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ACID PRECIPITATION AND BUREAU OF RECLAMATION WATER RESOURCES: POTENTIAL EFFECTS AND SENSITIVITY OF STORAGE RESERVOIRS

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16. ABSTRACT

Bureau of Reclamation storage reservoirs in the 17 Western States were evaluated to identify impoundments potentially at risk to damage from acid precipitation. Sensitive facilities were identified by visual overlay analysis of several geographic data layers including sensitive bedrock geology, surface water alkalinity, proximity to sources of atmospheric pollution, atmospheric deposition data, precipitation and prevailing winds, sensitive surface soils, and topography. Seventy-two storage reservoirs were identified as being in potentially acid-sensitive areas and were numerically ranked according to degree of sensitivity. Ten reservoirs were identified as sensitive, 24 as moderately sensitive, 29 as marginally sensitive, and 9 as not sensitive to acid precipitation. While current data do not indicate definitive or irreversible impacts from acid precipitation in the Western United States, acid precipitation has been observed during the past 10 years, and much of the mountainous West is known to be very acid sensitive. Thus, the potential for deterioration of water quality and damage to concrete and steel structures at very sensitive reservoirs should be considered if emissions of atmospheric acid precursors increase over the next 20 to 40 years.

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EXECUTIVE SUMMARY

Many issues contribute to the controversy surrounding acid precipitation: statistical uncertainty inherent in highly variable natural systems, inadequacy of current scientific and economic theory and models when applied to complex phenomena, the political nature of assessing responsibility for impacts and allocating costs for cleanup, and diplomatic aspects of air pollution transport across international boundaries.

While questions regarding the science and policy of acid precipitation remain to be resolved, sufficient evidence exists to implicate atmospheric pollutants from fossil fuel combustion in the formation of acidic precipitation. Acidic deposition is also suspected to have caused environmental damage in Scandinavia, a region similar to many mountainous locations in the Western United States.

Much of the attention of researchers and the national news media has focused on acid precipitation effects in the Eastern United States. Compared with the 17 Western States under Reclamation stewardship, the more populous and industrialized East has experienced substantially more acidic precipitation. Despite the lack of dramatic acidity-related damage, the Western States contain extensive mountainous areas that are extremely *sensitive* to acidification. Many Reclamation reservoirs and/or their watersheds are located in these sensitive areas.

The potential effects of acid precipitation that should concern Reclamation are related to the acidification of surface waters, ground water, and forest soils. The long-term results of this acidification could include:

- Mobilization of toxic trace metals, especially from exposed mine tailings, and the resulting risks to aquatic life and human health

- Increased corrosion of concrete and steel structures

- Forest dieback leading to increased erosion of the watershed and sediment loading in reservoirs.

While volume-weighted average precipitation pH is currently > 5.0 in the West, individual pH values < 4.7, generally accepted as acidic precipitation, have been reported at many western locations during the past 10 years. There have been no reports of permanent acidification of surface waters in very sensitive western subalpine ecosystems, but episodes of temporary lake and stream acidification have been observed.

Current emissions of the nitrogen and sulfur oxide acid precursors that cause acid rain are slightly below levels reported in the early 1980's. However, these emission levels are still higher than the full-production levels seen during World War II. Also, the U.S. Federal Highway Administration has reported steadily increasing numbers of motor vehicles, suggesting that nitrogen oxides emissions may increase over the next 20 to 40 years.

Fossil fuel emissions may decrease in response to concerns about global climate warming or because of legislative requirements; however, rapid industrialization in Mexico and other developing nations could have an opposite and negative effect on western acid deposition.

Seventy-two Reclamation storage reservoirs located in geographic areas considered to be acid sensitive were identified and ranked according to the degree of sensitivity using an overlay analysis of several geographic data layers. The data layers and their respective scoring criteria are detailed in the Methodology section and in appendix 2, and include bedrock geology, surface water alkalinity, elevation and topography, sensitive surface soils, precipitation volume, evidence of acidic deposition, and proximity to sources of atmospheric pollution versus prevailing wind directions. Data summaries for the overlay analysis may be found in appendix 4.

Of the 72 reservoirs included in the analysis, 10 were classified as "sensitive," 24 as "moderately sensitive," 29 as "marginally sensitive," and 9 as "not sensitive" (see page 11 for a discussion of these classification terms). The 10 reservoirs classified as sensitive are:

- Keechelus, Kachess, and Cle Elum Lakes, Bumping Lake, and Clear Lake (Clear Creek Dam), Yakima Project, Washington

- Lake Granby, Lake Estes (Olympus Dam), and Shadow Mountain Reservoir, Colorado-Big Thompson Project, Colorado

- Turquoise Lake (Sugar Loaf Dam), Fryingpan-Arkansas Project, Colorado

- Platoro Reservoir, San Luis Valley Project, Colorado.

These structures contain a total active capacity of approximately 1.52×10^6 acre-ft (1.88×10^9 m^3) - about 10 percent more volume than the active capacity in Theodore Roosevelt Lake, Arizona. Associated sensitive watersheds cover 1,200 mi^2 (3.11×10^5 ha), an area the size of Rhode Island. While reservoirs classified as sensitive could experience direct acidification effects in the long term, they are not as sensitive to acid deposition as most "very sensitive" subalpine or alpine lakes and watersheds in the West.

The moderately sensitive reservoirs account for an active capacity of 3.40×10^9 acre-ft (4.15×10^9 m^3) - 10 percent less than the volume of Flaming Gorge Reservoir, Wyoming-Utah. These reservoirs have a total watershed area of 17,000 mi^2 (5.73×10^{10} ha), an area twice the size of Massachusetts. These reservoirs are not likely to experience direct effects of acidification except under the most pessimistic emission forecasts. An exception to this statement applies to systems such as Ridgway Reservoir and the Dallas Creek watershed that have already experienced toxic metal problems caused by leaching of mine tailings in the watershed.

Current western acid deposition does not pose an immediate threat to Reclamation dams and water quality; however, an attitude of prudent vigilance should be maintained, and more detailed studies in sensitive watersheds should be considered. The extreme sensitivity of some watersheds coupled with the presence of mine tailings, potential increases in population, economic activity, or external events (such as operation of large, unregulated smelters in northern Mexico) could result in sudden impacts to Reclamation-managed resources.

Finally, while acid precipitation is a serious environmental problem, it is only one of several significant air pollution issues that could affect Reclamation resources. Atmospheric warming caused by greenhouse gases and depletion of stratospheric ozone caused by CFC's (chlorofluorocarbons) could have profound effects on climate and agricultural viability in the

Western United States over the next 30 to 50 years. If the current preliminary projections of global warming effects have *any* validity, the resulting impacts could dwarf worst-case scenarios for acid precipitation damage.

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SCOPE

This report represents an initial evaluation of Bureau of Reclamation water resources potentially at risk from the effects of acid precipitation. While some acid precipitation effects and processes unique to the Western United States will be mentioned, this report is not intended to be a primer or technical overview of the acid precipitation problem. The reader is referred to several excellent review/overview documents (Altschuller and Linthurst, 1984a, 1984b; Roth et al., 1985; Teasley, 1984) and an annotated bibliography (Stopp, 1985) that will provide background information.

This report provides pertinent information to Reclamation management and technical personnel involved with long-term planning, operation and maintenance of water projects, and environmental assessment and research. Additionally, it should be of general interest to all Reclamation employees and other Federal and State resource management agencies concerned with the acid precipitation problem.

INTRODUCTION

Acid precipitation is one of several consequences of the widespread burning of fossil fuels in industrialized and less-developed agrarian economies. The dimensions of the acid precipitation problem are vast and provide a great source of controversy among researchers, industrialists, environmentalists, and governments. Much has been written about this problem in the technical and popular literature, and the reader is encouraged to refer to the many references available on this subject for details. A glossary of some of the more common terms and acronyms used in the acid precipitation field may be found in appendix 1.

An Overview of the Acid Precipitation Problem

The process responsible for the formation of acid precipitation may be generally summarized as follows:

1. The combustion of fossil fuels containing sulfur (such as coal, fuel oil, diesel fuel, gasoline, or wood) releases oxides of sulfur and nitrogen (SO_x and NO_x) and VOC (volatile organic compounds) into the troposphere. NO_x is formed from the "burning" of atmospheric nitrogen during all air combustion, while SO_x is mainly associated with wood, coal, or oil burning.

2. Ozone, VOC, and ultraviolet light combine to form reactive compounds called radicals. The radicals then react with SO_x and NO_x to form nitric (HNO_3) and sulfuric (H_2SO_4) acids.

3. These acids are then dissolved in atmospheric water vapor, adsorbed onto suspended particulates and dust, or remain in a gaseous form. The acids can then return to the surface in a gaseous or particulate form as *dry deposition*, or dissolved in rain, snow, dew, fog, cloud moisture, or rime ice as *wet deposition*.

After deposition, the acids react with alkaline, acid-neutralizing components in the soil, bedrock, surface water, ground water, and building materials. Over time, the acid-neutralizing components may be depleted and subsequent acid deposition begins to cause environmental damage. For building materials, paint, and statuary, acid deposition begins to cause damage on first exposure.

Potential environmental damage from acid precipitation includes acidification of surface and ground waters and the associated loss of biological activity (McDonald, 1985; Leibfried et al., 1984; Reed and Henningson, 1984); growth inhibition and diebacks in forests, where acidity is thought to be one of several contributing factors (Hinrichsen, 1987; Puckett, 1982); loss of aquatic and terrestrial wildlife habitat; human health effects from acid-mobilized toxic metals (Trefry and Metz, 1984; Schmidt and Faust, 1984); and damage to building materials and statuary, primarily in urban areas (Reddy and Youngdahl, 1987). To date, the most significant effects from acid precipitation have occurred in the industrialized regions of Europe and North America.

In the United States, damage from acid precipitation has been observed primarily in the East, where population and industry are concentrated. Higher elevation lakes in the Northeast have experienced acidification and loss of biological activity (Driscoll and Newton, 1985; Davis et al., 1978), and acid precipitation is thought to be a factor in forest declines and diebacks observed throughout the Appalachians (Puckett, 1982). For these reasons, the majority of acid precipitation research and funding has been concentrated in the East.

Potential Acid Precipitation Damage to Reclamation Resources

The relative sensitivity of Reclamation water resources and current emission trends suggest that direct acidification damage is not likely during the next 10 years; however, there are several effects that should be considered possible over the long term (20 to 40 years).

Acidification of surface waters may cause deterioration of water quality and threaten aquatic and human health. The primary process that should be closely monitored is mobilization of toxic trace metals such as lead, cadmium, zinc, and aluminium present in the native geology and mine tailings located throughout the mountainous West. Rural communities with limited water treatment facilities could be exposed to toxic metals, and the viability of higher elevation fisheries could be threatened. Toxic metals problems could be exacerbated by increased frequency of episodic acidification during snowmelt and storm events.

While there is considerable debate concerning the role of acidic deposition in observed forest declines, there is little doubt that acids and other air pollutants contribute to this problem (Linthurst, 1984). Besides representing a potential loss of timber and wildlife habitat, forest declines may result in greater erosion in sensitive watersheds. If such erosion should find its way to Reclamation reservoirs, it would increase the rate of sedimentation and shorten project lifetimes.

Finally, acid precipitation can damage concrete and metal structures directly. Acidity damage can be observed at Buffalo Bill Dam, Shoshone Project, Wyoming, where natural sulfur springs near the dam have reduced the pH of the reservoir water. This natural acidification has increased corrosion of metal structures in and around the dam. Should atmospheric pollution levels increase and persist, similar damage to structures in sensitive watersheds can be expected.

Factors Affecting Acid Precipitation in the West

While the West experiences much lower levels of acid deposition than the East, western mountainous regions contain some of the most *acid-sensitive* areas in the world. These areas have many watersheds with steep gradients, little soil formation, and bedrock with poor ability to neutralize acidity. Surface waters throughout the mountainous West also have extremely low alkalinity (Omernik and Griffith, 1986). Because of these factors, slight increases in atmospheric pollution could result in sudden acidification of sensitive western watersheds (Roth et al., 1985; Tonnessen, 1984).

Some of the factors that are important in evaluating the acid sensitivity of western watersheds and reservoirs include:

General bedrock geology. - The Rocky Mountains and other western ranges contain large areas of recently exposed gneiss, granite, and volcanic bedrock that are poor acid neutralizers. The geologically recent exposure, caused by volcanic activity, uplifting, and glacial scouring, also results in poor soil formation.

Orographic effects. - Compared with the Appalachians, western mountains are steeper and much higher in elevation. Western topography has a large influence on local weather patterns [EPA (Environmental Protection Agency), 1978] and encourages precipitation and acid deposition in the mountains. Mountains are also exposed to cloud moisture and rime ice, two sources of deposition containing higher acidity than either rain or snow.

Precipitation patterns. - Orographic effects lead to significant precipitation in mountainous areas compared with the semiarid lower elevation areas. If precipitation contains excessive acids, this factor increases loading of acidifying compounds in higher elevation watersheds. Higher elevations in the West - with the exception of the Northwest Pacific coastal ranges - also receive the majority of their precipitation in the form of snow.

While precipitation volume may increase with elevation, it is important to note that higher elevation clouds tend to have lower concentrations of acidic precursors. The implication is that loading or deposition may not necessarily increase in direct proportion to the increased precipitation volume.

Episodic acidification. - During the onset of spring snowpack melt, deposited hydrogen ion is mobilized in an "acid pulse" that may temporarily acidify sensitive surface waters. Summer thunderstorms, some with pH observed as low as 4.05 (Denning, 1988), may also mobilize acids that have been deposited by dry deposition (McRae and Russell, 1984).

Role of alkaline dust. - While higher elevations often contain very sensitive and exposed bedrock, geologically recent soils found at lower elevations in the West are alkaline. Many Western intermountain basins are in semiarid or desert climatic zones, and these vast, sparsely vegetated areas are often exposed to high-velocity winds. Western air can therefore contain significant concentrations of suspended alkaline dust. This dust may neutralize atmospheric acidity while suspended, or it may be deposited on land and then act to neutralize subsequent acid deposition.

Morphology and size of lakes and reservoirs. - Lakes and reservoirs containing organic carbon that have sufficiently slow water exchange rates will support bacterial populations that can provide a source of ANC independent of mineral weathering. In deeper reservoirs that thermally stratify during summer and winter, bacterial activity in the hypolimnion (bottom) can be significant, resulting in production of bicarbonate ion. The duration and severity of thermal stratification will depend on many factors such as reservoir shape, runoff patterns, land use, and reservoir water release operations.

Some Comments on Natural Complexity and Controversy

Acid precipitation is a complex problem that involves many different natural and manmade processes. Almost all of these processes exhibit considerable variability, and the interactions among different processes (and a few of the individual processes themselves) are often poorly understood. Because of the neutralizing capacity of ecosystems, obvious acidification damage is often delayed for decades. Time lags for effects also act to obscure many more environmental interactions important to acidification.

Researchers are often asked to provide predictions for complex natural systems that can be used to justify difficult policy decisions. Some of the simulation models used for such purposes, besides ignoring many interactions, depend on the assumptions of smooth, continuous behavior and instantaneous equilibria. These assumptions - usually valid when applied to simple systems - are often violated in natural systems that behave in chaotic, discontinuous, and nonlinear ways (Nicolis and Prigogine, 1977). Application of slightly different models - or slightly altered initial conditions in the same model - can sometimes result in very different predicted behavior for identical data sets. The existence of several such predictions, each with a group of well-informed supporters, complicates the task of objectively developing policy.

The application of statistics also contributes to controversy surrounding acid precipitation. What is the appropriate confidence level (α error), and what constitutes an acceptable level of risk in statistical analyses of complex environmental data? For example, utility interests, who will have to make potentially expensive investments for pollution control, generally demand a higher degree of statistical certainty before capital expenditures are made. Environmentalists, on the other hand, would argue that a lower degree of certainty is sufficient when the potential risk of environmental damage is great. Depending on the particular vested interest, very different criteria of proof would seem appropriate.

While the intrinsic limitations and uncertainties of current scientific models and statistics are accepted and understood by scientists, many nontechnical people often assume that scientific results are precise and unambiguous. An unfortunate side effect of this assumption is the perception that controversy over the interpretation of ambiguous research results means that the problem is not serious or does not exist. Despite the controversy surrounding this subject, there is general agreement among researchers that acid precipitation is a real problem; it is caused by industrial and vehicular air pollution, and it has caused quantifiable environmental damage.

ACID PRECIPITATION RESEARCH RESULTS

Monitoring and Research in the Western United States

One of the problems facing acid precipitation evaluations in the West has been the eastern bias in research activity due to the disparity in population and observed acid deposition effects. While this factor has resulted in fewer deposition monitoring stations and long-term ecosystem studies in the

West, NAPAP (National Acid Precipitation Assessment Program) has recognized the need for more research to provide insight into western acid precipitation phenomena (NAPAP, 1986).

During the 1980's, more western deposition monitoring stations have been added by NADP/NTN (National Atmospheric Deposition Program/National Trends Network), thus enabling more accurate and precise estimates of deposition loading. Research has been funded to investigate the role of alkaline dust in western dry deposition (NAPAP, 1984), and western lakes and streams have been sampled and analyzed as part of the EPA National Surface Water Survey program.

Reclamation has helped support several NAPAP-sanctioned research programs that have been investigating watersheds in the Colorado Rocky Mountains. A major benefit of these programs is the development of a reliable set of baseline data from relatively pristine ecosystems that may be used to quantify natural system variability, help detect future impacts, and provide a better understanding of linked watershed processes. The National Park Service has been involved with a long-term integrated watershed study in Rocky Mountain National Park (Baron, 1983; Baron et al., 1985), and the USGS (U.S. Geological Survey) has been monitoring water quality in the Flat Tops (Turk, 1984) and Mt. Zirkel (Turk and Campbell, 1988) Wilderness Areas of northwestern Colorado.

Similar studies and data gathering activities of varying duration and detail are being performed by other Federal agencies, universities, and State water quality offices in the West. These include ecosystem studies of subalpine lakes at Mexican Cut near Crested Butte, Colorado (Harte et al., 1986); lake sensitivity studies in the Oregon (Nelson and Delwiche, 1983) and Washington (Logan et al., 1982) Cascade Ranges; monitoring of snowpack in the Montana Rocky Mountains (Pagenkopf, 1983); and evaluations of lake acidification in the Sierra Nevada Mountains (Melack et al., 1985).

Additionally, much of the national research effort in the NAPAP Natural Sources and Atmospheric Processes Task Groups is being performed in the West, where complex wind and weather patterns have long attracted atmospheric scientists (NAPAP, 1984). These studies deal with analytical chemistry of deposition monitoring, development and validation of atmospheric transport and chemistry models, and technical support for NADP/NTN monitoring efforts.

