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SPATIAL MODELING OF COPPER CONCENTRATIONS THROUGH AQUATIC ECOSYSTEM COMPONENTS OF SODA BUTTE CREEK, YELLOWSTONE NATIONAL PARK

by

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Approved by:

Vicki Watson
Chairperson

Dean, Graduate School

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SPATIAL MODELING OF COPPER CONCENTRATIONS THROUGH AQUATIC ECOSYSTEM COMPONENTS OF SODA BUTTE CREEK, YELLOWSTONE NATIONAL PARK.

Director: Dr. Vicki J. Watson VW

Soda Butte Creek is a major tributary of the Lamar River in Yellowstone National Park. Its headwaters originate in highly mineralized mountains that were mined for precious and base metals from 1933-1953, four miles northeast of the park boundary. In 1950, a flood thought to exceed the 100-year flood washed mining waste from an abandoned mill and tailings impoundment into the creek, contaminating an unknown amount of the creek.

Persistent release of metals and acid from the mill and impoundment sites and from the flood-deposited mine wastes in the stream are thought to be the cause of chronic degradation of water quality and biological diversity in upper SBC. This study attempted to determine the spatial extent of contamination in SBC and describe aspects of the creek that may aid in restoring it.

Bed sediment, benthic biofilm and macroinvertebrates were collected in high gradient riffles (HGR) from the creek's headwaters to its mouth. Bed sediment was also collected in the mouths of major tributaries. All samples were analyzed for a suite of metals, but only copper results are reported here. A geospatial database was developed and used to identify which tributary drainage provided the best reference watershed. Copper levels in its bed sediments were used to estimate background levels for SBC, and these were used to identify how much of SBC's bed sediments were elevated over background levels. The downstream pattern of copper in sediment and biota were analyzed as was a time series in sediment copper levels from 1994-1998.

Copper levels in SBC bed sediments were found to be significantly higher than in its tributaries. Although SBC sediment copper levels dropped significantly downstream, they exceeded background levels in high gradient riffle sediments throughout its length. Even when a more conservative background level based on sediments from a variety of stream unit types was used, SBC exceeded these background levels for 21 km below the source of contamination, including 14 km in the park. Copper levels in the two biotic components correlated well with sediment copper levels, possibly due to sediment contamination of these samples. Before reaching the park boundary, copper levels in stream macroinvertebrates dropped to levels that the literature suggests would likely have little measurable effect on macroinvertebrate communities.

Copper levels in bed sediments showed no pattern over the years from 1994 to 1998 that seemed related to high flow events, suggesting that a flood as large as the 1950 flood is likely needed to cause much change in distribution of mine the wastes. Removal of the contamination at the mill and impoundment before such a major flood is advised, so that sediment transport caused by such an event could have a beneficial rather than detrimental effect on the creek. This study provides no evidence of a need to remove mine wastes from the streambed; following clean up of the source of contamination, natural cleansing of the creek seems the best option.

ACKNOWLEDGEMENTS

I would like to extend my special thanks to the committee members involved in this project. Dr. Vicki J. Watson, Dr. Hans R. Zuuring, and Dr. Eric Edlund have all been very generous with their time, and have provided me with invaluable advice and commentary. Most of all, however, it has been a pleasure working with my committee.

I am grateful to have been involved in the investigation of fluvial, geochemical, and biological processes of Soda Butte Creek, and to have lived and learned in the inspiring setting of Yellowstone National Park. I feel this project embodies the true nature of interdisciplinary research and would not have been possible without the support of the following contributors:

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- Millsaps College Departments of Geology and Chemistry
- Montana State University Department of Earth Sciences
- The University of Montana, School of Forestry
- The University of Montana, Department of Environmental Studies
- The University of Montana, Social Science Research Laboratory
- Yellowstone National Park Center For Resources

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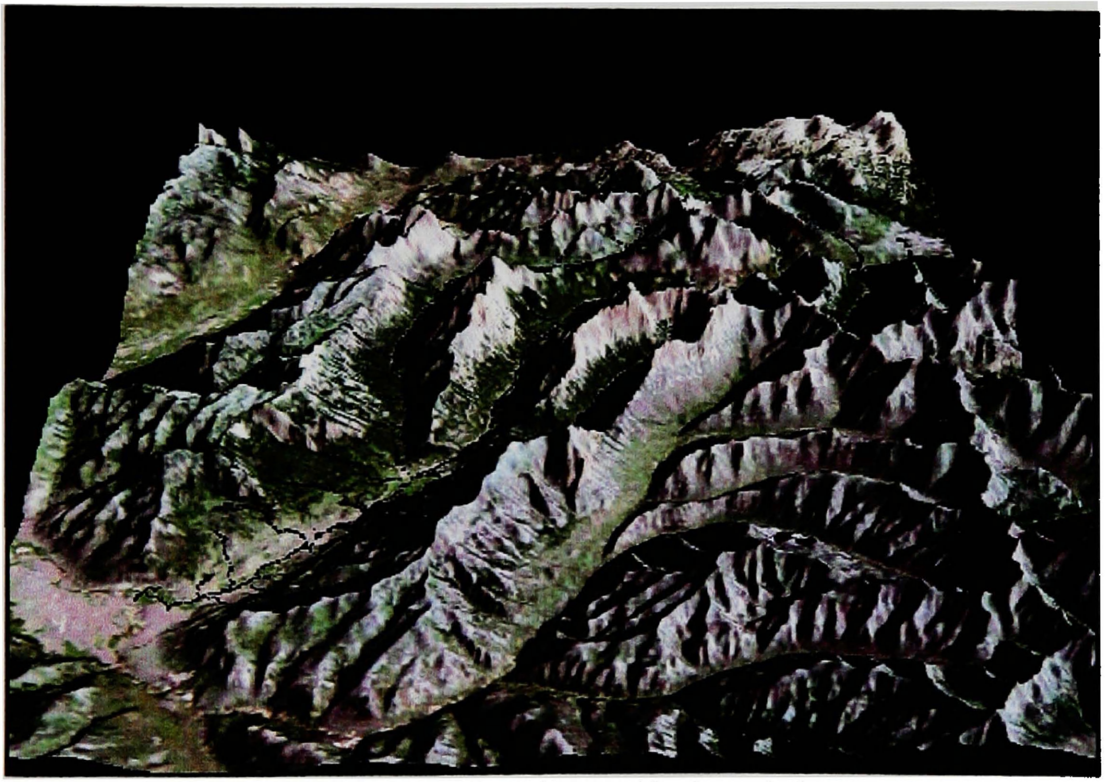


A 1991 LANDSAT TM Scene draped over a 30m Digital Elevation Model

by Robert S. Ahl

INTRODUCTION

Until about 200 years ago man was surrounded by vast, daunting, expanses of what was considered unending wilderness. Now it seems the devices of man surround small isolated patches of wilderness. The World Commission on Water for the 21st Century recently reported that misuse of land and water resources in both advanced industrial countries and developing countries has contributed to serious depletion and pollution of more than half of the world's major rivers (Cosgrove, 1999). The high and remote lands of the Yellowstone Plateau remain among the last relatively intact temperate ecosystems in the world. The nearly 18 million acres of private and public land that comprise the Greater Yellowstone Ecosystem (GYE) are thought to retain the full array of organisms and natural processes that existed before European settlement of the North American continent. The Yellowstone plateau is more than a home for native salmonids, numerous plant species, raptors, large ungulates and their predators; it forms the headwaters for many of the west's largest rivers, serving as a critical genetic and ecological anchor for impaired downstream riverine systems. This elevated landmass is located at a continental crossroads, trapping moisture as it sweeps down the spine of the Rocky Mountains. It acts as an enormous catchment basin, supplying continuous quantities of pure, freshwater to a large portion of the United States and eventually pouring into the Gulf of Mexico.

The volcanic origins of this region contribute to its geologic complexity. Prospectors began exploring this region in the late 1800s and late 1900s, and early geologic reports claim there are few places in the country that display as many surface indications of mineralization (Furniss, 1997). The abandoned McLaren mine is located approximately four miles northeast of Yellowstone National Park. Known as the New World Mining District, it spans the headwaters of three alpine stream networks, including Soda Butte Creek. Economically valuable deposits of precious and base metals have been identified within this region (Furniss, 1997), and Henderson Mountain is alleged to harbor one of the biggest gold deposits in the world, worth nearly 700 million dollars at present gold prices.

The large-scale extraction of metals is associated with waste management dilemmas and environmental degradation throughout the world (Moore and Luoma, 1990). In the United States alone, the Environmental Protection Agency has identified over 31,000 mining-related hazardous waste sites, of which only a small fraction have been adequately treated (Moore and Luoma, 1990). Many of the important processes that affect the fate of trace metal contamination are associated with oxidation-reduction reactions of sulfides and oxygen, determined by the ore and the process used to extract the desired metals from the surrounding rock (Moore and Luoma, 1990). As ore is extracted, it is common to expect 90% of the sulfur-bearing rock to be discarded as tailings, while the remaining concentrate is refined. The residue of these activities have often been deposited in tailings and slag piles, leading to arsenic, cadmium, copper, lead and zinc contamination that are orders of magnitude greater than ambient levels (Moore and Luoma, 1990). Mining sites throughout the world are afflicted by similar activities, yet reclamation efforts and subsequent ecological recovery leave much to be desired. Unraveling the complex interaction of geological and biological factors responsible for the ubiquitous loss of aquatic and riparian biodiversity associated with these actions must be understood for the effective management of mining wastes.

