposition will result in complete elimination of acid neutralizing capacity from one or more lakes.

APPENDIX C. OTHER AQUATIC MEASUREMENT METHODS

Loading/Response Relationships

The acidification of lakes has been considered to be analogous to the titration of a bicarbonate solution (acid neutralizing capacity, ANC) with acidic (sulfuric acid) atmospheric deposition (Henriksen 1979). When additions of acid consume ANC, pH decreases slowly at first, then more markedly as ANC is depleted (Small et al. 1988). Acidic deposition may also increase the weathering of base cations and not result in an equivalent consumption of ANC for each equivalent of acid deposited (Henriksen 1984). Lake ANC is produced from watershed weathering and exchange reactions. These reactions generate equivalent amounts of bicarbonate and base cations. Lake ANC can also be produced from in-lake processes, such as Ca exchange with sediments, and biologically mediated removal of nitrate and sulfate (Schindler 1986). The relative importance of in-lake versus watershed sources of alkalinity and the relationship between acid deposition and enhanced weathering of base cations is known for only a few ecosystems. These additional mechanisms, which act to reduce the effect of acidic deposition, cannot be included in a conservative estimate of the relationship between deposition amount and ecosystem impacts.

Our approach is analogous to the Henriksen empirical model where deposition amount, lake sensitivity (sum of base cations), and the results of lakes surveys are used to empirically derive, for lakes of a given sensitivity and deposition level, where the system will experience ANC decline and pH depression. We assume that in-lake alkalinity generation and enhanced weathering of base cations is negligible.

Graph Construction

Figures C-1 and C-2 show, for various deposition levels, the concentrations of non-marine Ca+Mg+K+Na in lakes having ANC of 10 to 25 $\mu\text{eq/l}$ and pH values of about 5.9 to 6.2, and in lakes with ANC between -20 and -5 and pH of about 4.8 to 5.2. Figure C-1 shows the Green Lines for these. The Green Lines indicate the deposition level below which lakes with various base cation concentrations should maintain ANC of at least 10 to 25 $\mu\text{eq/l}$ and pH of at least 5.8 to 6.2. Figure C-2 shows Red Lines. If subjected to a particular deposition level, lakes with base cation concentrations

less than those indicated by the Red Lines can be expected to become acidic with ANC falling below zero and pH reaching 5.2 or less.

The graphs are based on the assumption that, while lake HCO_3 decreases and is replaced by SO_4 in response to increasing S deposition, base cation concentrations do not change. In fact, as deposition increases, mineral weathering of base cations from the watershed may increase somewhat (Henriksen 1984). As a result, lakes with a given base cation concentration may be able to withstand a somewhat greater increase in S deposition than indicated by the nomographs. In-lake alkalinity production may also reduce the impact of S deposition (Schindler 1986). Because these effects are uncertain in magnitude and probably do not occur in all lakes, we have taken the conservative approach of protecting the lakes and have assumed that these processes are not significant.

The amount of runoff relative to the amount of precipitation on a watershed affects how lake chemistry responds to acid loadings. As more precipitation is lost to evapotranspiration and less is yielded as runoff, acid deposition is, in effect, concentrated, and its impact on a lake is greater. Consequently, the graphs show several Red and Green Lines for various amounts of runoff, expressed as percentages of annual precipitation.

N deposition is included for very low ANC (<50 $\mu\text{eq/l}$) waters in the western United States. The rationale for including N is based on observations that most N deposited on a watershed is retained in the watershed. At most, about 20% can be seen in surface waters. This is explained in the text. Deposition loading was determined as outlined in the surface water sensitivity section, page 12. Essentially, total deposition was determined by combining wet deposition data with dry deposition estimates. In the east, dry deposition was estimated to be 30% of wet deposition, while in the west dry deposition was assumed to be zero.

Within about 125 miles of the sea coast, precipitation contains significant amounts of sodium, magnesium, chloride, and sulfate and lesser amounts of other ions of marine origin. These ions increase the base cation concentration of lakes in these areas without adding HCO_3 or ANC. To correct for this effect, we assume that all chloride (Cl) in such lake water is from marine sources, and subtract from the base cation concentration an amount in proportion to the relative concentrations of Cl and base cation in seawater (Hem 1970).