Surface Water Alkalinity in the West

The spatial distribution of low-alkalinity waters in the West is probably best described by the map by Omernik and Griffith (1986). This map was based on 3,400 samples from lakes and streams, and the data were obtained from several sources such as the EPA STORET water quality data base, state water agency data, and university research. As such, there is a degree of uncertainty in the boundaries derived from these data due to temporal variations and varying degrees of precision in methodology.

In general, low-alkalinity waters (< 100 μeq/L) are found at the higher elevations in alpine and subalpine glacial lakes throughout the West. Low-alkalinity regions (using Omernik and Griffith's physiographic zone names) include the following:

Cascades:	Olympic Mountains (Washington) Cascades Range (Oregon and Washington)
Sierras:	Klamath Mountains (northern California) Sierra Nevada Range
Northern Rockies:	Selkirk Mountains (northern Idaho) Sawtooth Range (central Idaho) Bitterroot Range (western Montana) Cabinet Mountains (northwestern Montana) Wallowa Mountains (northeastern Oregon)
Central Rockies:	Beartooth Mountains (southwestern Montana) Absaroka Range (northwestern Wyoming) Wind River Range (western Wyoming) Uinta Mountains (northeastern Utah)
Southern Rockies:	Rocky Mountain National Park Mt. Zirkel Area (northwestern Colorado)

An analysis of data from the USGS Benchmark sampling stations network indicates that there has been a downward trend in pH and alkalinity at several western locations (Turk, 1983). However, reported downward pH trends in the Como Creek, Colorado watershed (Lewis and Grant, 1980) are now thought to have resulted from natural variability, dilution effects, and improper data treatment (Turk, 1984).

Results of Long-term Ecosystem Studies

The consensus opinion among researchers who have completed or are conducting ecosystem studies in the West is that no permanent acidification of ecosystems has yet occurred. Observation of some very sensitive alpine and subalpine lakes in Colorado has not yet indicated any trends other than natural variability and occasional episodic drops in pH. There is concern, however, that repeated episodes of temporary acidification, either during spring snowmelt or storm events, may yet overwhelm the buffering capacity of highly sensitive alpine ecosystems (Tonnessen, 1984).

Acid-related reproductive effects in subalpine amphibians, suggested by Harte et al. (1986), have yet to be conclusively demonstrated due to the high natural variability found at both the chemical and biological levels in alpine and subalpine ecosystems. Similarly, tree damage suspected to be caused by acidification near Gothic, Colorado, is now thought to be normal disease and drought damage (Bruck et al., 1985) common to western subalpine forests.

It is an irony of timing that most of the western watershed research received funding and began to gather data as pollution emissions started to decline from historically high levels in the mid-1970's. As a consequence, it would be surprising if significant evidence of progressive acidification had been observed.

Atmospheric Pollution in the West

While the Western United States does not experience SO_x, VOC, and NO_x emissions and acid precursor loadings similar to those in the East (typically 3 to 5 times less than the Ohio Valley levels, with hydrogen ion loading 10 times less than in the East), there are several important pollution sources that can cause acidic deposition in sensitive western watersheds.

Table 1 summarizes atmospheric emissions data contained in a study of haze and visibility in the West (Latimer et al., 1985a, 1985b) and other more generalized sources (Roth et al., 1985; NAPAP, 1985; USGS, 1970). Table 1 also indicates acid-sensitive areas within 250 miles (400 km) and downwind from each of the emission sources. These data represent emission levels observed in the early 1980's and are primarily intended to provide an indication of source locations and relative emission quantities.

Table 1 reveals that the major source of air pollution for the West is an extended urban-industrial zone that includes central and southern California, southern Arizona, and northwestern Mexico. Another source of emissions important to long-distance transport is the Seattle-Tacoma metropolitan area. With the exception of small, localized sources in nearby proximity to sensitive areas, such as the Four Corners Powerplant near the San Juan Mountains, many watersheds in the West receive a large portion of their deposition from these major emitting areas.

Thus, pollution from the Los Angeles metropolitan area, while more directly affecting the southern Sierra Nevada Mountains, will also be transported to the central Rocky Mountains. Similarly, smelter emissions from the southern Arizona/northern Mexico region affect not only the Mogollon Plateau in Arizona, but also the San Juan and Rocky Mountains in Colorado.

Emission and Deposition Trends

Recently, SO_x emissions and sulfate deposition in the West have declined due to shutdowns of refineries and smelters in Montana, California, and Arizona. The gradual installation of control equipment on powerplant smokestacks and replacement of older facilities have also contributed to this downward trend in sulfur emissions. Because SO_x is produced primarily by oil- or coal-burning industrial plants (point sources) and is subject to more easily enforceable legal and technological control strategies, future SO_x emissions within the United States will probably continue to decrease.

There are short-term uncertainties, however, that make the western SO_x future less optimistic. Recent and planned production increases in the northern Mexico smelting industry could more than compensate for any American decreases in SO_x emissions - a good example of a Western transboundary problem posed by atmospheric pollution. Because of prevailing wind patterns, enhanced SO_2 emissions from the Sonoran smelters in Nacozari and Cananaea may cause increased sulfur deposition throughout the intermountain airshed (Yuhnke and Oppenheimer, 1984.)

The national NO_x emissions trend for 1975-85 is not as encouraging for the West as was the SO_x trend. Wyoming, Colorado, and Arizona showed modest increases, while Washington, Utah, and New Mexico showed little or no change during this period (NAPAP, 1987).

Why have NO_x emissions not decreased along with SO_x? One reason is that all air combustion produces NO_x, and while scrubbers and other control equipment may reduce SO_x, no economically feasible control method is available for NO_x. Another important cause for the NO_x trend may be the observed increases in the total number of motor vehicles in the United States. Automobiles and trucks represent a major source of NO_x, VOC, and ozone emissions in most populous areas.

For the period 1980-87, data compiled by the U.S. Federal Highway Administration (1987) show that motor vehicles (cars and trucks) in the United States have increased from 156 to 181 million units, an increase of 25 million vehicles. This represents an approximate annual rate of increase of 2.3 percent per year (roughly 3.6 million new vehicles per year). The 1980-87 rate of increase is lower than the 4.4-percent per year rate observed from 1970 to 1980 when new vehicles increased at a rate of 4.7 million per year. While the rate of increase has slowed somewhat during the 1980's, urban vehicle pollution has increased despite improved gasoline mileage.

The increases observed for the 11 Far Western States (the 17 Western States minus the Plains States from North Dakota to Texas) have particular relevance for Reclamation's sensitive watersheds. Vehicle numbers increased from 20.8 million in 1970 to 37.4 million in 1987, with the greatest increases occurring in California (8.7 million new vehicles since 1970, 3.7 million since 1980). Only Wyoming has shown a decrease during the 1980-87 period, and Washington and Arizona have shown rates of increase similar to those for California (although numbers of vehicles for these states are about 10 to 20 percent of the California totals). Overall, the rate of increase in vehicles for the Far Western States was higher than the national rate during both the 1970's and the 1980's.

These data help explain the observed increases in NO_x emissions and suggest that economic and demographic trends such as population migration for jobs, emigration, and maturation of the baby boom can have direct influence on air pollution emissions.

In the short term, however, unexpected economic dislocations or natural disasters (forest fires or volcanic eruptions) may suddenly increase or decrease emissions in the West. A severe recession would act to further reduce air pollution, while a fuel embargo that stimulated the currently dormant oil shale industry would suddenly increase emissions in areas that are very sensitive to acidification. Similarly, an embargo on strategic metals or increases in Mexican metal refining could result in unanticipated smelting activity. Natural emissions are also important and unpredictable. Plumes of smoke from the 1988 summer fires in Yellowstone National Park were carried many hundreds of miles downwind, and ash from the 1980 Mt. Saint Helens eruption was deposited throughout the West. Clearly, potential damage to Reclamation water resources depends on many natural and economic uncertainties.

As for acid deposition and loading, recent NADP/NTN monitoring data suggest that average western precipitation pH, sulfate, and nitrate concentrations are relatively unchanged from early 1980's values (NADP, 1983), and all constituent concentrations are well below those observed in the East (NAPAP, 1987). In 1983, average volume-weighted precipitation data in the West were pH > 5.0, sulfate < 1.5 mg/L, and nitrate < 1.1 mg/L (Rinella and Miller, 1988). Once again, it is important to remember that variability for these data can be significant, and episodes of greater acidic deposition occur depending on emissions and weather patterns.

Finally, despite improvements in reducing emissions that have occurred, current emissions are still near the levels observed during the production peaks of World War II, and are significantly higher than the natural background levels (NAPAP, 1987). The implication is that some of the very sensitive western watersheds could be affected over the next 20 to 40 years even under a decreasing emissions scenario.

METHODOLOGY

Storage reservoirs were selected as the Reclamation water resource for acid sensitivity evaluation. The reasons for selecting storage projects are that diversion dams generally are smaller structures with more rapid water exchange rates, and irrigation canals, etc., are usually at lower elevations in areas containing alkaline soils. Also, storage reservoirs are the more visible of Reclamation water resources, often having significant recreational usage with national name recognition. The structures evaluated in this study are referred to by the reservoir or lake name. In cases where the reservoir or lake name is different from the dam name, the dam name is also included.

Overlay Analysis

Assessing the acidification potential of a given area is a difficult proposition, especially at the large scale used in this study. Because of the complexity and diversity of western ecosystems, no single factor, such as bedrock geology or elevation, can be applied to all areas to accurately predict sensitivity to acid precipitation. Each area has a unique "mix" of factors that interact to determine sensitivity, so this study used an overlay analysis that incorporated many of the factors considered related to acid vulnerability.

The primary criterion for including a reservoir in this analysis was whether or not the site is located in, or very near, an area with sensitive bedrock geology as defined and mapped by Norton et al. (1982). Norton zones 1 (extremely sensitive) and 2 (very sensitive) were digitized for direct overlay with project location maps for each of the 17 Western States. Sensitive bedrock geology was chosen since bedrock represents the principal source of acid-neutralizing materials in higher elevation western watersheds.

Sensitive Reclamation reservoirs were identified by comparing reservoir locations to several maps displaying acid sensitivity information. Reservoir locations, rivers, cities, and major Federal highways were digitized from USGS state maps, and other map information was digitized from various sources (app. 2).

The digitized information, including USGS elevation data, was plotted on transparent mylar using the same projection aspect at a scale of 1:1.75 million. A direct overlay method was used to compare reservoir locations with the different sensitivity information maps. Reproductions of the set of 1:1.75-million-scale maps used to evaluate Colorado reservoirs may be found in appendix 3. The digitized maps for all 17 Western States are also available on half-inch magnetic tape.

Other less precise information at scales of approximately 1:12 million were also used, and these data were visually compared with reservoir locations. These information layers vary in degree of precision due to differing map scales and age of data.

Appendix 2 describes the 11 variables and the scoring criteria used to classify reservoirs in this study, and also discusses the advantages and disadvantages of each variable. Four variables were given scores for the reservoir location, while seven other variables were scored for the larger watershed area associated with the reservoir. Some geographic information layers were used as variables twice, with different scoring used for the actual reservoir site (higher scores for identical data) and its surrounding watershed (lower scores). The total sensitivity score for a given reservoir is simply the sum of the 11 variable scores, with higher scores suggesting greater sensitivity to acidification.

A valid criticism of the selection of variables and relative scoring is that the process is somewhat arbitrary and involves generalizations not appropriate to more detailed studies at the watershed scale. Each watershed is unique and complex, and there have been no studies to establish the relative importance of the chosen variables to acidification processes.

The variety of Reclamation watersheds, the large area being evaluated, and the initial screening purpose of this study, however, would argue that the procedure described here (used with prudent skepticism) is appropriate.

Ranking of Reservoirs According to Sensitivity

A numeric scale was chosen to rank Reclamation reservoirs based on the total score from the overlay analysis. Data values and assigned scores may be found in appendix 4. Reservoirs were classified according to the following criteria:

> 25 points	Very sensitive
20 - 25 points	Sensitive
15 - 19 points	Moderately sensitive
10 - 14 points	Marginally sensitive
< 10 points	Not sensitive

These categories provide a convenient way to evaluate the degree of sensitivity of a given reservoir; however, the terms are relative and should not be confused with similar terms applied to acid-sensitive subalpine lakes. Many subalpine systems exhibit alkalinities of < 50 μeq/L, an unlikely situation for any of the reservoirs evaluated here.

For example, sensitivity scores were evaluated for Sky Pond, located in the Loch Vale watershed, Rocky Mountain National Park, Colorado (Baron et al., 1985); Lake Dorothy, a Cascades Range lake located in the Alpine Lakes Wilderness Area, Washington (Dethier et al., 1979); several low-alkalinity lakes in the Mt. Zirkel Wilderness Area, Colorado (Turk and Campbell, 1988); and several Sierra Nevada lakes (Melack et al., 1985). Sensitivity scores for these small, subalpine systems ranged from 33 to 36, approximately 10 points higher than the most sensitive Reclamation reservoir rated in this study. These systems are truly vulnerable to increases in acidic deposition.

The following explanations should help clarify the intended meaning of the different categories that apply to the reservoirs evaluated in this study:

> **Sensitive.** - These reservoirs are not as vulnerable as the subalpine lakes mentioned above; however, those with higher scores in this category may already experience direct acidification effects such as occasional episodic loss of alkalinity during spring snowmelt or storm events. Should acidic deposition increase, the smaller of these reservoirs and/or their watersheds could acidify over the long term and exhibit responses similar to damaged Scandinavian or Adirondack Mountain ecosystems. These reservoirs also would be the first to experience enhanced sediment loading and trace metal mobilization if their more sensitive watersheds are affected by acidification. As expected, these systems are usually headwater reservoirs.
>
> **Moderately sensitive.** - These systems probably will not be adversely affected unless acidic deposition increases or continues unabated for some decades to come. Direct effects from acidification are not generally expected, but secondary effects from acidification in sensitive upstream areas of their watersheds could enhance sedimentation and metals mobilization. Reservoirs in this category that already experience trace metal problems related to mine tailings, such as Ridgway Reservoir, Colorado, may have more problems if acidification continues.
>
> **Marginally sensitive.** - Unless special circumstances apply, such as proximity to a significant pollution source, these reservoirs probably will not be affected.
>
> **Not sensitive.** - These reservoirs are probably not at risk except under the most severe and long-term acidification scenario.

It is important to note that this classification represents a generalized analysis. More thorough, site-specific studies could provide information indicating that a given reservoir or its watershed is more or less sensitive than this study suggests.

RESULTS AND DISCUSSION

Reservoir Classification Results

Results of the reservoir classification overlay analysis (app. 4) are summarized in tables 2 and 3. No reservoirs from the Plains States (North and South Dakota, Nebraska, Kansas, Oklahoma, and Texas) were included due to the lower elevations, lack of sensitive bedrock, and the calcareous soils associated with this region.

Of the 72 reservoirs evaluated in the remaining 11 Western States, 10 were classified as sensitive (table 2), 24 as moderately sensitive (table 3), 29 as marginally sensitive, and 9 as not sensitive. Reservoirs classified as sensitive represent $\approx 1.52 \times 10^6$ acre-ft (1.880×10^9 m^3) of active storage capacity, with an associated watershed area of $\approx 1{,}200$ mi^2 (3.11×10^5 ha). Moderately sensitive reservoirs represent active storage of $\approx 3.4 \times 10^6$ acre-ft (4.15×10^9 m^3) and a watershed area of 17,000 mi^2 (5.73×10^{10} ha).

To gain some geographic perspective, consider that sensitive reservoirs represent a volume of water about 10 percent more than the active capacity of Theodore Roosevelt Lake, Salt River Project, Arizona, and their watersheds cover an area the size of Rhode Island. Moderately sensitive reservoirs contain about 10 percent less than the active capacity of Flaming Gorge Reservoir, Colorado River Storage Project, Wyoming-Utah, and have watersheds about twice the size of Massachusetts. On the scale of the 17 Western States, these potentially vulnerable reservoirs and their watersheds represent a small percentage of total Reclamation water resources.

Results from the overlay analysis show that all of the sensitive reservoirs and most of the moderately sensitive reservoirs are located in the Washington Cascade Ranges and the Colorado Rocky Mountains. Factors that make these regions sensitive include the bedrock geology, the widespread presence of very low-alkalinity surface water, and proximity to sources of pollution. All 10 of the sensitive reservoirs and their watersheds have also received acidic deposition and relatively heavy precipitation volumes, factors that may combine to produce episodic acid pulses from accumulated winter snowmelt and storm events.

Table 4 shows available water chemistry data from the sensitive and moderately sensitive sets of reservoirs. This information provides observed concentration values that may be compared - using appropriate precautions - with overlay analysis sensitivity scores. Major cation and anion data were obtained from published reports (Nesler, 1981; Sartoris et al., 1977; Keefe, 1980; and EPA, 1977), Reclamation's Denver Office Chemistry Laboratory and Project Office files, and the EPA STORET computer water quality data base.

The STORET data represent sample sets collected by the USGS, EPA, Reclamation, USFS (U.S. Forest Service), and state agencies. These data sources have varying degrees of quality control/quality assurance, sampling frequency over time, number of reservoir sites, and stratification of samples by depth.

Because of these variations, table 4 average values should not be interpreted as yearly, between-yearly, or total reservoir (areal- and depth-representative) averages. Typical data are collected for only 1 or 2 years at monthly summer intervals, and single-date sample data (noted with a superscript) are common. In fact, many of the single samples were collected months after spring runoff when concentrations are typically higher. Where available and appropriate, the range of observed values is listed beneath average values.

Figures 1a through 1r show the major ion chemistry for each of the table 4 reservoirs using Stiff diagrams (Stiff, 1951; Craft, 1986). These graphs give the reader a visual way to compare the different reservoir waters. In each diagram, the center vertical axis represents 0 meq/L with positive concentrations for cations to the left and anions to the right. All the data are plotted using a scale of 1 meq/L (1,000 μeq/L).

Sensitive Reservoirs in Washington

The sensitive reservoirs in Washington are associated with the Yakima Project and have watersheds that are part of the dominantly volcanic Southern Cascade Range. High sensitivity scores were the result of low bedrock neutralizing capacity (due to Eocene and Recent andesite and basalt flows), low surface water alkalinity, and significant amounts of both rain and snow observed in the watersheds for these reservoirs. These systems are also close to and downwind of the Seattle-Tacoma metropolitan area. Water chemistry data for these reservoirs may be found in table 4 and figures 1a to 1e.

Keechelus (fig. 2), Kachess (fig. 3), and Cle Elum Lakes (fig. 4) - listed from west to east and in order of sensitivity - are located in the Wenatchee National Forest and are part of the Wenatchee Mountains drainage. Notable peaks in the vicinity of these systems include Mt. Stuart [(9,470 ft (2886 m)] and Mt. Daniel [7,986 ft (2434 m)]. These northern Yakima Project reservoirs are located in the 200- to 400-μeq/L alkalinity zone (Omernik and Griffith, 1986) and receive < 50 μeq/L drainage from an area bounded by Mt. Daniel and Snoqualmie Pass. Bicarbonate concentrations as low as 66 μeq/L have been observed in the immediate vicinity of Kachess and Cle Elum, and ANC (acid neutralizing capacity) as low as 130 μeq/L has been observed at Keechelus.