The rivers and riparian systems of the GYE harbor greater species diversity than any other system, yet they occupy a very small percentage of the total land area. Because in-stream conditions are predominately determined by processes occurring within the watershed, they are often our best single indicator of the health of ecosystems as the cumulative impact of upslope processes manifest themselves in the biotic, chemical and physical characteristics of these aquatic resources.

Soda Butte Creek, located in the northeastern corner of Yellowstone National Park, is at first glance a typical mountain stream, originating from snowmelt high in the Absaroka Mountains of southwestern Montana and northwestern Wyoming. Remarkably, in less than twenty miles this creek exhibits a longitudinal pattern similar to the course of many major rivers. Within a relatively short distance, the stream transitions from a steep, (sometimes greater than 10% slope) to a nearly level, braided, meandering channel at its terminus. It grows from a mere trickle at ten thousand feet in elevation to a river with a wide and active floodplain near its confluence with the Lamar River, four thousand feet below. The Lamar River ultimately joins the Yellowstone River.

One of the most scenic watercourses in the park, Soda Butte Creek is an anomaly; it is polluted by persistent mining waste in its headwaters just outside of the park boundary. Once as bountiful and productive as other rivers of Yellowstone National Park, Soda

Butte Creek was considered a lost fishery by the mid 1900s and has only partly recovered since then (Meyer, 1993). The headwaters of the creek, north of Cooke City, MT have been actively mined for gold, silver and copper from 1933 to 1953. At one time it was said to have been the largest gold mine in the state of Montana, using both cyanide and arsenic in the extraction of gold from the ore (Meyer, 1993). The tailings impoundment associated with the McLaren mine is located immediately east of Cooke City, in a relatively level area at the junction of Miller and Soda Butte Creeks. This site is approximately four miles northeast of the park boundary and has long been identified as a principal source of trace metal contamination in Soda Butte Creek (Meyer, 1993). Reconstructive modeling of historic flooding by Grant Meyer suggests that a record breaking flood washed out approximately 30% of the McLaren tailing pond and transported tailings and contaminated sediment many miles downstream. Tailings were also deposited in the terraced floodplain of the lower Soda Butte drainage, more than 16 km downstream. The combination of past hydrologic events, and current acid mine drainage from the impoundment continue to transport heavy metals into Soda Butte Creek, degrading water quality and producing toxic conditions for aquatic life, (Meyer and Watt, 1998).

Although acidic drainage at the McLaren mine site has been attributed primarily to historic mining activity, evidence contained in local ferricrete deposits indicate that discharge of acidic, metal-laden water predates the mining disturbance by thousands of years (Furniss, 1997). Nonetheless, nearly five decades after mine abandonment, acid mine drainage from the McLaren tailings pile continues to leach elevated levels of trace metals directly into the stream, degrading water quality and biological diversity in aquatic and floodplain environments (Meyer, 1998; Nimmo and Willcox, 1996; Ladd, 1995; Stoughton, 1995).

Aquatic sediments can act as trace metal sinks or sources depending on chemical conditions, but concrete definitions of natural vs. elevated levels are lacking (Förstner and Wittmann, 1979). High sediment concentrations of cadmium, copper, zinc, lead, and arsenic have adversely affected more than 21,000 miles of rivers throughout the world (Moore, 1990). Yet, conditions that may impair water quality standards and the biological functioning of one system may constitute natural levels in another system. Water quality and quantity influence mobilization, availability, and bioassimilation of trace metals in aqueous environments.

Trace metal accumulation in macroinvertebrates can have a variety of direct and indirect effects. Although the ecotoxicology of trace metals in aquatic environments is still being explored, it is evident that long-term exposure to sub-lethal levels can be as harmful to aquatic communities as lethal levels for short periods. Long-term exposure to sub-lethal concentrations of trace metals can cause a significant delay in the growth, larval development, and reproduction of freshwater invertebrates (Rainbow and Dallinger, 1993). An alteration of a community's species composition and a reduction in the number of species has also been commonly reported for waters receiving metal-rich waste (Klerks and Levinton, 1993, In Rainbow and Dallinger, 1993).

Because watersheds can differ greatly in their natural (background) characteristics, it is necessary to identify a reference watershed to evaluate the biogeochemical conditions found in the anthropogenically altered Soda Butte Creek.

Research Goal

The ultimate goal of this research project is to describe and assess the spatial extent to which historic, large-scale hard rock mining activity and management of associated wastes outside of the northeast boundary of Yellowstone National Park influences the aquatic ecosystem of Soda Butte Creek inside the park.

Objectives

To address this goal I will:

- Describe Soda Butte Creek's hydrology
- Describe and compare the spatial and temporal distribution of copper concentrations in stream sediments, benthic biofilm and aquatic macroinvertebrates within SBC
- Identify relationships between high gradient riffle (HGR) sediment, biofilm and macroinvertebrate copper levels, from the tailings impoundment downstream to SBC's confluence with the Lamar River
- Determine if high flow events influence copper distributions in HGR sediments
- Compare SBC mainstem HGR sediment concentrations to those of its major unaltered tributary streams
- Select a local reference watershed (i.e. uncontaminated by mining wastes) for the Soda Butte Creek watershed (SBCW)

- Estimate maximum sediment copper background concentrations for Soda Butte Creek from levels observed in the reference watershed
- Develop a comprehensive geospatial database that spans the entire geographic extent of the SBCW
- Make recommendations regarding future research directions and management of the aquatic ecosystem of SBCW

To adequately manage persistent mining wastes it is necessary to understand the extent to which they influence natural processes. In order for land managers to manage at a landscape scale, long-term ecological data are needed to make informed decisions. And natural resource data are be most effectively interpreted in a spatial context.

Because the Soda Butte watershed is not wholly contained in any one jurisdiction, complete spatial data coverage is lacking. Therefore, the development and assembly of a geospatial database serves as the foundation for the modeling and analysis of copper concentrations of in-stream sediment, benthic biofilm and macroinvertebrate components of the Soda Butte Creek watershed. Furthermore, these geospatial data can be used to perform a series of comparative geographic analyses to assist in the identification of the most similar local reference watershed for Soda Butte Creek. Lastly, trace metal data can be used alone and in conjunction with the geographic data to plot and interpret the longitudinal distribution and potential relationships between copper levels in sediment, benthic algae and aquatic macroinvertebrates.

Hopefully the data collected for this project and the models derived from them will serve as a baseline for the long-term, ecological research and monitoring projects that are planned and ongoing in this watershed.

