SENSITIVITY OF AQUATIC ECOSYSTEMS OF THE MT. ZIRKEL WILDERNESS TO ATMOSPHERIC DEPOSITION: LITERATURE REVIEW

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INTRODUCTION

This review paper was written in conjunction with the certification of impairment process for the Mount Zirkel Wilderness area, Routt National Forest, Colorado (Figure 1). It addresses the potential sensitivity of aquatic ecosystems to atmospheric deposition of pollutants, and the contribution from the Craig and Hayden power plants. Air pollution impacts on visibility are described in a separate document (Ely et al. 1993).

DISCUSSION

Atmospheric deposition has been studied extensively throughout the world, including the United States, Canada, Sweden, Norway and Germany. Many publications summarize the effect of acid deposition on aquatic ecosystems. Perhaps most important is the 10-year summary of the U.S. National Acid Precipitation Assessment Program (NAPAP) entitled "Acidic Deposition: State of Science and Technology," especially volume II-- Aquatic Processes and Effects (Irving 1991). Other review publications summarize case studies of acidic precipitation (Adriano and Havas 1987) or the processes and effects of acid deposition in general (Atshuller and Linthurst 1984; NAS 1984; Schindler 1988; Norton et al. 1989; Bowersox, Sisterson and Olsen 1990; Mason 1992).

Extensive research on acid deposition and long-term acidification in the United States was conducted at Hubbard Brook, New Hampshire (Likens et al. 1979; Likens and Bormann 1974; Hall et al. 1990); and for the Adirondack Lakes of New York (Metcalf et al. 1990; Schaefer et al. 1990; NAPAP 1993; Baker et al. 1993). Although much of the research is from eastern states, specific studies to the western United States include the Western Lake Survey (Eilers et al. 1987; Landers et al. 1987), an assessment of the sensitivity of high-elevation lakes in northern New Mexico (Lynch et al. 1988), and studies of the Sierra Nevada Lakes, California (Irving 1991; Williams, Brown and Melack 1993). The Forest Service conducts atmospheric deposition research at the acid-sensitive Glacier Lakes Ecosystem Experiments Site (GLEES) in Wyoming (Musselman et al. 1994), and many publications are available describing the results. Research publications specific to the Rocky Mountains (Turk and Spahr 1987, 1991; Eilers et al. 1991), state of Colorado (Turk 1983; Corn et al. 1989; Campbell, Turk and Spahr 1991), and to the Mt. Zirkel Wilderness area (Turk and Campbell 1987; Turk 1988) are available. Although the magnitude of acid deposition is not as great as in the east, there is hope that we can minimize the frequency and severity of episodic events in the west by controlling pollution sources.

Air Quality Related Values

The Forest Service responsibility for wilderness areas is defined in the Wilderness Act and the Clean Air Act. Wilderness is managed to preserve pristine conditions and the natural state, with a minimum of noticeable changes due to human impacts. In accordance with the Clean

Air Act, the Forest Service has defined Air Quality Related Values (AQRV) for Mt. Zirkeland other Class I wilderness areas that include values related to aquatic ecosystems (Potter et al. 1991). A national screening procedure for determining impacts of increased acidification on aquatic ecosystems is based on acid-neutralizing capacity (ANC)1 and deposition loading rates for sulfur and nitrogen. Accordingly, most systems in the west fall within a "yellow-zone" of uncertainty which requires a case-by-case analysis of the potential for acidification (Fox et al. 1989; Nichols 1990).