Bumping Lake (fig. 5), Clear Lake (Clear Creek Dam) (fig. 6), and moderately sensitive Rimrock Lake (Tieton Dam) are located in the Snoqualmie National Forest approximately 30 miles (48 km) from Mt. Rainier [(14,410 ft (4392 m)]. These watersheds contain alkalinity from 50 to 100 μeq/L and are exposed to conditions very similar to those in the three reservoirs already mentioned. In this more-southern grouping, Bumping Lake shows the lowest average ANC ($\approx$ 285 μeq/L).

Another important sensitivity factor that particularly applies to the Southern Cascade Range reservoirs (and to a lesser extent the Central Valley and northern Sierra Nevada in California) is the frequent presence of heavy fog. Reclamation reservoirs in this area are exposed to heavy fog conditions 80 to 200 days each year (NAPAP, 1987). Because fog contains less water and forms near the surface where pollution may be high, concentrations of pollutants can easily be higher than in cloud water. During episodes when meteorological conditions are right and pollution is present, the resulting fog may have much greater acidity (pH as low as 3.0) and thus greater acidification potential to sensitive watersheds.

Sensitive Reservoirs in Colorado

Shadow Mountain Lake and Grand Lake (Shadow Mountain Dam and Dikes), Lake Granby (fig. 7), and Lake Estes (Olympus Dam) (fig. 8) - an eastern slope reservoir containing Grand Lake water transported across the Continental Divide by Alva B. Adams Tunnel - are all part of the Colorado-Big Thompson Project and contain water from the upper reaches of the Colorado River. Willow Creek Reservoir, just west of Lake Granby, drains the Willow Creek watershed.

All of these reservoirs have watersheds in and around Rocky Mountain National Park that contain glaciated drainage basins with poor soil formation, sensitive Precambrian granite/gneiss bedrock, and higher elevation alkalinity of < 50 μeq/L. Elevations at the nearby Continental Divide are typically greater than 12,200 feet (3660 m) with several peaks > 13,100 feet (4000 m), and the area receives snow in excess of 64 in/yr (162.6 cm/yr). This area receives continuous pollution from long-range sources and irregular episodic deposition from the Denver/Front Range metropolitan area during upslope weather conditions.

The Colorado-Big Thompson data (table 4 and figs. 1i through 1l), all collected in August 1973, show that major ion concentrations increase from Grand Lake to Lake Granby. Grand Lake has the lowest ANC, as low as 274 μeq/L; but by the time the water reaches Lake Granby, average bicarbonate is over 500 μeq/L. No water quality data were available for Lake Estes; however, its data are probably similar to those of Shadow Mountain Lake. Willow Creek Reservoir, with average bicarbonate above 800 μeq/L, is obviously not as sensitive as its overlay analysis score would suggest. An interesting feature of this group of reservoirs is the variety of alkalinity concentrations observed in the different influent streams, ranging from $\approx$ 100 μeq/L to > 1,000 μeq/L.

Turquoise Lake (Sugar Loaf Dam) (fig. 9), Fryingpan-Arkansas Project, is located near the Continental Divide in central Colorado. The primary sensitivity features of this system are its elevation of 9,879 feet (3011 m) and the reservoir basin and watershed bedrock (both Norton class 1). The watershed includes drainage from Mt. Elbert [14,443 ft (4399 m)] and Mt. Massive [14,421 ft (4396 m)]. Nearby Twin Lakes (fig. 10) is the location of the Mt. Elbert Pump-Storage Powerplant. Twin Lakes is less sensitive, but has recently begun to receive Turquoise Lake low-ANC water through a conveyance tunnel.

The water quality data available for these lakes (figs. 1m and 1n) clearly show the dilution effect of spring snowmelt resulting in observed lower bicarbonate of 150 μeq/L for Turquoise Lake and 200 μeq/L for Twin Lakes (table 4). Keep in mind that current Twin Lakes data, now diluted by Turquoise Lake inflows, are probably less concentrated than table 4 suggests.

Platoro Reservoir, San Luis Valley Project, located in southern Colorado on the Conejos River, is situated at an even higher elevation [10,048 ft (3063 m)] and is downwind from the Four Corners Powerplant. The watershed for Platoro Reservoir has a relatively steep gradient draining the eastern slope of the San Juan Mountains, and receives runoff from Montezuma Peak [13,131 ft (4002 m)], Summit Peak [13,372 ft (4045 m)], and Conejos Peak [13,180 ft (4017 m)]. If Platoro Reservoir experiences spring dilution effects similar to the other systems in this study, minimum alkalinity concentrations values could approach 200 μeq/L during snowmelt. The late-summer alkalinity data in table 4 (fig. 1p), collected by USGS in 1973, suggest that Platoro Reservoir is probably more sensitive than Shadow Mountain Lake.

Moderately Sensitive Reservoirs

California has a group of moderately sensitive reservoirs that are located in watersheds draining the northern Sierra Nevada. These impoundments drain into Lake Tahoe and include Boca Reservoir, Truckee Project, and Stampede and Prosser Creek Reservoirs, Washoe Project. While no water quality data were available for these reservoirs, some of the lower alkalinity values found in STORET for some Lake Tahoe locations (as low as 20 to 80 μeq/L) suggest that some influent stream watersheds may be more sensitive than the overlay analysis suggests.

Moderately sensitive impoundments in the Sierra Nevada western slope drainage include Sugar Pine Reservoir, Jenkinson Lake (Sly Park Dam), and Folsom Reservoir, all part of the Central Valley Project. The table 4 data for Folsom Reservoir support the observed sensitivity score. Despite the lower sensitivity scores for these reservoirs, potential future acidification may occur because of San Francisco urban area emissions coupled with the extreme vulnerability of the Sierra Nevada and the possibility of acidic fog conditions.

In Utah, the relatively greater distance from urban and industrial emissions and the associated lack of acidic deposition resulted in moderately sensitive classifications for Upper Stillwater Reservoir, Central Utah Project, Bonneville Unit, and Moon Lake, Moon Lake Project. Both of these reservoirs are located in the southern drainage of the Uinta Mountains at elevations > 8,000 feet (2440 m). While the crest of the Uinta Mountains [≈ 13,000 ft (4000 m)] shows alkalinity < 100 μeq/L, the lower elevations, containing Paleozoic and Mesozoic limestones, sandstones, and shales, have much higher neutralizing capacity.

The interesting situation with the Utah reservoirs, however, is the overlay analysis contradiction offered by the available water quality data. Moon Lake (fig. 1g), located on the Lake Fork River, has had alkalinity as low as 120 μeq/L. The recently filled Upper Stillwater Reservoir (fig. 1h), located on the boundary of the High Uintas Wilderness Area, has had ANC as low as 150 μeq/L during spring runoff. If alkalinity were the only factor used to rank acid sensitivity, these two reservoirs (along with Keechelus and Turquoise Lakes) would be the most sensitive Reclamation systems.

Montana and Wyoming each have one moderately sensitive reservoir. Como Lake, Bitter Root Project, Montana, receives drainage from the extremely sensitive Bitterroot Range (alkalinity < 50 μeq/L) and is located in Norton class 1 bedrock at an elevation of 4,249 feet (1296 m). If Como Lake begins to receive significant acidic deposition, it should be upgraded to a sensitive classification. Grassy Lake, Minidoka Project, Wyoming, is located near the southern boundary of Yellowstone National Park in Norton Class 1 bedrock; however, alkalinity in the watershed is generally > 400 μeq/L. Nearby Jackson Lake received a score of 14 points, just below the cutoff value for moderately sensitive classification.

Colorado has 12 moderately sensitive reservoirs, 7 with scores of 18 or greater that could be upgraded to sensitive depending on future deposition. Willow Creek, Green Mountain, and Horsetooth Reservoirs share many of the features mentioned above for sensitive Colorado-Big Thompson Project impoundments; however, the alkalinity data on Willow Creek (≈ 850 μeq/L) and Green Mountain (≈ 1,000 μeq/L - see fig. 1l) Reservoirs suggest a less sensitive classification score.

With the exception of basin bedrock, Twin Lakes and Ruedi Reservoir, Fryingpan-Arkansas Project, and Taylor Park Reservoir (fig. 1o), Uncompahgre Project, share many features with nearby sensitive Turquoise Lake. Twin Lakes, however, has about half the average alkalinity compared to Taylor Park Reservoir and is therefore more vulnerable than its sensitivity score would suggest. In July 1987, bicarbonate concentrations were as low as 700 μeq/L in the stilling basin below Ruedi Dam; however, several influent streams had > 1,000 μeq/L ANC. This is similar to the situation observed at Lake Granby, where several influent streams were well buffered and others very dilute.

Morrow Point and Crystal Reservoirs, Colorado River Storage Project, are west-central Colorado impoundments on the Gunnison River with alkalinity generally > 1,000 μeq/L, consistent with their sensitivity scores. While Morrow Point Reservoir has a higher sensitivity score, it contains water from Blue Mesa Reservoir which has 1,500 to 2,000 μeq/L alkalinity. Crystal Reservoir, downstream from Morrow Point Reservoir, would be expected to have similar buffering capacity. These reservoirs would not be expected to be directly vulnerable except under extreme episodes of acid loading from the San Juan Mountains northern slope snowmelt.

Ridgway Reservoir in the Dallas Creek Project, Lemon Reservoir in the Florida Project, Vallecito Reservoir in the Pine River Project, and Jackson Gulch Reservoir in the Mancos Project are all reservoirs with watersheds that drain the San Juan Mountains and share a proximity to the Four Corners Powerplant. In May and June 1987, alkalinity in influent streams for Ridgway Reservoir (Dallas Creek and Uncompahgre River) was 750 to 1,500 μeq/L. Similar values are seen in Lemon Reservoir (fig. 1q), contrary to its sensitivity score. However, Vallecito Reservoir (fig. 1r), with a late-summer alkalinity of 730 μeq/L, probably has lower ANC (possibly as low as 550 μeq/L) during snowmelt.

The only moderately sensitive impoundment in New Mexico is Navajo Reservoir, Colorado River Storage Project. Despite its proximity to an emission source, however, the low gradient, relatively large area, and high alkalinity of the watershed do not suggest that acidification will be a problem for Navajo Reservoir.

CONCLUSIONS AND RECOMMENDATIONS

The overlay analysis results suggest that several Reclamation reservoirs located at higher elevations could be vulnerable to the direct effects of long-term acidic deposition. These systems, while potentially at risk over the next several decades, are not as sensitive as smaller, higher elevation subalpine watersheds such as Loch Vale in Rocky Mountain National Park, Colorado.

The key factor that will determine whether sensitive Reclamation reservoirs experience direct acidification damage is the amount of future atmospheric pollution. If current atmospheric pollution trends improve, it is doubtful that dramatic or irreversible effects will occur in the sensitive reservoirs within the next several decades. With no change in current emission levels, the most likely acidification effects probably will be episodic and limited. Under a less optimistic emissions scenario, however, more serious environmental damage and water quality deterioration could be expected.

Indirect effects of acidification may cause problems for several moderately sensitive reservoirs that have mine tailings in their watersheds. Reclamation projects that already have experienced toxic trace metal problems, such as the Fryingpan-Arkansas and the Dallas Creek Projects in Colorado, can expect a worsened situation if acidification increases. Enhanced leaching of trace metals from tailings may, in fact, be the first observed acidification symptom that Reclamation will have to address. Ironically, this effect probably will be less likely for headwater reservoirs adjacent to wilderness areas or located upstream of previously mined areas than for less-sensitive reservoirs at slightly lower elevations.

Mitigation Measures

Should its reservoirs begin to develop symptoms of acidification, Reclamation will have to consider mitigation actions. Liming, where pulverized minerals such as limestone ($CaCO_3$), hydrated lime ($Ca(OH)_2$), or quicklime (CaO) are dispersed into an acidified lake, has been used to raise the pH of Scandinavian waters since the 1920's and has been recently applied to acidic Adirondack lakes. Screens and other neutralizing structures are used to raise the pH of flowing streams. Current methods for liming cost between \$10/acre (\$28/ha) and \$200/acre (\$500/ha) for each application, and would have to be continued on a regular basis as long as acidification remains a problem for a given lake (EPRI, 1987). Liming would also reduce acid corrosion of metal and concrete structures.

While liming will neutralize excess acidity in water and alleviate most water quality problems in lakes and streams, acidity damage to watershed soils will pose a more complex and expensive dilemma. Once forest soils have been acidified and trees are lost, greater effort and expense would be needed to neutralize soils and reintroduce forest cover or to correct erosion problems. Such mitigation treatment, assuming that the effort is even feasible, would also have to cover a significantly larger area at higher cost per acre (or hectare) compared to lake and stream liming. Costs would probably be similar to those associated with strip mine reclamation.

Suggested Further Studies

This study has provided a generalized screening that has identified reservoirs vulnerable to acid precipitation. As pointed out in the Results and Discussion section, there were several cases where the limited available water quality data contradicted overlay analysis results. Possible classification errors for these reservoirs, either false-negative or false-positive, cannot be definitively resolved without more detailed study to gather more information regarding watershed geology, hydrology, historical water quality, and internal reservoir processes.

The potential influence of acidity on trace metal leaching from mine tailings deserves further study. Many watersheds in the mountainous West contain mine tailings, and information regarding the distribution of tailings and the relation between acidity and trace metal mobility would be directly applicable to several Reclamation projects containing moderately sensitive reservoirs.

Another process not addressed in this study is the interaction of reservoir size, water exchange rate, degree of thermal stratification, and land use with biotic processes that produce bicarbonate ion. Bacterial respiration provides an important source of ANC that is independent of mineral weathering in reservoirs and may modify several of the sensitivity classifications in this study. In thermally stratified reservoirs, anaerobic bacteria in the hypolimnion can significantly alter the reservoir chemistry.

Finally, there is a general lack of high-quality baseline data on sensitive Reclamation reservoirs and watersheds. Acidification trends cannot be detected if natural water chemistry variability is unknown, or if a "non-acidified" data set is unavailable for future comparisons. The sensible application of acidity countermeasures, such as reservoir liming, cannot be possible without adequate baseline data on sensitive systems.

These deficiencies may be addressed by performing several in-depth studies in representative reservoir watersheds. Such studies would be particularly useful in the following systems:

> **Keechelus Lake, Washington.** - This reservoir is one of the most sensitive and is located downwind from the nearby Seattle-Tacoma urban area, a major air pollution source.
>
> **Turquoise Lake, Colorado.** - This reservoir would be representative of a sensitive system that is a greater distance from an air pollution source. Turquoise Lake has also been the subject of previous studies.

Ridgway Reservoir and the Dallas Creek watershed, Colorado. - This is a moderately sensitive reservoir located in a watershed that has seen significant past mining activity. Water quality data, including trace metals, are also available, and a study could double as the initial limnological characterization of this new impoundment.

These studies are all in watersheds that are relatively accessible and would provide positive public exposure for a Reclamation commitment to environmental protection. Similar studies should also be considered for Grand Lake, Platoro Reservoir, and Moon Lake.

The following three-stage approach is recommended to ensure cost-effective study design and quality data:

Stage I - Background. - Conduct a thorough search for available background data important to acid sensitivity that are specific to the site in question. This would include any available water quality data, biology, limnology, geology, or soil classification data from state agencies, water districts, university theses, and other pertinent sources. If such information is unavailable, an interdisciplinary team should perform a limited reconnaissance of the site and collect water, soil, and rock samples for analysis. This initial reconnaissance will provide the information necessary to develop a more detailed study plan.

Stage II - Initial survey and monitoring. - After the preliminary reconnaissance is completed, a more intensive and thorough sampling design should be prepared to adequately describe the biogeochemical and hydrological segments of the local watershed and the variability of these factors over time. This would include determination of permeability, mineralogy, trace metals, and base-exchange capacity of soils; petrography and weathering of the local bedrock; surveys of vegetative cover, wildlife, and the aquatic biology (microbiology, fish populations, plankton surveys, benthic invertebrates, etc.); sediment stratigraphy (using aromatic hydrocarbons or trace metal isotopes) of lake sediments; and finally, monthly regular monitoring of the reservoir and influent streams for water quality constituents (ions, nutrients, trace metals). The water quality and some biological monitoring should continue for at least 3 years to establish the degree of natural variability in the system. Additionally, an NADP deposition monitoring station should be established at the site.

Stage III - Long-term monitoring. - In addition to the NADP deposition monitoring, water quality and plankton biology should be determined twice each year: during peak runoff flow and in late summer. At longer intervals (5 to 7 years), more thorough biological and water quality surveys should be performed to detect loss of sensitive species or changes in species diversity or water chemistry.

Some of the sensitive reservoirs (Turquoise Lake, for example) have been the subject of previous studies and will thus not require all three stages. Also, a study may be terminated at any stage if there is definite evidence that the area is not as sensitive as originally thought. If these studies are not feasible, Reclamation should seriously consider supporting ongoing ecosystem research in the West and, at the least, support an NADP deposition monitoring station at each of the above primary and alternate sites.

The use of remote sensing techniques to detect watershed deterioration also could provide useful data. Such an approach, however, would require research to establish relationships between multispectral satellite data and the resulting acidity-related changes in the watershed.

The Significance of Air Pollution to Reclamation

Until recently, the principal concerns of Reclamation have involved civil engineering, construction, and water supply infrastructure development. In light of this practical, project-oriented emphasis, it is easy to see that while water quality protection could be part of the agency's mission, air pollution seemed a distant and unrelated problem. This was reinforced by the lack of ecological research and understanding, and poor communication among the different scientific and engineering disciplines.

Recent progress in environmental science, however, has provided some important new insights concerning the relationships among different ecosystems in the planetary biosphere. We now know that air pollution and water pollution are related issues and that damage in one ecological compartment will have impacts in other compartments. We also know that air pollution is implicated in other environmental problems besides acid rain. These insights suggest that Reclamation should take a more active interest in air pollution issues and their potential relevance to future resource management policy.

Air pollution impacts over the next 30 years will provide many challenges as well as opportunities. The foresight and prudent vigilance exercised today by the water resource management agencies will greatly influence the Nation's flexibility in meeting the environmental and water supply challenges of the next century.

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Table 1. - Summary of the emission sources affecting the Western United States. Data are from the early 1980's. (Latimer et al., 1985a, 1985b; Roth et al., 1985; NAPAP, 1987).