STUDY DESIGN

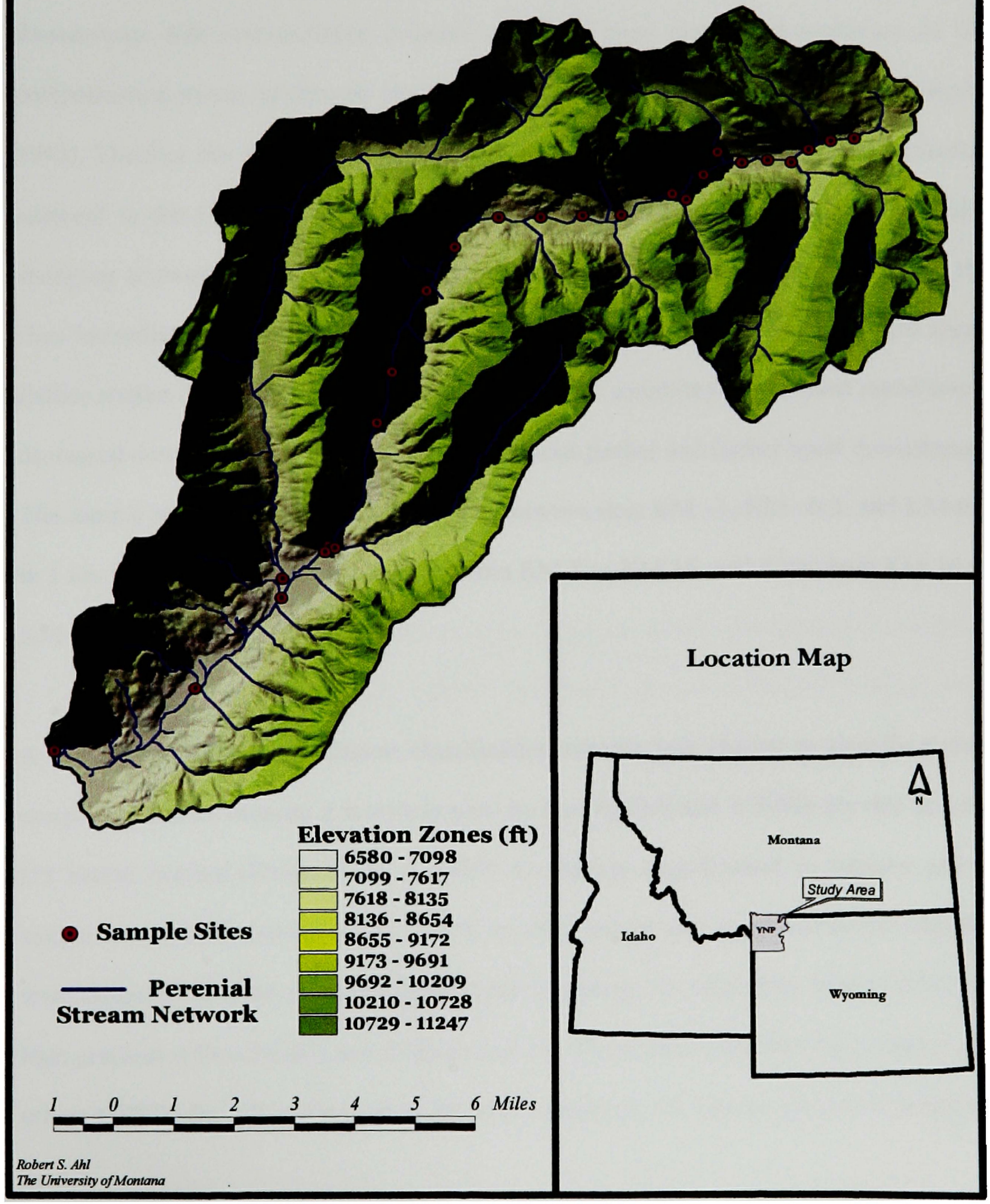
Study Area

The Soda Butte Creek drainage is a high, steep-sided, predominantly south and southeast-facing watershed in the northeastern corner of Yellowstone National Park (Fig. 1). Approximately 70% of this 60,000-acre basin is within the national park boundary. Roughly 16% of this watershed lies in Montana's Gallatin National forest, and 14% is located within the Shoshone National Forest of Wyoming. Pebble Creek and Amphitheater Creek are the two largest sub-watersheds within this drainage; other major tributaries are Republic, Sheep and No Name Creeks. The topography is primarily mountainous. Greater than 60% of the watershed area is situated above 8,000 feet, with nearly 5,000 feet of elevation gain in less than 20 miles (peak and base elevations of 11,247 ft and 6,580 ft, respectively). The majority of the hillsides have slopes steeper than 50 degrees. The climate is typical of the northern Rocky Mountains, with relatively short, cool summers and long, cold winters; approximately 300 inches of snow fall annually. The landscape is a mosaic of open valley bottoms, and steep, forested slopes, dominated by conifers. The small, high elevation headwaters, originating in alpine and glacial environments, pass through high elevation meadows and steep sided, forested valleys, and have steep gradients that cut through sedimentary and volcanic parent material. The larger, flatter waters farther downstream often do not sustain enough hydraulic energy to carry the sediment load generated by erosive forces in the higher elevations, and are often represented by meandering and braided channel networks. In the larger valley bottoms, the stream cuts through deep glacial till deposits and continually migrates laterally across the valley.

The flow in Soda Butte Creek is snow-pack dependent, and the rising limb of the hydrograph generally reaches peak flows in the month of June and returns to base level in early September. Peak flow coincides with spring runoff (Fig. 2), and diurnal fluctuations are evident during early to mid summer, following mid-day snowmelt. Despite heavily forested slopes, the stream responds quickly to short yet high intensity precipitation events during summer months, with rapid increases in runoff and sediment transport. Channel migration and substantial bank erosion occurs during high flows, especially in the open valleys, vegetated by sparse cottonwood galleries, and occasional willow shoots along the water's edge. Most of the channel shifting and bank erosion takes place during the months of May, June and July, but is not uncommon at other times of the year as well. Real-time and monthly stream flow data are available from the USGS gauging station upstream of the Lamar River confluence. A continuous eight-year flow record exhibits a mean high of 700 cubic feet per second (cfs) and lows near 25 cfs.

Figure 1.

The Soda Butte Creek Watershed, Yellowstone National Park



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Field Data Collection and Handling

Stream Sediment Sampling

Stream sediment samples were collected from 25 sites along the length of Soda Butte Creek and some of its major tributaries. The spacing of the sites varied with the distance downstream. Site nomenclature is based on linear road distance downstream of the contamination source, previously identified as the McLaren tailing impoundment (Meyer, 1993). The first site was located 1 km (km –1.0) upstream of the tailings impoundment, adjacent to the Gallatin National Forest Soda Butte Campground. Due to the rapidly changing contamination conditions in the more heavily impacted upstream reaches, the sites immediately above and below the tailing impoundment were spaced ½ km apart. Earlier studies (Marcus, 1998 pers. com.) showed that variability in sediment metal levels decreased downstream, so sample sites were spaced farther and farther apart downstream. The sample spacing increased from 0.5 km, between sites KM –1, KM –0.5, and KM 0.5 to 1 km from KM 1.5 to KM 8, to 2 km from KM 8 to KM 16, and 4 km from KM 16 to KM 24.

A modified version of the Bisson classification scheme was chosen to identify stream morphologic units because it is widely used by the US Fish and Wildlife Service and the US Forest Service (Overton, et. al. 1997) for habitat classification in streams and is simple to use in the field (Marcus, 1998). At each sample site, stream sediment samples were collected in three principal geomorphic sampling: 1) eddy drop zones (EDZ), 2) high gradient riffles (HGR), and 3) glides (GLD). These units, modified from Bisson and others (1982), are relatively easy to identify visually in the field at low flow based on shape, size, and water surface characteristics. For example, flow in the lee of an obstruction or attached bar often forms an eddy drop zone, which characteristically contains fine sediment particles. High gradient riffles generally occur at the tail of bars, contain emergent cobbles, and exhibit shallow and turbulent flow with bed gradients between 1 and 4%. Similarly, there is often a transition from the tails of lateral scour pools into shallow, fast flowing, low turbulence glides with gravel and cobble beds.

At each sample site, sediment from the EDZ, HGR and GLD geomorphic units was collected via a 20-liter bucket with the bottom removed. The bucket was pushed into the stream sediment to facilitate sampling by providing a barrier to the flow of water that would otherwise carry away the fine sediment particles that were being collected. After removing the surface armor of cobbles and gravel, approximately 375 to 500 ml of sand-sized and smaller sediments were removed at each sample site from the top 5 to 10 cm of the streambed. A one-third cup measuring spoon, constructed of heavy-duty plastic, was used to dig up the sediments. Plastic was used in order to avoid contaminating the sample with any metal fragments or shavings that could result from mechanical wear on metal instruments. As the sediments were excavated from the stream, they were placed in a plastic bucket. From the bucket, the sediment samples were transferred to labeled, double-bagged, heavy-duty Zip-Loc™ freezer bags. Air and water were forced out of the bags before they were sealed to further reduce potential contamination or geochemical alteration of the sediment samples.

After the sediment samples were collected and packaged, they were stored in a cool, dark, place until they could be processed in the lab. Once in the lab, samples were air-dried, then dry-sieved through a stainless steel sieve. The 2mm and finer fraction (sands and finer) was retained for metals analysis. A 1-gram sub-sample was sent to *Chemex Labs, Inc.* (contact information at end of section) for inductively coupled plasma-optical emission spectrometry (ICP) analysis. *Chemex* first digested the sediments in boiling aqua regia acid (three parts hydrochloric acid, one part nitric acid) for one hour. Aqua regia will digest secondary minerals and sulfur compounds, but not silicate structures. It therefore captures all the potentially environmentally mobile metals from the sediments.

Replicate samples within HGR sampling units from previous work (Marcus, 1996) indicated that metal concentrations were within ± 15% of the reported values, with lead (Pb) being a notable exception. Lead probably occurred in "nuggets", so concentrations in replicates could vary widely depending on whether a nugget was or was not within the sample. Lab error for HGR sediment copper levels was estimated at ± 10% of the reported values. For further information on quality control procedures, contact *Chemex Labs, Inc., 212 Brooksbank Ave., Vancouver, B.C., Canada,* V7J 2C1.