Sensitivity to acid deposition is detectable by monitoring aquatic biota, soils in the watershed, lake and stream chemistry, snowpack chemistry and snowmelt. "Water" is an AQRV for the Mt. Zirkel Wilderness, and indicators of aquatic ecosystem change include changes in water chemistry (e.g., total alkalinity, pH, and concentrations of anion, cations, metals, and dissolved oxygen) and changes in aquatic biota (e.g., plankton, necton, macroinvertebrates, etc.). According to the specific regional screening procedures for Mt. Zirkel Wilderness, if existing conditions show an ANC of 25-100 ueq/L, a 10% change in ANC would be acceptable: larger change could be acceptable if no adverse impact is predicted. For lakes with ANC greater than 100 ueq/L, a 10% change in ANC would be acceptable during ice-free conditions. An adverse impact to the wilderness would occur if any decrease in ANC occurs due to additional atmospheric sulfur or nitrogen deposition where acid-neutralizing capacity is less than 25 ueq/L. That criteria is based on a high probability of episodic acidification at very low ANC. The limit of acceptable change for total dissolved aluminum is 50 ppb in lakes, streams, vernal pools and snowpack. The specified levels of change are the cumulative effect of all sources over time (USDA Forest Service 1993).

Studies of the Mt. Zirkel Wilderness

The Western Lake Survey included 21 lakes in the Park Range group of the Southern Rockies, including 17 lakes in the Mt. Zirkel Wilderness. The lakes were randomly selected and sampled during the fall rather than the time of maximum sensitivity. The Park Range was characterized by bedrock of "Cretaceous sedimentary and Precambrian metamorphic material...[and] the fourth highest median ANC in the west" (Landers et al. 1987). It was estimated that 8 lakes out of a total of 134 in the Park Range have an ANC < 50 ueq/L. Lakes with the lowest ANC were: Seven Lakes, 36 ueq/L; Summit Lake, 56 ueq/L; Slide Lake, 42 ueq/L; and Middle Rainbow lake, 53 ueq/L. Conductivities were correspondingly low, i.e., < 10 mS/cm. Results are summarized in Table 1.

Additional studies of alkalinity measurements for 70 lakes in the Mt. Zirkel Wilderness showed that half had alkalinities less than 100 ueq/L, and one quarter had alkalinities less than 50 ueq/L (Turk and Campbell 1987). Worst-case estimates of an historic loss in acid-neutralizing capacity corresponding to 9 ueq/L (ibid) would represent an important departure from natural conditions, and be unacceptable at low ANC. This estimate is based on a conceptual model. Empirical data to support the estimate, however, are not available.

<u>Nitrogen and Sulfur Deposition (wet, dry, bulk, cloud, fog)</u>

In a comparison of bulk deposition patterns at 42 sites in Colorado during 1982-1983, the lowest atmospheric pH was observed along the ContinentalDivide. Atmospheric pH was

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1 The ability of surface water to neutralize acids is expressed in several ways: the sum of base cations minus the sum of strong acid ions, as carbonate alkalinity, or as acid-neutralizing capacity (ANC). In addition to carbonate alkalinity, ANC includes other bases such as borates, dissociated organic acids, and hydroxy-aluminum species (Landers et al. 1987).

Table 1. Data from the Western Lake Survey (WLS), Southern Rockies, Park Range, Sept. 1985.M1 These lakes are within the polygon 106.30-106.50 X 40.30- 41.00. The most sensitive lakes are those with ANC < 50 ueq/L. Low ionic strength (conductivity < 10 mS/cm) may indicate low ANC. Acidic lakes have an ANC < 0 ueq/L.M1 [Condensed from Eilers et al. 1987 and Landers et al. 1987.

equil. cond sulfate ueq/L ANC ueq/L mS/cm ueq/L

CODE	LAKE NAME	sum cations		pH, SU		elev m	
4E2007	West Fork Lake	516	444	7.86	47	2838	28
4E2008	Mica Lake	184	138	7.29	19	3180	35
4E2009	Seven Lakes	71	36	6.73	7	3273	13
4E2010	Gold Creek Lake	479	413	7.70	47	2914	44
4E2011	Bear Lakes	146	105	7.17	15	3153	35
4E2012	Twin Lakes	213	176	7.33	21	3009	32
4E2013	Martha Lake	301	264	7.49	29	3142	20
4E2014	Grizzly Lake	135	70	6.89	13	3111	30
4E2060	Summit Lake	88	56	6.91	9	3146	18
4E2062	Blue Lake	186	162	7.16	19	2993	27
4E1002	Ptarmigan Lake	392	308	7.69	37	3263	49
4E1003	Big Creek Lake	108	75	7.06	11	3239	15
4E1004	Fish Hawk Lake	149	94	7.12	15	2958	24
4E1005	Lake Margaret	131	81	7.14	13	3046	24
4E1006	Porcupine Lake	215	156	7.40	20	3190	14
4E1007	Slide Lake	78	42	6.93	9	3210	15
4E1008	Middle Rainbow	103	53	7.00	11	3007	28