Location	Types[1]	Emissions, kilotons/yr			Sensitive mountainous areas downwind from source
		NO_x	SO_x	VOC	
Seattle, WA[2]	U-V	300-500	150-300	150-300	Cascades, Coastal, Olympic
Spokane, WA	S-V	50-150	50-150	*	Blue, Wallowa, Bitterroot, Sawtooth, Clearwater, Salmon River
Yakima, WA	U-V	50-150	o	*	Cascade, Blue, Wallowa
Portland, OR	U-V	150-300	50-150	*	Cascade, Coastal
Eugene, OR	U-V	50-150	o	*	Coastal, Cascade
San Francisco, CA[2]	V-U-R	300-500	50-150	500-1,000	Sierra Nevada
Fresno, CA	V-R	0-50	0-50	50-150	Sierra Nevada
Bakersfield, CA	R-V-U	50-150	50-150	50-150	Sierra Nevada
Camp Irwin, CA	V-U	0-50	o	50-150	Sierra Nevada
Los Angeles, CA[2]	V-R-U	500-1,000	150-300	>1,000	Southern Sierra Nevada
Pocatello, ID	U	50-150	0-50	*	Absaroka, Wind River, Teton
Billings, MT	U-V	0-50	50-150	*	Bighorn
Great Falls, MT	S	0-50	0-50	*	No close proximity area
Ely, NV	S	o	50-150	o	Wasatch
Las Vegas, NV	U-V	50-150	0-50	0-50	No close proximity areas
Salt Lake City, UT	S-V-U-R	50-150	50-150	50-150	Wasatch, Uinta
Page, AZ	U	0-50	50-150	o	No close proximity area
Winslow, AZ	U	0-50	0-50	0-50	No close proximity area
Phoenix, AZ	V-U	50-150	0-50	50-150	Mogollon Plateau
Tucson, AZ[2]	S-V-U	50-150	>1,000	0-50	Mogollon Plateau
Douglas, WY	U	0-50	0-50	o	No close proximity area
Rock Springs, WY	U	0-50	50-150	o	Wind River, Teton, Rocky
Denver, CO	U-V-R	150-300	50-150	150-300	Front Range (Rocky)
Craig, CO	U	0-50	0-50	o	Medicine Bow, Rabbit Ears, Front Range, Laramie

Table 1. - Continued

Location	Types[1]	Emissions, kilotons/yr NO_x	SO_x	VOC	Sensitive mountainous areas downwind from source
Four-Corners, CO	U	50-150	50-150	o	San Juan, Sangre de Cristo
Albuquerque, NM	V-U	0-50	0-50	50-150	Sangre de Cristo
Hobbs, NM	R	50-150	50-150	0-50	No close proximity area
El Paso, TX	S-V	0-50	50-150	50-150	No close proximity area

[1] Emission types: R = refinery, U = utility, V = vehicle, S = smelter
[2] These sources also affect areas at long distances [> 500 mi (≈ 800 km)].
* = information unavailable
o = negligible source

Table 2. - Reservoirs classified as sensitive to acidification. (Dam name is provided in parentheses if reservoir name is different from dam name.)

Reservoir	State	Active capacity (acre-ft)	Watershed area (mi^2)	Score
Keechelus Lake	WA	157,800	55	24
Kachess Lake	WA	239,000	64	25
Cle Elum Lake	WA	437,000	203	25
Bumping Lake	WA	33,700	69	23
Clear Lake (Clear Creek)	WA	5,300	48	20
Lake Granby	CO	466,000	124	24
Lake Estes (Olympus)	CO	2,659	-	20
Shadow Mountain	CO	1,840	187	22
Turquoise Lake (Sugar Loaf)	CO	120,490	334	21
Platoro	CO	59,570	40	20

1 acre-ft = 1236.8 m^3
1 mi^2 = 259.2 ha

Table 3. - Reservoirs classified as moderately sensitive to acidification. (Dam name is provided in parentheses if reservoir name is different from dam name.)

Reservoir	State	Active capacity (acre-ft)	Watershed area (mi^2)	Score
Rimrock Lake (Tieton)	WA	198,000	187	15
Boca	CA	41,000	172	16
Stampede	CA	221,400	500	16
Prosser Creek	CA	29,000	50	16
Sugar Pine	CA	5,900	9	17
Jenkinson Lake (Sly Park)	CA	40,600	47	19
Folsom	CA	920,000	1,888	19
Upper Stillwater	UT	26,600	-	17
Moon Lake	UT	35,800	110	16
Lake Como	MT	35,100	55	16
Grassy Lake	WY	15,200	10	15
Horsetooth	CO	143,500	-	15
Willow Creek	CO	9,100	127	19
Green Mountain	CO	146,900	599	17
Twin Lakes	CO	68,000	75	18
Taylor Park	CO	106,200	4,420	19
Ruedi	CO	101,280	226	16
Morrow Point	CO	42,120	3,500	18
Crystal	CO	13,000	-	16
Ridgway	CO	55,000	264	17
Lemon	CO	39,030	68	19
Vallecito	CO	125,400	270	18
Jackson Gulch	CO	9,950	42	15
Navajo	NM	1,036,000	3,560	16

1 acre-ft = 1236.8 m^3
1 mi^2 = 259.2 ha

Table 4. - Major ion data for sensitive and some of the moderately sensitive reservoirs. (When available, low and high values are included beneath average values.)

Reservoir	Score	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Alkalinity (μeq/L)	pH	Data source
Keechelus Lake	24	3.71	0.413	1.49	0.477	13.1	1.01	1.67	215	6.96	[a]
		1.8-4.8	0.2-0.7	0.7-2.1	0.4-0.8	8.0-15	0.5-2.9	0.7-2.0	130-250	6.7-7.3	
Kachess Lake	25	5.66	0.801	1.25	0.552	22.5	1.28	0.530	369	7.10	[a]
		4.8-6.8	0.5-1.2	0.9-1.8	0.4-1.2	21-26	0.5-3.4	0.4-0.7	340-430	6.8-7.4	
Cle Elum Lake	25	4.38	2.02	1.02	0.532	24.9	1.76	0.350	408	7.25	[a]
		3.4-4.8	1.2-2.9	0.7-1.4	0.4-1.2	22-30	0.5-3.4	0.4-0.4	360-490		
Bumping Lake	23	4.23	0.538	1.71	0.845	17.4	1.80	0.492	285	7.10	[a]
		3.2-5.4	0.2-0.9	1.2-2.1	0.4-1.6	15-20	0.5-5.3	0.4-1.0	250-330	6.8-7.5	
Clear Lake	20	5.04	1.26	2.27	0.683	24.4	2.52	0.530	400	7.20	[a]
		3.6-6.0	0.9-1.7	1.4-2.8	0.4-1.2	20-32	1.4-4.3	0.4-0.7	330-530	6.9-7.5	
Folsom	19	8.07	2.25	3.36	0.814	35.6	3.32	3.00	584	7.24	[b]
		4.2-13	1.6-3.2	2.2-4.5	0.5-1.5	27-38	0.3-5.3	0.5-5.0	440-620	6.1-8.3	
Moon Lake	16	2.58	1.93	0.965	0.503	9.20	2.50	<0.1	151	6.55	[c]
		2.4-2.7	1.7-2.4	0.4-1.5	0.4-0.6	7.4-11	2.0-4.0	<0.1	120-180	4.7-6.6	

Table 4. - Continued

Reservoir	Score	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Alkalinity (μeq/L)	pH	Data source
Upper Stillwater	17	4.00	0.500	0.500	<1	12.0	6.50	<1	197	7.20	[d]
		3.0-5.0	<1-1.0	<1-1.0		9.0-15	4.0-9.0		148-246	6.4-8.0	
Grand Lake[1]	--[2]	4.35	0.600	1.60	0.450	19.0	3.40	0.700	311	6.70	[e,f]
						14-36			274-720	5.2-7.3	
Shadow Mountain[1]	22	6.80	1.30	2.95	0.750	29.5	3.60	0.700	484	6.60	[e,f]
						17-56			330-1120	5.6-7.2	
Lake Granby[1]	24	5.10	1.26	2.31	0.870	25.1	3.00	0.900	511	6.16	[e,f]
						23-48			460-960	5.7-8.3	
Willow Creek[1]	19	11.5	2.30	4.95	0.650	51.5	5.80	0.350	844	-	[e]
Turquoise Lake (Sugar Loaf)	21	3.81	0.977	1.02	0.780	11.8	5.94	0.823	194	6.41	[g]
		3.0-4.8	0.2-2.4	0.5-1.6	0.4-1.2	9.2-15	1.0-13	0.0-2.8	150-250	5.6-7.1	
Twin Lakes	18	10.2	1.97	1.07	0.910	25.4	13.2	1.52	416	7.37	[h,i]
		7.5-14	0.1-4.8			12-46	6.3-28		200-750	6.5-8.0	
Taylor Park[1]	19	12.0	2.55	2.55	0.600	48.5	6.35	0.200	795	7.80	[e]

Table 4. - Continued

Reservoir	Score	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Alkalinity (μeq/L)	pH	Data source
Platoro[1]	20	4.75	0.950	1.50	0.700	20.5	3.05	0.800	336	7.37	[j]
Lemon[1]	19	25.5	4.45	1.30	2.70	87.0	14.0	0.950	1420	8.17	[j]
Vallecito[1]	18	12.0	2.10	1.45	0.700	44.5	6.35	0.850	730	7.68	[j]

[1]These data represent duplicate samples taken one time at one site, and are not meaningful average values.

[2]Not rated in this study; however, probably similar to Shadow Mountain Reservoir sensitivity score.

[a] Reclamation Yakima Project STORET data, monthly samples during warm months April 1972 to August 1973, single site, surface samples.

[b] State of California STORET data, 16 samples 1973-74, 3 sampling sites, surface samples.

[c] Reclamation Central Utah Project data, 1988 pre- and post-snowmelt samples, single site, surface samples from dam outlet.

[d] Reclamation Moon Lake Project data, August 1981, 1 sampling, 5 sites at various depths.

[e] U.S. Geological Survey STORET data, August 1973, 1 sampling, single site, surface sample.

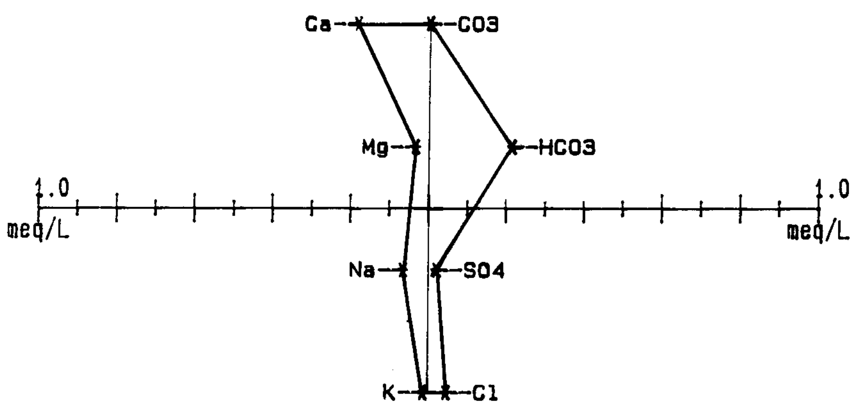
[f] USEPA, 1977.

[g] Nesler, 1981.

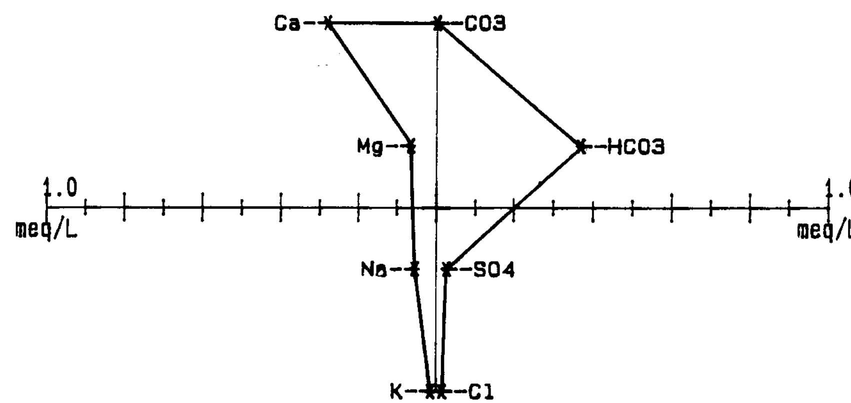
[h] Sartoris et al., 1977.

[i] Keefe, 1980.

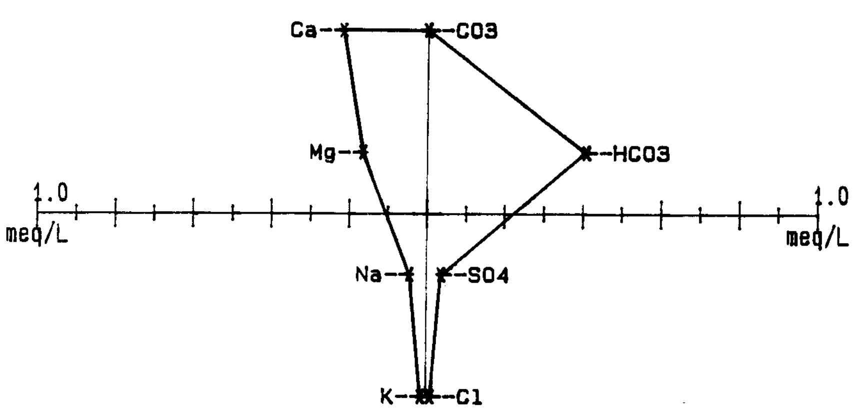
[j] U.S. Geological Survey STORET data, August 1974, 1 sampling, single site, surface sample.



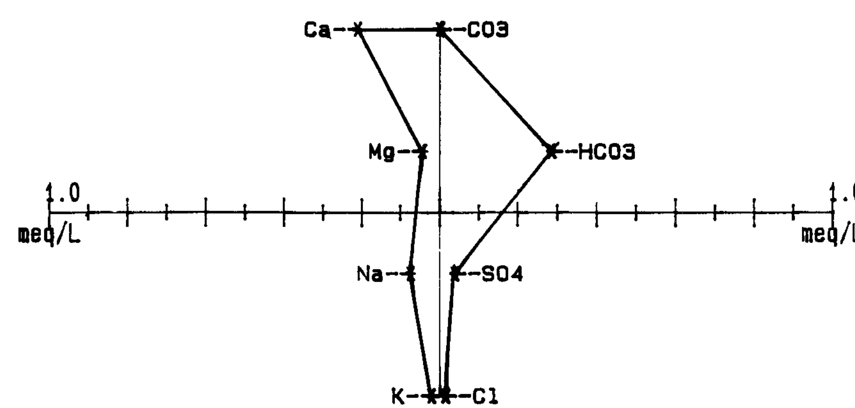
1a - Keechelus Lake 2-year averages: 1972 - 1973.



1b - Kachess Lake 2-year averages: 1972 - 1973.

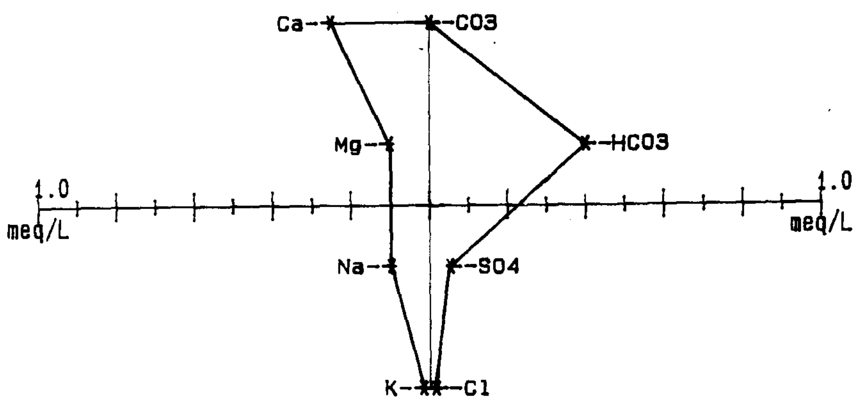


1c - Cle Elum Lake 2-year averages: 1972 -1973.

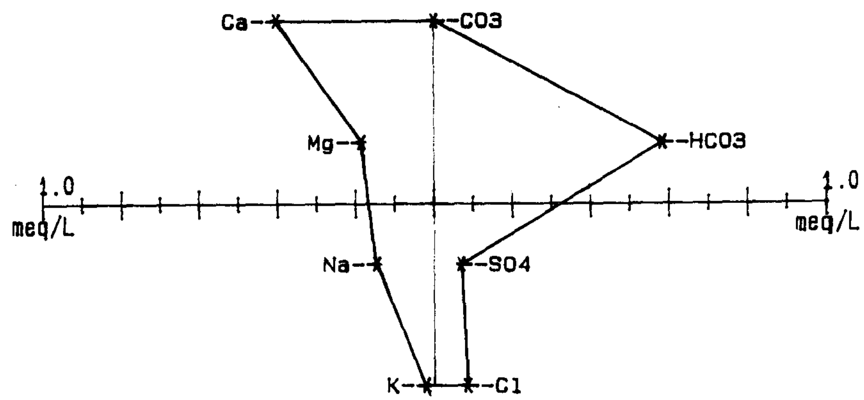


1d - Bumping Lake 2-year averages: 1972 -1973.

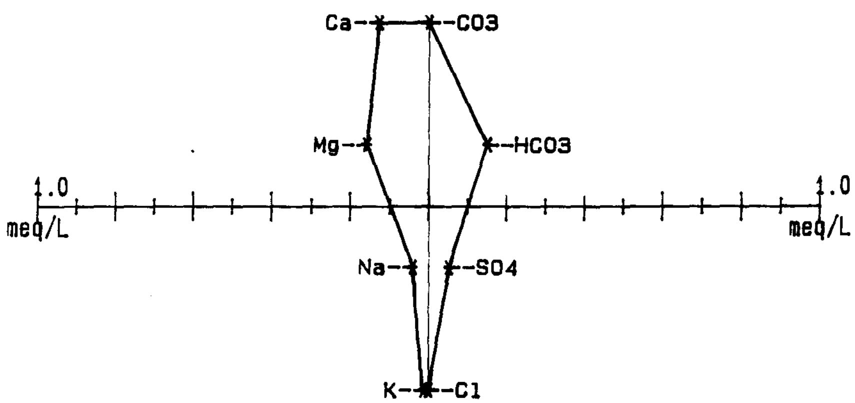
Figure 1. - Available major ion chemistry data displayed as Stiff diagrams for sensitive and some of the moderately sensitive Reclamation reservoirs.



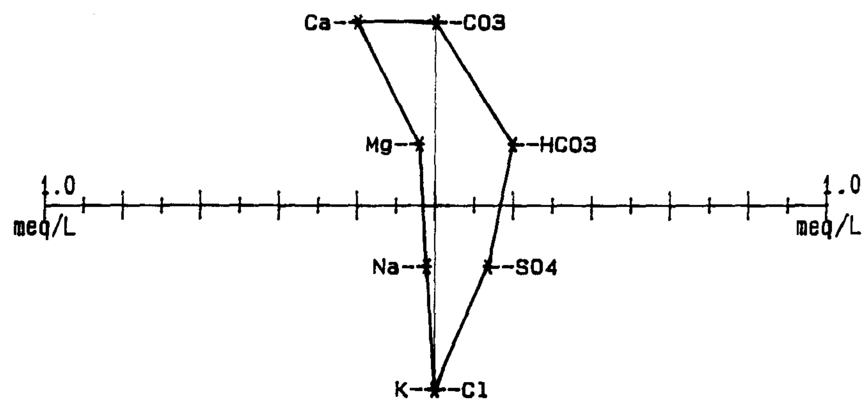
1e - Clear Lake 2-year averages: 1972 -1973.