Biofilm Sampling

Benthic biofilm samples, containing algae, bacteria, detritus, and microscopic insects were collected from the high gradient riffle (HGR) component at each sample site, where enough biological material was available to yield a sample large enough to analyze. A minimum sample consisting of one gram dry ash weight of biofilm was necessary for viable tissue metal concentration ICP analysis. Biofilm was scraped from cobble to boulder sized, submerged rocks with a thin, flexible plastic card. Three small (47 mm) petri dishes were filled with periphytic biomass. The biomass was drained and compressed in an effort to eliminate as much water as possible from the sample. The three petri dishes per site were closed tightly, wrapped in tin foil, labeled, and sealed in a Zip-Loc™ freezer bag, and placed in an ice-filled cooler while in the field. Upon return to the research station, biofilm samples were stored in a freezer. At the end of the sample collection period, biofim samples were packaged in a small cooler with dry ice and sent to *Activation Laboratories Ltd.* for trace metal analysis. A 0.25 gram aliquot of ashed sample was digested in a 1:1 nitirc acid / hydrogen peroxide solution at 90° C. One ml of the sample solution was diluted to 10 ml with > 18 megaohm water and analyzed using an ELAN 6000 ICP Mass Spectrometer. Analyses were based on dry ash weight, and lab error for biotic copper levels was estimated at ± 15% of the reported values. For further information regarding lab procedures, contact *Activation Laboratories, 1336 Sandhill Drive, Ancaster, Ontario, Canada, L9G 4V5, (905) 648-9611, (905) 648-9613 fax.*

Macroinvertebrate Sampling

Following the methods established by the USDA Forest Service R1 rapid bioassessment protocol (Overton, et. al. 1997), macroinvertebrate samples were collected in the high gradient riffle (HGR) geomorphic unit at each sample site for both diversity and metal analysis purposes. To obtain samples for diversity analysis, a D-Net was placed onto the sediments within an HGR and held at arm's length while vigorously kicking and dislodging the streambed materials in front and upstream of the net for exactly one minute. At the end of each minute the contents of the net were placed into a collection tub where detritus and macroinvertebrates were separated. Macroinvertebrates were then packaged in labeled whirl-pac bags containing 95% alcohol. Generally 70% alcohol is the recommended preservation agent for macroinvertebrates, but because the macroinvertebrates were still wet and in some cases were still mixed with remnant detritus, dilution of the alcohol was expected. This procedure was repeated so as to produce three replicate macroinvertebrate diversity assessment samples at each site.

Macroinvertebrate samples for trace metal analysis were collected in the same manner as the diversity assessment samples. However, sampling time was not limited to one minute per sample, rather it was the volume of the sample that dictated when sampling was complete. In order to obtain the minimum of one gram of ashed macroinvertebrate sample, it was necessary to gather a full whirl-pac bag of macroinvertebrates, often requiring repeated kick sampling with the D-Net in the HGR of the stream. Sampling was continued until the bag was full of macroinvertebrates. The resulting sample represents a composite of macroinvertebrates present in the HGR at each sampling location. Great care was taken to separate macroinvertebrates from detritus to reduce sediment contamination of the samples. These picked macroinvertebrates were placed in a dry, sterile whirl-pac bag and stored in an ice-filled cooler while in the field. Upon return to the research station, the macroinvertebrate samples for metal analysis were frozen. At the end of the study, frozen samples were packaged in a small cooler filled with dry ice and sent to *Activation Laboratories Ltd.* for Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) trace metal analysis, using the same process as described for biofilm metal analyses. Analyses were based on dry ash weight, and lab error for biotic copper levels was estimated at ± 15% of the reported values.

Macroinvertebrate Diversity Analysis

Macroinvertebrates were separated from remnant detritus. The species were identified, counted, and classified by a qualified taxonomist. The results were entered into a spreadsheet and diversity index values will be calculated. This is a work in progress and these data will not be included in this study.

Site Documentation

A minimum of four photographs were taken to document the three individual types of geomorphic sampling units (EDZ, HGR, GLD), and the overall juxtaposition of these units at each sample site. One photograph was taken of each unit and one summary photograph was taken to describe the site as a whole. The photos were taken with 35 mm film, and the prints scanned at 300 dpi and saved as .JPEG image files. The image files were linked, in a Geographic Information System, to the point features of the sample sites to facilitate visual interpretation of physical differences between sites.

Sample collection date, Global Positioning System file name, sample unit dimension, comments and a field sketch map of approximate locations of in-stream samples were also generated at each sample site.

Spatial Database Development

Digital Elevation Model

One of the first steps in developing a geospatial database for the Soda Butte Creek Watershed (SBCW) was to acquire a Digital Elevation Model (DEM) of the corresponding geographic region upon which all other geographic data could be overlaid. The SBCW extends from Yellowstone National Park into Montana's Gallatin National Forest and Wyoming's Shoshone National Forest. This watershed is comprised of eight (8) United States Geological Survey (USGS) seven and a half (7.5) minute quadrangle map sheets. The fact that the study area spans multiple political boundaries makes standardized digital data acquisition a troublesome task. DEMs downloaded from the USGS file transfer protocol (FTP) sites for Montana and Wyoming proved to be rather inefficient, as DEMs of varying quality were obtained and additional error was induced by applying edge matching techniques to "mosaic" the eight DEMs together.

As a result, a region-wide DEM was obtained from the Yellowstone Center for Resources Spatial Analysis Center (http://www.nps.gov/yell/technical/gis). Both the standard 30-meter pixel and a high-resolution 10-meter pixel DEM were provided. The 10-meter pixel DEM yielded little more useful information than the 30-meter pixel DEM, especially when modeling extensive landscapes, yet required approximately an order of magnitude more memory and processing time on a pentium™ based computer. Therefore only the 30-meter DEM was used for all analyses and GIS development. The Spatial Analysis Center was also able to supply a variety of other geospatial data layers relating to the park environment and infrastructure, such as geology, roads, trails, as well as vegetation, soils, fire mapping and hydrography. All of these layers, however, only span the political boundary of the park, and therefore have limited analytical and display utility for work in the Soda Butte Creek watershed. All geographic data layers in this Soda Butte Creek watershed collection are in the planar Universal Transverse Mercator (UTM, zone 12) projection, using the North American Datum of 1983 (NAD83).

DEM Dimensional Formatting

The Yellowstone Ecosystem region-wide DEM obtained from the Spatial Analysis Center was clipped to a rectangular boundary that encompassed the entire extent of the Soda Butte Creek watershed to reduce memory and processing time requirements on a personal computer. The clipping procedure was accomplished using ArcView GIS 3.1 software and the Spatial Analysis 1.1 extension. A clipping boundary polygon was interactively created, and converted to a grid. The resulting grid was used as an analysis mask. By setting the analysis to the dimensions of the entire DEM and the analysis mask to the dimensions of the mask grid, a new grid is cut from the DEM that matches the dimensions of the defined mask grid.

Watershed Delineation

Once the DEM was clipped to dimensions that closely matched the extent of the desired study area, I initiated a computationally efficient watershed delineation procedure, using ArcView GIS 3.1 software, the Spatial Analyst 1.1 extension and hydrologic modeling techniques (see Appendix I for more details).

The same procedure was used for the delineation of the Pebble Creek and Amphitheater Creek sub-watersheds of the Soda Butte Creek watershed. All watershed calculations were stored in both raster (grid) and vector (polygon) formats.

Hydrologic Modeling

A complete hydrography layer that spans the entire extent of the Soda Butte Creek watershed was not currently available from the National Park Service or any other federal or state agency. A specific hydrologic model for the Soda Butte Creek watershed had to be developed. Hydrologic modeling was accomplished by using a combination of ArcView GIS 3.1 software, Spatial Analyst 1.1, Arc/Info 7.2.1, and original hydrologic modeling Avenue Scripts.

There is currently no “black-box” technique to develop a synthetic stream network for a given watershed. Detailed knowledge of the physical dimensions of the features to be modeled is required, and trial and error computation is necessary to derive a model that is reasonably close to the real world. This is an iterative process (see APPENDIX I for more details).

A specialized Avenue Script (ESRI ArcView programming language) was written that utilized the previously derived flow accumulation grid and a user-specified flow accumulation threshold value to calculate a potential stream network. The resulting stream network database includes unique stream segment identifications, length (in meters), and stream order designations. The files were stored as Arc/Info coverages and ArcView Shapefiles.

An abundant literature base, dealing with the extraction of stream networks from digital elevation and remote sensing data, indicates that both the vector Triangulated Irregular Networks (TIN) and raster-based DEMs models have advantages and disadvantages (Band, 1999 in Longley, Goodchild, Maguire, and Rhind, 1999). Although finer detail of vector features may be achieved with a TIN, where a sequence of triangle edges can be defined as the stream channel, and the size of the triangles can be modified to the scale of the stream feature, these models require sophisticated software and high-level computing power. Raster models, on the other hand, have the obvious disadvantage of the fixed dimensions of raster cells and may slightly misrepresent the stream junctions and the area immediately around the stream channel. Due to such limitations, neither the surface area of the stream channel or the topography immediately around the channels can be precisely modeled. Nonetheless, despite their relative shortcomings, raster-based models are by far the most commonly used in GIS/hydrology applications. Their popularity is largely based on computational efficiency, the availability of raster elevation data, the compatibility with other data sources such as remotely sensed imagery, and established methodologies in geomorphic and hydrologic modeling applications (Band, 1999 in Longley, Goodchild, Maguire, and Rhind, 1999). It is important to note, that while detailed stream channel characteristics, such as width, depth or cross-section morphometry, may not be derived from the model itself, these data may be collected in the field and later appended to the model as feature attributes.

