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Guidelines for Evaluating Air Pollution Impacts on Wilderness Within the Rocky Mountain Region: Report of a Workshop, 1990

Abstract

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This document is the product of an ongoing effort begun at a 4-day workshop sponsored by the Rocky Mountain Region of the USDA Forest Service, held in December 1990 in Estes Park, Colorado. Workshop participants gathered in groups to work on pollution impacts in three specific areas: aquatic ecosystems; terrestrial ecosystems; and visibility. Because the groups met separately and subsequently worked independently, the reports they generated differ considerably in format and style. They all focus, however, on providing the Forest Service with information that may be used to identify and develop sensitive receptors and limits of acceptable change for assessing air pollution impacts on air quality-related values in wildernesses within the Rocky Mountain Region of the Forest Service. The reports also address needs and recommendations relating to modeling or predictive techniques, monitoring, and research.

Keywords: air quality, air pollution, wilderness, aquatics, visibility

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Cover photo of Continental Divide across Forest Canyon in Rocky Mountain National Park by Lane Eskew

Guidelines for Evaluating Air Pollution Impacts on Wilderness Within the Rocky Mountain Region: Report of a Workshop, 1990

Dennis Haddow, Robert Musselman, Tamara Blett, and Richard Fisher, Technical Coordinators

Contents

Acronyms

ANC	Acid neutralizing capacity
AQRV	Air quality-related value
BACT	Best available control technology
BART	Best available retrofit technology
BLM	Bureau of Land Management
EPA	Environmental Protection Agency
FLM	Federal land manager
GIS	Geographical information systems
ILWAS	Integrated Lake Watershed Acidification Study Model
IMPROVE	Interagency Monitoring of Protected Visual Environments
jnc	Just noticeable change
LAC	Limit of acceptable change
LD50	Lethal concentration for 50% of individuals; standard measure of toxicity
MAGIC	Model of Acidification of Groundwater Catchments
NADP	National Atmospheric Deposition Program
NAPAP	National Acid Precipitation Assessment Program
NPS	National Park Service
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PLUVUE	Plume visibility model
PM2.5	Particles smaller than 2.5 m in diameter
ppm	Parts per million
PREVENT	Pacific Northwest Regional Visibility Evaluation Using Natural Tracers
PSD	Prevention of Significant Deterioration
QA/QC	Quality assurance/quality control
RAIN	Reversing Acidification in Norway
TOPMODEL	A variable source area import hydrologic model
USDA	U.S. Department of Agriculture
USFS	USDA Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VISCREEN	Visibility Screening Model
VOC	Volatile organic compound
WHITEX	Winter Haze Intensive Tracer Experiment
WLS	Western lake survey
DE	Plume perceptibility - color contrast change between a plume and its background

Chemicals and Associated Terms

Al	Aluminum
Al^{+n}	Positively charged aluminum ion
Al_m	Monomeric aluminum species
A_s	Arsenic
C	Carbon
C_A	Sum of base anions
Ca	Calcium
Ca^{2+}	Calcium ion
C_B	Sum of the base cations
Cd	Cadmium
CH_3Hg	Methyl mercury
Cl^-	Chloride
CO_2	Carbon dioxide
Cu	Copper
D D	euterium
DO	Dissolved oxygen
F	Fluoride
H^+	Hydrogen ion
HF	Hydrogen fluoride
Hg	Mercury
HgS	Mercuric sulfide, cinnabar
HNO_3	Nitric acid
H_2SO_4	Sulfuric acid
K	Potassium
Mg	Magnesium
mg	milligrams
Mn^{2+}	Divalent manganese ion
N	Nitrogen
Na	Sodium
ng	Nanograms
NH_3	Ammonia
NH_4^+	Ammonium ion
NO_2	Nitrogen dioxide
NO_3^-	Nitrate ion
NO_x	Nitrogen oxides
O_2	Oxygen
O_3	Ozone
^{18}O	Isotopic oxygen
P	Phosphorus
Pb	Lead
P_{CO2}	Partial pressure of CO_2
pH	Negative log (base 10) of the hydrogen ion concentration, a measure of acidity or alkalinity in water
PO_4^{3-}	Phosphate ion
S	Sulfur
Se	Selenium
SO_2	Sulfur dioxide
SO_4^{2-}	Sulfate ion
Zn	Zinc

1. INTRODUCTION

In December 1990, the Rocky Mountain Region of the USDA Forest Service conducted a workshop in Estes Park, Colorado, to exchange facts and information for consideration by the Forest Service in evaluating air pollution impacts to wilderness areas within the Region. The information and opinions contained in this report along with any other relevant information obtained since the workshop was conducted will be used on a case-by-case basis by the Region to determine the acceptability or non-acceptability of air pollution impacts to the Region's wildernesses.

The goal of the workshop was for National Forest Managers, other federal land managers, air regulatory agencies, research scientists, and interested publics to conduct a workshop to exchange facts and information for consideration by the USDA Forest Service in identifying evaluation procedures for air pollution impacts to Wilderness within the Rocky Mountain Region.

The objectives of the workshop were as follows:

1. Compile a workshop report that represents a survey of facts and information that the Forest Service can consider along with subsequently obtained information to identify evaluation procedures and modeling techniques appropriate to predict, on a case-by-case basis, if existing or proposed air pollution sources will result in adverse impacts to wilderness. (Although consensus among participants was not discouraged it was not an objective of this workshop because the report was to represent a range of facts and information provided by the participants.)

2. Identify and prioritize any additional monitoring of air quality related values that should be conducted by the Forest Service within the Rocky Mountain Region to meet the following needs:

    - Develop information about which wildernesses within the Rocky Mountain Region have the greatest potential for air pollution impacts.

    - Add to the current base of information about sensitive receptors having potential for air pollution impacts. Identify additional sensitive receptors as needed, determine the current condition of these sensitive receptors, and determine change in these sensitive receptors attributable to existing air pollution in selected wildernesses.

    - Identify or refine evaluation procedures identifying change to sensitive receptors.

    - Develop a more complete information base about sensitive receptors in wilderness, to be able to better meet the needs of the air regulatory process.

3. Identify research needed within the Rocky Mountain Region to help meet the monitoring needs of Objective 2, above.

It must be noted that this report is not a binding document and leaves the Forest Service and its decisions makers free to exercise discretion and formulate policy on a case-by-case basis with respect to air quality related values, sensitive receptors, and limits of acceptable change.

Since the 1990 Workshop, new information not included in this report has become available that is used in the identification and protection of AQRVs and in the determination of LACs. This document is presented as a resource of background information available at the time of the 1990 Workshop.

The Role of the Forest Service

The USDA Forest Service, as a federal land manager of 88 Class I wilderness areas, is directly involved in implementation of the Prevention of Significant Deterioration (PSD) program. The Clean Air Act gives "... an affirmative responsibility to protect the air quality-related values (including visibility) of any such lands within a Class I area and to consider, in consultation with the Administrator, whether a proposed major emitting facility will have an adverse impact on such values." Examples of AQRVs in wilderness areas are listed in table 1.

Wilderness management premises

Workshop participants were provided with the following principles related to air quality and wilderness:

1. Wilderness is not merely a commodity for human use and consumption. Wilderness ecosystems have intrinsic values other than user/public concerns.

2. The objective of wilderness management is to offer a natural experience, rather than an enjoyable one. The amount of enjoyment is purely a personal matter for the individual user to decide.

3. All wilderness components are equally important; none is of lesser value than any other.

4. A wilderness component is important even if users of the wilderness are unaware of its existence.

5. All life forms are equally important. For example, microorganisms are as essential as elk or grizzly bears.

6. The goal of wilderness management is to protect not only resources with immediate aesthetic appeal (i.e., sparkling clean streams) but also unseen ecological processes (such as natural biodiversity and gene pools).

7. The most sensitive wilderness components are to be emphasized more than those of average or normal sensitivity. Sensitivity is generally determined by inertia (resistance to change), elasticity (how far the component can be "stretched" from its natural condition without being permanently modified), and resiliency (the number of times it can revert to its natural condition after experiencing human-caused change).

8. Each wilderness component is important in itself, as well as in terms of how it interacts with other components of the ecosystem. That is, the individual parts of the wilderness ecosystem are as significant as the sum of the parts.

9. The physical components of the ecosystem (for instance, lake chemistry) are as essential as its biological constituents (i.e., salamanders).

10. Wilderness components are to be protected from "human-caused change" rather than from "damage." Terms such as "damage" and "harm" are prejudicial, whereas "human-caused change" is value-neutral. (For example, deposits of nitrogen in a lake from nitrogen oxide, a common air pollutant, might result in more plant growth and bigger fish. This would, however, be an unnatural—and therefore unacceptable—change in the aquatic ecosystem.)

11. The goal of wilderness management is to protect natural conditions, rather than the conditions when first monitored. That is, if initial monitoring in a wilderness identifies human-caused changes, appropriate actions should be taken to remedy them to restore natural conditions.

12. The designation of a wilderness as Class I or II does not dictate the management goals for it; these are identified in the Wilderness Act. The designation only determines which options are available to meet the goals. Class I wildernesses, for instance, can be protected through the specific AQRV analysis provided for in PSD permitting regulations, whereas the protection of Class II wildernesses can be achieved using BACT requirements.

13. While it may not be possible to manage every wilderness in a natural or near-natural state, each should be managed in as pristine a condition as the specific (local) biophysical, legal, scientific, and social/political situation will allow. That is, the Region will do the best job possible of wilderness management, based on local constraints and opportunities. The extent of actual wilderness protection, therefore, may vary.

14. Although monitoring is critical to any PSD decision, it must not interfere needlessly with wilderness. For example, in mountain ranges or other geomorphic units of which only part is wilderness, much of the most intrusive monitoring and instrumentation should be conducted in the adjacent nonwilderness—if such areas adequately represent the wilderness of concern. Often, however, western wilderness occupies an entire high-elevation area for which there is no truly representative nonwilderness subjected to the same atmospheric deposition from a proposed source.

15. Limits of acceptable change (LACs) should be conservative. For use in this document, LACs are defined as those changes in the physical, chemical, biological, or social condition of an air quality related value that can occur without a loss of wilderness character. In the case of uncertainty, LACs should be identified to be over-protective rather than under-protective of wilderness. However, if for a specific wilderness any party can provide clear and convincing information which demonstrates that the selected LAC is either too restrictive or too lax, the LAC will be modified.

Workshop format

It was the intent of the Estes Park workshop to develop guidelines for use by Region 2 Forest Service managers in fulfilling their responsibilities to protect AQRVs related to aquatic and terrestrial ecosystems and visibility. The participants at the workshop were divided into three groups to address these three areas. The mission given the workgroups was to:

1. Develop a document that represents a survey of facts and information which the Forest Service can use to identify evaluation criteria and modeling techniques appropriate to predict if existing or proposed air pollution sources will result in adverse impacts on wilderness.

2. Identify and prioritize any additional monitoring of air quality-related values that should be conducted by the Forest Service within the Rocky Mountain Region to meet the following needs:

   - Develop information about which wildernesses within the Region are the most vulnerable to air pollution impacts.

- Add to the current base of information about sensitive receptors having potential for air pollution impacts. Identify additional sensitive receptors as needed, determine the current condition of these sensitive receptors, and determine change in these sensitive receptors attributable to existing air pollution in selected wildernesses.

3. Identify research needed within the Rocky Mountain Region to help meet the monitoring needs in item 2, above.

Within the context of the PSD process and legislated programs authorizing protection, AQRVs are defined as any wilderness component that can be modified by human-caused air pollution. Examples include flora, fauna, soil, water, visibility, and cultural objects. Practically speaking, this concept of AQRVs is sufficiently broad as to encompass virtually any aspect of wilderness.

To determine whether AQRVs may be adversely impacted, it is necessary to identify sensitive receptors that can provide a measure of change related to air pollution impacts. Sensitive receptors may be specific objects, processes, attributes, or species within the broader categories of AQRVs. It is important that sensitive receptors have the following characteristics:

- They must be able to be detected, monitored, and measured;
- They must be sensitive and directly responsive to change; and
- Changes in receptor behavior and response can be modeled and predicted.

Limits of acceptable change are identified relative to certain attributes of sensitive receptors. They are the criteria the Region will use to determine if existing or potential air pollution impacts on wilderness are acceptable or not. LACs are not air pollution or atmospheric deposition standards. LACs are numbers that represent an anthropogenic change in a physical, chemical, or biological component of the ecosystem or the visibility within wilderness. The acceptable change needs to be small enough to prevent deterioration of the wilderness resource, but large enough so as not to unnecessarily hinder development within the range in which wilderness resources can easily coexist. It must be noted that this document represents only one source of information that the Region will use to identify LACs and that any recommendations, definitions, or opinions contained in individual work group reports are not binding on the Forest Service.