1f - Folsom Reservoir 2-year averages: 1973 - 1974.

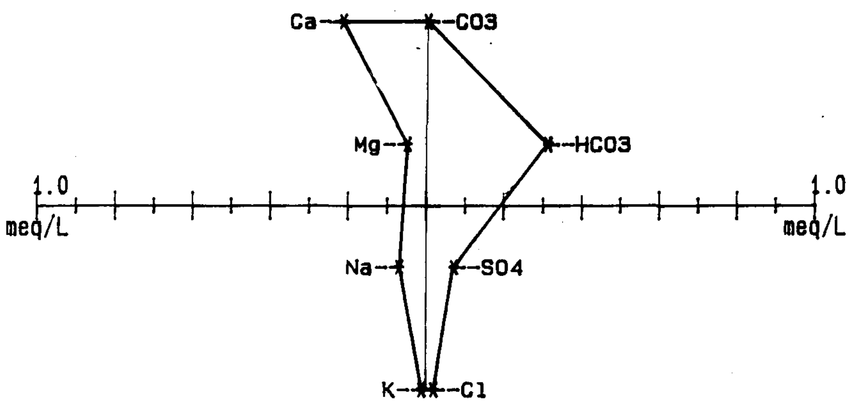


1g - Moon Lake Reservoir: 1988 averages (2 samples).

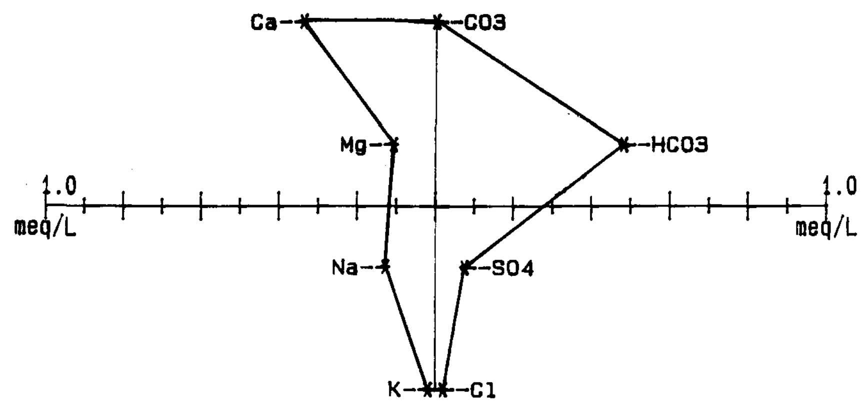


1h - Upper Stillwater Reservoir: August 1981 averages.

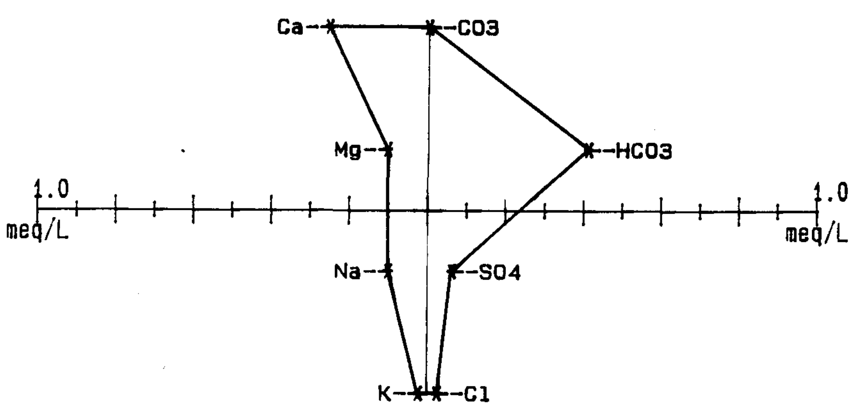
Figure 1. - Available major ion chemistry data displayed as Stiff diagrams for sensitive and some of the moderately sensitive Reclamation reservoirs (continued).



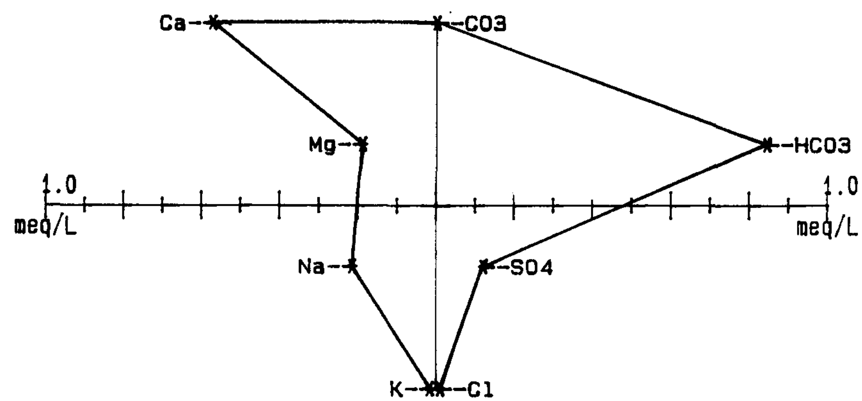
1i - Grand Lake: single surface sample - August 1973.



1j - Shadow Mountain Lake: single sample August 1973.

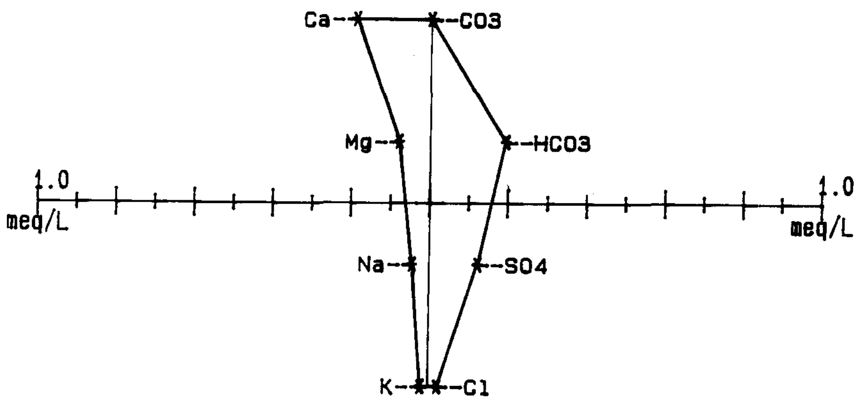


1k - Lake Granby: single sample August 1973.

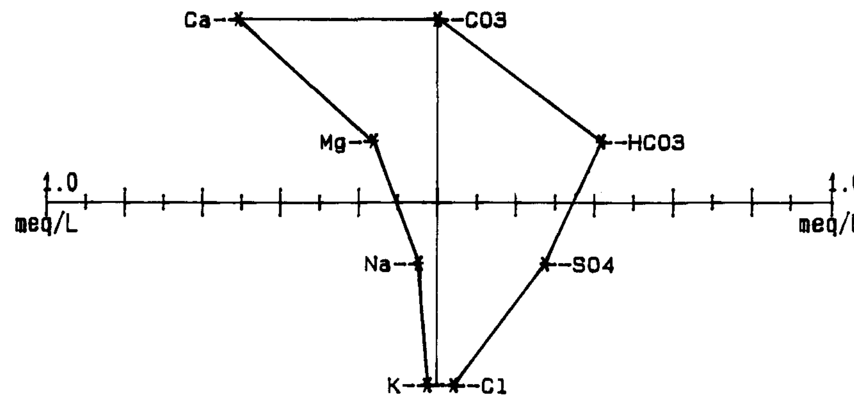


1l - Willow Creek Reservoir: single sample August 1973.

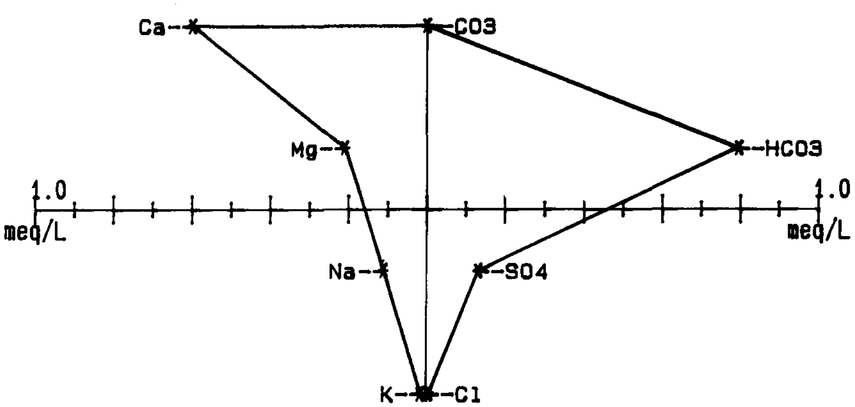
Figure 1. - Available major ion chemistry data displayed as Stiff diagrams for sensitive and some of the moderately sensitive Reclamation reservoirs (continued).



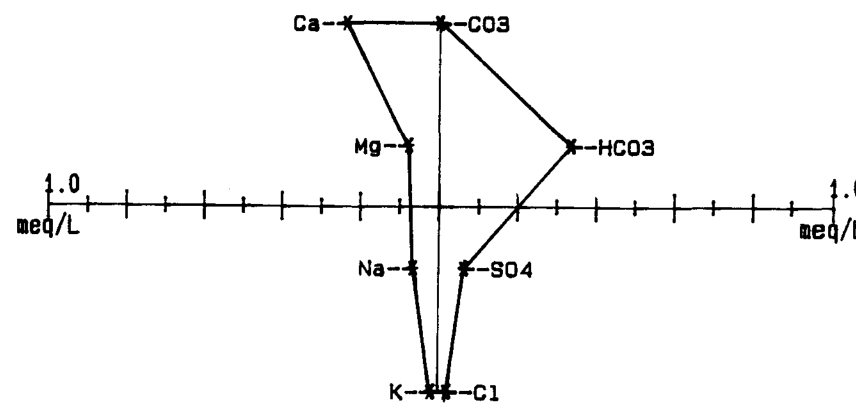
1m - Turquoise Lake: 1975 - 1979 averages.



1n - Twin Lakes: 1975 - 1979 averages.

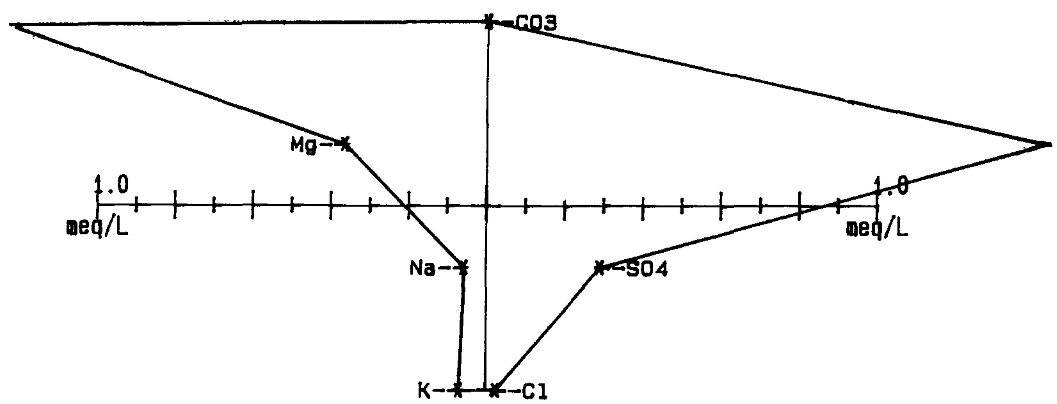


1o - Taylor Park Reservoir: single sample August 1973.

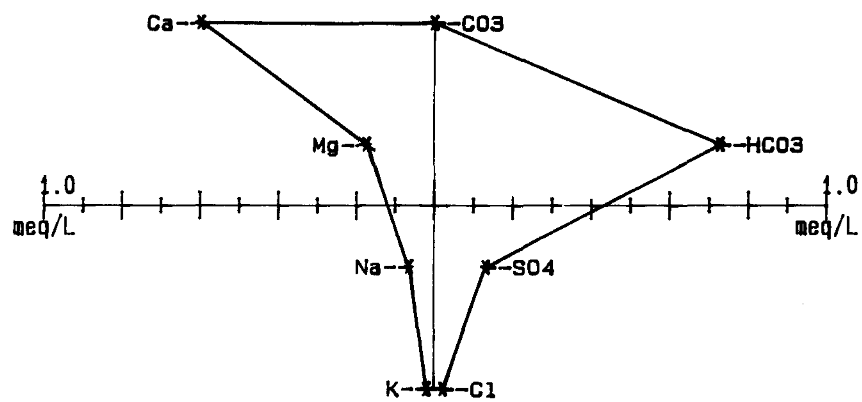


1p - Platoro Reservoir: single sample August 1974.

Figure 1. - Available major ion chemistry data displayed as Stiff diagrams for sensitive and some of the moderately sensitive Reclamation reservoirs (continued).



1q - Lemon Reservoir: single sample August 1974.



1r - Vallecito Reservoir: single sample August 1974.

Figure 1. - Available major ion chemistry data displayed as Stiff diagrams for sensitive and some of the moderately sensitive Reclamation reservoirs (continued).

Figure 2. - Keechelus Lake and Dam, Yakima Project, Washington. P33-100-724-I.

Figure 3. - Kachess Lake and Dam, Yakima Project, Washington. P33-100-858-l.

Figure 4. - Cle Elum Lake and Dam, Yakima Project, Washington. P33-100-863-I.

Figure 5. - Bumping Lake and Bumping Lake Dam, Yakima Project, Washington. P33-100-857-I.

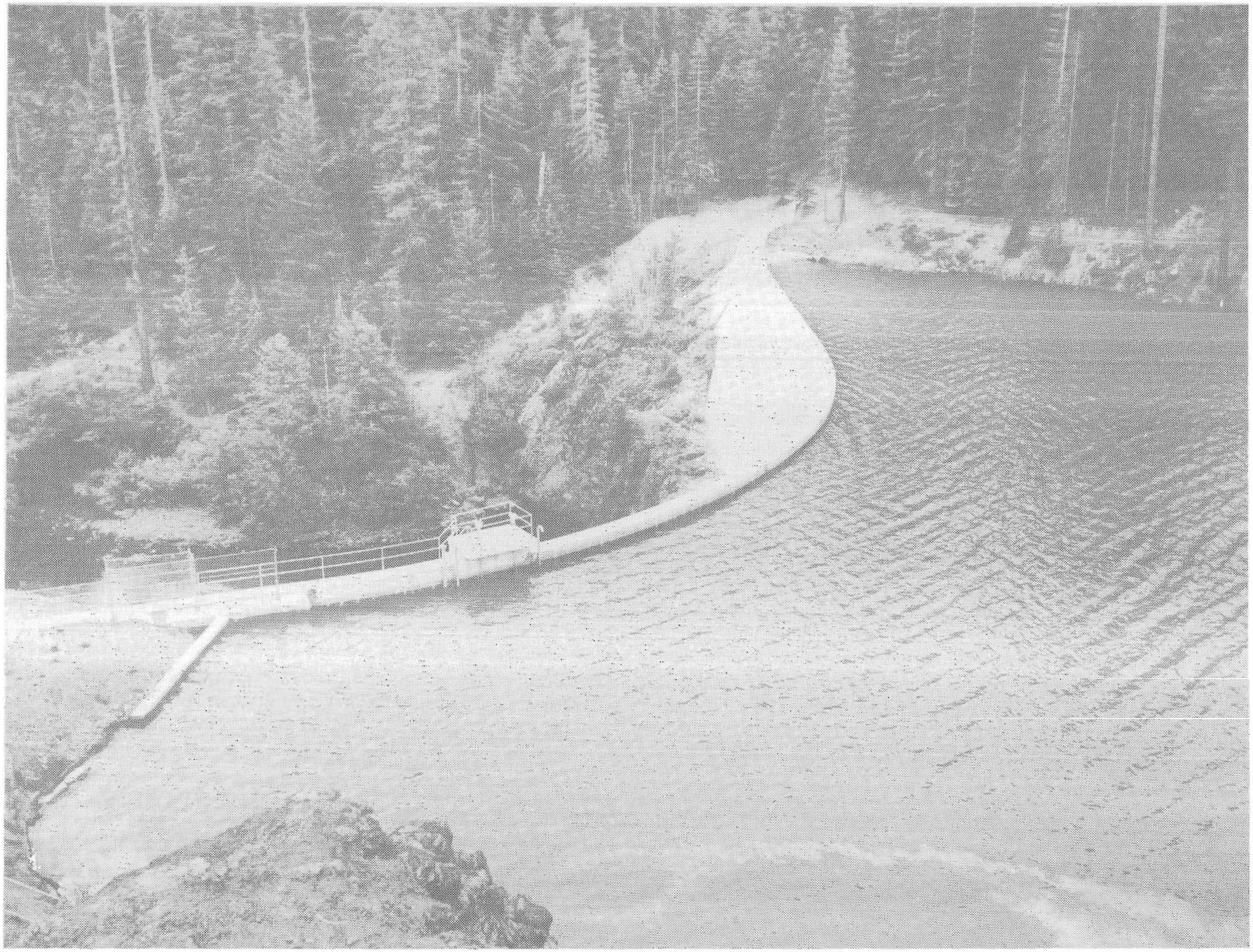


Figure 6. - Clear Lake and Clear Creek Dam, Yakima Project, Washington. P33-100-774-I.

Figure 7. - Lake Granby and Granby Dam, Colorado-Big Thompson Project, Colorado. P245-700-2670 NA.