Sample Site Point Features

A point feature was created for each stream sample site location, using a Trimble Navigation GeoExplorer II Global Positioning System receiver to gather point feature data (see Appendix I for more details).

A point feature representing the USGS stream gauging station was also added to the geospatial data collection. To facilitate real-time stream flow data for this site, the Internet address for the Soda Butte Creek USGS stream flow web site was linked to this point feature. The geographic coordinates of these point features were in the UTM zone 12 coordinate system and used the North American Datum of 83 (see Appendix I for more details).

Hydrologic Data Collection

Stream flow data for SBC, recorded in cubic feet per second, were obtained from the USGS Water Data Retrieval Internet site (http://waterdata.usgs.gov/nwis-w/wy/?statnum=06187950) for the period of record, from October 1, 1988, to September 30, 1997. The flow data were measured at the footbridge stream gauge upstream of the Lamar Ranger Station, YNP. This gauging station is approximately two miles upstream of the Lamar River / Soda Butte Creek confluence.

Mean Monthly Discharge

To determine the typical seasonal cycle of discharge, a mean monthly discharge value for each month of the year was determined by averaging all the daily values for that month, for the period of record from October 1, 1990 to September 30, 1997.

Peak Flow

To determine the timing of the high water events with the greatest hydrologic discharge magnitude, I constructed a graph representing single day peak flow events (discharge events greater than 700 cfs – which represents the mean annual high water discharge value).

Exeedence Probability and Partial-Duration Series Frequency

To determine the probability of a given discharge event, I calculated exceedence probabilities of hydrologic discharge, for the period of record. To construct the hydrologic frequency curve, the discharge data were first ranked from the largest to the smallest value, and then each value was assigned a probability of exceedence, otherwise known as the plotting position. The *Weibull* formula was used to calculate probability plotting positions: $P(x) = (m/N + 1)$, where $P(x)$ is the exceedence probability, m is the rank of each value (1 for the largest value), and N is the total number of observations. The return period, T, for an event is calculated from the inverse of the exceedence probability: $T = 1/P(x)$ (Haan, 1977).

Partial-duration analysis uses all independent events above a specified base level (700 cubic feet per second in this case). For a partial-duration frequency series, the exceedence probability is the number of events that will exceed a certain magnitude per 100 years (Table 2), (Haan, 1977).

Geospatial Reference Watershed Analysis

To determine how much copper concentrations in Soda Butte Creek differed from those found in a comparable system not affected by mining, it was necessary to identify a local reference watershed. A watershed that shares similar geologic, physical geographic, landcover, and meteorological characteristics is most desirable for a comparison of hydrologic, geochemical, and biotic conditions. The physical dimensions of the Soda Butte Creek watershed and its major tributaries and associated sub-watersheds were calculated. Drainage density, hypsometric, slope, aspect, geologic and landcover (vegetation) distributions were analyzed to determine the suitability of using the Pebble Creek, and / or Amphitheater Creek sub-watersheds as reference watersheds to the Soda Butte Creek watershed.

Drainage Density Comparison

Drainage density (defined as the sum of all stream channel lengths, divided by the watershed area) provides an efficient relative comparison of drainage patterns between watersheds (Brooks, 1997). Using the previously developed hydrologic and watershed delineation models, drainage density was calculated for the Soda Butte Creek watershed, as well as for the Pebble Creek and Amphitheater Creek sub-watersheds. The hydrologic model provided the basis for summarization and comparison of stream lengths and drainage patterns. The watershed delineation procedure for Soda Butte Creek, Pebble, and Amphitheater creeks facilitated the calculation of area, and perimeter for the delineated watersheds. Using a GIS, drainage density was calculated for Soda Butte Creek watershed by summing the stream vector lengths and dividing them by the total watershed area. Clipping the stream network to the sub-watershed polygon dimensions provided the derivation of the sub-watershed drainage density. The resulting clipped stream networks were summed and divided by the respective watershed areas. Drainage density was reported as stream length per watershed area. Relative drainage density values can be compared for the Soda Butte Creek watershed and Pebble Creek and Amphitheater Creek sub-watersheds. Generally speaking, the higher the drainage density value, the "flashier" (rapidly responsive to precipitation events) the watershed hydrology is likely to be.

Hypsometric Comparison

ArcView GIS 3.1 software with the raster-based Spatial Analyst 1.1 extension was used to derive and describe hypsometric attributes for SBCW and Pebble Creek and Amphitheater Creek sub-watersheds. A 30-meter DEM was used in the derivation of relative area within 1000-foot contour intervals. The number of 30 x 30 meter pixels within each 1000-foot contour interval was summed, and the area was calculated. To provide a relative comparison between watersheds, the area within each contour interval was divided by the corresponding watershed area.

Slope Comparison

The 30-meter DEM, and ArcView GIS 3.1 software with the raster-based Spatial Analyst 1.1 extension were used to derive and describe slope attributes for Soda Butte Creek watershed and Pebble Creek and Amphitheater Creek sub-watersheds by applying the GRID.SLOPE request. In this way the maximum rate of change, from each cell to its neighbors was computed and an output grid theme in degrees of slope was produced. Degree of slope is a value between 0 and 90 for each cell location (ArcView Help). Slope was classified into 10 categories. The sum of the number of pixels in each slope class was converted to an area calculation and divided by the corresponding watershed area, to provide a relative comparison between watersheds.

Aspect Comparison

The 30 meter DEM; and ArcView GIS 3.1 software with the raster-based Spatial Analyst 1.1 extension was used to derive and describe aspect attributes For Soda Butte Creek watershed and Pebble Creek and Amphitheater Creek sub-watersheds by applying the GRID.ASPECT request. Aspect represents the steepest down-slope direction from each individual cell to its neighbors. The values of the output grid theme represent the compass direction of the aspect; 0 is true north, a 90 degree aspect is east, 180 degrees is south, and so forth. (ArcView Help). Aspect was classified into 9 categories. The sum of the number of pixels in each aspect class was converted to an area calculation and divided by the corresponding watershed area, to provide a relative comparison between watersheds.

Landcover Comparison

A 1991 LANDSAT Thematic Mapper image was acquired from the Yellowstone National Park Spatial Analysis Center and clipped to the dimensions of the mask grid from the DEM clipping operation. Twenty-five iterations of the ISODATA clustering routine in ERDAS IMAGINE version 8.3 software (Jensen, 1995), with a 0.95 convergence threshold, were used to classify this image. From the perspective of the macro-level watershed comparison, it was desirable to identify major landcover classes to assess relative recharge and evapotranspiration potential between the watershed and major sub-watershed. Ultimately, seven data clusters were identified in the image as 1) forest (condensed from three forest types), 2) burned forest, 3) mesic and 4) xeric vegetation, and 5) suspected bare ground.

The classified image was exported from ERDAS as an Arc/Info grid file, and further clipped to the dimensions of the Soda Butte Creek watershed. The relative proportion of each landcover class was calculated for the whole watershed and the Pebble Creek and Amphitheater Creek sub-watersheds. Data were exported to a spreadsheet to facilitate further graphical comparisons.

Geologic Comparison

The Yellowstone National Park Spatial Analysis Center has produced a detailed geologic coverage of YNP. The limit of this coverage, however, is defined by the park boundary and therefore omits the eastern / northeastern portion of the Soda Butte Creek watershed. A digital generalized geologic Arc/Info coverage spanning the entire Soda Butte Creek watershed, was obtained from NRCS, 1999, but yielded little useful information. Due to a lack of reliable spatial geologic data, a computer-assisted quantitative geological comparison between SBCW and the Pebble Creek and Amphitheater Creek sub-watersheds was not possible. I therefore consulted with Dr. W. A. Marcus, who confirmed that all three watersheds had very similar proportions of the same parent materials.

Data Analysis

Soda Butte Creek Hydrology

Hydrologic data were electronically downloaded from the USGS web site for the Soda Butte Creek gauging station at the footbridge near the confluence of the Lamar River. Data for the entire period of record were obtained in ASCII text format and imported into EXCEL. Descriptive data tables, line graphs and scatter plots were produced.

1998 Copper Distribution in Sediment, Biofilm and Macroinvertebrate Samples

A table and histogram, produced in EXCEL described the spatial distribution of copper. Spatial models to display the distribution of copper in SBC sediments were developed in ArcView 3.1 GIS software. Maps of the watershed and graduated point symbols were produced to represent copper concentration values at each sample site.

Correlations between Copper Levels in HGR Sediment, Biofilm and Macroinvertebrates

Because the distributions of metal contamination data are generally non-normal, a log10 transformation was applied to the sediment, biofilm and macroinvertebrate copper concentration data to reduce inherent skew. Unless otherwise specified, nonparametric methods were used in sediment and biological copper correlation analyses. To identify relationships between these multi-dimensional data, I developed a correlation matrix, in the Statistical Package for Social Sciences (SPSS) version 8.0, using the log-transformed data and Spearman's rho, with a 2-tailed distribution.