Table 1 provides a general identification of AQRVs with examples of sensitive receptors and pollution-caused changes for which acceptable limits of change could be defined.

The individual work group reports present the perspectives of each group and their efforts to identify sensitive receptors and limits of acceptable change. Each report further addresses needs and recommendations relating to modeling or predictive techniques, monitoring, and research.

Table 1. Examples of air quality-related values, sensitive receptors, and potential air pollution-caused changes.

Air quality-related values	Sensitive receptor examples	Potential air pollution-caused changes
Flora and fauna	lichens, zooplankton, subalpine fir, mosses, raspberry	rate of growth, mortality, reproduction; direction of succession; amount of visible injury, genetic diversity, productivity, and abundance
Soil	alpine soils	cation exchange capacity, base saturation, pH, structure, metals concentration
Water	vernal pools, alpine lakes, deposition of rain/snow	total alkalinity; pH; concentration of anions, cations, metals, and dissolved oxygen
Visibility	high-use vista	contrast, visual range, coloration
Biological diversity	diatoms	loss or depletion of a species
Cultural-archaeological and paleontological	cave drawings	decomposition rate
Odor	wilderness user	anthropogenic odors

2. AQUATIC ECOSYSTEMS

By Jill Baron and John Turk

Perspective

This section presents recommendations of the Aquatic Ecosystems Group. We discussed the state of our understanding of processes by which ecosystems respond to air pollutants, the possibility for future threats, and the monitoring and research needs for Region 2 wilderness areas.

The group felt fortunate in being able to take advantage of the results of the 10-year National Acid Precipitation Assessment Program (NAPAP). As a result of NAPAP, there has been a large increase in understanding of aquatic ecosystem processes and organismal response to pollutants. Several members of the group have been active participants in NAPAP-funded research and were able to bring their expertise to bear on the questions of maintaining aquatic resource integrity in wilderness areas.

Aquatic ecosystems in wilderness areas include watersheds, lakes, streams, springs and groundwater, riparian areas and wetlands, ephemeral surface water (such as vernal pools), wet cave environments, and glaciers.

There was consensus that the chemical composition of different types of precipitation (snow, rain, fog, clouds, rime ice) can provide early and sensitive detection of the presence of many airborne pollutants. The chemical composition of lakes and streams was thought to be a good indicator of air pollutants, although the effective use of surface water chemistry requires a good understanding of annual biogeochemical variation. This is not common knowledge for most wilderness areas. Organisms or whole communities in lakes and streams can be good indicators of change due to airborne pollutants, although these again require foreknowledge of the natural variation inherent in Rocky Mountain aquatic populations, the sensitivity of individual species to each pollutant type, and possibly the sensitivity of communities (inferred by pollutant-specific indices). Bioaccumulation of mercury (Hg) in fish and possibly other aquatic species make organisms especially appropriate indicators of mercury contamination. Other possible sensitive receptors mentioned included aquatic habitat attributes and soil chemical composition.

Acceptable change is change in chemical concentrations, biological populations, or physical attributes of aquatic ecosystems from natural variability. Natural variability can be caused by seasonal cycles of temperature, precipitation, solar radiation, and hydrology. It can also result from natural disturbances such as wildfires, pest outbreaks, avalanches, drought, floods, debris falls, or erosional processes. The limits of acceptable change, then, define the boundary conditions beyond which impacts would be considered adverse or unacceptable. The Aquatics Group tried to choose limits that could accurately and precisely indicate a pollutant-caused trend, but would be below a critical threshold of damage to aquatic organisms. In all cases, LACs were interpreted to represent the cumulative effect of all emission sources, and not only the effect caused by each individual PSD permit applicant.

To protect wilderness areas in a cost-effective way, the Aquatics Group recommended that categories of pollutants be ranked according to their likelihood of occurrence and severity of impact. This will aid in prioritizing appropriate monitoring and research in wilderness areas. The Aquatics Group focused on what were thought to be the most critical threats, based on current knowledge, to Rocky Mountain wilderness aquatic resources. These threats include:

- acidic deposition, including wet, dry, and occult deposition of sulfuric acid (H_2SO_4) and nitric acid (HNO_3);
- air toxic compounds, including pesticides, herbicides, volatile organic compounds (VOCs), and fugitive organic compounds from industrial processes;
- nitrate (NO_3^-) or other nutrients such as phosphate (PO_4^{3-}) or ammonium (NH_4^+); and
- mercury (Hg).

Sensitive Receptors and Limits of Acceptable Change

This section suggests appropriate receptors and limits of acceptable change relating to the priority threats identified above.

Acidic deposition

Whether acidic atmospheric deposition will cause adverse effects on aquatic ecosystems is a complex function of depositional loading of strong acid anions in rain, snow, or other precipitation, and the sensitivity of the ecosystems receiving the deposition. Sensitivity itself is complex, and depends upon the bedrock and overlying material (including soil) composition, residence time of water within the basin (related to topographic relief, hydrologic cycle, and annual precipitation distribution), and vegetation types and cover. A summary of sensitive receptors and LACs relating to acidic deposition is presented in table 2.

Sensitive receptor: Chemical composition of wet deposition, including rain and snow. The first evidence of an increase in acid deposition pollutants will be changes in the composition of precipitation. Deposition (both wet and dry) is the necessary link between pollutant emissions and aquatic ecological effects, so detection of change in deposition is required before any causal relationship can be established. More than half of the annual precipitation to Rocky Mountain wildernesses falls as snow. Wet deposition is monitored throughout the Rocky Mountain region at both high- and low-elevation sites through the National Atmospheric Deposition Program network (NADP 1991). Title IX of the 1990 Clean Air Act Amendments requires monitoring of inputs to western high-elevation watersheds, so additional deposition monitoring sites may be established.

There is interannual variability in deposition. Deposition also exhibits seasonal trends; summer precipitation is slightly more acidic than winter precipitation (Baron and Denning 1993). Individual weeks can have very acidic precipitation. Limits of acceptable change established for wet precipitation will have to reflect the potential for acidic deposition to cause both chronic loss of acid neutralizing capacity (ANC) and episodic acidification, such as may occur during snowmelt. Time series will need to be carefully screened to remove confounding seasonality, skewness, and serial correlation for long-term trend analysis. Short-term acidification needs to be considered in light of the potential for coincidence of acidic "pulses" with exposure of sensitive organisms (Corn and Vertucci 1992).

LAC: Where current snowpack pH is <6.0, acidic deposition should not be more than double current snowpack H^+ concentration. Before this is adopted, the possible effects of this scenario on most sensitive aquatic ecosystems should be explored through research and model simulations.

Sensitive receptor: Acid neutralizing capacity of surface waters.

The acid neutralizing capacity (ANC) of a specific aquatic ecosystem can be an indicator of acidic atmospheric deposition. For the purpose of determining appropriate LACs, aquatic ecosystems were considered in three separate categories based upon whether their open water period ANC was >100 μeq L^{-1}, 25-100 μeq L^{-1}, or <25 μeq L^{-1}.

LAC: Where ANC >100 meq L^{-1}, 10% change from established baseline (determined by long-term trend analyses or through simulation).

Aquatic ecosystems in areas where the bedrock or overlying material is easily weathered (such as limestone, dolomite, and many shale types) generally will not be sensitive to increased acidic deposition. These areas should have ANC of >100 μeq L^{-1} during the ice-free season. The LAC recommended by the group was considered the maximum acceptable change, based on the premise that this amount of change is detectable but is not sufficient to lead to significant changes in the solubility of H^+ or metals such as Al^{+n} or Hg that would affect biological populations.

LAC: Where ANC = 25-100 μeq L^{-1}, 10% change from established baseline.

In areas underlain by silicate or other minerals that resist to weathering or are low in base cations (such as granite, basalts, highly metamorphosed sedimentary rocks, sandstones), surface waters may have ANC <100 μeq L^{-1}. Where ANC is between 25 and 100 μeq L^{-1}, Forest Service managers need to be aware of both the potential for long-term (chronic) loss of ANC leading to acidification and for episodic acidification. Episodic acidification, or temporary consumption of ANC, results from titration of ANC by strong acid anions in snowmelt of storms (Baker et al. 1991). Snow represents 60-80% of total annual precipitation in the Rocky Mountains, and snowpacks do not melt throughout the winter (Denning et al. 1991, Turk and Spahr 1991). Snowmelt could potentially cause acidic episodes in Rocky Mountain wilderness areas. Even though this loss of ANC is temporary, it can be detrimental to aquatic organisms. The Aquatics Group recommended

Table 2. Sensitive receptors and limits of acceptable change related to acidic deposition.

Sensitive receptor	Ambient condition	Limits of acceptable change
Chemical composition of wet deposition	current snow pack pH < 6.0	not more than double current snowpack H^+ concentration
ANC of lake or stream surface waters	ANC > 100 μeq L^{-1}	10% change from established baseline
	ANC = 25-100 μeq L^{-1}	10% change from established baseline
	ANC < 25 μeq L^{-1}	no further decrease is acceptable
Aquatic organisms		none recommended

that the LAC should be split between chronic and episodic losses. Chronic losses can be determined through long-term monitoring and also through simulation.

Note that the recommended LAC is the same for lakes with ANC >100 µeq L^{-1} and for those with ANC between 25 and 100 µeq L^{-1}. This allowable variance becomes more restrictive as ANC decreases; thus for lakes with ice-free ANC values of 100 µeq L^{-1}, ANC can range from 90 to 100 eq L^{-1}, but if the ice-free value is 25 µeq L^{-1}, ANC can only range from 22.5 to 27.5 µeq L^{-1}. In order to protect against the possibility for episodic acidification, the Forest Service manager must have information specifically on surface water responses to snowmelt. A deviation of 10% from the baseline springtime surface water minimum ANC (determined from long-term snowmelt monitoring and from simulation) was thought to be an appropriate LAC.

LAC: Where ANC <25 µeq L^{-1}, no change.

Surface waters in the Rocky Mountain Region with ANC <25 µeq L^{-1} are considered to already be at critically low ANC levels. These bodies have a high probability of episodic acidification. In this case, the LAC has already been exceeded, and further degradation should be avoided. Remedies for existing conditions should be sought.

An alternative to the three categories of LAC based upon ice-free or snowmelt period ANC was voiced by some members of the Aquatics Group. This alternative required a minimum ANC of 200 µeq L^{-1} at any time of observation. However, there are lakes throughout the Rocky Mountains with naturally ice-free ANC <200 µeq L^{-1} (Baron 1992, Eilers et al. 1987, Turk and Spahr 1991). Dilution during snowmelt also causes large natural declines in ANC that are unrelated to anthropogenic acidification (Baron and Bricker 1987, Denning et al. 1991, Stoddard 1987). For these two reasons, it was felt that an arbitrary region-wide ANC value was unrealistic and unduly restrictive.

Sensitive receptor: Aquatic organisms.

Information is available on the effects of acidification on biological communities in aquatic ecosystems from whole lake acidification experiments, mesocosm experiments, and field surveys (Baker and Christensen 1991). This research indicates many aquatic species are acid-sensitive. The number of species present in an aquatic ecosystem declines with increasing acidity although net primary production and biomass may stay the same or even increase (Schindler et al. 1985).

There is some documentation of stream and lake benthic macroinvertebrate species in Rocky Mountain alpine and subalpine ecosystems. Arthropod taxa that are known to be acid-sensitive, including the mayflies *Baetis* and *Drunella*, are common to abundant in Loch Vale watershed and other Front Range systems (Bushnell et al. 1987, Radar and Ward 1989, Short and Ward 1980, Spaulding et al. 1992, Ward 1986). A freshwater clam, *Pisidium*, has been observed in The Loch and in the Green Lakes Valley (Bushnell et al. 1987, Spaulding et al. 1992).

Previous experimental work on alpine lakes in the Sierra Nevada mountains indicates that the effects of acidification on phytoplankton and zooplankton were dramatic at pH 5.6 and below, but little change was observed above pH 5.6 in lakes with ice-free natural pH values above 6.3 (Melack and Stoddard 1991). Short-term in situ acidification experiments at The Loch, Rocky Mountain National Park, did not show any response of the dominant spring diatom, *Asterionella formosa*, to pH values of 3.2, although when the experiment was repeated with the dominant fall alga, *Oscillatoria limnetica*, populations dramatically declined (McKnight et al. 1990).

Many Rocky Mountain wilderness lakes and streams support trout populations. Most high-elevation lakes were originally fishless, and were stocked with rainbow, cutthroat, or brook trout early in the 20th century. All three species are sensitive to acidification (Farag et al. 1993; Woodward et al. 1989, 1991; Booth et al. 1988).