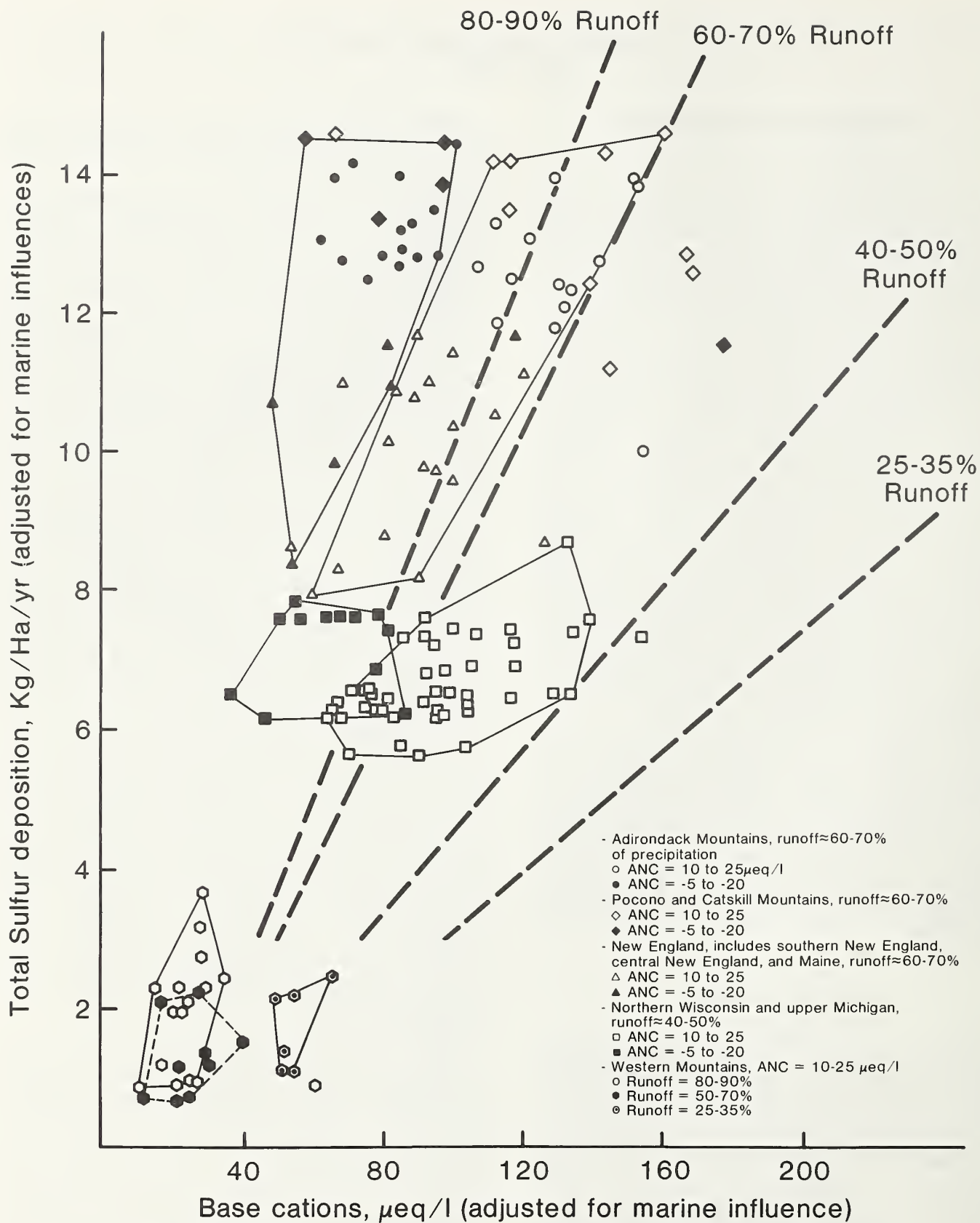


Figure C-1.--Base cations/deposition relationship for Green Lines. Lakes to the right of the appropriate runoff lines are not considered to be acidic. (Data from Kanciruk et al. 1986 and Eilers et al. 1987.)