Effect of High-Discharge Hydrologic Events on HGR Sediment Copper Concentrations

Soda Butte Creek has experienced major hydrologic events in the past several years. Sediment data for SBC have been collected from 1994 to 1998. Historic data matching the sampling sites of 1998 were used to identify temporal variation of copper in the sediments of SBC. Only the seven sites sampled every year from 1994-98 were used in this analysis (i.e. sites km 1.5, 2, 3, 4, 6, 8, 28). A grouped histogram with standard error bars, comparing these variables was prepared in EXCEL, while a box-plot with whisker bars was produced in SPSS version 8.0, yielding slightly different perspectives of temporal variation in these data.

Comparison of HGR Sediment Copper Levels in Mainstem and Tributaries

High gradient riffle sediment copper data were log10 transformed to reduce skew and separated into tributary and mainstem categories. Two-sample t-tests were applied to log-transformed data to test the hypothesis that tributary sediment values have significantly lower copper values than the mainstem of SBC. Republic Creek data were excluded from this analysis because it did not meet the unaltered tributary assumption, due to residual smelter deposits near its mouth.

Reference Watershed Identification

Spatial data in grid attribute tables, and in vector database files were imported into either EXCEL or SPSS for analysis. Tables, maps, and graphs were produced to facilitate visual interpretation and quantitative identification of the most similar reference watershed for Soda Butte Creek. The GIS output of landcover characteristics, drainage density, hypsometric, slope, and aspect analyses were imported into EXCEL to produce comparative data tables, and histograms. The Statistical Package for Social Sciences (SPSS) version 8, was used to perform a Pearson bivariate correlation analysis of these data.

Natural Background Copper Concentrations

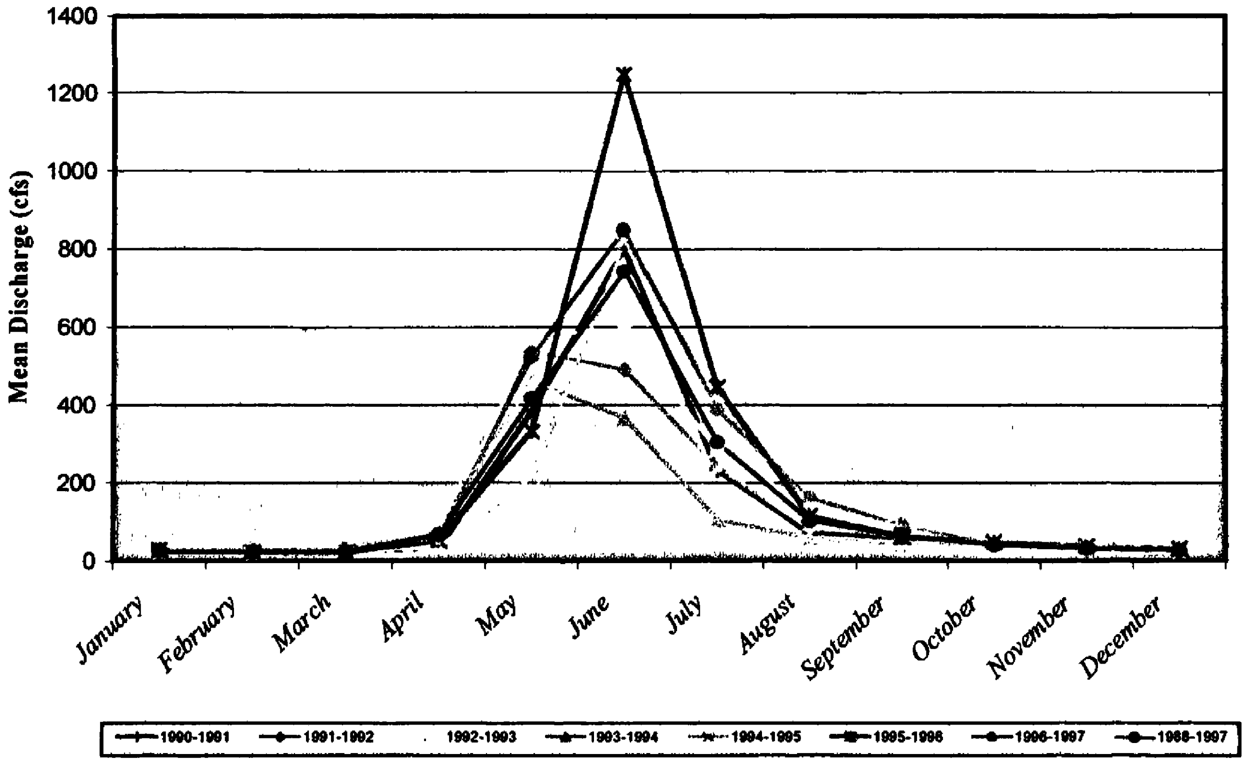
Once a reference watershed was selected – its sediment copper concentrations were assumed to represent the natural average and variability. That is, I assumed that any sediment copper value that fell within the 99% confidence interval of the Pebble Creek data could not be statistically distinguished from that uncontaminated watershed's sediments. Therefore only those sediment copper concentrations that fall outside of this 99% confidence interval can be said to be contaminated with a high degree of certainty. Thus the criteria for a contaminated sediment sample is one that exceeds the mean value of the Pebble Creek concentration values by three standard deviations.

RESULTS AND DISCUSSION

Soda Butte Creek Hydrology

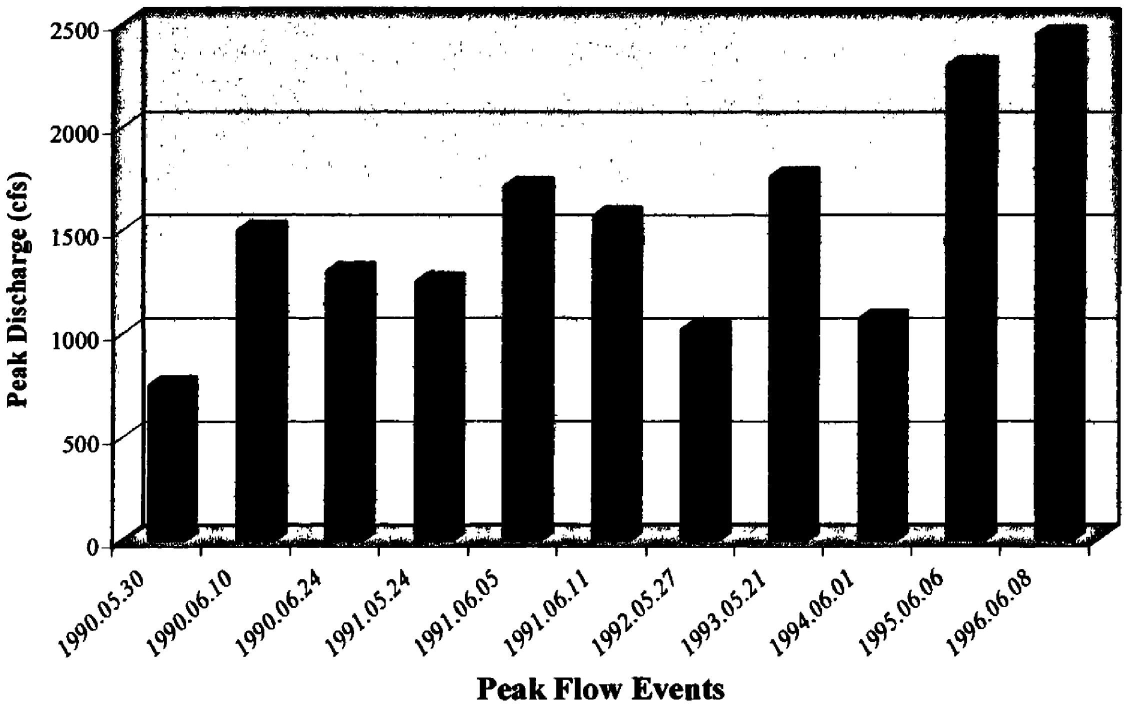
Mean monthly discharge values were calculated for Soda Butte Creek, based on the period of record from October 1, 1988 to September 30, 1997, from the USGS gauging station near the confluence of Soda Butte Creek and the Lamar River. The mean monthly discharge hydrograph indicates that Soda Butte Creek is a snowmelt-dominated watercourse, with the rising limb beginning in late April to early May, and peak flow occurring in the month of June. Conversely, the falling limb of the hydrograph occurs from late June until August. Base flow levels are generally reached between late August and September (Fig. 2; mean monthly discharge data are available in APPENDIX II).

Figure 2. Soda Butte creek Mean Monthly Discharge (cfs), 1990-1997



Soda Butte Creek experienced higher than average monthly discharge levels (> 700 cfs) in 1990, 1991, 1992, 1993, 1994, 1995, and 1996 (Fig. 3). The years of 1995-1996 exhibited above average flow during peak discharge in early June as well as during late June, July and August. In contrast, peak discharge levels in 1991 were above average but were followed by a rapid decrease and below average flow through the summer. Exceedence probability statistics suggested that there was less than a 0.1 probability that discharge levels greater than 700 cfs would occur at any given time.