POPULATION ESTIMATES AND STATISTICS FOR PARK RANGE:

Total number of lakes sampled during WLS 21

Estimated number of lakes (total population) 134

Estimated number of lakes with ANC < 50 ueq/L*

Median ANC, ueq/L 345

Median Conductance, mS/cm 39

Median lake area, ha 3.2

*Estimated ANC is a population estimate by extrapolation from sampled lakes to the population of 134 lakes throughout the Park Range. ANC in the upper portion of the table is the observed value for the lakes that were sampled.

< 5.0 SU near Mt. Zirkel, notably lower than background pH of approximately 5.6 SU. It is widely accepted that an annual mean precipitation pH of 5.0 or less strongly indicates an anthropogenic effect (Roth et al. 1985; Schindler 1988). Both sulfate deposition > 18 $mg/m^2/wk$) and nitrate deposition (> 2.5 - 3.5 $mg/m^2/wk$) were high in the northern mountains along the Divide, downwind from the Craig and Hayden power plants which are located within the Yampa River Valley (Lewis et al. 1984). In contrast, Turk and Spahr (1991) concluded that data from wet deposition in the Rocky Mountains indicate that "snowmelt and runoff are unlikely to be acidic enough to neutralize much ANC and still produce large decreases in pH."

Prevailing winds in Colorado are from the west during all seasons at mountain levels and higher elevation, with some shift between northwest and southwest directions (Lewis et al. 1984). Therefore, pollutants from areas such as the Yampa River Valley are likely to be transported and deposited at the Mt. Zirkel wilderness.

<u>Bedrock Geology and Hydrologic Factors</u>
Surface-water sensitivity to acidification is influenced by bedrock geology and hydrologic factors such as flushing rate and length of the flow path of water to the lake or stream (Reuss and Johnson 1986; Reuss et al. 1987; Irving 1991; Schafran and Driscoll 1993). Lakes with potential sensitivity include those for which direct precipitation onto the lake surface contributes a large portion of the hydrologic budget, and lakes that have a high hydrologic input due to snowmelt. Short hydrologic flow paths that characterize headwater streams and cirque lakes do not provide the reaction time necessary to dissolve acid-neutralizing material. Lakes located in non-reactive or slow-weathering bedrock (e.g., quartzite, monzonite, granite or basalt) also tend to have low alkalinity, even if flow paths are deep. These acid-sensitive conditions often occur at high elevation.

Precambrian granitic bedrock occurs commonly within the watersheds of Mt. Zirkel lakes, either exposed or covered by only shallow soils at high elevation (Turk and Campbell 1987). Low alkalinity lakes occur in the areas of felsic gneiss or quartz monzonites at elevations above 3500 m (ibid).

Episodic Acidification
Episodic acidification is defined as "the short-term decrease of acid neutralizing capacity from a lake or stream. This process has a time scale of hours to weeks and is usually associated with hydrological events" (Irving 1991). Thus, it refers to pulses of acidic input that generally are infrequent but may cause severe damage. Episodic acidification can also result in an increase in inorganic-monomeric aluminum2 concentration, due to atmospheric deposition of nitric and sulfuric acids. In watersheds where snowmelt is the dominant source of water, such as in the Mt. Zirkel Wilderness, episodic acidification most likely would occur during early snowmelt, perhaps before ice-free conditions in major lakes.