Some species of salamanders have been shown experimentally to be sensitive to acidification and associated loss of Ca^{2+} and increase in Al^{+n} (Freda and Dunson 1985). Dose-response experiments on Rocky Mountain tiger salamanders showed that egg survivorship was inversely related to acidity, and an LD_{50} (50% mortality) of salamander embryos was pH = 5.6 (Harte and Hoffman 1989). However, there may be too little known about salamander life histories and sensitivity to other stresses to make them good indicators of acidic deposition effects (Corn and Vertucci 1992).

LAC: None recommended.

While the preservation of natural aquatic communities may be the major reason for protecting Rocky Mountain wilderness lakes and streams from acidic deposition, it is not recommended that fluctuation in organismal populations be used to set LACs. Limits are being established to determine trends which will lead to ecological damage, but by the time a species response is observed, ecological damage will have already occurred. It is recommended that monitoring of biological populations be initiated so that information will be available to support chemical evidence of acidification, should LACs be exceeded in future years.

Air toxic compounds

Some evidence exists for atmospheric transport and deposition of toxic organic trace substances to high-elevation Rocky Mountain lakes. The occurrence of polychlorinated biphenyls (PCBs) in lake sediments of Rocky Mountain National Park provides unequivocal evidence of atmospheric transport, since PCBs are solely produced by commercial industrial processes (Heit et al. 1983). These authors suggest that possible sources for

PCBs should include Denver, Salt Lake City, and/or fall-out from globally mixed sources. Polycyclic aromatic hydrocarbons (PAHs) may originate through both natural (such as forest fires) and industrial processes. While the PAH fluoranthene was found in the surface sediments of four Rocky Mountain lakes, it is difficult to evaluate its source. Sediments taken at depth had lower concentrations of fluoranthene than those from the surface, implying inputs have increased recently. Concentrations of both PCBs and PAHs of Rocky Mountain lakes were found to be typical of values reported from other remote lakes, and were found to be far lower in concentration than the levels found in severely polluted ecosystems (Heit et al. 1983).

LAC: EPA standards (1986).

LACs for air toxic compounds are based upon EPA standard values. Exposure to levels of air toxic compounds exceeding EPA standard values is not acceptable. While the PSD permit process may not provide the Forest Service manager control over sources of these compounds, he or she must be alert for the possibility that exceedances could occur. A partial list of air toxic compounds is found in table 3.

Airborne nutrients

Most wilderness ecosystems are strongly nutrient-limited, and inadvertent fertilization via atmospheric deposition could alter AQRVs. However, old growth forests, unvegetated areas such as talus slopes, and areas with alder represent exceptions to this condition.

Sensitive receptor: NO_3^- concentrations in late summer.

LAC: None now recommended.

Among the consequences of increased industrial activity is increased NO_x emissions. These can be transported and converted to NO_3^-, and deposited via deposition to Rocky Mountain wilderness areas as either HNO_3 or as nitrogen salts. The Aquatics Group thought that late summer NO_3^- concentrations greater than 1 μeq L^{-1} indicated that the LAC has been exceeded. However, Wetzel (1983) states "Oligotrophic lakes are often limited by phosphorous and contain an excess of nitrogen." Phosphorous is nearly always below detection limits in high-elevation Rocky Mountain lakes (Baron 1992, Eilers et al. 1987). Because the source for these high NO_3^- concentrations is not known, and may not necessarily be related to air pollution, no LAC is recommended at this time. Further research is necessary to determine the source of NO_3^- concentrations.

Sensitive receptor: Ammonium NH_4^+, concentrations during ice-free period.

LAC: NH_4^+ = 2 μeq L^{-1}.

Ammonia from feedlots, agricultural fertilization, or oil-shale retorting can be atmospherically transported and deposited in high-elevation watersheds as NH_4^+ salts. Ammonium ion is a more energy efficient and easily assimilated source of N by organisms than NO_3^-. Because of this, NH_4^+ is preferentially consumed over NO_3^- in aquatic ecosystems (Wetzel 1983). In Rocky Mountain high elevation lakes NH_4^+ is present only in very low

Table 3. Selected air toxic compounds and water quality thresholds[1] (EPA 1986)

	Priority pollutant	Freshwater, acute[2]	Freshwater, chronic[2]	Water and fish ingestion
Arsenic (pent)	no	850	48	-
Cadmium	yes	39	11	10
Copper	yes	18	12	170 ng
Cyanide	yes	22	5.2	200
DDE	yes	1,050	-	-
DDT	yes	11	0.001	0.024 ng
Dieldrin	yes	2.5	0.0019	0.071 ng
Fluoranthene	yes	3,980	-	42
Lead	yes	82	32	50
Nickel	yes	1,800	96	13.4
PCBs	yes	2	0.014	0.079 ng
PAHs	yes	-	-	2.8 ng
Selenium	yes	260	35	10
Silver	yes	4.1	0.12	50
Toxaphene	yes	1.6	0.013	0.71 ng
Zinc	yes	320	47	5 mg

[1] *Values are in mg L^{-1} unless otherwise noted.*

[2] *Lowest observed effect level.*

amounts through most of the year (Baron 1992, Eilers et al. 1987). A temporary rise in NH_4^+ concentrations occurs during spring snowmelt in the Loch Vale watershed, and this has also been reported from eastern North America, where NH_4^+ is elevated in precipitation (Dillon and Molot 1990, NADP 1991). Detection of NH_4^+ in aquatic ecosystems is indicative of either a gross increase in emissions or ecosystem malfunction (van Breeman et al. 1982).

Sensitive receptor: Lake dissolved oxygen, DO.

LAC: DO = 5.0 ppm O_2 under ice cover for 2/3 of the lake; or where DO is already <5.0 ppm in 1/3 or more of the lake, 10% change.

A concern raised by the Aquatics Group was that nutrient enrichment could lead to summer algal blooms. Microbial decomposition of these blooms under lake ice the following winter could deplete lake dissolved oxygen (DO), causing fish kills from anoxia.

Sensitive receptor: Winter lake O_2 concentrations.

LAC: None recommended

There are several problems with establishing strict LAC values for winter lake O_2 concentrations. The first is that it constitutes an indirect effect of airborne pollutants, and thus violates the condition that sensitive receptors must be sensitive and directly responsive to change. Another problem is that high-quality winter measurements of wilderness lake conditions are logistically difficult to obtain and hard to monitor; it is, therefore, difficult to track the spatial variability of dissolved oxygen. In the absence of more synoptic and experimental information on annual DO variability, it is recommended that no limit be established at this time.

A summary of sensitive receptors and LACs relating to airborne nutrients and mercury (as discussed in the following section) is provided in table 4.

Mercury

Sensitive receptors: Hg concentrations in water, sediments, and fish tissue.

LAC: None recommended.

Mercury is a toxic metal that has been found in elevated concentrations in fish from some remote temperate lakes. As collection and analytical techniques for mercury have improved over the past 15 years, concentrations of Hg in temperate lake bodies have been shown to be two orders of magnitude lower than previously reported values, making the high tissue concentrations found in game fish of remote lakes all the more intriguing (Fitzgerald and Watras 1989). Mercury is concentrated in fish tissue by about a factor of 10,000 over aqueous concentrations (Pat Davies, pers. comm.).

There is a negative correlation between the level of Hg bioaccumulation and both pH and ANC, and a positive correlation between the body Hg concentrations and total fish length (Lathrop et al., 1991). Studies and experiments in Wisconsin lakes showed highest body Hg concentrations in the longest fish in the most acidic lakes with the lowest ANC (Lathrop et al. 1991). The acute and chronic toxicity standards that have been recommended as Colorado state standards are orders of magnitude greater than expected concentrations: 2.4 µg L^{-1} in water, acute instantaneous 24-hour maximum; 0.1 µg L^{-1} in water, acute instantaneous 24-hour maximum; 0.1 µg L^{-1} in water,

Table 4. Sensitive receptors and limits of acceptable change related to airborne nutrients and mercury.

Sensitive receptor	Limits of acceptable change
Relating to airborne nutrients	
NO_3^- concentrations in late summer	now: None recommended
NH_4^+ concentrations during ice-free period	2 µeq L^{-1}
DO	5.0 ppm O_2 under ice cover for 2/3 of lake; or where DO < 5.0 ppm O_2 in 1/3 or more of lake: 10% change
O_2 winter lake concentrations	none recommended
Relating to mercury	
Hg concentration in water	none recommended
Hg concentration in sediments	none recommended
Hg concentration in fish tissue	none recommended

chronic 30-day-average concentration (these are also EPA standard values). The fish tissue residual for acute and chronic toxicity are 0.12 µg L^{-1} and 1.3 µg L^{-1}, respectively.

Methyl mercury (CH_3Hg^+) is the form most readily accumulated in fish, comprising 95% or more of the Hg in fish in northern temperate lakes (Grieb et al. 1990). The microbial methylation of Hg in lakes and sediments is an important process affecting Hg bioavailability to fish (Rudd et al. 1983, Wiener et al. 1990).

Mercury inputs occur via wet and dry deposition, and many lakes have a large sedimentary reservoir from which remobilization can occur (Fitzgerald and Watras 1989, Wiener et al. 1990). Using ultra-clean techniques, Bloom and Watras found concentrations of total Hg from rain and snow (from both the Olympic Peninsula of Washington and northern Wisconsin) to range about 2-15 ng L^{-1} (Bloom and Watras 1989). Methyl mercury comprised 2-10% of the total Hg, with reactive Hg making up most of the rest. This suggests atmospherically deposited methyl mercury is sufficient to account for much of the tissue concentrations found in game fish in remote inland waters (Bloom and Watras 1989).

Mercury in the atmosphere comes from natural and industrial sources. An estimated one-third of atmospheric mercury is derived from oceans, while another one-third comes from natural terrestrial sources (such as deposits of cinnabar, HgS, and other sulfur minerals). The remaining atmospheric mercury is thought to originate from industrial activity: 50% from coal-fired electricity generation, 25% from chlor-alkali plants, and the remainder from mining, volatilization from old paint (federal law now prohibits the occurrence of mercury in paint), dentistry, manufacturing, and weapon production and testing (Nriagu 1989, Nriagu and Pacyna 1988).

The concentrations of mercury in high Rocky Mountain lakes, sediments, and fish are unknown. Because of the occurrence of mineral ores in Colorado, there is some possibility of natural and mining-related mercury leaching into some wilderness lakes. Atmospheric deposition undoubtedly contributes additional mercury. Because ambient concentrations are not known, no limits of acceptable change can be recommended.

The recent research into mercury biogeochemistry strongly suggests monitoring cannot be casually undertaken. Trace-metal-free techniques must be employed to detect pico to nanogram concentrations (Bloom 1989). Preliminary results from the research conducted in Wisconsin suggest monitoring temporal trends in the ratio of methyl mercury to total mercury may be a sensitive indicator of adverse impact (Watras and Bloom 1992). Watras suggests unimpacted lakes may have ratios of 10-30% methyl mercury; this ratio may change to 70-90% methyl mercury in an impacted system. The impact is not increased deposition of mercury, since total Hg appears to be ubiquitous in the atmosphere and lake sediments, but rather a decrease in lake pH, which affects the availability of methyl mercury. It is not clear yet whether pH acts directly to partition the mercury, or whether pH affects the biogeochemical pathways by which CH_3Hg is produced. These may include microbial methylation, the bioavailability of substrate mercury to organisms that methylate mercury, or some other process (Bloom and Hurley 1991).

The Aquatics Group recommended that current Hg levels in wilderness lake water, sediments, and fish be determined for a few Rocky Mountain lakes. Because of the extreme difficulty in obtaining high quality results, it is further recommended that Region 2 contract this work out to a laboratory with proven expertise in the area of mercury sampling and analysis.

Analyzing and Predicting Adverse Impact

The PSD permit process for evaluating potential threats to wilderness aquatic ecosystems is a game of futures by which the Forest Service manager must predict the effects of potential development in advance of their occurrence. Dynamic models of watershed and aquatic processes provide a reasonable approach to prediction. Models, however, differ greatly in their assumptions, their predictive capability, and their input data requirements, so they should not be used carelessly. Since the quality of model output is only as good as the quality of data input, there is a strong need for long-term, high-quality data sets. As some data are required to parameterize models, and thus cannot be used to test model performance, other long-term data sets will need to be made available for model validation. This is critically important, since the actual use of models to predict the effects of new pollution sources cannot be rigorously validated. The Aquatics Group discussed the relative merits and disadvantages of several models that are currently used to assess lake and watershed acidification. This discussion, augmented with statements from the literature (primarily Munson and Gherini 1991), is presented below. A table comparing the resolution and processes of the three most widely applied models was put together by Malanchuk and Turner (1987); other models have been added to it (table 5).