Figure 3. Single Day Peak Flow Events Exceeding 700 cfs



When only single day peak flow events (> 700 cfs) were considered, only dates in 1991, 1993, 1995 and 1996 had discharge values greater than 1,500 cfs, which represented nearly twice the magnitude of the average annual peak. On June 6, 1995, and August 6, 1996, peak discharge exceeded 2,000 cfs. Partial-duration frequency analysis indicated that peak flow events such as those experienced in 1995 and 1996 are only likely to be exceeded 17 and 8 times per 100 years, respectively (Table 1).

Table 1. Soda Butte Creek Partial-Duration Series Frequency Analysis for discharge events > 700 cfs, during the period of record from Oct. 1, 1988 to Sept. 30, 1997

Event Date	Discharge (cfs)	Exceedence Probability	Exceedence per 100 yrs.
1996.06.08	2450	0.08	8
1995.06.06	2300	0.17	17
1993.05.21	1760	0.25	25
1991.06.05	1710	0.33	33
1991.06.11	1570	0.42	42
1990.06.10	1500	0.50	50
1990.06.24	1300	0.58	58
1991.05.24	1250	0.67	67
1994.06.01	1070	0.75	75
1992.05.27	1020	0.83	83
1990.05.30	750	0.92	92

1998 Copper Distribution in Sediment, Biofilm and Macroinvertebrate Samples

Fluvial sediment transport has major implications for the fate of trace metals in the aquatic and riparian environment. Not only are sediment-adsorbed metals, such as copper, physically transported downstream, but geochemically mobilizing reactions also occur when sediments are deposited on top of older, well-oxygenated sediments. In highly oxygenated water, metals are usually bound to sediment particles, but when covered by new sediments, decomposition of interstitial detritus consumes oxygen, and releases carbon dioxide, lowering pH. These conditions release trace metals into the surrounding sediments and water column. Hydrologic head, forcing water through the sediments may, in turn, create microplumes of toxic water in the leeward area of such deposits (Schrader 1999, pers. com).

Marcus (1996) suggested that stream morphology also plays a major role in controlling spatial variations in sediment copper concentrations of sand-size (0.06 mm) and smaller fractions. He concluded that copper and other sediment bound metals segregate into discrete subpopulations at the scale of individual morphologic units, but not over the shorter distances within units, or over longer distances along stream reaches. Based on sampling conducted in 1995, Dr. Marcus reported that the highest copper concentrations in Soda Butte Creek bed sediments occurred in attached bars, eddy drop zones, and high gradient riffles, while lowest concentrations were often found in low gradient riffles and glides.

Stream life is most abundant in the coarser gravel and more oxygenated waters of high gradient riffles than in the finer sediments of eddy drop zones, or shallower and more oxygen-depleted glide environments. Aquatic macroinvertebrates and algae are considered good indicators of local conditions because they are more sessile than fish (Metcalfe-Smith, J.L. in Petts, G and P. Callow, 1996). Although sediment and biological samples were analyzed for a suite of metals, only copper results are presented here (Table 2).

Copper concentrations were determined for sediment samples collected from eddy drop zone (EDZ), glide (GLD) and high gradient riffle (HGR) stream geomorphic units at each sample site along the length of Soda Butte Creek and its major tributaries. Because biofilm and macroinvertebrate samples were only collected from high gradient riffles

(HGR), only HGR sediment samples were included in analyses of spatial and temporal variation in copper levels, and biological correlation.

Table 2. Copper concentrations in sediment, macroinvertebrate, and biofilm samples collected in high gradient riffle stream units at each sample site. Lab error is reported as ± 10 % for sediment samples and ± 15% for biotic samples. Certain analyses required a log10 transformation of the data, the results of which are reported in the log column.

Sample Sites		**Sediment (ppm)**				**Macroinvbrt. (ppm)**				**Biofilm (ppm)**			
#	Distance (km) / Name	Cu	10%	-10%	log	Cu	15%	-15%	log	Cu	15%	-15%	log
1	*-1*	27	30	24	1.4	50	58	43	1.7	138	159	117	2.1
2	*-0.5*	334	367	301	2.5	25	29	21	1.4	97	112	82	2.0
3	*0.5*	243	267	219	2.4	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
4	*Republic Creek*	26	29	23	1.4	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
5	*1.5*	38	42	34	1.6	14	16	12	1.1	*N/A*	*N/A*	*N/A*	*N/A*
6	*2*	54	59	49	1.7	19	22	16	1.3	*N/A*	*N/A*	*N/A*	*N/A*
7	*Sheep Creek*	21	23	19	1.3	*N/A*	*N/A*	*N/A*	N/A	*N/A*	*N/A*	*N/A*	*N/A*
8	*3*	45	50	41	1.7	13	15	11	1.1	*N/A*	*N/A*	*N/A*	*N/A*
9	*No Name Creek*	23	25	21	1.4	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
10	*4*	47	52	42	1.7	14	16	12	1.1	43	49	37	1.6
11	*5*	32	35	29	1.5	35	40	30	1.5	40	46	34	1.6
12	*6*	34	37	31	1.5	1	1	1	0.0	42	48	36	1.6
13	*7*	29	32	26	1.5	3	3	3	0.5	28	32	24	1.4
14	*8*	32	35	29	1.5	3	3	3	0.5	33	38	28	1.5
15	*10*	34	37	31	1.5	2	2	2	0.3	35	40	30	1.5
16	*12*	28	31	25	1.4	8	9	7	0.9	38	44	32	1.6
17	*14*	26	29	23	1.4	9	10	8	1.0	19	22	16	1.3
18	*16*	23	25	21	1.4	2	2	2	0.3	47	54	40	1.7
19	*Above Amphitheater*	22	24	20	1.3	1	1	1	0.0	17	20	14	1.2
20	*Amphitheater Creek*	11	12	10	1.0	N/A	N/A	N/A	N/A	15	17	13	1.2
21	*Below Amphitheater*	20	22	18	1.3	2	2	2	0.3	25	29	21	1.4
22	*Pebble Creek*	13	14	12	1.1	1	1	1	0.0	*N/A*	*N/A*	*N/A*	*N/A*
23	*20 / Below Pebble*	20	22	18	1.3	2	2	2	0.3	*N/A*	*N/A*	*N/A*	*N/A*
24	*24 / Braided*	18	20	16	1.3	4	5	3	0.6	29	33	25	1.5
25	*28 / Confluence*	20	22	18	1.3	10	12	9	1.0	37	43	31	1.6

N/A insufficient quantity at site to produce a metal analysis sample

Copper Concentrations in Sediment

Assuming similar within site variability to that observed in an earlier study (Marcus, 1996) field replicate variability was in the range of ± 15%, while lab error for sediment trace metal analysis was estimated at ± 10%. HGR sediment copper levels decreased as distance downstream from the tailings impoundment increased. The observed gradient had a stair-step pattern, and I divided the concentrations into five partitions (334-243, 54-32, 29-21, 20-18, 13-10) (Table2, Figs. 4a, 5a). The highest sediment copper concentrations were observed immediately above and immediately below the tailings impoundment, at km –0.5 (334 ppm) and km 0.5 (243 ppm). From km 1.5 to km 4 mainstem HGR copper concentrations ranged between 38 and 54 ppm. Then, from km 5, below the small settlement of Silver Gate, to km 10, mainstem copper levels ranged from 29 to 34 ppm. Following, from km 12 to immediately above the confluence of Soda Butte Creek and Amphitheater Creek, mainstem copper concentrations between 22 and 28 ppm were observed. Lastly, the copper concentration range for mainstem sites from below Amphitheater Creek to the mouth of Soda Butte Creek at the Lamar River confluence was between 18 and 20 ppm. The concentration one kilometer upstream from the tailing site was similar to those observed between km 12 and Amphitheater Creek (i.e. between 26 and 28 ppm).

Soda Butte Creek sediment copper levels are similar to those found in Montana's heavily mining-impacted Clark Fork River Complex, which represents the nations' largest "superfund" site. Sediment copper concentrations in the Clark Fork vary greatly, but Moore and Landrigan (1999) report a range between 300-700 ppm in river sediments in the downstream end of the superfund site. These levels are similar to those sampled above and below the McLaren tailing impoundment in the upper reaches of Soda Butte Creek. Although the Blackfoot River has also experienced mining near its headwaters, it is still relatively uncontaminated and often used as a reference for the Clark Fork River. In a recent study, Moore and Landrigan (1999) found sediment copper concentrations of 20 ppm in the Blackfoot, which are comparable to those of the lower reaches of Soda Butte Creek. Axtmann et al. (1997) also found similar sediment copper background levels in the Rock Creek tributary to the Clark Fork River. It is important to realize, however, that the volume of water passing through both the Blackfoot River and Rock Creek was approximately 11.5, and 3 times greater than that of Soda Butte Creek, (mean annual peak of 8,000 cfs, and 2,000 cfs, as compared to SBC's 700 cfs, based on USGS streamflow data from 1988 - 1998). Direct comparisons of sediment copper levels between the much larger Blackfoot River and Soda Butte Creek may not be entirely appropriate because of possible volumetric dilution effects due to their respective hydrologic characteristics. While the lower reaches of SBC's sediments may not be devoid of persistent mining waste, they are in line with those of the Blackfoot River and Rock Creek, which are known to support moderately sensitive aquatic life and have high aesthetic and recreational values.