Episodic acidification and aluminum elevation can adversely affect the most acid-sensitive aquatic biota, especially early life stages or reproducing individuals. Some phytoplankton and diatom species are very sensitive to pH and water chemistry, and occur only within a small range of pH or ionic concentrations (Mason 1992; Anderson and Renberg 1992; Nicholls 1992). Also, snowmelt can flush aquatic systems rapidly, causing an abrupt change in water chemistry or aquatic biota. Headwater streams, vernal pools, and high-elevation lakes with low buffering capacity are particularly susceptible.

2 Inorganic monomeric aluminum "occurs as a free ion, Al^{+3}, simple inorganic complexes [e.g., with fluoride or hydroxide ligands]...but not in polymeric form" (Irving 1991).

Episodic acidification or ANC depression has been documented to occur in the Adirondack Lakes as measured in lake outlets or upper lake waters. The mechanism is dependent on baseline ANC: low ANC lakes were influenced by nitrate increases while high ANC lakes were influenced by dilution of base cations (Schaefer et al. 1990). Freshwater ecosystems in Canada experience episodic acidification caused by snowmelt, rainfall onto snow, and rainfall events. In some cases, the greatest decline in pH can occur after continuing freeze-thaw episodes (Mason 1992; Tranter et al. 1994). Similar processes could occur in Western U.S. lakes.

High elevation lakes are influenced by fog, clouds and snow that capture sulfates and nitrates. Cloud water generally is more acidic and contains higher concentrations of base cations than rain water, and can contribute substantially to total loadings (Hemmerlein and Perkins 1992). At mountain sites frequented by clouds and fog, acid deposition from clouds may equal or exceed that from precipitation due to foliar interception of cloud droplets and subsequent "drip" (Irving 1991).

In the west, acid precipitation is likely to result in episodic, rather than long-term acidification (Landers et al. 1987; Irving 1991; Turk and Spahr 1991). At high elevations and steep slopes, snowmelt can run off rapidly and have little soil contact time. The initial snowmelt can be many times more acidic than precipitation, and cause a rapid pH decline or "acid pulse." Synoptic sampling3 has shown that snowpack downwind of the Yampa River Valley in Colorado has a pH of 4.9 SU prior to melting, with about twice the concentration of sulfate and nitrate compared to snowpack at other high-elevation sites in Colorado. The northern Colorado snowpack also contains lower concentrations of alkaline ions to neutralize acidity. Thus, the initial snowmelt would be expected to have a pH much less than the bulk snowpack pH of 4.9 SU. Sulfur isotope ratios indicate a localized source of sulfate that affects lake chemistry in the southern portion of the Mt. Zirkel Wilderness area (Turk et al. 1992; Ely et al. 1993).

Glacier Lakes Ecosystem Experiment Site (GLEES)

The GLEES site is located in Wyoming, i.e., 30 km north of the Mt. Zirkel Wilderness at an elevation of 3200-3400 m (Figure 2). This alpine and subalpine area is characterized by "massive winter snowpack, harsh climate for terrestrial vegetation, exposed and slow-weathering bedrock [quartzite], shallow immature soils having low base saturation, and lakes with extremely low acid neutralizing capacity" (Musselman et al. 1994). The upper portion of the site contains three cirque lakes with extremely low ANC that are primarily fed by a

permanent snowfield. Precipitation over the watershed represents a smaller portion of the hydrologic budget. There are also several streams and ponds, including Meadow and Cascade Creeks. Both wet and dry deposition data are collected within the GLEES boundary from sites within the National Atmospheric Deposition Program (NADP) and the National Dry Deposition Network (NDDN). Meteorological data are also available from the Snow Range Observatory
network of the University of Wyoming (about a 25 year record).

3 Synoptic sampling conveys conditions at a point in time over a broad geographic area (Irving 1991).

Recent results from GLEES include evidence for episodic acidification characterized by a decline in alkalinity of 20 ueq/L and a decline in pH that exceeds 0.5 standard units (or more than a five-fold increase in hydrogen ion concentration). These measurements were made during snowmelt at the outlet of West Glacier Lake (Musselman et al. 1994). Deposition of pollutants in dry and wet deposition is noted in snowmelt chemistry and input to aquatic ecosystems. Similarly, snowpit chemistry shows ionic pulses with concentrations 4-10 times above the average concentrations (ibid). Thus, there is strong evidence that atmospheric deposition affects aquatic chemistry at GLEES.