Dynamic models

The three models most commonly applied in the United States include MAGIC, (Model of Acidification of Groundwater In Catchments; Cosby et al. 1985), ILWAS (Integrated Lake Watershed Acidification Study Model; Chen et al. 1983) and Enhanced Trickle Down (Schnoor et al. 1984). The models have been used to identify processes operating in watersheds, and also for prediction given different atmospheric deposition scenarios (Munson and

Table 5. Comparison of processes and resolution in dynamic and empirical models (after Malanchuk and Turner 1987).

	ILWAS	MAGIC	TRICKLE DOWN	BIRKENES	HENRIKSEN -WRIGHT	RED/GREEN/ YELLOW	TWO BOX MIXING
Atmospheric input	E,A	A,M,LT	A,LT	A,D	LT	LT	variable
Hydrology	E,A	A,M,LT	A,LT	E,D	N/A	A	E
Weathering	A,LT	LT	LT	LT	variable	N/A	LT
Anion retention							
SO_4^{2-}	+	+	-	+	-	-	-
Nitrification	+	-(+)	-	-	-	-	-
Denitrification	+	-(+)	-	-	-	-	-
Base cation buffering							
% base saturation	+	+	+	+	+	-	-
Al kinetics	+	+	-	+	+	-	-
Biological							
Uptake	+	-	-	-	-	-	+
Excretion, decomposition	+	-	-	-	-	-	-
Transformation	+	-	-	-	-	-	+
Respiration	+	-	-	+	-	-	-
SO_4^{2-}	+	-	-(+)	+	-	-	+
Spatial resolution	V,H, watershed watershed	V,H, regional,	V, lake	V, catchment	regional	lake, regional	V, catchment
Temporal Resolution	D	M	D	D	N/A	N/A	variable

Key: A = annual
M = monthly
LT = long-term
D = daily
E = episodic
V = vertical
H = horizontal
N/A = not applicable
+ = the model specifically addresses these processes
- = the model does not address these processes
-(+) = the model provides the option of addressing or ignoring these processes

Gherini 1991). The models differ in their input requirements, assumptions, and complexity; but all three have been used successfully to recreate existing data sets and can deliver assessments of surface water acid neutralizing capacity (Rose et al. 1991).

MAGIC: Model of Acidification of Groundwater Catchments: The MAGIC model runs on a monthly or yearly time step. It predicts or postdicts average soil and stream response to long-term acidic deposition or cessation of acidic deposition. Each model run can cover 140 years, starting from background conditions 140 years ago and continuing up to the present, or establishing some future scenario and exploring watershed response. Runs beginning in the 1850s are particularly useful for estimating how well the model recreates conditions present in the 1990s. This provides a means of testing the fit of the model to watershed processes in different ecosystems. Scenarios of current and potential atmospheric deposition have been built into the model for different regions of the United States based upon EPA-estimated regional emissions, or the user has an option of building another deposition scenario. The model uses lumped parameters based on watershed basin physical and chemical characteristics. These parameters are aggregated horizontally over a watershed and broken out vertically into two soil layers and one completely mixed stream or lake. The hydrologic portion of the model is calculated using TOPMODEL, a variable source area input hydrologic model.

Inputs to the model (the empirical field data needed to run the model) include atmospheric deposition (including dry sulfate deposition estimates) and weathering rates for base cations and strong acid anions, expressed as fluxes. Physical data required are mean annual or monthly hydrologic flux (precipitation in and stream discharge out), soil and streamwater temperatures, the partial pressure of soil carbon dioxide (soil P_{CO2}), depth, and porosity. Soil chemical parameters required are cation exchange capacity, percent base saturation or selectivity coefficients for Ca-Na, Mg-Na, K-Na, Al-Ca, the aluminum hydroxide solubility constant, sulfate adsorption capacities, and half saturation constants of the particular soils. The model calculates changes in soil and surface water chemical properties.

The MAGIC model has been calibrated and tested for watersheds throughout the world (including Loch Vale watershed in Rocky Mountain National Park and the Glacier Lakes in the Snowy Range in southeast Wyoming). Among its test sites were two manipulated watersheds in Norway where acid deposition has been experimentally changed as part of the RAIN project (Reversing Acidification in Norway). The Sogndal watershed, originally pristine, has been acidified via acid deposition, and the Risdalsheia watershed, which had been acidified, has been covered over to exclude acid rain (Wright et al. 1990). A modified, monthly version of MAGIC was developed for the RAIN project in which snowpack accumulates during the winter and melts during the spring. MAGIC successfully reproduced the past four years of stream and soil chemistry in these manipulated systems. This model has been recommended.

ILWAS: Integrated Lake Watershed Acidification Study Model: The ILWAS model is the most spatially explicit and process-intensive of the three models, and thus has extreme data input requirements. There are 37 types of input coefficients needed in order to run ILWAS, compared with 13 needed for MAGIC. Within individual hydrologic subcatchments, there are model compartments to represent forest canopy processes, snowpack, and up to five separate soil layers. A lake can be thermally stratified to calculate temperature and water quality profiles. Physical and chemical processes that change the acid-base characteristics of water are simulated by rate and equilibrium expressions, and include mass transfers between gas, liquid, and solid phases. The model produces time trends of all major ions, aluminum dynamics, dissolved organic carbon, and inorganic carbon. The Aquatics Group felt that ILWAS could best be applied in research watersheds but is generally not suitable for Rocky Mountain wilderness lakes because of limited data availability.

Enhanced Trickle Down Model: The Enhanced Trickle Down model is a lumped parameter model that formulates all processes in terms of their direct effects on ANC. The model runs on a direct time step, and predicts seasonal fluctuations in lake acid-base characteristics, as interpreted via ANC. Parameters are lumped spatially over a watershed. Water can be routed through three soil horizons and a completely mixed lake. All chemical processes of the model are rate-limited except for sulfate adsorption and CO_2-carbonic acid equilibria. Mass balances are calculated for ANC, SO_4^{2-}, and Cl^- (as a check of hydrologic balance). The Enhanced Trickle Down model has been tested in seepage lakes of the midwest and drainage lakes of the eastern United States. The Aquatics Group did not feel confident that western weathering processes were adequately represented and recommended that this model not be used for PSD permit applications.

Birkenes Model: The Birkenes model is very similar in theoretical construct to the MAGIC model. Chemistry is based on SO_4^{2-} flux of wet and dry deposition passing through soils. As it moves, SO_4^{2-} can either be adsorbed, desorbed, mineralized from organic forms, or leached. Charge balance is maintained with soil cations, and cations are required to meet equilibrium constraints of their controlling minerals. A hydrologic submodel consists of two soil reservoirs, a snow reservoir, and a stream. This model has been applied to Scandinavian and Canadian catchments, and may be modified for Rocky Mountain systems.

Empirical models

Henriksen-Wright Model: The Henriksen-Wright model is an empirical model that has been used in Scandinavia, eastern North America, and the Rocky Mountains to estimate historical loss of ANC from increased deposition of sulfate (Henricksen 1982, Wright 1983). In this model, alkalinity is defined as the sum of the base cations (C_B), total monomeric aluminum species (Al_m), and divalent manganese (Mn^{2+}), less the sum of the strong acid anions C_A, (SO_4^{2-}, NO_3^-, Cl^-, F) (Henriksen 1979):

$$ANC = [C_B] - [C_A] + 2[Al_m] + 2[Mn^{2+}].$$

Increased non-sea-salt sulfate (SO_4^{2-}) deposition affects ANC two ways: by increasing the release of base cations from the watershed and by direct replacement of bicarbonate alkalinity with SO_4^{2-} (Wright and Henriksen 1983). The proportional change in the base cations relative to SO_4^{2-} is referred to as the F-factor.

The Henriksen-Wright model gives a static view of surface water chemical composition, and H^+ could be used in a simple predictive model to estimate the loss of ANC due to some projected increase in strong acid anion deposition. The model, however, is not dynamic and does not take any biological, hydrologic, or specific mineralogic processes into account, so its capacity is limited. For this model to be rigorously applied to Rocky Mountain lakes, F-factors will have to be determined for each bedrock type; but once completed, the model could be used to provide a screen for most sensitive waters.

Green/Yellow/Red Model: Similar to the Henriksen-Wright model, the Green/Yellow/Red model is not so much a simulation of processes as it is a classification scheme. Developers of the model attempted to provide a "critical load" guide for managers confronted with a PSD permit application. Lakes are located on a nomograph according to their surface water base cation composition, their total deposition of S and in some areas N, and the estimated percentage of total annual precipitation that effluxes as runoff. Depending on where they fall relative to lines of demarcation, surface water bodies are at risk of acidification (red line), not at risk (green line), or in an uncertain category (yellow zone) where further information is required. Crude predictions of the effect of a new emission source can be made with the nomograph by varying the amount of total S and N deposition.

This approach provides a good screening technique for determining possible sensitivity to acidic deposition. Several critical points were raised by members of the Aquatics Group. Notably, they are also stated as cautions in the Green/Yellow/Red documentation itself (Fox et al. 1989). The model is only applicable to lakes without a watershed S source. Episodic acidification events such as brought on by snowmelt fall beyond the context of this model. The biggest problem raised with this model is that most western lakes fall in the yellow zone, where clear management guidance on how to address a new source permit is lacking. This, unfortunately, makes the Green/Yellow/Red model insensitive to Rocky Mountain wilderness areas unless steps are taken to correct this problem. As with all other models, extensive testing is required before it can be used as a screening tool.

Two Box Mixing Model: The Aquatics Group briefly discussed the possibility of using a Two Box Mixing model for determining the proportion of water in a water body attributable to either precipitation or groundwater. This technique has been applied to Canadian watersheds to determine sources of hydrologic flowpaths and the possibility for episodic acidification due to snowmelt (Bottomley et al. 1986, Maule and Stein 1990). The model requires that the species that are mixed act conservatively, that is, their sources can be traced by their chemical or isotopic signatures even after mixing. Distribution between precipitation and groundwater sources of water can be determined using naturally occurring isotopes ^{18}O and deuterium as hydrologic tracers. Isotopic separation increases with decreasing temperature, thus allowing the ^{18}O and D values of snow to be distinguished from rain and groundwater. The waters from the different sources are then mixed proportionally according to the equation

$$Q_P = Q_T[(\delta_T - \delta_E)/(\delta_P - \delta_E)]$$

to derive the amount of water supplied from each source. This has been used to infer the contribution of accompanying acidic solutes to water bodies (Bottomley et al. 1986).

This method of evaluating sources and flowpaths of water has potential, but there are several problems with trying to use it in a predictive mode. Isotopes are expensive, nonroutine analytes requiring a mass spectrometer. The only place in the Rocky Mountains we know of where this technique has been applied is Rocky Mountain National Park, and preliminary results suggest the presence of glaciers, late melting snowbanks, and rock glaciers confounds the temperature-based technique for determining sources of water during snowmelt (Back 1994.). While the inference of precipitation-derived acid solutes from this mixing model is no less robust than other simulation methods that calculate sources of solutes from equilibrium and kinetic equations, other models (particularly MAGIC) have been tested in many aquatic ecosystems. Finally, it is not possible to use the mixing model in a predictive mode because the water isotopes do not shed light on processes affecting ANC.

The Two Box Mixing model can also be applied to solutes. One example is sulfur, which has distinctly different isotopic signatures depending on source. Distribution between precipitation and mineral sources of sulfur is the subject of current research (Turk et al. 1993). The technique has been successfully applied in Loch Vale watershed to detect mineral sulfur sources that had not been detected by more conventional techniques. In watersheds without sulfur-bearing minerals, however, the model does not contribute to understanding the effects of increased S deposition on ANC, nor can it be used for trend analysis.

Monitoring

Monitoring of aquatic systems is necessary to provide data with which to make sound PSD recommendations to protect wilderness areas. Such monitoring needs to be undertaken well before a PSD permit application is received to assure that sufficient information will be available to allow a timely response. The filing of a PSD application may necessitate higher frequency sample collections or additional parameters to be collected from an ongoing monitoring program. Because our present level of knowledge is limited with respect to prediction of the effects of emissions on wilderness, monitoring after an emission source is permitted may also be necessary to calibrate empirical or numerical models. This will advance our general ability to protect wilderness areas and to determine if the new permitted source has caused unforeseen effects.

Although monitoring is critical to any PSD decision, such monitoring needs to be conducted in such a way as to not interfere with the wilderness. For example, in mountain ranges or other geomorphic units of which only part is designated wilderness, instrumentation can be located in adjacent nonwilderness, if these areas adequately represent the areas of concern. Often, however, western wilderness areas occupy entire high-elevation areas for which there is truly no representative nonwilderness area subjected to the same atmospheric deposition from a proposed source.

