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Protection of Headwater Catchments From Future Degradation: San Miguel River Basin, Colorado

A study of high-elevation catchments in the San Miguel River Basin of southwest Colorado was conducted during the summer of 1997 to develop a scientifically based tool for water resources management. The authors mapped landscape types and associated water quality parameters with those types, enabling sensitivity assessment at the landscape unit scale, thus addressing catchment heterogeneity. Landscape-type maps and derived sensitivity maps were entered into a geographic information system (GIS). They proved effective visual tools for use in policy decisions and public presentations. Water quality issues addressed were sensitivity to acidification and nutrient enrichment. Landscape types associated with surface waters having growing season acid neutralizing capacity (ANC) < 50 μeq/L were considered sensitive to acidification and included talus and mining-related areas. Types sensitive to nutrient enrichment were those having average growing season NO_3^- concentrations > 9.0 μeq/L, and included tundra, talus, and rock glaciers. Using the results of this study, San Miguel County commissioners adopted regulations for restricting development in sensitive high-elevation areas, including limits on building footprints and bans on septic systems. The adoption of these regulations lays the foundation for future application of this approach to headwater catchments in other western US locations.

Keywords: *Water quality; land use regulations; headwater catchments; New West; trace metals; nitrate; GIS; United States.*

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Introduction

Mountain areas throughout the western United States have experienced a surge in popularity in the last decade, with unprecedented recreational tourism and growth of mountain towns becoming an important factor in the changing landscapes and demography that characterizes the New West (Riebsame 1997). The resulting impacts are of particular concern for high-elevation ecosystems and water resources. These areas are more sensitive to ecological stressors than downstream systems due to high levels of precipitation, large areas of exposed bedrock, rapid hydrological flushing during runoff, and limited soils and vegetation (Williams et al 1993). Researchers in high-elevation areas have reported water quality problems such as decreasing alkalinity or ANC (Caine 1995), episodic acidification (Williams et al 1996a), and increased nitrate concentrations (Williams et al 1996b; Baron and Campbell 1997). In addition, there are conflicting beliefs in the New West regarding natural resource use, especially water. Traditional economic interests, recreational users, and environmentalists all have opposing priorities. Thus, resource managers and planners in these high-elevation areas face increasingly critical and controversial watershed protection decisions.

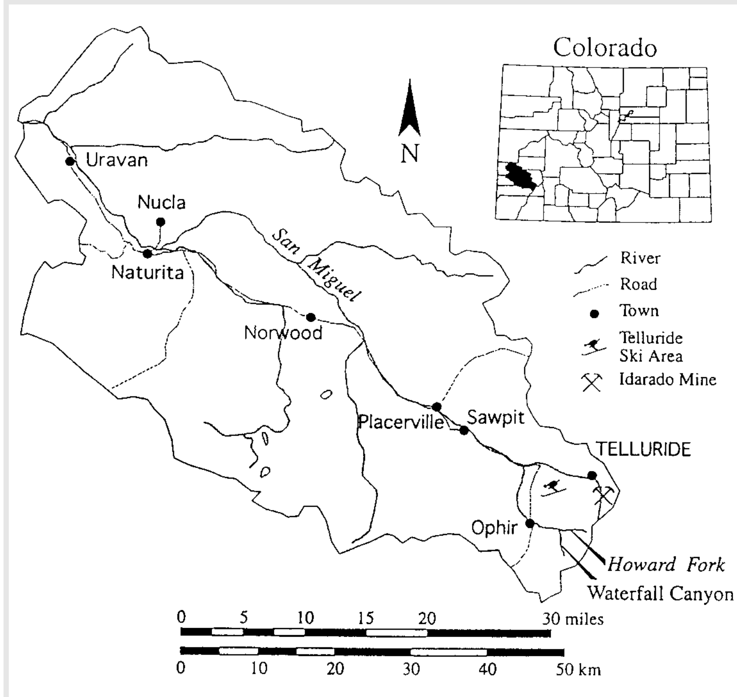
At the same time, public policies and statutes place limitations on management strategies and outcomes. At the federal level in the United States, the Federal Lands Policy and Management Act of 1976 directs that public lands be managed in a way that protects the quality of ecological, environmental, and water resource values (Coggins and Wilkinson 1990). The Clean Air Act Amendments of 1990 require the US Environmental Protection Agency (EPA) to monitor and report on the states of ecosystems, including surface water quality (EPA 1995). At the state level, the Clean Water Act recognizes the rights of the states to control pollution, but all state water quality programs must meet EPA regulations for high water quality (Getches 1997). Additionally, county-level managers must adhere to local policies and regulations to protect sources of domestic drinking water.