Research at GLEES suggests that sulfur dioxide in the atmosphere can react with naturally-occurring hydrogen peroxide and incorporate high concentrations of sulfur compounds into snow (Richard Sommerfeld, GLEES, pers. comm.). Other mechanisms of sulfur accumulation are sulfur dioxide adsorption to ice, and sulfur dioxide oxidation to sulfate in supercooled cloud droplets that deposit as rime on snow (ibid).

Biotic Effects

The most acid-sensitive aquatic organisms are eliminated by pH values as high as 6.0 SU and diversity declines occur as pH decreases during spring snowmelt (Schindler 1988). Resident species of aquatic ecosystems that can be affected by atmospheric deposition include the following: microbial communities, plankton (Havens, Yan and Keller 1993), macroinvertebrates (France 1992; Griffiths and Keller 1992), periphyton and fish (especially salmonids). Transient species of aquatic ecosystems that can be adversely affected include amphibians, mammals, and birds (Irving 1991; McNichol and Wayland 1992).

Effects on aquatic birds are primarily due to changes in the availability and nutritional value of prey species (i.e., fish and invertebrates) that influence choices in breeding habitat, or due to bioaccumulation of toxic trace metals. Several species of waterfowl depend exclusively on invertebrate prey during the breeding season (McNichol and Wayland 1992). Over 200 species of birds inhabit the Mt. Zirkel Wilderness as resident or transient populations, including the resident American peregrine falcon and bald eagle that are on the Federal and Colorado State endangered species list (USDA Forest Service, Mt. Zirkel Wilderness area map; J. Friedlander, pers. comm.).

Listed sensitive species (as determined by the Regional Forester for the Rocky Mountain Region) that are found within the Mt. Zirkel Wilderness are: thenorthern leopard frog (Rana pipiens), wood frog (Rana sylvatica), tiger salamander (Ambystoma tigrinum), colorado river cutthroat trout (Oncorhynchus clarki pleuriticus), western boreal toad (Bufo boreas boreas) and

Rocky Mountain capshell snail (Acroloxus coloradensis). The western boreal toad is on the State of Colorado list of endangered species. Candidates for Federal listing under the Endangered Species Act (category 2) are the colorado river cutthroat trout and western boreal toad (Joan Friedlander, pers. comm.; USDA Forest Service, Mt. Zirkel Wilderness area map). Eggs and larval stages of the leopard frog are very sensitive to low pH. Adult tiger salamanders are also acid-sensitive, while the wood frog is acid-tolerant (Corn et al. 1989; Irving 1991). Another acid-sensitive amphibian species that may be found in Colorado wilderness areas is the chorus frog (USDA Forest Service 1993). If temporary breeding ponds with low ANC are characterized by the pH measured in snowpack, then those aquatic ecosystems would be toxic to amphibian species (John Turk, pers. comm.; Campbell, Turk and Spahr 1991). However, breeding pools have notbeen surveyed for water chemistry. Salmonid species within the wilderness include rainbow, brook and cutthroat trout (Lupe Marquez, pers. comm.; USDA Forest Service, Mt. Zirkel Wilderness area map). The critical pH for rainbow trout is about 5.5 SU (Irving 1991). An immediate surface water response to deposition input would be expected, as observed in the Flat TopsWilderness (Campbell, Turk and Spahr 1991).

Paleolimnolgical studies are conducted to reconstruct historic lake pH levels from the record of fossil diatom communities. Sediment cores are examined for changes in species composition and dated using isotopes of lead, carbon or cesium. Changes in species composition and corresponding diatom pH-preferences can then be compared to atmospheric deposition data (Anderson and Renberg 1992; Dixit et al. 1992; Mason 1992). For example, two high-elevation lakes in the northern New Mexico Rocky Mountains appear to be shifting toward more acid tolerant species than in earlier years (Lynch et al. 1988). Conversely, a paleolimnological study of four subalpine lakes in Rocky Mountain National Park showed no influence on pH due to atmospheric deposition (Baron Norton and Herrmann 1986). Other procedures such as exposure experiments or bioassays (Irving 1991; Havens, Yan and Keller 1993) and in-situ acidification experiments are used to characterize plant and animal sensitivities to acidification.