Prior to initiation of a monitoring program, the Forest Service manager is advised to consider data already available. These include:

1. The Western Lake Survey, conducted by the Environmental Protection Agency (EPA) (Eilers et al. 1987). In some areas there may be sufficient information to define the prevalence of sensitive aquatic systems. However, the Western Lake Survey (WLS) was a stratified systematic sample of a list frame that did not specifically search for the most sensitive aquatic systems.

2. The Environmental Monitoring and Assessment Program, initiated by the EPA. Approximately 800 lakes will be sampled nationally per year, with a sample repetition rate of every 5 years. As with the WLS, sampling is probability-based rather than targeted for sensitive systems.

3. The Hydrologic Benchmark Program of the USGS, operating since about 1966. Several Hydrological Benchmark watersheds drain western wilderness areas.

4. Long- and short-term research and monitoring programs conducted by universities and state and federal agencies including USGS, NPS, USFS, BLM, and USFWS.

Before designing a monitoring program, the appropriate maps, journal articles, and books that may describe the geologic, hydrologic, biotic, or other characteristics of the wilderness area should be assembled. For example, aquatic chemistry is very dependent on geology; thus, knowledge of what parts of a wilderness have a particular bedrock composition aid the search for the most sensitive aquatic system. If possible, each wilderness manager should project the most likely future sources of emissions, assemble a map of present sources, and gather any other type of information, such as prevailing wind direction, that can help describe the most likely areas of greatest deposition and sensitivity.

The design of a monitoring program requires two major efforts:

1. A synoptic survey to identify sensitive aquatic systems and relate these to geologic, hydrologic, and other characteristics that are associated with the sensitive systems. Such a survey may also help to identify sensitive organisms associated with aquatic systems. These data are used to select the most sensitive systems to be used in predicting, modeling, and monitoring PSD effects.

2. A long-term monitoring program to define the natural and pollution-related fluctuations and trends within these most sensitive systems.

Work related to acid deposition has provided knowledge on how to effectively conduct synoptic sampling in wilderness areas. However, this knowledge is directed at finding aquatic systems sensitive to acid deposition. These systems are not necessarily the most sensitive to other possible threats, such as air toxic compounds. Maps and models of lake ANC indicate ANC is a function of bedrock geology and hydrology. Bedrock geology can affect lake ANC through control of weathering rates per unit area and volume of watershed minerals. To have the least ANC and to be the most sensitive to acidification, a lake needs to be on any one of the slow-weathering bedrock types common to the Rocky Mountain region, such as quartzite, quartz monzonite, granite, or basalt. These slow-weathering bedrock types result in minimal lake ANC because of slow rates of weathering per unit area of mineral. Within each of these bedrock types, the most sensitive lakes will have minimal amounts of material that can form the matrix of an aquifer, e.g., glacial till or alluvium. These materials not only provide a large surface area per unit volume for mineral dissolution and ANC production, but they also provide a continuous flow of ANC into a lake or stream.

Hydrology can also affect lake ANC. The most sensitive lakes and pools will occur at the beginning of hydrologic flowpaths, rather than farther downstream. Longer flowpaths provide additional time for reaction between groundwater and the minerals that dissolve to produce ANC. Thus, sensitive lakes are likely to be on or near topographic highs, such as saddles, cirques, and mesa tops. These water bodies are in groundwater recharge areas dominated by precipitation inputs rather than in groundwater discharge areas, such as stream valleys. Temporal variations in hydrologic processes, such as snowmelt, may cause changes in flowpaths that can decrease ANC by minimizing mineral surface area exposed to reaction and contact time of water and mineral surface. For example, saturation of soils during snowmelt may cause a large fraction of flow to a water body to occur as overland flow. As the zone of saturation thins during the summer, most of the flow might come from groundwater.

Given that we know the geologic and hydrologic conditions that are likely to result in a sensitive lake, how do we select which lakes to sample? If the number of potential lakes is small enough that there is sufficient money and labor, all lakes can be sampled (a census). This is the ideal goal of all resource inventory and monitoring programs. In some cases, however, this may require a phased sampling over several years. In other cases it may not be possible to sample all lakes. The best approach in this case is to either sample the lakes thought to be the most sensitive, or collect a representative subsample of the sensitive systems. The most sensitive lakes based on geology would be on quartzite followed by granite, gneiss, monzonite, rhyolite, and basalt. Similarly, the highest elevation lakes within the local topography are likely to be the most sensitive. Such information can help reinforce the idea that there are sensitive aquatic ecosystems and that, perhaps, more money and manpower are needed to adequately sample the rest of the lakes.

A stratified random survey can also be collected by assigning water bodies to some common characteristic and collecting a random sample from within these groups of characteristics. This was the approach taken to stratify lakes for sampling in the Western Lake Survey (Eilers et al. 1987). Lakes and other aquatic systems can be grouped according to bedrock and surficial geology, as mapped on readily available USGS geologic maps. Within each of these groups, further subgroups can be determined by delineating altitudinal ranges. Each water body within each subgroup is assigned a number. A random number approach is then used to select which lakes within each subgroup should be sampled. This is a statistically desirable approach, but does not take into account problems of access or efficiency in moving from one selected lake to another.

The initial synoptic sampling for lakes sensitive to acid rain can be used to thoroughly address a full suite of chemistry, or it can utilize several levels of analysis. An example of a two-stage sampling design might start with specific conductance and ANC analyzed for all samples; whereas the full suite of major ions and other constituents of interest, such as organisms, might be determined for a 10% subsample. Thus, the wilderness area could be sampled completely at little analytical cost for the most direct measure of sensitivity to acid deposition ANC, while still having sufficient detail in some samples to more adequately determine the causes and effects of high or low ANC.

To assure the quality of data collected and to enhance comparability of results among wilderness areas within a region, it is recommended that a team of experts be selected to advise the USFS manager for each wilderness area on how best to initiate monitoring. Each USFS manager must operate under the assumption that these data may have to be defensible in a court of law. It is critical that generally accepted methods be used and that all steps of data collection and analysis be documented. In this regard, the Aquatics Group noted that the screening procedure of Fox et al. (1989) is not sufficiently detailed or defensible enough to be used as a guideline. With proper expert guidance, synoptic sampling need not be prohibitively expensive, and much of it might be accomplished by volunteer labor.

Long-term monitoring

After the initial sampling, great care needs to be taken in selection of aquatic systems for long-term monitoring. Long-term monitoring must be considered as an indefinite commitment, with explicit institutional support. Breaks in the monitoring record seriously limit the ability to detect trends. Systems selected for long-term monitoring should include the most sensitive aquatic ecosystems, but access to these sites must be taken into consideration. Some sites may require mechanized access during the critical period of snowmelt. A combination of most sensitive sites supplemented (but not replaced) with less sensitive but more accessible locations might be established.

Long-term monitoring sites are necessary to detect trends from human-caused disturbance. They also serve an important function in defining the limits of natural variability in the chemical and biotic characteristics of the aquatic system. Such variation is a function of season, climate, natural succession, and natural disturbance in addition to the emissions effects we would like to detect. Long-term monitoring in advance of new emissions sources is necessary to define how large a change is needed to qualify as statistically significant within the context of natural background variations.

It is difficult to specify the minimum number of samples necessary to develop a good long-term record. The number varies with the natural controls that cause changes in lake chemistry or biota, and it will also vary based on the chemical constituent or organism being monitored. We recommend seasonal and annual sources of variation be determined before finalizing a long-term monitoring plan. That is, enough samples need to be taken at each site in the first few years to determine whether there is a significant difference among seasons and years. These initial findings can then be used to guide the number of samples taken in subsequent years. Initial data are also required to determine how many samples may be needed to detect a violation of an established limit of acceptable change.

In addition to monitoring the chemistry and biology of sensitive aquatic ecosystems, additional information will be necessary. For example, a direct measure of atmospheric inputs is required in order to identify airborne pollutants as a cause of adverse impact. This can include measurement of snowpack amount and chemistry. If a model has been chosen, the watershed characteristics needed as input parameters must be obtained. Samples for some aspects of biology or chemistry can be collected and archived for later analysis if funds are not available for immediate analysis. Changes over the last century or longer can be evaluated using paleolimnological methods.

Data base management

It is critically important that an appropriate data base management system be established Region-wide for access to information, quality assurance procedures, and analyses of data collected. The US Forest Service Air Resources Program is developing a system-node database. Many USFS offices do not yet have access to personal computer technology. This should be remedied by supplying field offices with personal computers linked by modem to a central office and data repository. Each wilderness area office should store and back up their data bases regularly. In addition, Region 2 data should be stored and backed up at a central location (perhaps at the analytical laboratory). Analytical results need to be reviewed as soon after completion as possible in order to check quality of analyses and possible need for re-analysis. This task may best be accomplished for all sites at one central locale, so as not to burden each individual field office with excessive detail. The National Atmospheric Deposition Program network provides a good model to follow.

Monitoring priorities

The following monitoring priorities are recommended:

1. The USFS must commit to long-term monitoring of sensitive aquatic ecosystems. This commitment should be incorporated into each Wilderness Area Forest Plan.
2. The USFS Regional Office and individual area managers together must develop a common sampling and analysis strategy in order to develop a scientifically sound data base. It is strongly suggested that a central analytical laboratory be established, perhaps at the Rocky Mountain Research Station, with adequate staff and budget to prepare sample bottles, conduct analyses, impose a strict quality control program, tabulate data, take responsibility for shipping of samples and results, and answer questions from field personnel.
3. The USFS Regional Office, in conjunction with the central analytical laboratory, must adopt and staff a central, logical, computer-based system for data archiving, analysis, summary, and retrieval in response to user needs. While individual field offices will receive data from their own studies, a central archive is necessary for rapid regional-scale analyses. A central data archive may also provide a permanent home for all data and limit potential lapses in data management caused by staff turnover at field offices.
4. Synoptic sampling is recommended for each wilderness area to define the presence and distribution of sensitive receptors. This sampling should be guided and coordinated by a regional team of experts to assure quality and comparability.
5. The seasonal and yearly variability of sensitive receptors, and especially episodic changes such as occur during snowmelt, should be defined for wilderness areas. These data should then be used to estimate the sampling frequency required to identify changes caused by emissions that exceed LACs.
6. Periodic sampling of snowpack for amount and chemistry of water should be initiated for wilderness areas. If existing NADP sites are not located near enough to the wilderness areas, each area should consider joining the NADP network. Additional western high-elevation monitoring sites are proposed by NADP/EPA to fulfill obligations of the 1990 Clean Air Act Amendments; Region 2 managers should work closely with NADP/EPA personnel to ensure that these sites are located where they can provide deposition data for wilderness areas of concern.
7. The MAGIC model is recommended to predict emissions effects on aquatic systems. Data required to parameterize the model will need to be collected for each long-term monitoring site.
8. Wilderness area managers might begin an archive collection of organisms and other items that will be used in the future to define pre-source conditions of the wilderness area. Standabout protocols should be used for collecting, steering, and archiving these samples. Suggestions include diatoms (for later community analyses) and animal tissues (such as feathers, hair, body organs, etc., for later determination of toxic element concentrations).
9. Each wilderness area should contract for paleolimnological sampling to determine how present conditions differ from background conditions. This research should be coordinated through the regional office.

Research Needs and Recommendations

The goals of monitoring can be thought of as defining the status of and trends in a system. For example, the goal may be to define how sensitive the lakes of a wilderness area are to acidification and whether these lakes are becoming acidic. In this context, the goal of research is to provide the understanding necessary to determine why sensitive lakes are so sensitive and the cause for change in acidification status. Thus, research is needed to help design effective monitoring programs and to correctly predict or evaluate the effect of one source among a great number of complexities, both natural and humanmade, that can also influence the behavior of an aquatic system.

As an aid in monitoring we need to improve our ability to relate a given level of pollutant or nutrient emissions to a chemical or biological response. In particular, our understanding of the dose/response relationship of western fish, macroinvertebrates, and plankton is minimal. Vernal pools are a common western aquatic system, but little is known of their chemistry or the sensitivity of their biota. Virtually no data exist on the effects of hormonal analogues on biotic growth and reproduction. It is even difficult to recommend the best way to conduct some types of sampling, such as for macroinvertebrates in very rocky littoral areas. Prevention of Significant Deterioration applications often deal with the major pollutant from one source; however, many sources may also generate small amounts of toxic substances or nutrients not addressed by the PSD permit.

Priorities

The following research priorities are recommended (without regard to cost or time in assigning priority):

1. The USFS, in conjunction with other land management agencies, needs to initiate a program to develop appropriate instrumentation and sampling techniques for wilderness areas. Techniques are needed for both biological and chemical sampling.