The authors' objective was to work with local stakeholders in an attempt to prevent future degradation of headwater catchments in the San Miguel River—a drainage typical of high-elevation catchments of the New West—while providing for reasonable economic and recreational activities. A research approach was designed to address environmental concerns in the catchments, and to present results in a manner that was understandable and of use to planners. A further goal was to provide a scientifically based management tool for use in setting water resources policy not only in San Miguel County but also in other mountain areas of the West.

Specific objectives were to:

- Provide a spatial framework to study and evaluate ecosystem processes by mapping important landscape units.
- Develop water quality indicators of current ecosystem health and sensitivity to anthropogenic change.
- Provide geographically referenced data for resource managers and concerned citizens to make informed decisions.
- Use this information as the basis for developing planning decisions designed to protect headwater catchments from future degradation.

FIGURE 1 The San Miguel River Basin drainage area.



In particular, we addressed water quality and ecological sensitivities related to acidification and nutrient enrichment as well as planning approaches for each. In addition, by focusing on landscape types, we avoided the type of one-size-fits-all approach for developing planning decisions that may not withstand legal challenge.

Study area

The predominantly free-flowing San Miguel River extends for 80 miles from high alpine meadows and waterfalls above the town of Telluride to a deep canyon confluence with the Dolores River (Figure 1). The San Miguel watershed is considered one of the few remaining ecologically and hydrologically intact river systems in the West, but it faces many problems occurring throughout the New West. Past mining activity (gold, silver, lead, and zinc; Vhay 1962) has left a legacy of acid mine drainage. Destruction of federally protected wetlands during expansion of the ski area bordering the town of Telluride (elevation 2575 m; see Figure 1) resulted in a fine of US$1.1 million in 1997 to Telluride Ski and Golf Company by the EPA. Population increases have resulted in overappropriation of water and the reduction of in-stream flows in the Upper San Miguel River below quantities necessary to support fish habitat (San Miguel Watershed Coalition Planning Team 1997). High-elevation catchments in the county are currently largely undeveloped but contain many patented mining claims that have become valuable as future home construction sites.

Research was conducted in 18 headwater basins of the San Miguel River watershed, located in the San Juan Range of the Rocky Mountains of southwest Colorado. The basins studied are situated at elevations ranging from 2710 to 3950 m. Intensive work was carried out in 5 of the basins selected by local stakeholders based on regional development and source water issues. We chose Waterfall Canyon as the main catchment for study due to its importance as a source water area for domestic water supply for the town of Ophir (Figure 1).

Methods

The water quality issues targeted were sensitivities to acidification and to nutrient enrichment. The acidification problems addressed were acid mine drainage and the acidification of surface waters (EPA 1995) as well as atmospheric deposition of acidity due to higher amounts of precipitation at higher altitudes (Williams et al 1996a). ANC was chosen as the measure of landscape sensitivity to acidification because it provides a measure of the capability of surface waters to neutralize acidic inputs (Williams et al 1995; Herlihy et al 1996).

Alpine and subalpine surface waters in San Miguel County are particularly sensitive to nutrient enrichment. Phosphate (PO_4^{3-}) is the limiting nutrient in many aquatic systems. The 1985 EPA Western Lakes Survey data show that the area in and near the county has the highest amounts of PO_4^{3-} in the western United States (Eilers et al 1987), most likely from volcanic rocks (Stoddard 1994). Furthermore, previous research has shown anomalously high levels of NO_3^- in surface waters of high-elevation areas in the vicinity (Inyan et al 1998). Since nutrient enrichment is most likely to occur where both nitrogen (N) and phosphorus (P) levels are high (Elser et al 1990), we chose NO_3^- and PO_4^{3-} in surface waters as measures of sensitivity to nutrient enrichment.