Aquatic biota can also be adversely affected by contamination with toxic trace metals from the atmosphere. Industrial sources of lead, zinc, nickel, copper and cadmium are found in the atmosphere throughout the world (Verry and Vermette, 1992). Also, conversion of aluminum at low pH to the toxic inorganic monomeric form can impede fish respiration and other physiological processes at concentrations >30 - 50 mg Al/L (Driscoll et al. 1980; Schindler 1988; Irving 1991; Mason 1992). Deposition of anthropogenic mercury can also cause aquatic ecosystem effects, e.g., impairment to fish populations (Nater and Grigal 1992). The chemical and biological benefits of reducing sulfur dioxide and trace metal emissions from smelters near Sudbury, Canada, have been demonstrated in aquatic ecosystems (Keller, Gunn and Yan 1992; Keller, Pitblado and Carbone 1992).

Case Studies of Experimental Acidification

Several case-studies in experimental lake or stream acidification are available to evaluate the effects on aquatic ecosystem composition and function. Biogeochemical cycles, decomposition, and community composition and interactions can be affected by acidification (Hendrey 1984; Rudd et al. 1988). The case studies discussed here are: Little Rock Lake, Wisconsin, a glacial lake in a forested watershed; Lake 223, Ontario; and Norris Brook, New Hampshire. Other examples can be found in the literature, including the experimental acidification of alpine catchments in Norway for a period of eight years (Wright, Lotse and Semb 1994).

Little Rock Lake, Wisconsin, was divided by a vinyl curtain in 1984 to allow experimental acidification of the north basin to pH levels of 5.5, 5.0 and 4.5 SU. The south basin is used as a control. The lake was an ideal study area since almost all of the water entering it is from precipitation (there is no surface inlet or outlet) and alkalinity was about 27 ueq/L in both basins. Many individual experiments such as in-situ enclosures have been conducted and these results are summarized in Table 2. Effects on aquatic biota were detected at each of the three pH levels (Brezonik et al. 1986; King, Mach and Brezonik 1992; Webster et al. 1992; Brezonik et al. 1993). During a reverse experiment to increase pH at Max Lake, Wisconsin, the recovery for zooplankton, macroinvertebrate and fish communities was poor (Garrison et al. 1994). Thus, the the rate of biotic recovery is lower than the rate of biotic decline (Paul Garrison, pers. comm.).
S 12

Table 2.M1Summary of definite ecosystem effects on aquatic biota, Little Rock Lake acidification experiment, Wisconsin. Other possible effects were also reported. Original lake pH was ~ 6.1 SU, alkalinity 27 ueq/L. M1 [Condensed from Brezonik et al. 1993.] S 10

	pH 5.6 SU (1985-87)	5.1 SU (1987-89)	4.7 SU (1989-91)
Phytoplankton		Loss of blue-green algae sp.; increase in sulfur bacteria within hypolimnion	
Pelagic Zooplankton	7/34 dominant taxa declined, 2/34 taxa increased	14 taxa decreased; 4 taxa increased; cladoceran biomass increased (total)	20 taxa declined, 8 increased; loss of species diversity; biomass decline;

Littoral Zooplankton	1/9 dominant taxa declined, 2/9 increased;increased abundance/biomass ratio	5 taxa increased due to algal mat; 1 taxa almost gone; 1 new taxa noted; biomass and abundance increased	Taxa: 1 lost, 3 declined, 1 incr.; both abundance & biomass increased
Benthos	Chironomidae emergence decline or disruption	1 taxon increased due to algal mat; loss of mayfly Leptophlebia sp.	Caenis sp. lost; Chaoborus emergence increase; increased predaceous insect larvae
Algal mat	large increase in mat (areal coverage of lake bottom)	larger increase in mat (areal coverage of lake bottom)	
Fish	rock bass survival reduced; largemouth bass year classes reduced	year-class reductions for black crappie, rock bass, largemouth bass	rock & largemouth bass year-class failure;lost young-of-the-year yellow perch