2. Techniques need to be improved for defining background and natural fluctuations for sensitive receptors. These, in turn, will need to be incorporated into models so that additional disturbance from industrial emissions can be detected with confidence that adverse impacts are not confused with natural fluxes.

3. Experimental dose-response research, both laboratory and in situ, must be conducted to determine the potential of toxics and limiting nutrients to affect biotic sensitive receptors.

4. At selected research sites we need to define the importance of processes and patterns of spatial variability that affect atmospheric pollutants.

5. Toxicity models need to be developed for nonfish biotic sensitive receptors.

6. Target loading of pollutants must be developed, perhaps from European mountainous areas where damage is detectable.

7. Study is needed of the transport and transformation of pollutants to, within, and from the snowpack.

8. Much more linkage, validation, and testing of atmospheric transport models with ecological and biogeochemical process models are necessary before we can confidently address any air-transported pollutant through the PSD permit process.

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3. TERRESTRIAL ECOSYSTEMS

By Anna Schoettle and William Moir

Perspective

The majority of Class I wilderness areas in Region 2 is high-elevation wilderness. Management of these areas is also regulated by the Wilderness Act of 1964, which states that these areas should be managed such that humans cause little if any impact. When considered in concert with the Clean Air Act, this implies that an adverse impact in a wilderness area is any unnatural change, regardless of whether it may be perceived by humans as positive or negative. With this in mind, the Terrestrial Ecosystems Group proceeded to identify sensitive receptors and LACs in support of our efforts to protect AQRVs.

The consensus of the Terrestrial Group was that everything—all wilderness components, from fungi and soil microorganisms to trees and mammals, regardless of their known or unknown ecosystem role—should be protected from adverse impacts from air pollution. There was considerable discussion of whether AQRVs should be limited to ecosystem functions rather than components; it was concluded that not enough is known about what controls ecosystem functions and therefore all components should be protected. The Terrestrial Group determined AQRVs to be any wilderness component that has the potential to be modified by human-caused air pollution; and sensitive receptors to be objects or processes, biological or otherwise, that can be identified as having low thresholds of tolerance to air pollutants. This is consistent with the perspective of the National Park Service, which considers *all* components of ecosystems as AQRVs needing protection. It was also acknowledged that humans are part of the "natural" processes in wilderness, and therefore some human effects upon wilderness ecosystems and biota are inevitable and not incompatible with the Wilderness Act. However, anthropogenic air pollutant impacts were not considered to be compatible with wilderness.

It is important to realize that the PSD process provides a means for the Forest Service manager to protect AQRVs in Class I areas only by recommending that the state deny a permit based on predictions of potential impacts prior to the start-up of a new source. As a result, it is critical that predictive techniques be applied during the permit review process and that they be scientifically sound and defensible. Increased control devices can be required after the source has begun operation, provided deleterious effects in Class I areas have been detected. Our goal, however, is to prevent impacts in Class I areas in the first place—not after a pollution source has started operating. It was also agreed that if the techniques were biased, the recommendations should be made toward over-protection of the Class I area, until better projections can be made. An attempt has been made to limit the list of sensitive receptors and LACs to those for which information is available that allows predicting impacts from a given change in air quality. This was not always possible since there are few predictive techniques available for components of terrestrial ecosystems.

The monitoring required to implement predictive techniques was discussed. The Terrestrial Group also discussed what information appears to be lacking from our scientific understanding of the sensitivity of Class I areas in Region 2, which potentially restricts Forest Service managers from effectively exercising the Clean Air Act mandate. The group has suggested research needs that could be pursued to provide for more effective review of PSD permits and protection of Class I areas from air pollution impacts.

Sensitive Receptors and Limits of Acceptable Change

There was a consensus that only the most sensitive components of the terrestrial ecosystem should be emphasized in the PSD review process to predict potential pollutant impacts. The Terrestrial Group considered the following attributes of ecosystem condition and function to be indicative of potential adverse impacts that should be addressed in defining LACs:

- loss of *any* species (over and beyond a natural extinction rate), even if general ecosystem function appears to be little affected;
- unnatural changes in species composition (floristics and faunistics) of communities or ecosystems;
- fertilizer effects that lead to accelerated or diminished productivity within ecosystems;
- landscape changes in the proportions of species or ecosystem mosaics as a result of air pollution;
- interruption or breaks in ecosystem function (e.g., air pollution-induced changes in the "hidden diversity" of ecosystem food webs such as mycorrhizal fungi or litter cryptozoans); and
- unnatural deterioration of archaeological or cultural objects.

Several review papers on effects of air pollutants upon ecosystems and specific plant or animal species were prepared for this workshop (Mangis et al. 1990, Bunin 1990). This information proved to be useful in the group discussions. However, there was a consensus that a more thorough literature review is necessary for the most suitable LACs to be identified. With this caveat in mind, the specific sensitive receptors and LACs which this group recommends for consideration are summarized in table 6. In the construction of table 6, the group focused on identifying sensitive receptors likely to be impacted by the most probable pollutants. The pollutants addressed were SO_2, ozone, acidic precipitation (SO_4^{2-}, NO_3^-, NO_x), and metals. Consideration was given to CO_2, but we did not specify LAC guidelines. Threatened and endangered species require special attention in relation to all pollutants. The tolerance limits, or LACs, for those species should be 0% change from population levels in an unpolluted environment. This recommended LAC might change when direct sensitivity testing data become available.

Predictive Techniques

In the PSD review process, the Forest Service manager must predict whether a change in air quality (supplied from the atmospheric transport models and the stack emissions of the proposed source) will cause a change in the sensitive receptor which will exceed the LAC. The group considered that the review of potential vegetation impacts would be accomplished with projected air quality information and any sensitive receptor monitoring information that was available (figure 1).

The relationship between atmospheric concentrations of pollutants and sensitive receptors is seldom known. Our techniques must be able to predict when an LAC will be exceeded in a given atmospheric chemistry and what critical pollution concentration will cause the LAC to be exceeded. This aspect of the application of terrestrial sensitivity to pollutants for use in the PSD permit process is the weakest. Pollutants have little effect on biological processes until deposition or uptake occurs. The calculation of pollutant uptake is difficult. Several studies on pollutant uptake have been completed, yet few studies have been conducted that assess the effects of long-term, low-exposure pollutant regimes. Two predictive techniques were discussed by the Terrestrial Group.

Direct impact projections

Direct impact projections may be obtained from controlled exposure/impact (dose-response) studies. This approach eliminates the need to know the uptake levels (figure 1), yet must be conducted for each species of concern. The relationships are established on a species-by-species basis and are usually conducted under controlled environmental conditions that rarely incorporate the natural stresses of the species. In addition, most of these studies are conducted over only 1-3 seasons with seedlings and at relatively high dosages. It is still uncertain if the sensitivity of a species is constant throughout its life. Regardless of these shortcomings, this type of data, coupled with field observations of impacts from elevated pollutant exposure, would be the most defensible for the PSD review process. However, these data are sparse and expensive to collect, especially in high-elevation ecosystems. In situ dose/response studies with wet deposition (e.g., McKenna 1991, Funk and Bonde 1989) are needed and are much more feasible than those with gaseous pollutants (see recommended research topics below).

Gaseous pollutant uptake

Another predictive technique is presently being developed (Schoettle 1995) that takes advantage of the fact that the relationship between pollutant uptake and impact are much more consistent among species than the relationships between pollutant exposure and impacts (Reich and Amundson 1985, Reich 1987). This technique will use

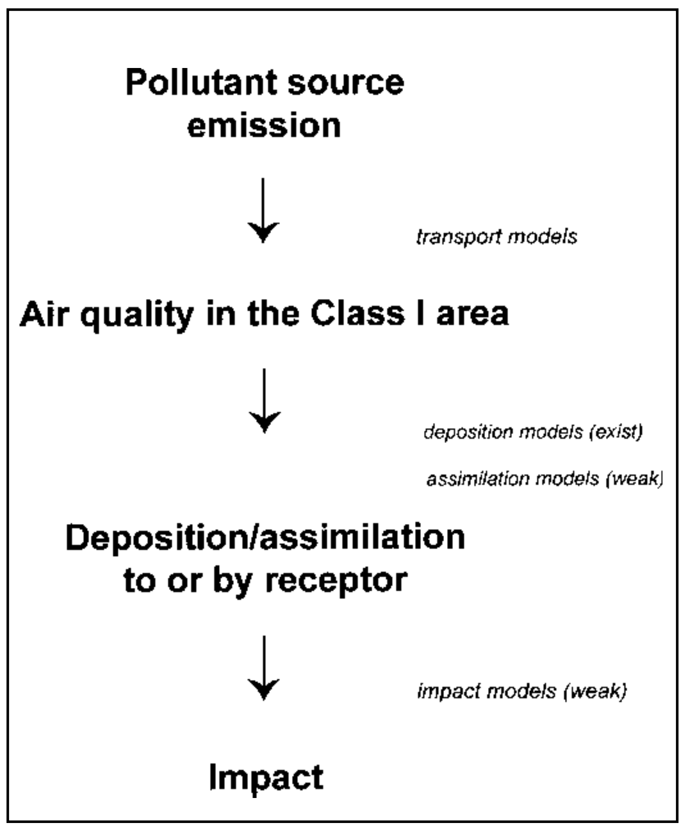

Figure 1. Scheme of information needed to predict terrestrial impacts caused by air pollution.

Table 6. Sensitive receptors and limits of acceptable change (LACs) relating to probable pollutants for terrestrial ecosystems in Class I wilderness areas of USDA Forest Service Region 2. LACs are suggested for impacts due to SO_2, O_3, SO_4^{2-}, NO_x, metals and VOCs, fluoride, and all pollutants.

Sensitive receptor Indicator (comments)	**Limits of acceptable change** (change from baseline)
RELATING TO SO_2	
Lichens (especially foliose-fruticose forms and epiphytes)	
Loss of species	0%
Species composition change	0%
Mosses, loss of species	0%
Vascular plants (fast growing species and riparian species may be the most sensitive due to high stomatal conductance)	
Species change	0%
Photosynthesis	<10% decrease
Conifers, foliar lesion	<5%
Conifers, leaf tissue S	<10% increase
Deciduous, foliar injury	<5%
Deciduous, leaf tissue S	<10% increase
Insects (especially pollinators)	
Species composition	0%
Fecundity	0%
Tissue content	0%
RELATING TO OZONE	
Vascular plants (fast growing species and riparian species may be the most sensitive due to high stomatal conductance)	
Species composition	0%
Phenology	0%
Tissue respiration	<10% increase
Photosynthesis	<10% change
Seedling mortality	0%
Conifers, foliar lesions	<5%
Conifers, leaf retention	<10% decrease
Conifers, foliated shoot length	<10% decrease
Deciduous, foliar injury	<5%
RELATING TO SO_4^{2-}, NO_x	
Vascular plants	
Growth (radial or shoot)	±5%
Species cover	±5%
Species composition	±5%
Tissue nutrient ratios (trees on poor soils, e.g., Dystric Cryochrepts, may be most sensitive)	
N/P (low N/P may be most sensitive)	LIT[1]
C/N (high C/N may be most sensitive)	LIT[1]
Bud break or set	±0 days

Continued

Table 6. (Continued)

Sensitive receptor Indicator (comments)	**Limits of acceptable change** (change from baseline)
RELATING TO SO_4^{2-}, NO_x (Continued)	
Vascular plants (Continued)	
Seedling mortality	0%
Leaf tissue S	<10% increase
Soils	
Base saturation (should be about 20 meq/l)	
Low elevation	<15% decrease
High elevation	0%
pH	±.5 unit
Deposition (NO_x)	<5kg/ha/yr
Soil flora and fauna	
Decomposition rate	LIT[1]
Earthworm abundance	0%
Cultural resources, petroglyphs (especially on basic rock)	0%
Lichens (same as above for SO_2)	
RELATING TO METALS AND VOCS	
Lichens, tissue concentration (lichens may contain high levels of metals without injury, values represent pristine conditions; consult vast literature for details)	
Pb 200 ppm	<10% increase
Zn 400 ppm	<10% increase
Hg 2 ppm	<10% increase
As 1 ppm	<10% increase
Cd 1 ppm	<10% increase
Se 1 ppm	<10% increase
Cu 100 ppm	<10% increase
Mosses	
Species composition	0%
Tissue composition	LIT[1]
Soils (sensitive soils will be those with low base saturation, i.e., Dystric Cryochrepts, Pergelic subgroups, and many Histosols)	
Concentration in inorganic soils	0%
Concentration in organic soils (peat)	<10% increase
Cu 100 ppm	<10% increase
Zn 400 ppm	<10% increase
Pb 200 ppm	<10% increase
Cd 1 ppm	<10% increase
Hg 2 ppm	<10% increase
Se 1 ppm	<10% increase
As 1 ppm	<10% increase
F 3 ppm	<10% increase

Continued

Table 6. (Continued)

Sensitive receptor Indicator (comments)	Limits of acceptable change (change from baseline)
RELATING TO METALS AND VOCS (Continued)	
Soil Fungi (same as above for SO_4^{2-} and NO_x)	
Vascular plants (cushion plants in exposed alpine areas may be most likely to accumulate due to year-round exposure)	
Tissue concentration (metals and values same as those given for lichens above)	<10% increase
Bees (domestic bees may be surrogate)	
Brood size	<10%
Tissue concentration	<0-10%
Loss of queen	0%
Bats	
Guano concentration	LIT[1]
Tissue concentration	LIT[1]
Birds	
Tissue concentration	LIT[1]
Nesting success	LIT[1]
RELATING TO ALL POLLUTANTS	
Threatened and endangered species	
Population levels	0% change from unpolluted environment

[1] *The Terrestrial Group recommended a thorough review of the literature for these LAC values. The group was confident that the information is available but did not have the expertise to identify the appropriate limits with any level of confidence.*

gaseous pollutant uptake and flux as a predictor of impact; it is based on the fact that stomatal conductance, a relatively easily measured value, is the primary determinant of gaseous uptake in plants. As a result, plants with higher stomatal conductance during pollutant exposure are more likely to be impacted than those with low stomatal conductance (Reich 1987). Knowledge of the average stomatal conductance to gases and the ambient pollutant concentration enables an estimate of pollutant assimilation from which impacts can be estimated.