Due to time and funding constraints, sedimentation—a water quality concern in much of the western United States—was not addressed.

Landscape mapping

The spatial distribution and areal extent of landscape types were mapped in all 18 basins, from subalpine areas just below treeline upwards to the watershed divide. The mapping was intended to provide a comprehensive delineation of landscape types in the catchments. Landscape types were mapped by physical surveys on enlarged 7.5-minute quadrangles from the US Geological Survey (USGS). Field observations were supplemented with black and white aerial photographs (1:24,000) obtained from the US Forest Service. We estimate vertical landscape boundary accuracy to be

TABLE 1 Total range of ANC and NO_3^- concentrations for major landscape types.

		ANC (μeq/L)		NO_3^- (μeq/L)	
Landscape type	**N**	**Low**	**High**	**Low**	**High**
Forest	21	533	1031	0.0	17.9
Mining activity[a]	7	−80.1	324	5.7	13.5
Riparian	29	229	3630	3.6	29.2
Rock glacier	4	384	749	15.9	44.7
Talus	5	18.4	372	10.3	15.6
Tundra	22	10.5	1033	3.5	24.7
Wetland	48	54.2	1965	0.0	14.5

[a]Mine adit, waste rock.

approximately 2 contour lines, or about 24.2 m. Information from field maps was transferred to base maps that were further enlarged, and then was entered into ARCINFO, a geographic information system (GIS). Information from additional sources was added as separate layers in the GIS, including avalanche zones, watershed boundaries, and source water protection areas.

Water chemistry

Field methods: Although all landscape types found in the basins were included in the mapping, water samples were collected primarily from waters draining major landscape types, including forest, riparian, tundra, talus, and wetlands. Samples were also collected from rock glaciers, mine adits, and mine waste sites. Water samples were also collected as a time series from 5 streams at the catchment scale. Results from Waterfall Canyon are reported here, where water samples were collected weekly from approximately 1 June through 30 June 1997, generally a period of high flows following the hydrograph peak in late May. Samples were collected biweekly from 1 July through 31 August 1997, when discharge decreased.

Sample collection for water quality analysis followed the protocol established by Williams and Melack (1991) and Williams et al (1996c). Filtered and unfiltered water samples were frozen locally within 1–4 hours of collection and kept frozen during transport to the Kiowa Environmental Chemistry Laboratory operated by the National Science Foundation's Niwot Long-Term Ecological Research (LTER) site and the University of Colorado's Mountain Research Station. Analysis for pH, ANC, and specific conductance was performed locally on unfiltered sample water 24–48 hours after collection.

Laboratory analysis: Samples were analyzed for concentrations of major solutes following the protocol of Williams and Melack (1991) and Williams et al (1996c). The same protocol was used as for all other samples analyzed for the LTER project. Analyses were performed for the strong mineral anions (Cl^-, NO_3^-, and SO_4^{2-}), major cations (Ca^{2+}, Mg^{2+}, Na^{2+}, and K^+), NH_4^+, total N, and total P. A subset of samples was reanalyzed for pH, specific conductance, and ANC to verify the accuracy of field measurements. The detection limit for NO_3^- was 0.077 μeq/L and precision was 0.5% ($n = 58$). For PO_4^{3-}, the detection limit was 0.087 μeq/L and precision was 2.76% ($n = 61$). The precision for ANC was ±4 μeq/L.

Results

Landscape mapping

For the 18 basins as a whole, we mapped 33 landscape types plus the locations of water quality sampling sites. About 78% of the total basin area was composed of tundra (25%), forest (20%), bedrock (18%), and talus (15%). We also mapped 111 avalanche chutes, 67 wetlands, 48 mine waste piles, and 3 draining mine adits. Mine delineations were not comprehensive due to the existence of numerous abandoned mines. The mapping of landscape units provided an inventory of the landscape resource and thus a spatial framework for evaluating surface water chemistry.