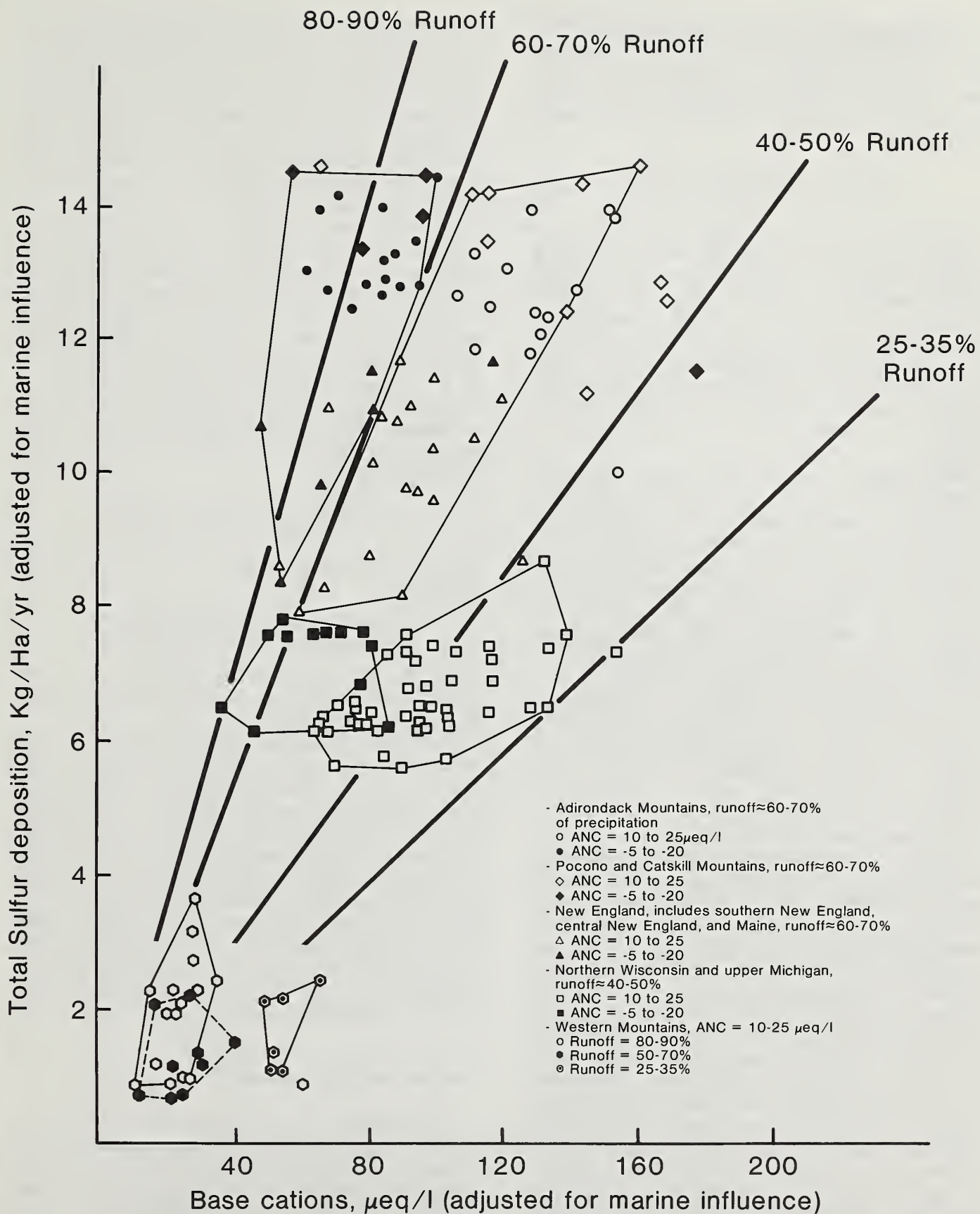


Figure C-2.--Base cations/deposition relationship for Red Lines. Lakes to the left of the appropriate runoff lines are likely acidic. (Data from Kanciruk et al. 1986 and Eilers et al. 1987.)

Inland lakes generally have low concentrations of Cl and Cl-associated base cations, but natural geologic sources and contamination by road salt may increase them. The base cation concentration of these lakes also must be corrected for this influence. This is done by assuming:

$$\text{Non-marine Ca+Mg+K+Na} = \text{Total Ca+Mg+K+Na} - (\text{Cl} \times 1.115)$$

Concentrations of all ions are expressed in $\mu\text{eq/l}$.