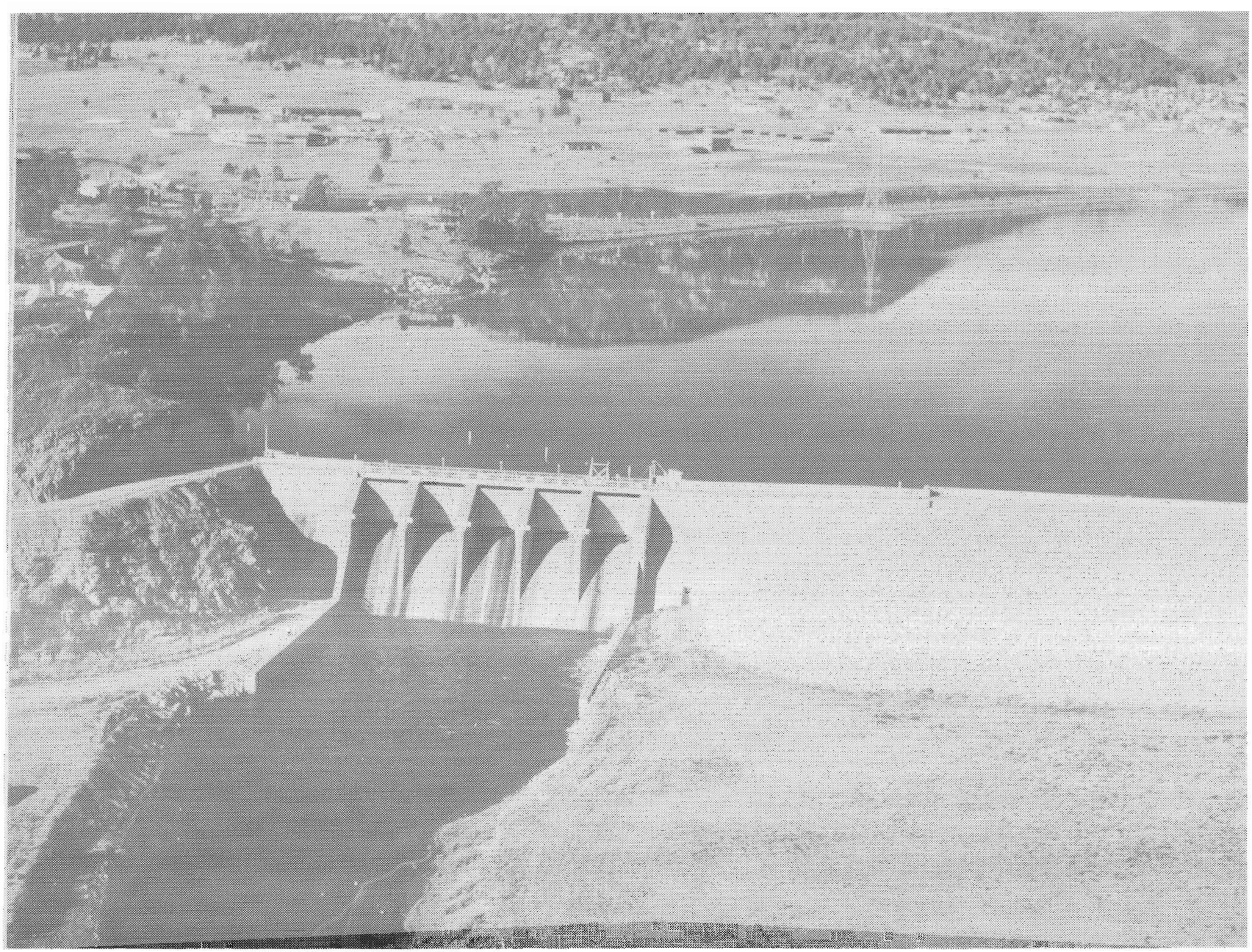


Figure 8. - Lake Estes and Olympus Dam, Colorado-Big Thompson Project, Colorado. P245-700-2831 NA.

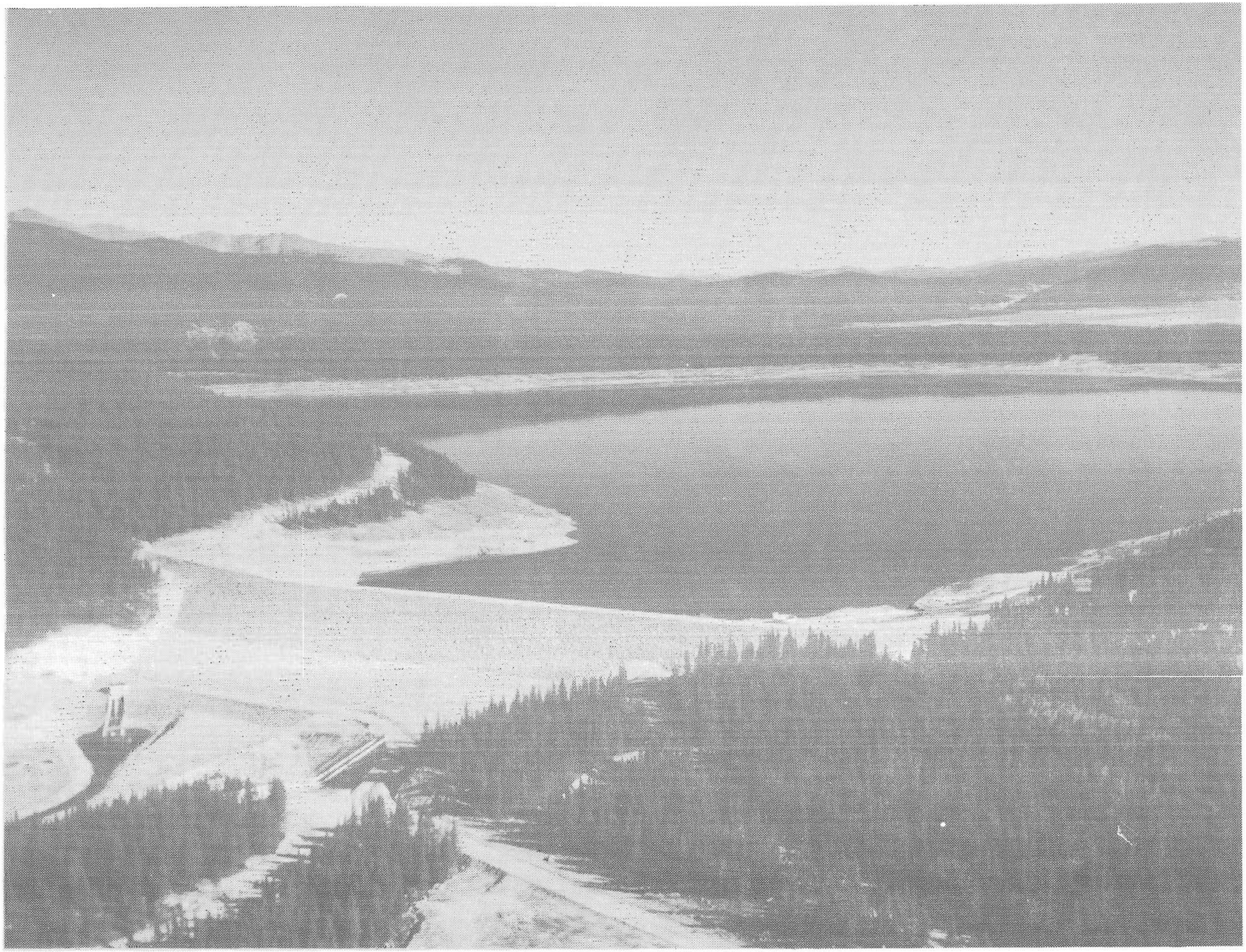


Figure 9. - Turquoise Lake and Sugar Loaf Dam, Fryingpan-Arkansas Project, Colorado. P382-706-10076A.

Figure 10. - Twin Lakes and Mt. Elbert. P382-700-935 NA.

APPENDIX 1

Glossary

These nontechnical definitions correspond to general usage in acid precipitation research. Technical discussions are available elsewhere (Altschuller et al., 1984a and 1984b; Teasley, 1984).

Acid. - In water, a chemical compound that can dissociate to form a free proton (as hydrogen ion, H^+, or hydronium ion, H_3O^+). A compound that can accept or bind free electrons is also called an acid. Some common examples include:

$$HNO_3 + H_2O \Longrightarrow H_3O^+ + NO_3^-$$

$$H_2SO_4 + 2H_2O \Longrightarrow 2H_3O^+ + SO_4^{2-}$$

Acid deposition. - Acidic or acidifying compounds from the atmosphere, whether gaseous, liquid, or solid.

Acid precipitation. - Rain, snow, dew, etc., having an average pH value less than 4.7 - 5.0.

Alkalinity. - A measure of the ability of a water to neutralize acids. As measured, alkalinity usually includes carbonate ion (CO_3^{2-}), bicarbonate ion (HCO_3^-), and other constituents that neutralize acids.

Alpine. - An ecological zone located at high mountainous elevations above the tree line.

Anaerobic. - Without oxygen.

ANC. - Acid neutralizing capacity, a term applied to water that refers to the ability of the water to neutralize acids, usually measured as alkalinity.

Anion. - A negatively charged dissolved chemical constituent.

Aromatic hydrocarbons. - Organic chemical compounds with alternating double-bonds between carbons, usually containing six-member ring structures. These compounds are primarily manmade and are often toxic.

AWWA. - American Water Works Association.

Base. - A chemical compound that reacts with and neutralizes an acid to form water and a salt. Compounds containing carbonate (CO_3^{2-}) or hydroxide (OH^-) are usually bases.

Base-exchange capacity. - A term used to describe the acid-neutralizing capacity of soils, analogous to alkalinity in water. Refers to the concentration of base cations (calcium, magnesium, and potassium) on soil particles available for exchange with hydrogen ion from acids.

Biotic. - Relating to or originating from living organisms.

Buffer. - A dissolved chemical constituent able to react with added acids or base, thus preventing changes in pH.

Buffering capacity. - A term loosely applied to waters, rock, and soils, generally referring to the acid-neutralizing capacity.

Cation. - A positively charged dissolved chemical constituent.

CFC. - Chlorofluorocarbons, a class of relatively unreactive compounds with different combinations of chlorine and fluorine atoms bound to a central carbon atom. Used as refrigerants (Freon) and in the manufacture of plastic foams, these chemicals gradually migrate unchanged into the stratosphere, where higher energy ultraviolet radiation causes CFC's to break down into reactive free-radicals. These free-radicals, especially the chlorine free-radical, then react with and break down stratospheric ozone.

Dry deposition. - Atmospheric compounds in gaseous or solid form deposited on land surfaces, but not associated with precipitation.

EDF. - Environmental Defense Fund, a private environmental organization concerned with emission control regulations.

Energy end-use efficiency. - An economic variable that measures how much energy is used or wasted to perform work.

EPA or USEPA. - U.S. Environmental Protection Agency.

EPRI. - Electric Power Research Institute, a private research and environmental policy organization funded by the electric power utilities.

GIS. - Geographical Information System.

HNO_3. - Nitric acid.

H_2SO_4. - Sulfuric acid.

H^+ or H_3O^+. - Hydrogen ion or hydronium ion - common chemical names for the free proton available from dissociation of an acid. This is the chemical form that is directly measured with a pH electrode and meter.

Hydrology. - The study of the distribution and properties of water and its interactions with soil, underlying rocks, and the atmosphere.

Hypolimnion. - The bottom layer of water in lakes or reservoirs that stratifies into layers due to water temperature differences during summer and winter.

Inertia. - The tendency for a moving object (or process) to continue moving or a nonmoving object to remain still. In general, the tendency for a system to resist change.

Isopleth. - A line of equal value, usually superimposed on a map.

Loading. - A term used to describe the amount of pollutant compounds deposited onto the surface of a defined watershed or region in a given time period, usually expressed in kilograms per hectare on an annual basis.

μeq/L and meq/L. - Microequivalents and milliequivalents per liter, concentration units for ionic chemical species in water.

μg/L and mg/L. - micrograms and milligrams per liter.

NADP/NTN. - National Atmospheric Deposition Program/National Trends Network, the organizations responsible for collecting atmospheric deposition data from its network of sampling sites.

NAPAP. - National Acid Precipitation Assessment Program, the Federal interagency task group formed to provide data and impact assessment to the President and Congress, and to coordinate acid precipitation research performed by Federal agencies. Composed of the following agencies: Departments of Agriculture, Commerce, Energy, Health and Human Services, Interior, and State; Council on Environmental Quality, EPA; NASA; NOAA; NSF; and TVA.

NASA. - National Aeronautics and Space Administration.

NOAA. - National Oceanic and Atmospheric Administration.

Non-point source. - A source of pollution discharge that originates from many small locations and is thus diffuse, such as vehicle exhaust in an urban area, or herbicide residues from lawn-care products applied over a drainage basin.

NO_x/SO_x. - Various oxides of nitrogen and sulfur in the atmosphere, the precursors of nitric and sulfuric acids in precipitation. Pronounced "knox" and "socks."

NSF. - National Science Foundation.

Nutrients. - A water quality term that usually refers to the different forms of suspended and/or dissolved nitrogen and phosphorus in water.

Orographic effects. - Local meteorological effects, such as cloud formation, updrafts or downdrafts, caused by mountains or abrupt changes in elevation.

Particulate. - Associated with or bound to small solid particles.

Permeability. - A property of solid materials, such as rock and soil, that describes how fluids (usually water) will flow under different pressures.

Petrography. - The study of rock identification and classification.

pH. - A measure of acidity (usually in water) that represents the negative logarithm of the hydrogen ion concentration. A water with pH < 7 is considered acidic; pH $= 7$ neutral; and pH > 7 basic or alkaline.

Point source. - A stationary source of pollution such as a smokestack on a powerplant or a drain pipe discharge from a chemical plant.

Precursor. - A parent chemical compound (reactant), acted on by other chemicals, heat, or light to form another chemical compound (product).

Radical. - An uncharged, highly reactive chemical compound containing an unpaired electron. Usually a short-lived intermediate specie that facilitates other chemical reactions.

Respiration. - The process whereby organisms obtain oxygen from chemical compounds in their environment. Air-breathing animals use atmospheric oxygen, while anaerobic bacteria are able to utilize the oxygen in sulfate.

Rime ice. - Ice that forms directly from cloud water, common at higher elevations.

Sediment stratigraphy. - A technique used to help describe past water quality and atmospheric conditions for a lake by vertical sectioning (slicing thin layers from top to bottom) of sediment cores samples. The individual sediment sections are then analyzed for different chemical compounds or isotopes.

STORET. - A computerized data base managed by EPA that contains water quality data from many Federal, State, and local government agencies. The name is short for STOrage and RETrieval.

Subalpine. - An ecological zone located at higher mountainous elevations just below the tree line and the alpine zone.

Synergist. - An effect or variable that enhances a given response when combined with another effect or variable. Examples: Low salinity can enhance mortality (the response) of fish exposed to cadmium. Tree damage (the response) from acidity may be enhanced when combined with ozone.

Thermal stratification. - A phenomenon where distinct density layers will form in deeper lakes or reservoirs during summer and winter. It is caused by differences in surface and bottom water temperatures and is affected by reservoir operations and other factors related to reservoir shape and water exchange rate.

Titration. - A technique in chemistry where one dissolved chemical is gradually added to another dissolved chemical, resulting in chemical reaction. An example would be the addition of acidic precipitation to lake water resulting in depletion of ANC, acidification, and increases in sulfate and nitrate.

TVA. - Tennessee Valley Authority.

USBR. - United States Bureau of Reclamation.

USFS. - United States Forest Service.

USGS. - United States Geological Survey.

VOC. - Volatile organic compounds.

Weathering. - The process where rocks and minerals are partially or completely dissolved by water to form other minerals and ions.

WRI. - World Resources Institute, a nonprofit organization interested in environmental and resource management issues.

APPENDIX 2

Variables chosen and numerical scoring used to assess sensitivity of Reclamation reservoirs

The following variables were assigned a score related to the value associated with the location for each of the 72 reservoirs identified as potentially sensitive and their associated watersheds. R1, R2, W1, W2, etc., refer to the variable labels used in the appendix 4 tables for each reservoir evaluated in this study. The "R" prefix indicates that the variable represents data at the reservoir site, while "W" prefixes represent data in the reservoir watershed.

Reservoir Variables

R1 - Elevation at dam crest (1 ft = 0.31 m).

Elevation (ft)	Points
<5,000	0
5,000-6,000	1
6,000-7,000	2
7,000-8,000	3
8,000-9,000	4
9,000-10,000	5
10,000-11,000	6
>11,000	7

USGS digital elevation data were plotted on mylar transparency using false-color 1,000-foot (305-m) intervals for direct overlay comparison to reservoir location maps (scale = 1:1.75 million).

The degree of acid sensitivity in surface waters, bedrock geology, and soils has been observed to correlate with elevation (Turk, 1984). This factor represents a general rule, so a particular reservoir may not be sensitive despite high elevation.

R2 - Acid-neutralizing capacity of bedrock geology (Norton et al., 1982) at the reservoir site.

Norton bedrock class	Points
>2	0
2	1
1	2

Geographic information was digitized from Norton maps and plotted on transparency for direct visual overlay comparison to reservoir location map (scale = 1:1.75 million).

Watershed sensitivity to acid precipitation is inversely related to the acid-neutralizing capacity of bedrock geology. At higher elevations, where bedrock is often at the surface, this relationship is more pronounced. Factors that may complicate a straightforward interpretation of the Norton zones include the extent and neutralizing capacity of soil cover, the morphology and permeability of the bedrock formations, and possible biotic ANC in larger reservoirs. These zones were derived from state-level geology maps, and inconsistencies across state boundaries are also possible.

R3 - Alkalinity of surface waters at reservoir site (Omernik and Griffith, 1986).

Alkalinity (μeq/L)	Points
>400	0
200-400	2
100-200	4
50-100	6
<50	8

Reservoir location was visually compared to alkalinity zones on the EPA map (scale 1:2.5 million). Note that scores are double those values for watershed alkalinity.

Low alkalinity suggests that surface water in the vicinity of the reservoir has low acid-neutralizing capacity and thus is more sensitive. The alkalinity zones may exaggerate low alkalinity by overlooking small catchments and watershed sections with much higher runoff ANC. Lines of equal concentration on the EPA map also contain inherent variability due to the mathematical technique used to generate isopleths. Mistaken high alkalinity is also possible because zone boundaries are based on limited sampling over time that may underestimate the extent of low alkalinity during spring runoff and does not account for year-to-year variations.

R4 - Located in an EPA- (Altschuller and Linthurst, 1984b) or WRI- (Roth et al., 1985) designated acid-sensitive zone.

YES = 1 point NO = 0 points

Reservoir locations were visually compared to identified sensitive regions on WRI map (scale = 1:12 million).

While this information represents an independent corroboration of the overlay analysis used in this study, the EPA- and WRI-sensitive regions represent a generalized analysis not suitable for more detailed, site-specific evaluations.

Watershed Variables

W1 - Presence of acidic precipitation (pH < 4.7) in the watershed within the past 10 years (Roth et al., 1985; NADP, 1983; NAPAP, 1987).

YES = 5 points NO = 0 points

Watershed locations were visually compared with acid precipitation regions on WRI map (scale = 1:25 million), and then cross-checked with 1983-86 data from NADP/NTN sampling stations.

Watersheds receiving acid precipitation indicate recent atmospheric deposition of acids and probable proximity to sources of SO_x and NO_x. However, precipitation chemistry has been sampled in a designed network for less than 10 years, and NADP/NTN sites are sparsely concentrated in the American West. Data appear to exhibit wide seasonal and daily variability, along with natural variability associated with precipitation pH measurements.

W2 - Alkalinity of surface waters in the reservoir watershed (Omernik and Griffith, 1986).