This approach will reduce the need to study the pollutant response of each species, yet is limited to gaseous pollutants. There are biochemical factors that can increase the tolerance of some species to pollutant impacts, yet the current understanding of these factors and their roles in tolerance is not sufficient to incorporate them into predictions at this time. This is, of course, a source of error in the technique. This technique is founded on firm empirical data that supports its application (Reich 1987), but verification with native, field-grown plants is required before it can be implemented (and be defensible) in the PSD permit evaluation process. If this technique proves robust, it will enable predictions of impact to be made for many more species than could technically and economically be assessed using exposure/impact studies.

Recommendations

The Terrestrial Group recommended that more dose-response work be conducted for determining wet deposition sensitivity, and that the stomatal conductance modeling approach be further explored for predicting gaseous pollutant sensitivity.

Monitoring

As the Terrestrial Group developed sensitive receptors and LACs, it became apparent that baseline measurements are essential. The LACs identified represent unnatural changes from the baseline condition. Two important information needs are implicit in the context of considering change from a baseline condition: (1) baseline data for potentially threatened Class I wildernesses and (2) an understanding of the variation in that baseline that is a result of natural (nonhuman-caused) environmental changes (this might be called a natural baseline). This latter requirement is most difficult if pollutants are already present at the time baseline measurements are taken. Baseline levels are sometimes determined in the initial monitoring effort (this might be called a monitoring baseline), but need not be limited to this. Indeed, the current condition may be inappropriate if pollution levels are already high, yet this information will also be useful in the review process. Baselines can also be determined from archived collections, previous studies, or from similar, but more pristine (or at least less polluted) environments elsewhere. Baseline quantities should include means, seasonal and year-to-year variations, skewness, and other descriptive statistics against which comparisons of nonbaseline data can be made. Since effects of pollutants on populations of sensitive receptors are likely to be subtle (Gough 1991), good sample design is necessary. Of course, lack of baseline measurements precludes any implementation of the LACs (i.e., change from what?).

The purpose statement for developing and continuing a wilderness monitoring program can include additional benefits other than the factual basis for reviewing PSD permit applications. Most importantly, perhaps, managers and their public will have a data base with which an important aspect of wilderness "condition" can be assessed. While the purpose of the monitoring program will be to gather information on the current condition of the resource, the continuation and long-term data base will be valuable for evaluating and revising the predictive techniques, in the event that the new source is constructed. Such information will be valuable in future permit application reviews and should feed back into the review process to improve the management and protection of Class I areas.

A clear and concise monitoring manual of field locations and methods used is strongly recommended. The manual should be written, looking to the future, for people who will be responsible for updating and maintaining the records if the purpose continues to be persuasive. Managers in Region 2 are advised to consider the methods and design strategies of this monitoring program for use with National Forest System wilderness lands.

Another essential feature of monitoring is to build the decision-maker (the land manager who is responsible for making the recommendation to the state regulatory agency) into a monitoring feedback loop. Experience has shown that if this person is not part of the monitoring system, it will falter and eventually be abandoned.

What to monitor

The Terrestrial Group recommended that baseline measurements of the sensitive receptor attributes begin immediately in each Class I area. Priority sensitive receptors for monitoring should include those that are most at risk, in light of projected changes in air quality in the Region.

In addition to monitoring air quality related values, the Terrestrial Group recommends that the current air quality near Class I areas be monitored. Specifically, the Group recommends continuous monitoring of ozone (O_3) during the growing season or, if possible, year-round. Measurements of sulfur dioxide (SO_2) and nitrogen oxides (NO_X) would also be useful when reviewing a permit application.

Table 6 is not exhaustive, but suggests AQRV monitoring opportunities. Monitoring techniques are available for lichens, perhaps one of the easiest subjects to measure (but requiring a specialist at first) (see Stolte et al., 1993). Conifers, too, may be sensitive to several pollutants (O_3, SO_2, HF, NO_X, acid rain). Conifers at high elevations, such as species of *Abies*, *Picea*, and *Pinus*, may be quite sensitive. Alpine plant communities often grow in N-deficient environments and thus might be responsive to increased loadings of N-based pollutants. Some plants are exposed to pollutants during most of the year (including pollutant burdens discharged from melting snow) and tend to be accumulators (e.g., of heavy metals and S-based pollutants). Mosses, similarly, are accumulators, amenable to easy measurement and collection (again by a specialist), and are found in sensitive environments such as snowmelt areas where pollutants may build up. Top carnivores, both vertebrates and invertebrates, may accumulate toxins as part of the food web. Some, such as earthworms, have high exposure to soil contaminants or aluminum toxicity, and readily show toxic symptoms (Root 1990).

The Terrestrial Group often noted how little is known by scientists outside their immediate field of specialization. It is therefore recommended that literature searches be conducted on life histories or physiological tolerances to pollutants of the numerous organisms that might serve as biological monitors of wilderness pollution. Some literature searches have already been completed but may need updating (e.g., for animals see Newman and Schreiber 1984; for vascular plants, see Bunin 1990; for lichens, see Jackson et al. 1992, Stolte et al. 1993; for forests, see Olson et al. 1992, NAPAP 1991, Nuorteva 1990).

A recommended monitoring approach

At present, with some exceptions, air pollution in Region 2 is at low levels. Projected emission estimates, however, show both SO_2 and NO_x substantially increasing to levels potentially detrimental to nearby wilderness areas. Levels of nonlocal pollutants will also probably increase. Because the window of opportunity is both immediate and likely to be short-lived, the Terrestrial Group make the following recommendations:

1. Keep monitoring as simple as possible, but don't degrade monitoring to avoid more complicated or expensive techniques. Remember, monitoring is a service to future managers and publics.
2. Acquire current condition and air quality baseline information immediately. Baseline needs given in table 6 are not necessarily exhaustive, but include measurements of community composition (both plants and animals); tissue chemistry; distribution and abundance of threatened, endangered, or sensitive species; soil properties such as cation exchange capacity; elemental content of organic matter; condition of important cultural features; and other properties likely to be adversely affected by pollutants. (This recommendation parallels information needs given by Fox et al. 1989.)
3. Use established field and laboratory techniques, including updated QA/QC methods. Employ experts or specialists where needed (for example, lichenologists).
4. Design the monitoring system regionally; implement the system locally.
5. Incorporate into the design as many replicate samples as necessary to permit some degree of statistical interpretation in the future. Document field plots and samples thoroughly. Keep in mind that some plots will invariably be lost or otherwise rendered useless in the future, so there is a need to build redundancy into the system.
6. Make use of photographic reference points as often as possible, making sure the reference points are well documented and relocatable.
7. Leave room in the plans so that additions can be made as new information and technologies become available. Ensure that monitoring methods are not changed over time without complete documentation and cross-comparison to former methods.

Research Recommendations

The Terrestrial Group suggested a number of research topics. The group further recommends a high degree of integration and communication with other land managers responsible for Class I areas within Region 2 to make best use of research dollars and information. The following list of research recommendations is not prioritized at this time:

- Conduct comprehensive literature reviews periodically to evaluate new information and technologies for the revision and completion of table 6.
- Expand the data base of direct dose-response relationships for native species common to Class I areas in Region 2. Comparative studies with other more well-known species sensitivities would be useful. Sensitivity testing should ideally be conducted in the field, yet controlled environment studies would also be useful.
- Expand research to develop and test predictive techniques.
- Improve estimates of pollutant deposition to the terrestrial ecosystem.
- Expand the understanding of sensitive species' life cycles. Related to the above, research here would focus on critical aspects of life histories (for example, seed germination, pollination) affected by exposure to, or uptake of, specific pollutants.
- Expand the understanding of the food chain on which threatened and endangered species are dependent. Specifically concentrate on links that may accumulate pollutants and the determination of critical tissue concentrations for animals.
- Expand the understanding of pollutant/impact relationships of natural communities in already impacted regions with special attention to monitoring along pollution gradients. Research is needed on the efficacy of applying direct and indirect gradient analysis to determine pollutant effects upon plant communities or plant population attributes.
- Efficiency monitoring. Can monitoring systems be reduced to some minimum sampling level, in both space and time, and retain their power of detection? Closely associated is research into the manner in which sampling efficiency can be evaluated when determining baseline levels of tissues, population structure, and community composition.

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4. VISIBILITY

By Douglas Latimer

This report summarizes the discussion and major conclusions and recommendations of the Visibility Group. Although the group did not reach consensus on the precise definition of criteria for identifying adverse visibility impairment, general consensus was reached on the objectives of visibility protection; guidelines for future development of criteria for judging impacts of new and existing emission sources on visibility; and modeling, monitoring, and research needs related to visibility protection. These areas of discussion are summarized below.

Perspective

Certainly, the 1977 and 1990 Clean Air Act Amendments and EPA and state visibility regulations provide a useful starting point in terms of what the specific objectives of visibility protection need to be. The visibility provisions of the Clean Air Act (section 169A) direct EPA, the states, and federal land managers (including the Forest Service) to remedy existing and prevent future visibility impairment, resulting from humanmade air pollution, in Class I wilderness areas.

Section 165 relating to Prevention of Significant Deterioration provisions gives the USDA Forest Service "...an affirmative responsibility to protect the air quality-related values (including visibility) ... and to consider ... whether a proposed major emitting facility will have an adverse impact on such values" (42 USC 7475).

The Forest Service needs to take an affirmative responsibility to prevent future degradation of visibility and to continually improve visibility in wilderness areas, with the ultimate goal being as close to natural, pristine conditions as possible. An imperceptible amount, perhaps 15% above natural baseline, could be considered acceptable. Both the currently existing visibility baseline and the pristine baseline should be used in visibility regulation. The air resource should be managed such that future conditions never deteriorate beyond current conditions and that future conditions continually move toward natural visibility conditions.

The Visibility Group concurred with the dual federal visibility strategy: both to prevent additional visibility impairment and to continually improve existing visibility. The metaphor that the group developed was as follows: we (our wilderness areas) are currently carrying a heavy backpack (visibility impairment). We want to take action to start reducing the backpack's load at the same time we prevent perceptible additions to the load.

Considerable discussion was devoted to whether the ultimate aim of visibility regulation should be to return to a natural, pristine condition (i.e., one that would exist without human population impacts) or to prevent any degradation from a stated baseline visibility. Several alternate baselines were proposed, including 1) current conditions, 2) estimated natural conditions, 3) conditions in some recent year, but not the current year, and 4) the cleanest year in the past 10 years. Use of current conditions as a baseline drew objections because many felt that current conditions were unacceptable. It was also pointed out that unless "current conditions" were carefully defined, there could be gradual degradation of visibility caused by cumulative impact of several small emission sources, although each one independently might contribute only insignificant levels of pollution. Problems were identified with using the year with the cleanest measured visibility because the good visibility might have resulted from unique meteorological conditions that would be unlikely to occur again.

Two baseline visibilities should be considered in visibility protection policy. The current visibility would be used as one baseline from which to measure progress and the estimated natural visibility; the pristine baseline would be the long-term goal toward which visibility management activities would continually strive.