Lake SO_4 generally increases with increasing S deposition, but natural geologic sources also contribute variable amounts of SO_4 to lakes (Loranger and Brakke 1988, Eilers et al. 1987). Base cations associated with geologic SO_4 add significant variability to the ANC:base cation relationship. In figures C-1 and C-2, much of the scattering of data points for any given deposition level and runoff percentage can be attributed to geologic SO_4 and associated base cations.

This approach is similar to the so-called Hendriksen model, which has been shown to have limitations (Reuss et al. 1986, Vertucci in press). However, the Red Line values used here are based on an empirical fit to the data on acidified lakes. The Green Line values essentially represent a simple balance of increased sulfate (and nitrate) against ANC. This is an approximation that Wright (1988), among others, suggests can be improved by the introduction of a factor "f" representing the ratio of change in base cation concentration to net sulfate (that attributable to anthropogenic sources). The model here assumes f to be zero. A nonzero f would make the Green Lines steeper. Since this is intended as a worst case screening technique that errs on the side of conservatism, and actual f values are unknown, we felt it was appropriate to use an f factor of zero.

In cases where little cation data exist, conductivity was considered as an alternate measure of sensitivity. Since conductivity is easily and cheaply measured in the field, conductivity data may be more widely available for surface waters than are cation data. Easy and cheap don't necessarily equate with accurate, however, and field conductivity data must be closely screened to ensure reliability. Electrical conductivity (usually expressed as $\mu\text{Siemens/cm}$ at 25 degrees C) is a measure of the total amount of ions dissolved in the water. Consequently, conductivity is related to the sum of the base cations and anions. Waters that are inherently sensitive to acid deposition have little buffering or acid neutralizing capacity, low concentrations of base cations, and low conductivity.

Figures C-3 and C-4 are similar to C-1 and C-2, but show lake conductivity in place of base cation concentration as a measure of lake sensitivity. Because conductivity is an indicator of the total

concentration of ions dissolved in the waters, it is used as a substitute for the base cation concentration. Since the contribution of SO_4 and HCO_3 to conductivity are about the same, we assume that the conductivity of a lake does not change with increasing S deposition. As with figures C-1 and C-2, we ignore the fact that base cations, and consequently conductivity, may increase somewhat at greater deposition levels, due to increased mineral weathering.

As with base cations, conductivity must be corrected for marine influences. This correction is even more critical for conductivity, because conductivity is influenced not only by the ocean-derived base cations, but also by the Cl and SO_4 . In addition to the adjustments for marine contributions, conductivity must also be corrected for hydrogen ion (pH) influences. In acidic waters, hydrogen contributes heavily to conductivity, and this contribution must be subtracted. All the lake conductivity data in figures C-3 and C-4 are corrected for both pH and marine influences. This is done by assuming:

$$\text{Non-marine conductivity} = \text{measured conductivity} - (\text{Cl} \times 0.1422)$$

with Cl expressed in $\mu\text{eq/l}$ and conductivity in $\mu\text{Siemens}$.

$$\text{Adjusted conductivity} = \text{measured conductivity} - (\text{H} \times 0.34965)$$

where H is the hydrogen ion concentration in $\mu\text{eq/l}$ ($\text{H}=10$ raised to the -pH power, then that quantity multiplied by 1,000,000).

Differences in natural sources of SO_4 add much variation to the ANC:conductivity relationship. This effect is greater than that on ANC:base cations because both SO_4 and the associated base cations contribute to conductivity. For any particular deposition level and runoff percentage, the scatter among the data points and the overlap between groups of acidic and non-acidic lakes is greater in figures C-3 and C-4 than in C-1 and C-2. Therefore, base cations rather than conductivity should be used as a measure of lake sensitivity where cation data are available. Conductivity is useful as a rough tool to separate lakes into non-sensitive and possibly sensitive groups.

Detailed Information Needs

Surface water chemistry data can be collected by means of special purpose surveys, by census, or by estimating values based on previous surveys in similar geographic terrains. As an example of the last approach, an approximate characterization of the surface water chemistry of seven of the nine wilderness ecosystem types is presented in table C-1.