Water chemistry

We collected a total of 182 samples of surface waters from 75 different sites in the 18 basins (Table 1). Surface waters draining forest, riparian, and rock glaciers had the consistently highest ANC concentrations. ANC values for forest ranged between 533 and 1031 μeq/L, for riparian between 229 and 3630 μeq/L, and for rock glaciers between 384 and 749 μeq/L. Waters draining areas where mining activity once took place had the lowest ANC concentrations, ranging between −80.1 and 324 μeq/L (Table 1).

There were similar variations in NO_3^- concentrations. Surface waters draining forest and wetland areas had minimum NO_3^- concentrations below detection limits and maximum values of 17.9 and 14.5 μeq/L, respectively. Surface waters with the highest NO_3^- concentrations were those draining rock glaciers, 15.9–44.7 μeq/L, and talus, 10.3–15.6 μeq/L (Table 1).

To take a conservative approach in evaluating the above results as indicators of current ecosystem health and sensitivity to anthropogenic change, these parameters were examined closely during the growing season. The growing season is defined as mid-July through August, when there is little overland flow and when most water contributing to stream flow is from subsurface discharge (Williams et al 1993). Subsurface water has undergone geochemical weathering reactions and has higher ANC values. Similarly, microbial activity and plant uptake in the subsurface environment have the potential to assimilate inorganic N and reduce the export of NO_3^- to surface waters.

There were significant differences in ANC concentrations among landscape types during the growing season (Figure 2). A one-way analysis of variance test (ANOVA) for ANC concentrations shows a significant difference ($P < 0.001$; df = 4, 19) at the alpha = 0.05 level. Forested sites had the highest ANC concentrations, with values ranging from 582 to over 800 μeq/L. Waters draining talus sites consistently had relatively low ANC concentrations, ranging from 18 to 59 μeq/L. Median concentration of ANC values from draining mine adits and waste rock were less than 0 μeq/L, with a minimum of −80 μeq/L.

There were also significant differences in NO_3^- concentrations among landscape types during the growing season. An ANOVA test for NO_3^- concentrations shows a significant difference ($P = 0.005$; df = 4, 19) at the alpha = 0.05 level (Figure 3). Forested sites had the lowest NO_3^- concentrations, with a mean value of 3.5 μeq/L and a range of 3–5 μeq/L. Riparian areas had a similar mean value of about 5 μeq/L but a wider range of 1–12 μeq/L. Somewhat surprisingly, NO_3^- concentrations in surface waters draining tundra areas were elevated, with a mean concentration of 9.7 μeq/L and a range of 3–13 μeq/L. Nitrate concentrations in talus areas ranged from 10 to 15 μeq/L, with a mean of 13 μeq/L.

Inorganic phosphate (PO_4^{3-}) was found in most samples ($n = 168$) at low concentrations. Measurable concentrations ranged from 0.1 to 4.2 μeq/L, with little difference among landscape types.

Time series of water quality results at the basin scale for Waterfall Canyon confirm the results from the landscape types. ANC concentrations were about 600 μeq/L near the start of snowmelt runoff, decreased to an annual minimum of about 200 μeq/L in late July, and then began to increase in August. NO_3^- concentrations at the basin scale in Waterfall Canyon were surprisingly high (Figure 4). Concentrations ranged from a high of almost 30 μeq/L on 19 June to an annual minimum of 10 μeq/L on 29 July.

Discussion

Sensitivity analysis

Surface waters with mean growing season ANC less than 50 μeq/L were defined as sensitive to acidification (Herlihy et al 1996), and surface waters with ANC less than 0 μeq/L were considered acidified. ANC concentrations at the basin scale in Waterfall Canyon and for most landscape types were well above the sensitivity threshold. Surface waters draining talus, however, met the criteria for sensitivity to acidification. Surface waters from mine adits and mine waste piles also had low ANC concentrations but were separately classified as being at risk for toxic metal contamination. Acidity is

FIGURE 2 A box and whisker plot of acid neutralizing capacity (ANC) concentrations during the growing season. A one-way analysis of variance test shows that ANC concentrations vary significantly with landscape type ($P = 0.001$; df = 4, 19).