Alkalinity (μeq/L)	Points
>400	0
200-400	1
100-200	2
50-100	3
<50	4

Except for assignment of point scores, this variable was evaluated in the way same as R3 above.

While low watershed alkalinity suggests that episodic inflows of low-alkalinity water are possible, this may or may not be serious depending on other watershed factors such as precipitation volume, size, drainage gradient, or sensitivity of surface soils or bedrock.

W3 - Drainage gradient of watershed (1 m/km = 5.28 ft/mi).

Estimated gradient (m/km)	Points
0 - 50	0
50 - 100	1
> 100	2

Major influent stream lengths were measured from source to reservoir and compared with the number of 1,000-foot elevation zones crossed (scale = 1:1.75 million).

Higher gradient factors indicate greater steepness in the watershed and imply less residence time for surface runoff to react with acid-neutralizing components in soils and bedrock; however, these data are rough estimates and do not reflect the complex surface morphology of typical watersheds.

W4 - Acid-neutralizing capacity of bedrock geology (Norton et al., 1982) in the reservoir watershed.

Highest Norton class in watershed	Points
> 2	0
2	1
1	2

This variable was evaluated as for reservoir variable R2. This may not correlate with actual reservoir sensitivity depending on the extent of sensitive zone coverage, gradient factors, precipitation amounts, the nature of storm events, or proximity to air pollution sources.

W5 - Presence of acid-sensitive soils in the watershed (Altschuller et al., 1984b; Roth et al., 1985).

YES = 1 point NO = 0 points

Watershed locations were visually compared to WRI map detailing regions containing sensitive soils (scale = 1:25 million).

Like bedrock, soils vary in their sensitivity to acid deposition. Inceptisols and ultisols are two soil types known to be acid sensitive. This information is very generalized, however, and is not appropriate for detailed, site-specific analysis.

W6 - Amount of precipitation in the watershed as average rain and snow (Miller et al., 1973; Gale Research Company, 1985; Roth et al., 1985) (1 in = 2.54 cm).

Average rainfall (in)	Average snowfall (in)	Points
< 48	< 64	0
> 48	< 64	2
< 48	> 64	2
> 48	> 64	4

Average annual precipitation maps were digitized, plotted on transparency (scale = 1:1.75 million), and directly overlaid on reservoir location maps. WRI map (scale = 1:25 million) was used to corroborate precipitation maps.

Two factors influence the loading of acids into a watershed: the concentration of acids in the rain or snow, and the volume of precipitation that falls on the watershed. Areas receiving larger volumes of acidic precipitation will tend to receive greater loadings of acids that can exhaust the acid-neutralizing capacity of the watershed bedrock, soils, and surface waters.

This information may fail to corroborate actual reservoir sensitivity due to the high variability of precipitation and acidic pollutant concentrations. More importantly, dilution of pollutant concentrations in higher elevation precipitation will sometimes counteract the "high precipitation, high loading" generalization. Also ignored is the influence of dry deposition in the arid West and the important role of alkaline dust.

W7 - Proximity of watershed to NO_x and SO_x sources and direction of seasonal wind patterns (Latimer et al., 1985a and 1985b; Yuhnke and Oppenheimer, 1984; USGS, 1970; Gale Research Company, 1985) (1 mi = 1.6 km).

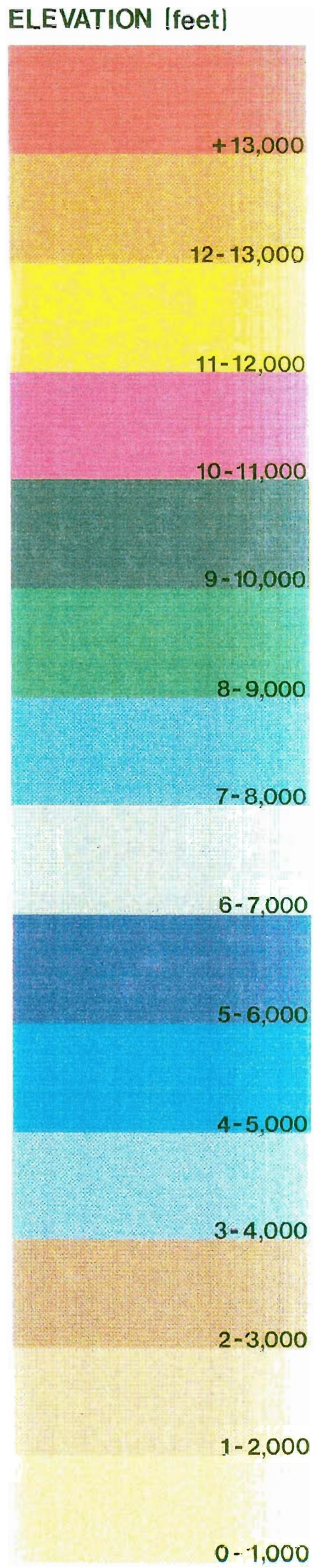
Distance from pollution source (mi)	Points
> 500	0
100 - 500	1
< 100	2

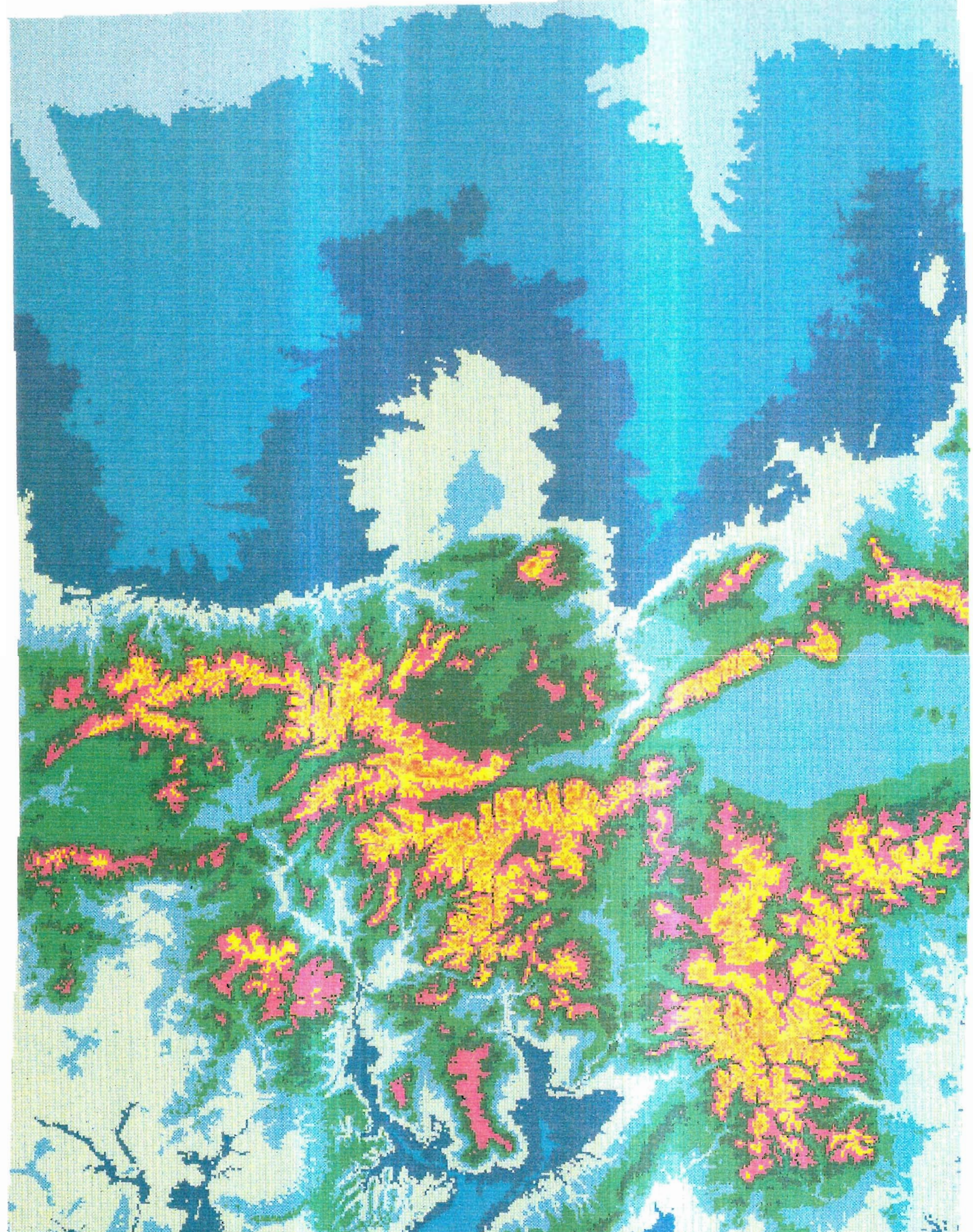
Watershed locations were visually compared to air pollution emissions maps (scales of 1:2.5 million and 1:500,000) and confirmed by checking seasonal wind vector and wind roses maps (similar to emission map scales). No points were scored if the watershed was not downwind of a pollution source.

Watersheds will be impacted to a greater degree by nearby air pollution sources compared to distant sources. However, emission data from the early 1980's may overstate or understate the danger to sensitive watershed, and winds will vary seasonally.

APPENDIX 3

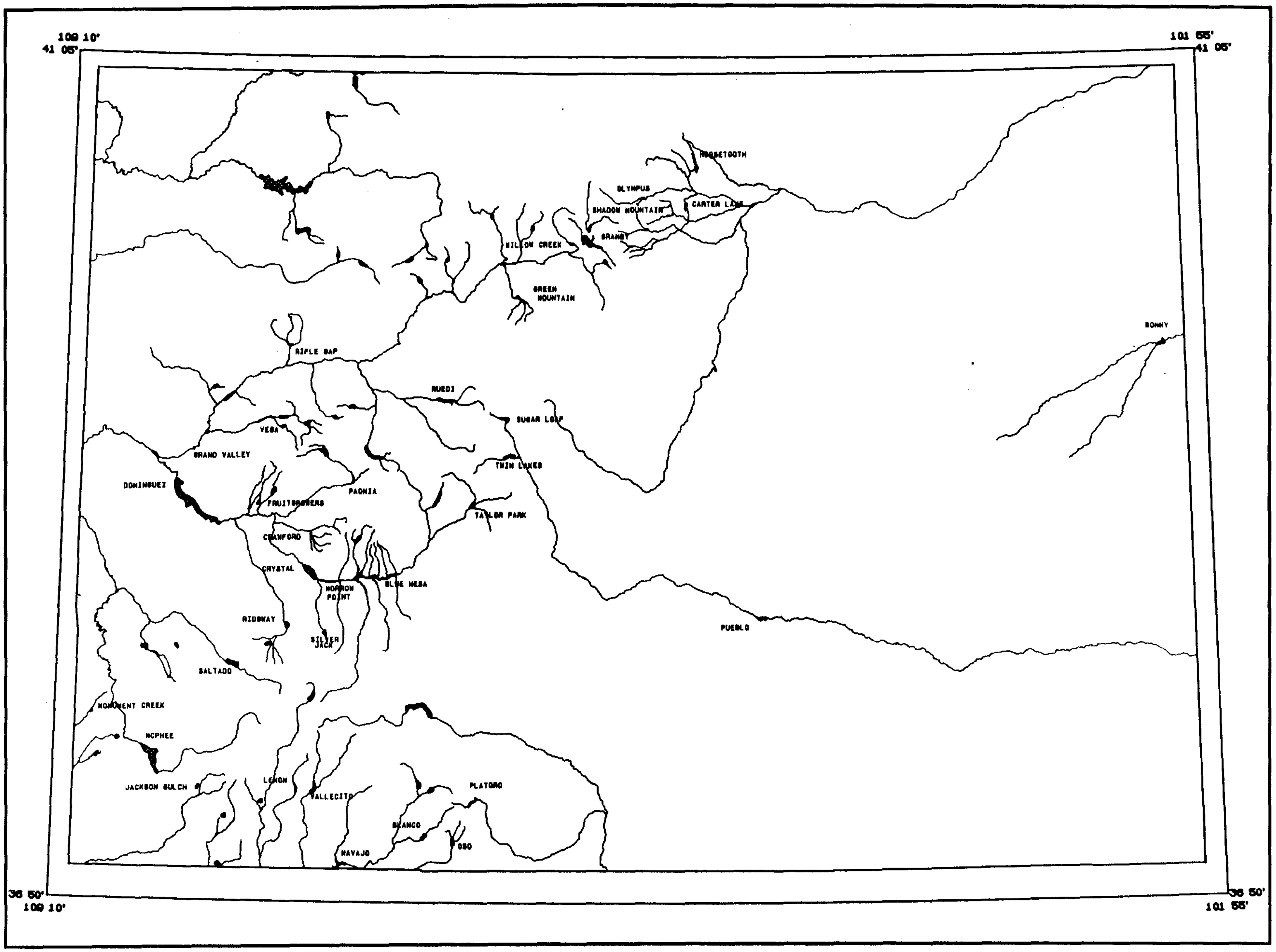
Digitized Colorado maps used for overlay analysis
(1 ft = 0.303 m)


ELEVATION (feet)
+13,000
12-13,000
11-12,000
10-11,000
9-10,000
8-9,000
7-8,000
6-7,000
5-6,000
4-5,000
3-4,000
2-3,000
1-2,000
0-1,000

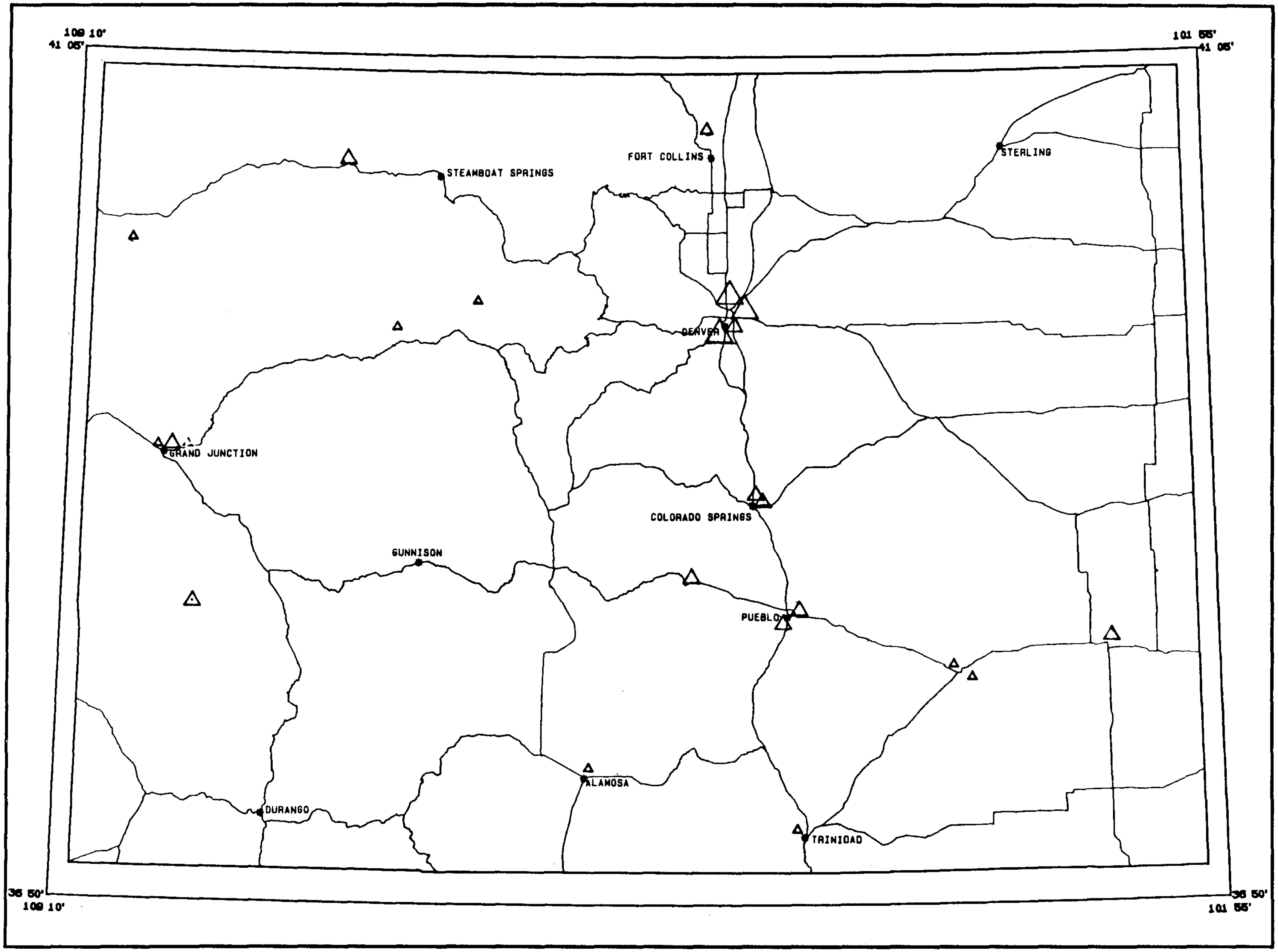


Colorado - Norton bedrock zones 1 and 2.

Colorado - Average precipitation.



Colorado - Bureau of Reclamation reservoir locations and rivers.



Colorado - Major highways, cities, and powerplants (triangles).