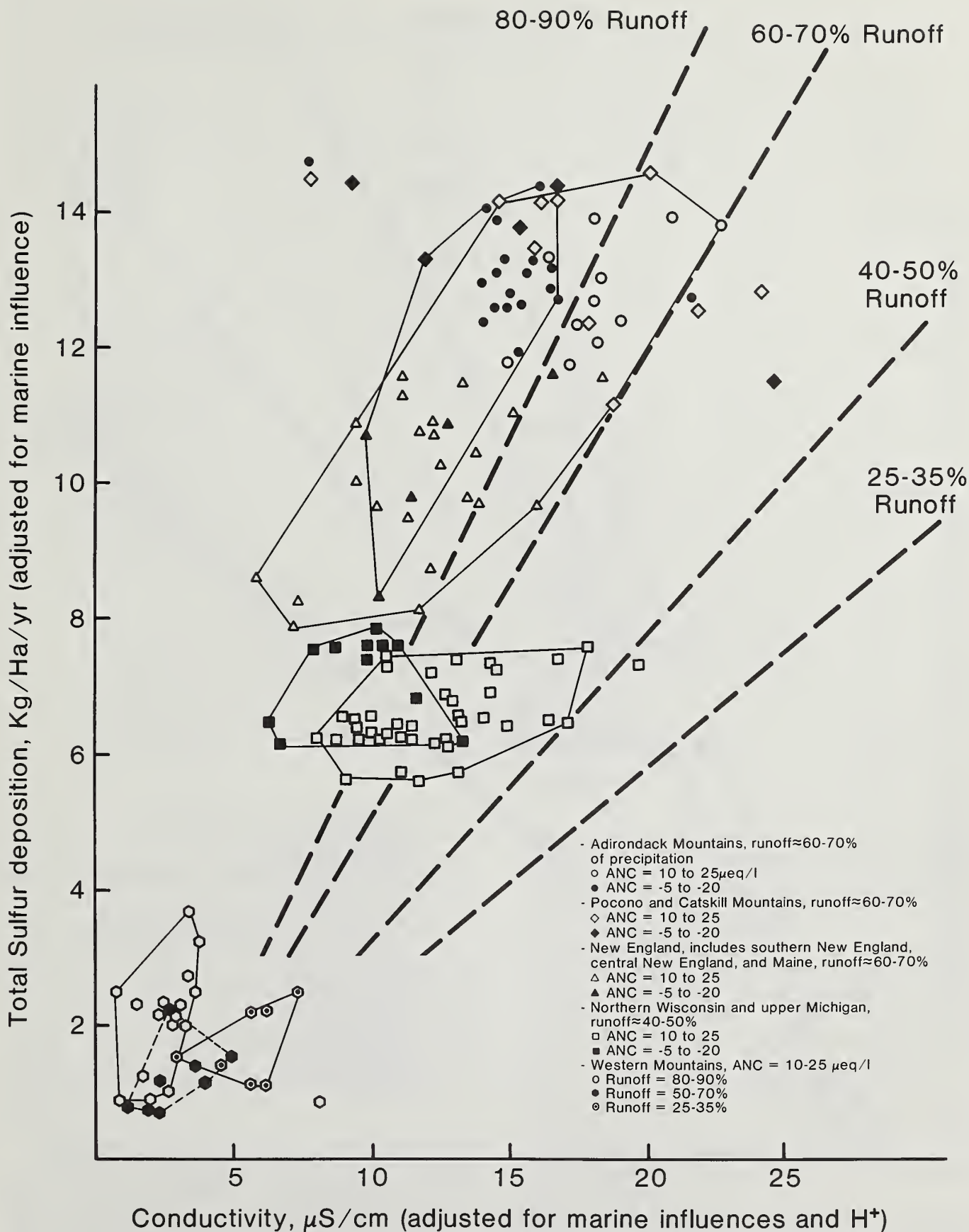


Figure C-3.--Conductivity/deposition relationships for Green Lines. Lakes to the right of the appropriate runoff lines are not considered acidic. (Data from Kanciruk et al. 1986 and Eilers et al. 1987.)