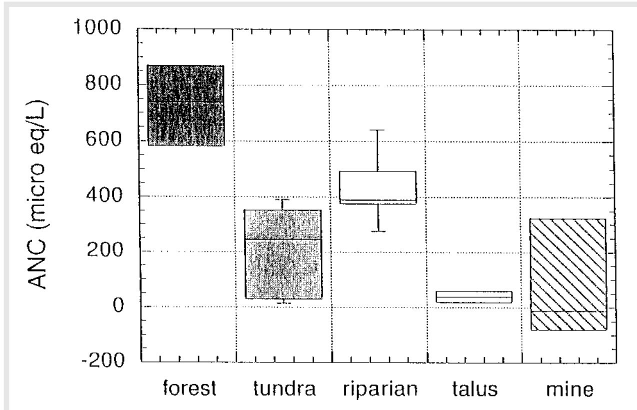


FIGURE 3 A box and whisker plot of NO_3^{2-} concentrations during the growing season. A one-way analysis of variance test shows that NO_3^{2-} concentrations vary significantly with landscape type ($P = 0.005$; df = 4, 19).

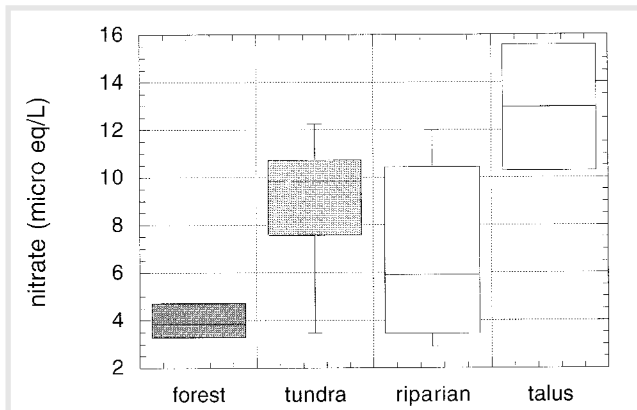
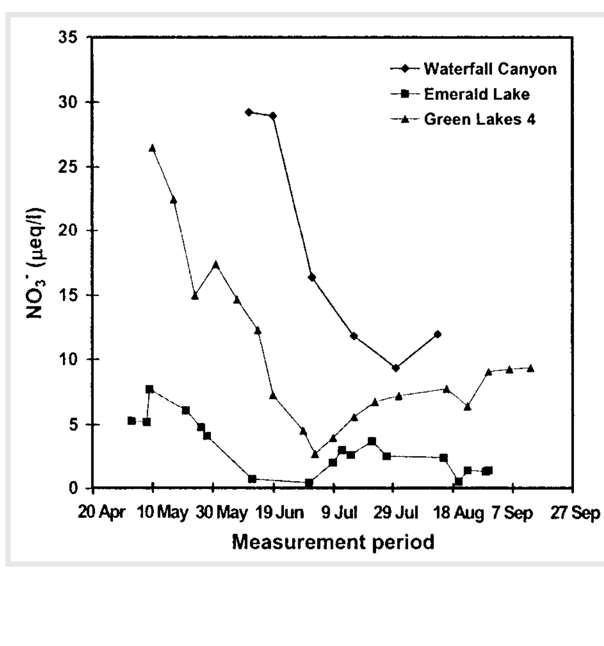


FIGURE 4 NO_3^{2-} concentrations in Emerald Lake reflect the expected pattern of being highest during runoff, then decreasing to near detection limits during the growing season. NO_3^{2-} concentrations in Waterfall Canyon remain above 9 μeq/L throughout the growing season and are consistently higher than those in Green Lakes Valley, an area known to be highly disturbed.



a particular problem in those areas since toxic metals go into solution in low pH water and may then be transported downstream or infiltrate into groundwater (EPA 1995). Acidity also affects the early life stages of aquatic amphibians and fish, with harm occurring at a pH of about 5.5 (Barmuta et al 1990).

The term nutrient enrichment is used here to refer to elevated nutrients in surface waters and associated algal blooms (Harper 1992). Nutrient enrichment can lead to fish kills from higher water temperatures and decreased oxygen content in surface waters. In addition, nutrient enrichment can affect terrestrial ecosystems, where increases in NO_3^- inputs can result in changes in species abundance and composition, especially in alpine locations where plant species are adapted to low N availability (Bowman and Steltzer 1998).