The Visibility Group suggested that visibility protection should be provided to all wilderness areas, and some vistas outside wilderness—not just to Class I areas. For example, certain views should be protected: from outside to inside a wilderness, from inside to outside, and from inside one wilderness area to the outside to inside another wilderness (the view from one mountain to another).

Potential fire-related visibility policy was discussed. Fire is natural, to some extent, and therefore should not be eliminated; however, consideration of the visibility impacts of burning should be factored into the timing of prescribed fires. Although prescribed fire is a tool used by humans in forest and range management, it should be considered a part of natural visibility impairment and thus should be exempt from visibility regulation. This conclusion was derived from the fact that wild fire, in the absence of humankind's influence, would occur in natural ecosystems and thus is a part of natural visibility impairment.

Linkages were discussed between emissions, particles, atmospheric optical conditions, and visual effects. Changes in all four categories are important. If visibility is to be improved, reductions are required in:

- emissions of particles and gaseous precursors of particles, e.g., SO_2, NO_x, NH_3, and VOCs;

- ambient concentrations of NO_2 gas and particles, especially the most optically active particles such as sulfate, nitrate, light-absorbing carbon, and other $PM_{2.5}$ (particles small than 2.5 m in diameter);
- light scattering, absorption, and extinction coefficients; and
- perceptible plume or haze layer parameters such as just noticeable change (jnc), plume contrast, plume perceptibility (ΔE), and uniform haze parameters such as terrain or viewing object contrast, jnc, or visual range.

It is important to stress the interrelationships among these four categories of parameters and to emphasize that visibility protection requires limitations and reductions in emissions.

Sensitive Receptors and Limits of Acceptable Change

In order to implement the two-fold visibility goals of preventing future visibility impairment and restoring natural visibility conditions, alternative criteria for judging whether an existing or proposed emission source might cause adverse visibility impairment were considered. The two-fold visibility goal requires that visibility not be degraded beyond currently (admittedly unacceptable) conditions; thus, it was generally agreed that a stringent test should be given to any new emission source that might cause potential degradation. The Visibility Group felt that any perceptible degradation from existing conditions could not be tolerated. The criterion for judging future emission sources should therefore be defined at the marginally perceptible level.

The entire frequency distribution of visibility conditions should be used when evaluating visibility impacts. Various statistical measures such as percentiles could be used to characterize distribution. Problems were identified with this approach, however. Definition of the just noticeable change (jnc) for plumes, haze layers, and uniform haze could take years of research. A number of alternate quantitative parameters descriptive of jnc could be used as surrogates in regulation; however, jnc might be difficult to identify. For example, current estimates of a jnc for plumes and haze layers range from less than 2 percent contrast to 5 percent, depending on the viewing conditions and the observer. There currently is no research that would allow one to objectively define a jnc for uniform haze when visibility varies naturally from day to day and when the observer is comparing current visibility conditions to memories of previous conditions. Observers have been able to detect changes in uniform haze between two photographs viewed simultaneously. However, such viewing conditions are not at all representative of typical viewing conditions.

Significant or adverse visibility impairment due to plumes, layered haze, or uniform haze should be defined as 1 jnc from the pristine baseline, if it occurred more than 1 daylight hour per year. The measurement of jnc would be refined over time with recommended perception research; however, to start, changes in contrast, light extinction coefficient, or visual range greater than 5% would be judged adverse or significant. (Table 7 summarizes this recommendation.)

One member of the group felt strongly that defining significant or adverse visibility impairment at 1 jnc would be too restrictive and impractical to implement. Even small emission sources quite distant from wilderness areas might be expected to cause impacts of 1 jnc or more for at least a few hours per year.

The recommended definition of adverse visibility impairment would deal very strictly with each new increment of emissions. However, if this were the only policy followed to prevent significant deterioration, there would not be movement toward the second goal of restoring natural conditions. Thus, each allowed increment in new emissions should be offset by a decrease in emissions, greater than the proposed increase, from other sources. This would result in a net decrease in total regional emissions with each new source addition. An offset policy of this type would be difficult to structure equitably, but it must be pursued.

Aggressive movement toward natural visibility conditions will require more than regional emission offsets. The Forest Service should encourage the states and EPA to control existing sources of pollution. Controls should not be sought just for major industrial sources, but also for minor sources such as wood stoves and motor vehicles generally associated with more urbanized areas. Existing power plants or other point sources that are not controlled with state-of-the-art technology could be required to install retrofit technology. The Forest Service should work with federal, state, and local governments to reduce emis-

Table 7. Sensitive receptors and limits of acceptable change relating to visibility.

Sensitive receptor	Limits of acceptable change
Contrast	now: <5% change from baseline
Light extinction coefficient	future: <1 jnc from pristine baseline for 1 daylight hour per year
Visual range	<5% change from baseline

sions associated with currently uncontrolled major and minor sources.

Modeling Recommendations

Existing visibility screening and modeling techniques for plume visual impact (the EPA Visibility Workbook, VISCREEN, and PLUVUE) were generally considered to be adequate, but continuing refinement and testing were recommended.

For uniform and layered haze resulting from multiple sources of particles, SO_2, NO_x, and VOCs, the Forest Service needs to support and encourage the development, documentation, refinement, evaluation, and application of screening models and sophisticated deterministic and receptor models. These models need to be able to address existing emissions, new emissions, new emission offsets, and controls on existing sources. And, further, these models need to address the common worst-case meteorological condition in the Rocky Mountain Region—namely, stagnation in valleys and basins.

Existing tools are not adequate to calculate the impact of proposed new sources and to evaluate the impacts of existing sources on uniform haze, especially in rugged terrain. The types of visibility impacts that were identified at the Grand Canyon that led to the recent EPA proposal to retrofit the Navajo Generating Station were not related to whether the plume itself was identifiable as a coherent plume. The major impacts of Navajo (and most other sources) are believed to be increases in haze caused by emissions once the plume is uniformly mixed with background air. The plume itself is not visible but the plume contributes to increased haze that is perceptible. These impacts are largely due to sulfate particles and associated water formed in the atmosphere from sulfur dioxide (SO_2) emissions. In other cases, nitrate particles and associated water converted from NO_x emissions may be important.

Visibility models must be able to predict the effect of a given spatial and temporal distribution of light scattering and absorbing chemical species on the appearance of various landscape features and on observer perceptions. Different vistas have different sensitivities to increase in haze. For example, the sensitivity of a vista may depend on the distance and apparent size of various terrain features in the landscape, as well as their form, line, color, and texture.

Most analyses of proposed future changes—either increases in emissions from new sources or decreases in emissions from existing sources—require deterministic model capability. Deterministic models utilize quantitative knowledge of emissions, meteorology, diffusion, deposition, and chemical conversion to project future conditions. However, analysis of the impacts of existing sources can also be studied using receptor models. Receptor models use measurements of source and ambient concentrations and chemical composition to deduce the impact of a given source. Further development and refinement of receptor models is necessary to support activities to encourage the retrofit of existing pollution sources.

Monitoring Recommendations

The Forest Service should design, implement, and coordinate a comprehensive, long-term (in perpetuity) monitoring program to document visibility baselines and trends in areas representative of both high and low elevations of all wilderness areas. In addition, special monitoring should be carried out at existing sources suspected of causing visibility impairment in wilderness areas and in areas where future emission growth is anticipated.

Monitoring is required for a number of reasons. First, through photographic documentation, it may be possible to qualitatively demonstrate the existence of a visibility problem deserving additional monitoring, analysis, and remediation. Second, monitoring is needed to document existing conditions and trends in conditions over time. Monitoring of meteorological and ambient conditions is necessary to provide input for deterministic and receptor modeling of existing and new emission sources. Finally, monitoring of existing sources is needed to document their impact on wilderness areas and provide the necessary technical information to support implementation of emission retrofitting and other cleanup activities.

Trend and baseline visibility monitoring is needed in each wilderness area or in an area that is representative of a given wilderness area. Monitors in the mountainous wilderness areas of the Rocky Mountain Region need to be located at both high and low elevations. At high elevations, ambient concentrations tend to be lower and reflect regional contributions. At low elevations, concentrations are higher and reflect more local influences. Monitoring at low elevations is also necessary because layered haze, especially in winter, is trapped at the low elevations; thus, high-elevation monitoring would not be representative.

The type of monitoring equipment depends on the specific monitoring objectives. For example, if one needs to document qualitatively an existing visibility problem, photographs taken with an automated system over at least one year might suffice. However, to document the current baseline and trends, one needs to measure atmospheric optical parameters and particle concentrations, size, and chemical composition as well. Further, trend monitoring requires continuous monitoring over many years. It may require more than 10 years of data to identify trends because of year-to-year variability in meteorological conditions. Monitoring should be a perpetual, ongoing activity; it should not be started only to be stopped later.

Trend monitoring should use the technology and monitoring, data analysis, and quality assurance and control protocols of IMPROVE (the existing EPA and FLM monitoring network) in areas where electrical power is available. In more remote areas, solar-powered technologies should be developed, tested, and applied. It is likely that many low-elevation areas can be monitored with IMPROVE technology, while most high-elevation sites will require solar powered technology.

Trend monitoring needs to consist of three elements:

1. View monitoring - Photographs of given vistas with automated cameras, taken at least three times per day (at 0900, 1200, and 1500).
2. Atmospheric optical monitoring - Measurements of light extinction and the scattering and absorption components of light extinction. (Transmissometers, nephelometers, filters for light absorbing carbon.)
3. Particle monitoring - Mass, size distribution, and chemical composition. Important size categories: 0-2.5 µm and 2.5-10 µm. Important chemical species: sulfate, nitrate, organic carbon, elemental carbon, soil and trace elements with atomic numbers from sodium to strontium.

Specific monitoring strategies, siting policies, data analysis, and archival and quality assurance protocols need to be developed and coordinated with other monitoring agencies. These strategies and protocols should be designed to fit with the specific needs of Forest Service field personnel.

In areas where future emission growth is anticipated (e.g., the Piceance Basin), visibility baseline and trend monitoring, as well as meteorological and ambient concentration monitoring, should be started as soon as possible. In such areas financial support might be obtained from developers. In other areas, use of volunteers for photographic monitoring may be useful.

Research Recommendations

Research is needed to support the policy objectives and the modeling and monitoring recommendations presented earlier. The Forest Service visibility protection program must be flexible to allow evolution of our understanding of visibility and its relationship to atmospheric optics, ambient concentrations, and regional emissions. Conversely, our visibility research must be designed to support the specific needs of the visibility regulator.

The Forest Service needs to become a major player in visibility research and needs to coordinate such research with other agencies and industry. Research and development should be directed to continually improving and testing modeling and monitoring technology. Research should be performed in areas directly related to the specific needs of visibility policy, namely to protect and continuously improve visibility. To understand visibility, the "soft" sciences of psychology, perception, and economics are just as important as the "hard" sciences of physics and chemistry.

The following research topics were recommended by the Visibility Group:

1. **Modeling and monitoring development:** Since modeling and monitoring are major technical tools required in visibility regulatory activities, it is imperative that these technologies be continually refined and tested prior to application. Models need to incorporate new understanding and new algorithms as they are developed. Models need to be evaluated by comparing model calculations with field measurements. Monitoring technology needs to be refined and tested also. Considerably more work is needed to develop monitoring techniques that can operate unattended in remote wilderness locations without electrical power.
2. **Source attribution:** To aggressively strive for natural visibility conditions, special studies of suspected source contributions to impairment in wilderness areas need to start. Such studies are necessary to develop sufficient technical information so that regulatory agencies can pursue Best Available Retrofit Technology (BART) on currently uncontrolled sources. For example, the WHITEX, PREVENT, and Mohave studies could be used as models for such source attribution studies. Areas where such studies should commence immediately are wildernesses close to currently uncontrolled power plants in Colorado and Wyoming (e.g., Mt. Zirkel near the Hayden Power Plant).
3. **Remote sensing and geographical information systems (GIS):** Research should be devoted to the remote monitoring of ambient concentrations important to visibility and to the use of satellite imagery in GIS. Technology transfer in many different areas, such as remote sensing, should be explored.
4. **Data analysis:** With extensive monitoring networks employed, large quantities of data need to be routinely analyzed, interpreted, and visualized. New techniques, including scientific visualization and other computer hardware and software approaches, should be explored.

5. **Socio-economic and psychological research**: Further research needs to be performed to understand user preferences for wilderness areas, willingness to pay for improvements in visibility, psychological attributes of observers important in evaluating visibility, perceptual cues and parameters for use in impairment documentation, and better definition of the just noticeable change (jnc).

6. **Policy research:** Policy and implementation alternatives need to be studied to determine which are most efficient, cost-effective, and acceptable.

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