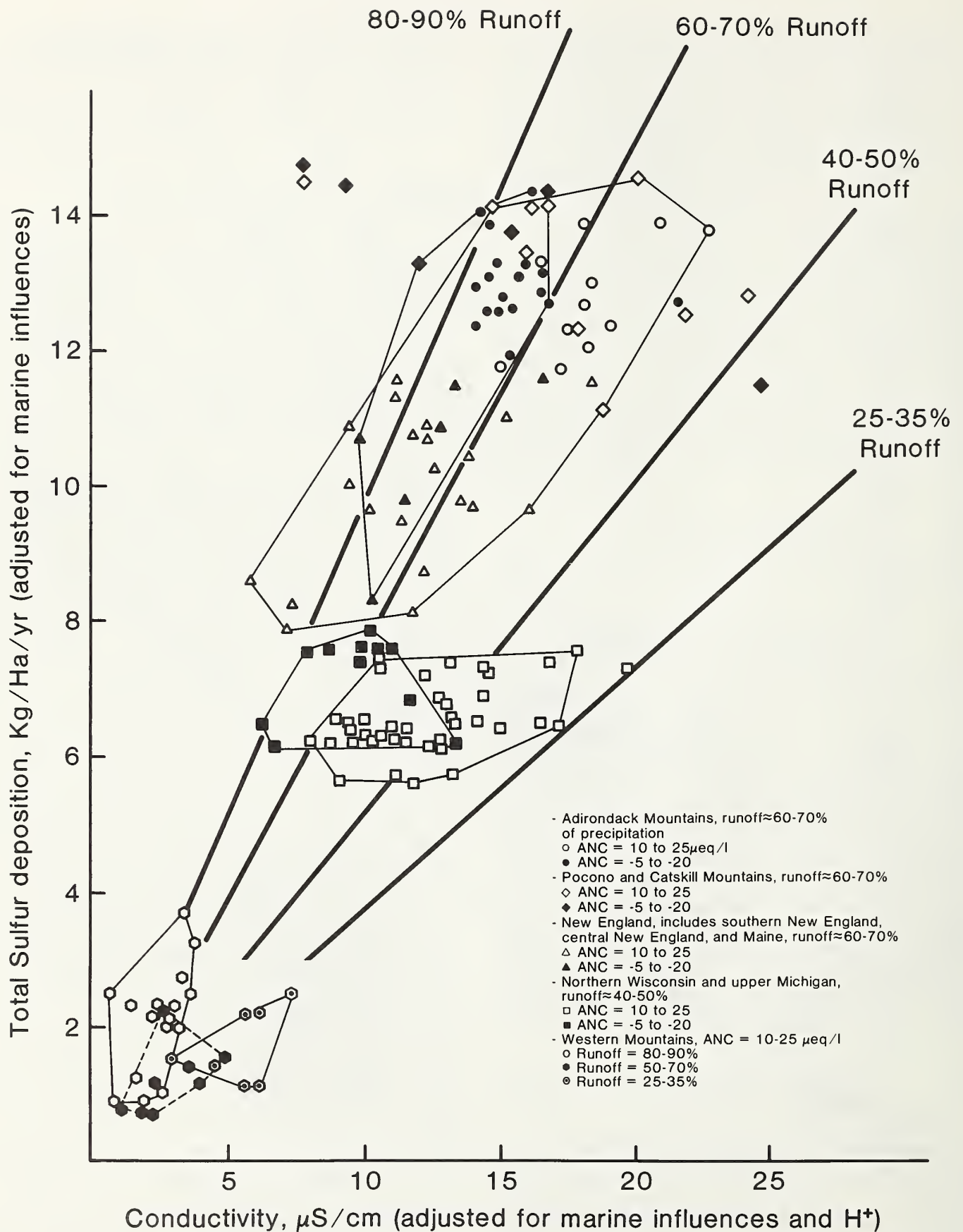


Figure C-4.--Conductivity/deposition relationships for Red Lines. Lakes to the left of the appropriate runoff lines are likely acidic. (Data from Kanciruk et al. 1986 and Eilers et al. 1987.)

Table C-1.--Conductivity and neutralizing capacity, and pH statistics for geographic regions represented by seven wilderness ecosystem types.

Wilderness area and NSWS region	Chemical factor								
	Conductivity			ANC			pH		
	Min.	Q ₁	Med.	Min.	Q ₁	Med.	Min.	Q ₁	Med.
	<i>μS/cm</i>			<i>μeq/l</i>					
Alpine Lakes, Glacier Peak (PNW ¹)	>2	9/6	14/4	>4	54/52	196/105	>5.8	6.6	6.9
Hoover, Dome Land (SNM ²)	>2	5	8	7/13	34	60	>5.8	6.6	7.0
Bob Marshall (NR ³)	>3	9	39	72	77	342	6.3	6.9	7.1
Bridger (ALP ⁴)	>7	12	15	39	74	109	>5.8	6.9	7.1
Joyce Kilmer, Slickrock (EHW ⁵)	10	14	21	16	87	120	6.4	6.8	7.0
Otter Creek, Great Gulf (NH ⁶)	19	33/22	69/35	-48	20/52	110/119	4.4	5.7/6.3	6.6/6.8
Boundary Waters Canoe Water Area (C ⁷)	18	22	30	34	98	185	5.6	6.6	6.9

1WLS Pacific NW, Middle Washington and Wenatchee Mtns.