In determining sensitivity to nutrient enrichment, both PO_4^{3-} and NO_3^- levels were considered. PO_4^{3-} is most likely the limiting nutrient when NO_3^- concentrations are elevated (Stoddard 1994). Under these conditions, PO_4^{3-} can generate 500 times its weight in living algae (Wetzel 1983), and thus small amounts of PO_4^{3-} are likely to be sufficient for growth of algal blooms. High algal activity, however, requires sustained amounts of PO_4^{3-} (Wetzel 1983). The finding of measurable, although low, levels of PO_4^{3-} in all landscape types throughout the growing season meets these requirements.

Surface water NO_3^- levels in both forested and high-elevation ecosystems are normally elevated during spring runoff but decrease below detectable limits during the growing season (Stoddard 1994; Williams et al 1996b). Growing season surface water NO_3^- concentrations were also compared with NO_3^- concentrations in wet deposition. At Molas Pass and Wolf Creek Pass, high-elevation wet precipitation collection sites in southwestern Colorado, average annual volume weighted mean NO_3^- concentrations for 1997 range from 9.5 to 12.5 μeq/L (NADP/NTN 1997). When NO_3^- concentrations in surface water approximate those in wet deposition, the watershed approaches a state in which it is no longer a net NO_3^- sink (Stoddard 1994).

These considerations led us to designate landscape types with average growing season NO_3^- concentrations above 9.0 μeq/L as sensitive to nutrient enrichment and those with concentrations above 5.0 μeq/L as moderately sensitive. Tundra, talus, and rock glaciers meet the criteria for sensitivity. Riparian areas are moderately sensitive.

A comparison of NO_3^- results from Waterfall Canyon with results from Emerald Lake basin in the Sierra Nevada (1.2 km^2) and Green Lake 4 basin in the highly populated Colorado Front Range (2.2 km^2) provides context (Figure 4). Emerald Lake basin has been shown to be N limited (Williams et al 1995), with NO_3^- concentrations ranging from 8 μeq/L down to detection limits of less than 1 μeq/L, values expected in an undisturbed watershed. Elevated levels of inorganic N in wetfall have been shown to cause N saturation and increased NO_3^- in surface waters at Green Lake 4 and other catchments in the Front Range (Williams et al 1996b; Baron and Campbell 1997; Fenn et al 1998). Nitrate concentrations in surface waters from Waterfall Canyon were always greater than at Emerald Lake and Green Lake 4.

There is evidence that sedimentary bedrock may contribute a large amount of NO_3^- to surface waters in some watersheds in California (Holloway et al 1998). Although there are large amounts of sedimentary rock in San Miguel County at subalpine elevations, the seasonal pattern of NO_3^- levels is distinctly different from that in the California studies.

Although there is growing recognition of excess N in many North American ecosystems (Vitousek et al 1997; Fenn et al 1998), the finding of elevated NO_3^- in high-elevation basins in San Miguel County was unexpected. Compared with many other high-elevation lakes around the world, most Rocky Mountain lakes are relatively pristine, with median NO_3^- concentrations less than 1 μeq/L (Psenner 1989). In addition, previous studies in western Colorado have found little or no NO_3^- in surface waters during the growing season (Eilers et al 1987; Inyan et al 1998).

Geographically referenced sensitivity maps

The association of specific landscape types with sensitivity to acidification or nutrient enrichment was the basis for developing 3 additional layers of GIS maps, derived directly from the landscape types layer. Talus areas, considered to be sensitive to acidification, were mapped directly as acidification areas. An area of 200 feet extending downslope of mine adits and mine waste piles was mapped as at risk for toxic metal contamination. The landscape types sensitive to nutrient enrichment were mapped as nutrient enrichment areas.

Science and public policy

The authors worked directly with the San Miguel County planning department and legal staff to draft amendments to the Land Use Code (LUC) to protect these headwater catchments from future degradation. The intent of these LUC amendments was to protect headwater catchments while allowing reasonable development. Decisions on specific strategies to avoid aggravating existing sensitivities were issues of public policy, as much political as scientific in nature.