The results of experimental acidification from a pH of 6.8 to 5.0 SU over eight years were summarized for Lake 223, a coldwater lake in Ontario. Changes in community structure were noted for phytoplankton species. Fish reproduction stopped, and benthic crustaceans were eliminated. Populations of filamentous algae were found in the littoral zone only after acidification. In contrast, the acidification did not reduce primary production, rates of decomposition or nutrient concentrations. Key fish-food organisms were eliminated at a pH of 5.8 SU (Schindler, Turner and Hesslein 1985). The diversity of most algae, zooplankton, benthos and fish declined (Mills and Schindler 1986; Schindler et al. 1985). At a pH of 6.13 to 5.93 SU, phytoplankton species composition was altered, zooplankton species were lost, one invertebrate species sharply declined, and fathead minnow recruitment failure was detected (Irving 1991).

Norris Brook, New Hampshire, was experimentally acidified from a pH of 5.7-6.0 down to a pH of 4.0 SU. Invertebrates were adversely affected by decreased emergence, increased drift downstream during the first week, and declines in density (Irving 1991). Periphyton biomass increased. Hyphomycete fungus density fell while basidiomycete fungus density grew, covering more than 70% of the stream bottom (Hall et al. 1980; Mason 1992). Mats of fungus may affect nutrient exchange between sediments and lake water (Mason 1992).

These studies provide essential information regarding the potential for aquatic ecosystem effects at varying levels of acidification under controlled conditions. Extrapolations to other areas can be made with caution.

CONCLUSIONS

In summary, the aquatic ecosystems of Mt. Zirkel Wilderness are sensitive to acid deposition and currently receive anthropogenic contributions of sulfur and nitrogen. This sensitivity is evident based on the following conditions:

1. High elevation location along the Continental Divide - elevations of the Mt. Zirkel Wilderness range from 2,256 to 3,712 m and include alpine and subalpine lakes;

2. Watersheds composed of non-reactive bedrock with slow weathering rates;

3. A minimum of 18 lakes in the Mt. Zirkel Wilderness with observed alkalinity < 50 ueq/L, and some lakes with < 10 ueq/L;

4. Precipitation chemistry with higher concentrations of sulfur and nitrogen than background-- evaluation of sulfur isotopes indicate that local sources contribute to this condition (Ely et al. 1993, Turk 1992);

5. Presence of acid-sensitive amphibians, salmonids and other biota;

6. Conceptual modeling that indicates a loss of buffering capacity has probably occurred in some lakes within the Mt. Zirkel Wilderness;

7. Potential for episodic acidification during snowmelt;

8. Potential response of aquatic ecosystems to increases in acid deposition; and
9. Proximity to sources of nitrogen and sulfur that can be transported to the wilderness by prevailing winds. This includes the Hayden and Craig electric-generating stations upwind from the wilderness, and sources located at greater distances.

Based on the information available, aquatic ecosystems of the Mt. Zirkel wilderness have probably been affected by anthropogenic sources of acidic deposition. Direct observations of aquatic chemistry support the certification of impairment by the Rocky Mountain Region. Further evidence could be obtained using additional models such as "MAGIC" (Model of Acidification of Groundwaters in Catchments) or the Henriksen model with modifications by Brakke, or by conducting a paleolimnological study of diatom assemblages. However, such indirect methods may not be as definitive as the studies that have already been conducted by the U.S. Geological Survey. Direct chemical measurements from temporary breeding ponds with low ANC could be obtained to determine whether the pH is similar to that measured in snowpack, and therefore, lethal to sensitive amphibian species that inhabit the Mt. Zirkel Wilderness.

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Figure 1. Map of Mt. Zirkel Wilderness area, USDA Forest Service.