APPENDIX 4

Sensitivity scores for Reclamation storage reservoirs

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Washington

Name of Dam:	Keechelus		Kachess		Cle Elum		Bumping Lake	
Project:	Yakima		Yakima		Yakima		Yakima	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	2517	0	2254	0	2223	0	3435	0
R2. Norton Zone of Basin	2	1	2	1	2	1	1	2
R3. Alkalinity (ueq/L)	100-200	4	100-200	4	100-200	4	200-400	2
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	< 50	4	< 50	4	< 50	4	100-200	2
W3. Gradient (m/km)	44	0	70	1	68	1	130	2
W4. Norton Zone	1	2	1	2	1	2	1	2
W5. Sensitive Soils?	yes	1	yes	1	yes	1	yes	1
W6. Rain > 48 inches?	yes	2	yes	2	yes	2	yes	2
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	< 100 mi	2	< 100 mi	2	< 100 mi	2	< 100 mi	2
Other Information:								
Active Capacity (acre-ft)	157800		239000		437000		33700	
Watershed Area (sq mi)	55		64		203		69	
TOTAL SCORE:		24		25		25		23

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Washington

Name of Dam:	Clear Creek		Tieton	
Project:	Yakima		Yakima	
Reservoir Factors:	value	score	value	score
R1. Elevation (feet)	3015	0	2918	0
R2. Norton Zone of Basin	2	1	2	1
R3. Alkalinity (ueq/L)	200-400	2	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1
Watershed Factors:				
W1. Acid Precipitation?	yes	5	yes	5
W2. Alkalinity (ueq/L)	100-200	2	> 400	0
W3. Gradient (m/km)	66	1	66	1
W4. Norton Zone	2	1	2	1
W5. Sensitive Soils?	yes	1	yes	1
W6. Rain > 48 inches?	yes	2	yes	2
Snow > 64 inches?	yes	2	yes	2
W7. Proximity to NOx/SOx	< 100 mi	2	100-500	1
Other Information:				
Active Capacity (acre-ft)	5300		198000	
Watershed Area (sq mi)	48		See Clear Creek	
TOTAL SCORE:		20		15

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Oregon

Name of Dam:	Crane Prairie		Wickiup		Crescent Lake		Mason	
Project:	Deschutes		Deschutes		Crescent Lake Dam		Baker	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	4455	0	4347	0	4860	0	4082	0
R2. Norton Zone of Basin	2	1	2	1	2	1	2	1
R3. Alkalinity (ueq/L)	200-400	2	200-400	2	200-400	2	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	no	0	no	0	no	0	no	0
W2. Alkalinity (ueq/L)	100-200	2	100-200	2	100-200	2	< 50	4
W3. Gradient (m/km)	75	1	75	1	131	2	35	0
W4. Norton Zone	2	1	2	1	2	1	2	1
W5. Sensitive Soils?	yes	1	yes	1	yes	1	no	0
W6. Rain > 48 inches?	yes	2	yes	2	yes	2	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	> 500 mi	0	> 500 mi	0	> 500 mi	0	100-500	1
Other Information:								
Active Capacity (acre-ft)	55300		200000		86900		90500	
Watershed Area (sq mi)	482		See Crane Prairie		61		910	
TOTAL SCORE:		13		13		14		10

Acid Precipitation Sensitivity Data for Reclamation Reservoirs   STATE: California

Name of Dam:	Trinity		Shasta		Whiskeytown		Boca	
Project:	CVP Shasta/Trinity		CVP Shasta/Trinity		CVP Shasta/Trinity		Truckee	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	2395	0	1077	0	1210	0	5589	1
R2. Norton Zone of Basin	2	1	> 2	0	> 2	0	> 2	0
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	200-400	2	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	no	0	no	0	no	0	yes	5
W2. Alkalinity (ueq/L)	< 50	4	< 50	4	200-400	1	100-200	2
W3. Gradient (m/km)	57	1	12	0	30	0	60	1
W4. Norton Zone	2	1	> 2	0	> 2	0	> 2	0
W5. Sensitive Soils?	yes	1	yes	1	yes	1	yes	1
W6. Rain > 48 inches?	yes	2	yes	2	yes	2	yes	2
Snow > 64 inches?	no	0	yes	2	no	0	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1	100-500	1
Other Information:								
Active Capacity (acre-ft)	2135000		3965000		213550		41000	
Watershed Area (sq mi)	719		6665		59		172	
TOTAL SCORE:		12		11		8		16

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: California

Name of Dam:	Stampede		Prosser Creek		Lake Tahoe		Sugar Pine	
Project:	Washoe		Washoe		Newlands		CVP Folsom South	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	5970	1	5761	1	6233	2	3649	0
R2. Norton Zone of Basin	> 2	0	> 2	0	> 2	0	> 2	0
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	200-400	2	200-400	2
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	no	0	yes	5
W2. Alkalinity (ueq/L)	100-200	2	100-200	2	100-200	2	100-200	2
W3. Gradient (m/km)	60	1	60	1	44	0	35	0
W4. Norton Zone	> 2	0	> 2	0	> 2	0	> 2	0
W5. Sensitive Soils?	yes	1	yes	1	yes	1	yes	1
W6. Rain > 48 inches?	yes	2	yes	2	yes	2	yes	2
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1	< 100 mi	2
Other Information:								
Active Capacity (acre-ft)	221400		29000		732000		5900	
Watershed Area (sq mi)	500		50		1429		9	
TOTAL SCORE:		16		16		13		17

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: California

Name of Dam:	Sly Park		Folsom		Friant		Casitas	
Project:	CVP Sly Park		CVP Folsom		CVP Friant		Ventura River	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	3482	0	480	0	560	0	585	0
R2. Norton Zone of Basin	> 2	0	1	2	> 2	0	2	1
R3. Alkalinity (ueq/L)	200-400	2	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	no	0
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	no	0	yes	5
W2. Alkalinity (ueq/L)	100-200	2	100-200	2	50-100	3	> 400	0
W3. Gradient (m/km)	42	0	26	0	46	0	58	1
W4. Norton Zone	1	2	1	2	1	2	1	2
W5. Sensitive Soils?	yes	1	yes	1	no	0	no	0
W6. Rain > 48 inches?	yes	2	yes	2	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	no	0
W7. Proximity to NOx/SOx	< 100 mi	2	< 100 mi	2	< 100 mi	2	< 100 mi	2
Other Information:								
Active Capacity (acre-ft)	40600		920000		433800		251000	
Watershed Area (sq mi)	47		1888		1675		41	
TOTAL SCORE:		19		19		10		11

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: California

Name of Dam:	Bradbury	
Project:	Cachuma	
Reservoir Factors:	**value**	**score**
R1. Elevation (feet)	766	0
R2. Norton Zone of Basin	2	1
R3. Alkalinity (ueq/L)	> 400	0
R4. EPA Acid Zone?	no	0
Watershed Factors:		
W1. Acid Precipitation?	yes	5
W2. Alkalinity (ueq/L)	> 400	0
W3. Gradient (m/km)	59	1
W4. Norton Zone	2	1
W5. Sensitive Soils?	no	0
W6. Rain > 48 inches?	no	0
Snow > 64 inches?	no	0
W7. Proximity to NOx/SOx	< 100 mi	2
Other Information:		
Active Capacity (acre-ft)	202000	
Watershed Area (sq mi)	417	
TOTAL SCORE:		10

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Idaho

Name of Dam:	Cascade		Deadwood		Arrowrock		Anderson Ranch	
Project:	Boise		Boise		Boise		Boise	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	4840	0	5340	1	3210	0	4206	0
R2. Norton Zone of Basin	> 2	0	2	1	1	2	2	1
R3. Alkalinity (ueq/L)	200-400	2	200-400	2	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	no	0	no	0	no	0	no	0
W2. Alkalinity (ueq/L)	100-200	2	100-200	2	50-100	3	50-100	3
W3. Gradient (m/km)	40	0	17	0	63	1	40	0
W4. Norton Zone	1	2	2	1	1	2	2	1
W5. Sensitive Soils?	yes	1	yes	1	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1	100-500	1
Other Information:								
Active Capacity (acre-ft)	653200		161900		286000		423200	
Watershed Area (sq mi)	N/A		N/A		N/A		2680	
TOTAL SCORE:		11		12		12		9

Acid Precipitation Sensitivity Data for Reclamation Reservoirs — STATE: Idaho

Name of Dam:	Little Wood River		Island Park		Palisades	
Project:	Little Wood River		Minidoka		Palisades	
Reservoir Factors:	value	score	value	score	value	score
R1. Elevation (feet)	5249	1	6309	2	5630	1
R2. Norton Zone of Basin	> 2	0	2	1	> 2	0
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1
Watershed Factors:						
W1. Acid Precipitation?	no	0	no	0	no	0
W2. Alkalinity (ueq/L)	200-400	1	200-400	1	200-400	1
W3. Gradient (m/km)	58	1	15	0	40	0
W4. Norton Zone	1	2	1	2	1	2
W5. Sensitive Soils?	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1
Other Information:						
Active Capacity (acre-ft)	30000		127200		1200000	
Watershed Area (sq mi)	279		481		5208	
TOTAL SCORE:		9		10		8

Acid Precipitation Sensitivity Data for Reclamation Reservoirs — STATE: Utah

Name of Dam:	Causey		Lost Creek		Upper Stillwater		Moon Lake	
Project:	Weber basin		Weber Basin		CUP Bonneville		Moon Lake	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	6870	2	6022	2	8167	4	8145	4
R2. Norton Zone of Basin	> 2	0	> 2	0	2	1	2	1
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	200-400	2	200-400	2
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	no	0	no	0	no	0	no	0
W2. Alkalinity (ueq/L)	> 400	0	> 400	0	50-100	3	50-100	3
W3. Gradient (m/km)	119	2	48	0	101	2	76	1
W4. Norton Zone	> 2	0	> 2	0	2	1	2	1
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	< 100 mi	2	< 100 mi	2	100-500	1	100-500	1
Other Information:								
Active Capacity (acre-ft)	6870		20010		26600		35800	
Watershed Area (sq mi)	298		N/A		N/A		110	
TOTAL SCORE:		9		7		17		16

Acid Precipitation Sensitivity Data for Reclamation Reservoirs — STATE: Utah

Name of Dam:	Flaming Gorge		Currant Creek		Soldier Creek	
Project:	CRSP		CUP Bonneville		CUP Bonneville	
Reservoir Factors:	value	score	value	score	value	score
R1. Elevation (feet)	6047	2	7692	3	7383	3
R2. Norton Zone of Basin	2	1	2	1	2	1
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1
Watershed Factors:						
W1. Acid Precipitation?	no	0	no	0	no	0
W2. Alkalinity (ueq/L)	< 50	4	> 400	0	>400	0
W3. Gradient (m/km)	24	0	87	1	52	1
W4. Norton Zone	2	1	2	1	2	1
W5. Sensitive Soils?	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1
Other Information:						
Active Capacity (acre-ft)	3515000		1000		951000	
Watershed Area (sq mi)	N/A		N/A		N/A	
TOTAL SCORE:		12		10		10

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Arizona

Name of Dam:	Horseshoe		Bartlett		Morman Flat		Horse Mesa	
Project:	Salt River		Salt River		Salt River		Salt River	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	2040	0	1748	0	1666	0	1915	0
R2. Norton Zone of Basin	1	2	1	2	1	2	1	2
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	no	0	no	0	no	0	no	0
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	> 400	0
W3. Gradient (m/km)	46	0	46	0	57	1	57	1
W4. Norton Zone	1	2	1	2	1	2	1	2
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	no	0	no	0	no	0	no	0
W7. Proximity to NOx/SOx	< 100	2	< 100	2	< 100 mi	2	< 100 mi	2
Other Information:								
Active Capacity (acre-ft)	100000		150000		57900		150000	
Watershed Area (sq mi)	6160		See Horseshoe		5824		See Morman Flat	
TOTAL SCORE:		11		11		12		

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Montana

Name of Dam:	Lake Como		Fresno	
Project:	Bitter Root		Milk River	
Reservoir Factors:	value	score	value	score
R1. Elevation (feet)	4249	0	2575	0
R2. Norton Zone of Basin	1	2	2	1
R3. Alkalinity (ueq/L)	200-400	2	> 400	0
R4. EPA Acid Zone?	yes	1	no	0
Watershed Factors:				
W1. Acid Precipitation?	no	0	no	0
W2. Alkalinity (ueq/L)	< 50	4	> 400	0
W3. Gradient (m/km)	170	2	11	0
W4. Norton Zone	1	2	2	1
W5. Sensitive Soils?	yes	1	no	0
W6. Rain > 48 inches?	no	0	no	0
Snow > 64 inches?	yes	2	no	0
W7. Proximity to NOx/SOx	> 500 mi	0	> 500 mi	0
Other Information:				
Active Capacity (acre-ft)	35100		86700	
Watershed Area (sq mi)	55		5844	
TOTAL SCORE:		16		2

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Wyoming

Name of Dam:	Grassy Lake		Jackson Lake		Bull lake		Buffalo Bill	
Project:	Minidoka		Minidoka		PSMBP Riverton		Shoshone	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	7210	3	6777	2	5813	1	5370	1
R2. Norton Zone of Basin	1	2	1	2	2	1	> 2	0
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	no	0
Watershed Factors:								
W1. Acid Precipitation?	no	0	no	0	no	0	no	0
W2. Alkalinity (ueq/L)	100-200	2	200-400	1	50-100	3	100-200	1
W3. Gradient (m/km)	52	1	157	2	75	1	45	0
W4. Norton Zone	1	2	1	2	1	2	2	1
W5. Sensitive Soils?	yes	1	yes	1	yes	1	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1	100-500	1
Other Information:								
Active Capacity (acre-ft)	15200		847000		151700		375000	
Watershed Area (sq mi)	10		824		1891		1520	
TOTAL SCORE:		15		14		13		6

Acid Precipitation Sensitivity Data for Reclamation Reservoirs — STATE: Colorado

Name of Dam:	Horsetooth		Granby		Olympus		Shadow Mountain	
Project:	Colo Big Thompson		Colo Big Thompson		Colo Big Thompson		Colo Big Thompson	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	5440	1	8260	4	7481	3	8375	4
R2. Norton Zone of Basin	2	1	1	2	1	2	2	1
R3. Alkalinity (ueq/L)	> 400	0	200-400	2	200-400	2	200-400	2
R4. EPA Acid Zone?	no	0	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	200-400	1	50-100	3	200-400	1	50-100	3
W3. Gradient (m/km)	51	1	100	2	65	1	56	1
W4. Norton Zone	1	2	1	2	1	2	1	2
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	< 100 mi	2	100-500	1	100-500	1	100-500	1
Other Information:								
Active Capacity (acre-ft)	143500		466000		2659		1840	
Watershed Area (sq mi)	N/A		124		N/A		187	
TOTAL SCORE:		15		24		20		22

Acid Precipitation Sensitivity Data for Reclamation Reservoirs — STATE: Colorado

Name of Dam:	Willow Creek		Green Mountain		Paonia		Fruitgrowers	
Project:	Colo Big Thompson		Colo Big Thompson		Paonia		Fruitgrowers Dam	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	8140	4	7928	3	6460	2	4460	0
R2. Norton Zone of Basin	2	1	2	1	2	1	2	1
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	100-200	2	> 400	0	> 400	0	> 400	0
W3. Gradient (m/km)	104	2	145	2	97	1	174	2
W4. Norton Zone	2	1	1	2	2	1	2	1
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1	100-500	1
Other Information:								
Active Capacity (acre-ft)	9100		146900		18150		4460	
Watershed Area (sq mi)	127		599		810		N/A	
TOTAL SCORE:		19		17		14		13

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Colorado

Name of Dam:	Twin Lakes		Sugar Loaf		Taylor Park		Reudi	
Project:	Fryingpan-Arkansas		Fryingpan-Arkansas		Uncompahgre		Fryingpan-Arkansas	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	9210	5	9879	5	9330	5	7788	3
R2. Norton Zone of Basin	> 2	0	1	2	> 2	0	> 2	0
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	200-400	1	200-400	1	100-200	2	200-400	1
W3. Gradient (m/km)	70	1	174	2	66	1	80	1
W4. Norton Zone	1	2	1	2	1	2	1	2
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1	100-500	1
Other Information:								
Active Capacity (acre-ft)	68000		120490		106200		101280	
Watershed Area (sq mi)	75		334		4417		226	
TOTAL SCORE:		18		21		19		16

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Colorado

Name of Dam:	Morrow Point		Crystal		Crawford		Ridgway	
Project:	Colo River Storage		Colo River Storage		Smith Fork		Dallas Creek	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	7165	3	6772	2	6578	2	6886	2
R2. Norton Zone of Basin	2	1	2	1	2	0	2	1
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	100-200	2	200-400	1	> 400	0	200-400	1
W3. Gradient (m/km)	50	1	61	1	70	1	70	1
W4. Norton Zone	1	2	1	2	1	2	1	2
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	100-500	1	< 100 mi	2
Other Information:								
Active Capacity (acre-ft)	42120		13000		14064		55000	
Watershed Area (sq mi)	3500		See Morrow Point		116		264	
TOTAL SCORE:		18		16		14		17

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Colorado

Name of Dam:	Lemon		Vallecito		Platoro		Oso (diversion)	
Project:	Florida		Pine River		San Luis Valley		San Juan Chama	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	8148	4	7673	3	10048	6	7677	3
R2. Norton Zone of Basin	> 2	0	> 2	0	2	1	> 2	0
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	200-400	2
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	100-200	2	100-200	2	> 400	0	200-400	1
W3. Gradient (m/km)	80	1	59	1	140	2	145	2
W4. Norton Zone	1	2	1	2	2	1	2	1
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	< 100 mi	2	< 100 mi	2	< 100 mi	2	100-500	1
Other Information:								
Active Capacity (acre-ft)	39030		125400		59570		N/A	
Watershed Area (sq mi)	68		270		40		N/A	
TOTAL SCORE:		19		18		20		18

Acid Precipitation Sensitivity Data for Reclamation Reservoirs STATE: Colorado

Name of Dam:	McPhee		Jackson Gulch			
Project:	Dolores		Mancos			
Reservoir Factors:	value	score	value	score		
R1. Elevation (feet)	6936	2	7831	3		
R2. Norton Zone of Basin	2	1	2	1		
R3. Alkalinity (ueq/L)	> 400	0	> 400	0		
R4. EPA Acid Zone?	no	0	no	0		
Watershed Factors:						
W1. Acid Precipitation?	yes	5	yes	5		
W2. Alkalinity (ueq/L)	200-400	1	> 400	0		
W3. Gradient (m/km)	26	0	87	1		
W4. Norton Zone	2	1	2	1		
W5. Sensitive Soils?	no	0	no	0		
W6. Rain > 48 inches?	no	0	no	0		
Snow > 64 inches?	yes	2	yes	2		
W7. Proximity to NOx/SOx	< 100 mi	2	< 100 mi	2		
Other Information:						
Active Capacity (acre-ft)	229000		9950			
Watershed Area (sq mi)	809		42			
TOTAL SCORE:		14		15	0	0

Acid Precipitation Sensitivity Data for Reclamation Reservoirs   STATE: New Mexico

Name of Dam:	El Vado		Heron		Navajo		Stubblefield	
Project:	Middle Rio Grande		San Juan Chama		Colo River Storage		Vermejo	
Reservoir Factors:	value	score	value	score	value	score	value	score
R1. Elevation (feet)	6914	2	7190	3	6108	2	6137	2
R2. Norton Zone of Basin	2	1	2	1	2	1	2	0
R3. Alkalinity (ueq/L)	> 400	0	> 400	0	> 400	0	> 400	0
R4. EPA Acid Zone?	yes	1	yes	1	yes	1	yes	1
Watershed Factors:								
W1. Acid Precipitation?	yes	5	yes	5	yes	5	yes	5
W2. Alkalinity (ueq/L)	> 400	0	> 400	0	200-400	1	> 400	0
W3. Gradient (m/km)	18	0	18	0	17	0	17	0
W4. Norton Zone	2	1	2	1	1	2	2	1
W5. Sensitive Soils?	no	0	no	0	no	0	no	0
W6. Rain > 48 inches?	no	0	no	0	no	0	no	0
Snow > 64 inches?	yes	2	yes	2	yes	2	yes	2
W7. Proximity to NOx/SOx	100-500	1	100-500	1	< 100 mi	2	100-500	1
Other Information:								
Active Capacity (acre-ft)	195400		400000		1036000		12200	
Watershed Area (sq mi)	11400		See El Vado		3558		642	
TOTAL SCORE:		13		14		16		12

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.