Nonetheless, it was important that the LUC amendments were directly related to research results and that the authors were willing and able to defend them in court. For example, development activities that add nutrients to the basins and would thus aggravate existing sensitivity are described here. Septic tanks and associated leach fields are potential sources of both NO_3^- and PO_4^{3-} from improperly functioning drainage fields, unsuitable septic tank location, or lack of maintenance. Landscape fertilizers are direct inputs of NO_3^- and PO_4^{3-}. Due to their compacted surfaces and impermeability, roads provide direct hydrologic pathways to creeks and streams (Jones and Grant 1996) and so limit the opportunity for biological uptake of NO_3^-.

While specific building footprints or road widths, for example, are not scientifically defensible based on the present research, the scientific basis for limiting those dimensions is defensible. The LUC amendments were based on potential water quality impacts of the activities described above. They applied only to areas determined to be ecologically sensitive. This is illustrated by the following subset of the proposed LUC amendments for areas sensitive to nutrient enrichment:

- Residences shall have footprints of 800 square feet or less.
- Individual sewage disposal systems that rely on absorption to dispose of waste shall not be allowed.
- Landscaping or fertilizer shall not be allowed unless required by an approved state or federal permit for mining reclamation.
- New roads and/or driveways shall only be allowed with Board of Commissioners review, and only if (a) roads and driveways are no wider than 10 ft and (b) winter plowing and maintenance are prohibited.

An explanation of the intent behind some of the amendments will clarify their impact on land use. The limitation on the size of building footprints allows a reasonable residence of 2400 square feet (3 stories are allowed) but precludes large trophy homes and their increased environmental impact. New roads may be built, but the 10-foot width limitation means that emergency service vehicles will not have access. That restriction, along with the prohibition on winter plowing and maintenance, encourages shorter and fewer new roads.

These and additional proposed LUC changes were presented to San Miguel County officials at a public workshop on 11 March 1998 and to the Board of County Commissioners, who would make the final decision on the amendments, on 6 May 1998. There was extensive public notification of the meetings, and both advocates and opponents of the amendments attended. Discussions were lively, extensive, controversial, but collegial. On 3 June 1998, the Board of County Commissioners for San Miguel County formally accepted and legally adopted the proposed LUC amendments to protect 18 headwater basins of the San Miguel River Basin from future degradation.

The science protocol was important in their decision. Many questions were asked about sampling frequency and quality assurance and control. In addition, the comparison of NO_3^- concentrations in Waterfall Canyon to Emerald Lake and Green Lake 4 was very effective in putting values in a context understandable to the public. The GIS maps proved to be very useful in the process, providing an easily understood visual presentation of areas with potential water quality problems. County planners effectively used the maps in their planning process. The maps allowed the general public to quickly and easily visualize the geographic extent of areas sensitive to perturbation and to assess which areas would be affected by potential land use regulations.

Conclusions

Significant water quality differences among landscape types in both ANC and NO_3^- provided the basis for determining sensitivity to acidification and nutrient enrichment. The landscape type and ecological sensitivity GIS maps proved to be powerful tools for managers and planners in developing resource management options. In addition, the GIS maps greatly facilitated community involvement, an important consideration in resource management decisions at the federal, state, and local levels.

The landscape-types approach to ecological sensitivity analysis was shown to have several strengths as a scientifically based method for use in high-elevation catchments:

- It is particularly applicable in high-elevation catchments due to their spatial heterogeneity.
- It can show sensitivities before ecological damage is apparent through observation and so provides an opportunity for action to prevent future degradation.
- Mapping landscape types is straightforward and inexpensive.

Adoption of LUC amendments in San Miguel County lays the foundation for future application of the landscape-types approach to other high-elevation catchments in the western United States and sets a precedent that could be instrumental in preserving the scenic beauty of the West for the future. Although implementation of management practices to protect high-elevation watersheds is ultimately a matter of political will, the adoption of the LUC amendments in San Miguel County shows that this will exists when change is supported by scientific evidence. This analysis, along with the extensive community involvement that occurred, can open the way for protecting precious mountain resources, especially in the West, with its constituency of conflicting interests.

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