2WLS California, Sierra Nevada.

3WLS Northern Rockies, Lewis Range.

4WLS Central Rockies, Wind River.

5NSS Southern Blue Ridge.

6NSS N. Appalachians, ELS C. New England.

7ELS NE Minnesota.

WLS = EPA Western Lake Survey.

ELS = EPA Eastern Lake Survey.

NSS = National Stream Survey.

These data are based on the National Surface Water Survey (NSWS), which measured the chemistry of a large statistical sample of lakes and streams in regions of the United States. expected to have surface water with low acid neutralizing capacity. In several cases (such as the Bridger Wilderness), many lakes were sampled. In most cases, however, only a few lakes or streams were actually included. As an approximation, the chemical data in table C-1 were aggregated to include the geographic units nearest to exact wilderness that approximate the geology of the corresponding regions, based on the NSWS data. No data were collected in southern California nor in Arizona.

Half of the lakes or streams in each region are expected to fall below the median value for each region. Twenty percent of the systems are expected to fall below the first quintile (Q₁). Minimum values represent the lowest value observed in the sample, and do not necessarily represent the lowest lake or

stream in the region. Lake chemistry was measured following fall overturn. Stream chemistry was sampled in the spring between snowmelt and leaf-out, avoiding rain storms. Streams affected by acid mine drainage and polluted lakes were avoided.

These data are statistically valid randomly selected samples of water quality in all areas. To obtain a better estimate of the true chemistry distributions in a particular wilderness, a random sample of approximately 50 lakes can generally give acceptable confidence bounds if the area is not too heterogeneous. If 50 represents less than 5% of the total population of lakes, or if the area is highly diverse, a larger sample size may be needed to reduce uncertainties in the estimates. Field sampling, while inexpensive, must follow protocols for wilderness areas (Fox et al. 1987).

Annual runoff can be calculated from estimated precipitation and evapotranspiration measurements on site, or measured at a gauged stream site in the region

of interest. In the absence of such data, published values of mean annual runoff from state and federal agencies in state water atlases and other publications can be used. Annual variations in runoff are not a significant concern in using figure 1, provided long term data are available.

Dry deposition of sulfate and nitrate are often estimated from obtaining wet deposition data from the nearest National Acid Deposition Program (NADP) site. As a rule of thumb, in rural areas removed from point sources of pollution, dry deposition of sulfur can be assumed to equal 30% of the wet deposition value. Dry nitrogen deposition may be somewhat greater than the wet value. These factors are subject to considerable local variations, including impaction of particles on dry surfaces, and adsorption of gaseous species (SO_2 and HNO_3) by moist surfaces, including lakes and the open stomata of vegetation. If air concentration data of S and N are available, dry deposition can be calculated using assumed values of deposition velocity taken from the Air Resource Handbook. Still more desirable are dry deposition estimates from a nearby NDDN (National Dry Deposition Network) site. These are currently being installed throughout the United States.

Conversion of Deposition Values

Deposition loadings are presented in kg/ha-yr of S and N. Deposition measurements are often reported as deposition of SO_4 and NO_3 in $\text{mg/m}^2/\text{yr}$. Land managers may also be familiar with applications of S and N in lb/A/yr. The following conversion factors may be useful:

Multiply S deposition by 3.0 to determine SO_4 deposition

Multiply N deposition by 4.43 to determine NO_3 deposition

Multiply kg/ha by 0.89 to determine lb/A

Multiply kg/ha by 100 to determine mg/m^2

Multiply kg/ha by 0.1 to determine g/m^2

To convert from mg/l to $\mu\text{eq/l}$, multiply mg/l of Ca by 49.90, Mg by 83.26, K by 25.57, Na by 43.50, Cl by 28.21, and SO_4 by 20.82.

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Rocky
Mountains



Southwest



Great
Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526