Copper Concentrations in Biofilm

The epilithic benthic biofilm, which contains algae, bacteria and probably some sediment, was scraped from cobble to boulder sized substrate in the HGR stream units at each sample site and analyzed for trace metal concentration. Lab error for copper analysis of biofilm samples was estimated at ± 15%. No field replication variability estimates are available for these data.

The highest biofilm copper concentrations were upstream of the mine tailing impoundment. This may be related to the old and abandoned mill site upstream of the actual tailings impoundment. The soil of the old mill site was exposed to surface weathering and erosion and lies adjacent to the km –0.5 stream sampling site, and likely contributes trace metals to the headwaters of Soda Butte Creek at that location. By km 10, biofilm copper levels ranged from 15-40 ppm, with slight downstream decreases (Table 2, Figs. 4b, 5b).

Benthic substrates were slippery with biofilm at all but the ferricrete-coated site at km 0.5. However, the major tributaries, Republic, Sheep, No Name, and Pebble Creeks, as well as SBC at the km 2.0, and km 3.0 sample sites did not yield sufficient quantities of biofilm for trace metal analyses, but did not appear to be impaired by ferricrete deposits, or lack of available light. Since these sites were located in the upper part of the watershed, and in high gradient, low-order tributary streams, substrate instability and oligotrophy may have been limiting factors in biofilm production. It is difficult to infer toxicological impacts on biofilm from these data because there are no background biofilm levels for comparison. It is evident, however, that biofilm are not present at sites where excessive ferricrete deposits carpet the stream bed from the tailings impoundment to the confluence with Republic Creek 1.5 km downstream.

Copper Concentrations in Macroinvertebrates

Macroinvertebrate samples were collected in the riffle stream components at each sample site and subsequently analyzed for trace metal concentrations. Lab error copper analysis of macroinvertebrate samples was estimated at ± 15%. No field replication variability estimates are available for these data.

As in biofilm and sediment data, copper concentrations in macroinvertebrates declined with distance downstream (Table 2, Figs. 4c, 5c). Macroinvertebrate copper concentrations observed at km 5.0, km 12, km 14, km 24 and km 28 were unexpectedly high. The highest macroinvertebrate copper concentrations were observed at km –1.0 (50 ppm) and km 5.0 (35 ppm), while the lowest mainstem concentrations were detected at km 6.0 (1 ppm) and above Amphitheater Creek (1 ppm). Although macroinvertebrates were present at all sites, insufficient quantities prevented the collection of samples large enough for trace metal analysis at the km 0.5 ferricrete-coated site and all of the tributary stream sites, except Pebble Creek. Macroinvertebrate copper concentrations can be grouped into two broad classes (>10 ppm, and <10 ppm). Concentrations above 10 ppm were observed from the most upstream sample sites down to km 5.0, while copper levels were below 5 ppm at all other sites except km 12, km 14, and km 28.

Studies of Montana's Clark Fork River represent one of the best examples of ecotoxicological studies of metals in a mining-contaminated western river. The Clark Fork is severely contaminated by a massive abandoned mine complex in it's headwaters. Near that complex, copper levels in the stream invertebrates are around 200-250 ppm (Axtmann, et al. 1990; Hornberger, et al. 1997), and effects on the macroinvertebrate community are pronounced (McGuire 1990). However, 50-100 km downstream, invertebrate copper levels drop to between 50-100 ppm, and effects on the community are slight. About 150 km downstream, levels drop below 50 ppm, and there are no measurable effects on the macroinvertebrate community (Axtmann, et al. 1990;

Hornberger, et al. 1997; McGuire 1990). Copper levels in macroinvertebrates in the Clark Fork's relatively uncontaminated tributaries are around 8-10 ppm.

Although SBC macroinvertebrate copper levels in the first 5 km below the tailings were elevated above these "background" levels, they were well below levels found to have detectable effects on the macroinvertebrate community in the Clark Fork, except right at the old mill and tailings impoundment sites in the headwater reaches. Downstream of the km 5 site, SBC macroinvertebrate copper levels were well below the Clark Fork's tributary levels.

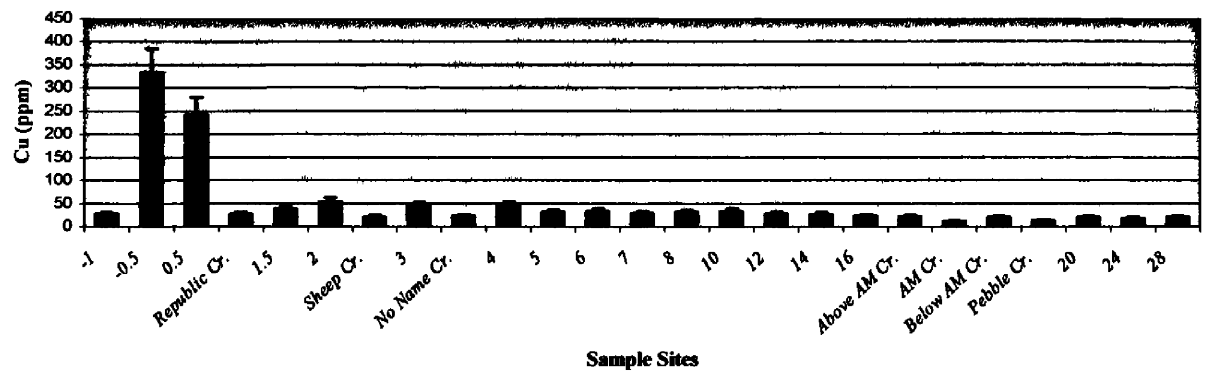


Figure 4a. 1998 HGR Sediment Copper Concentrations (ppm)

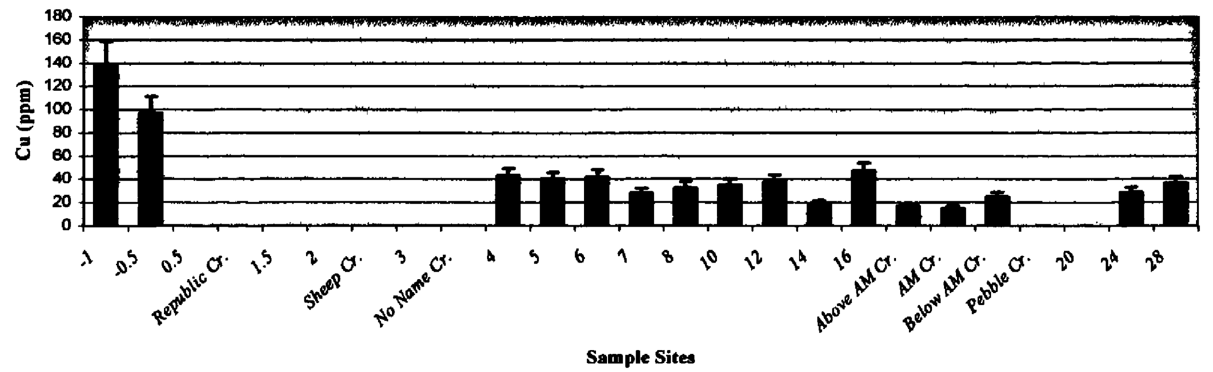


Figure 4b. 1998 Biofilm Copper Concentrations (ppm)

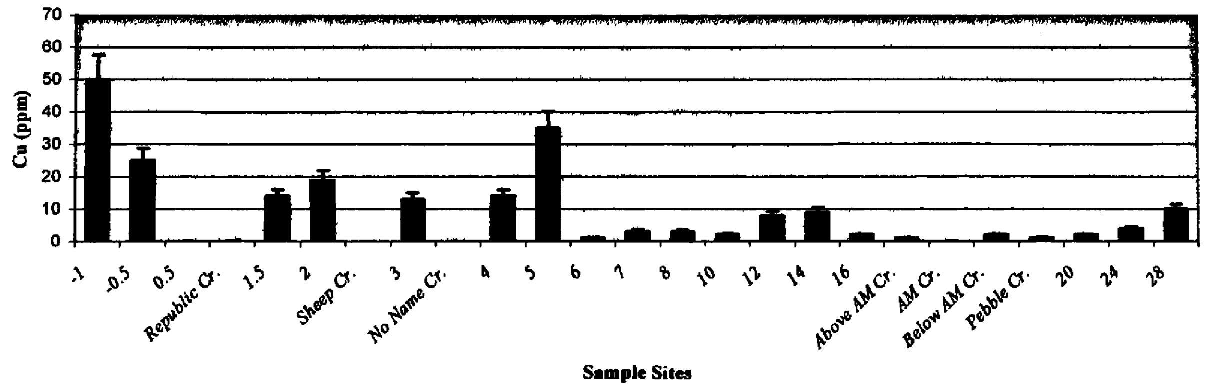
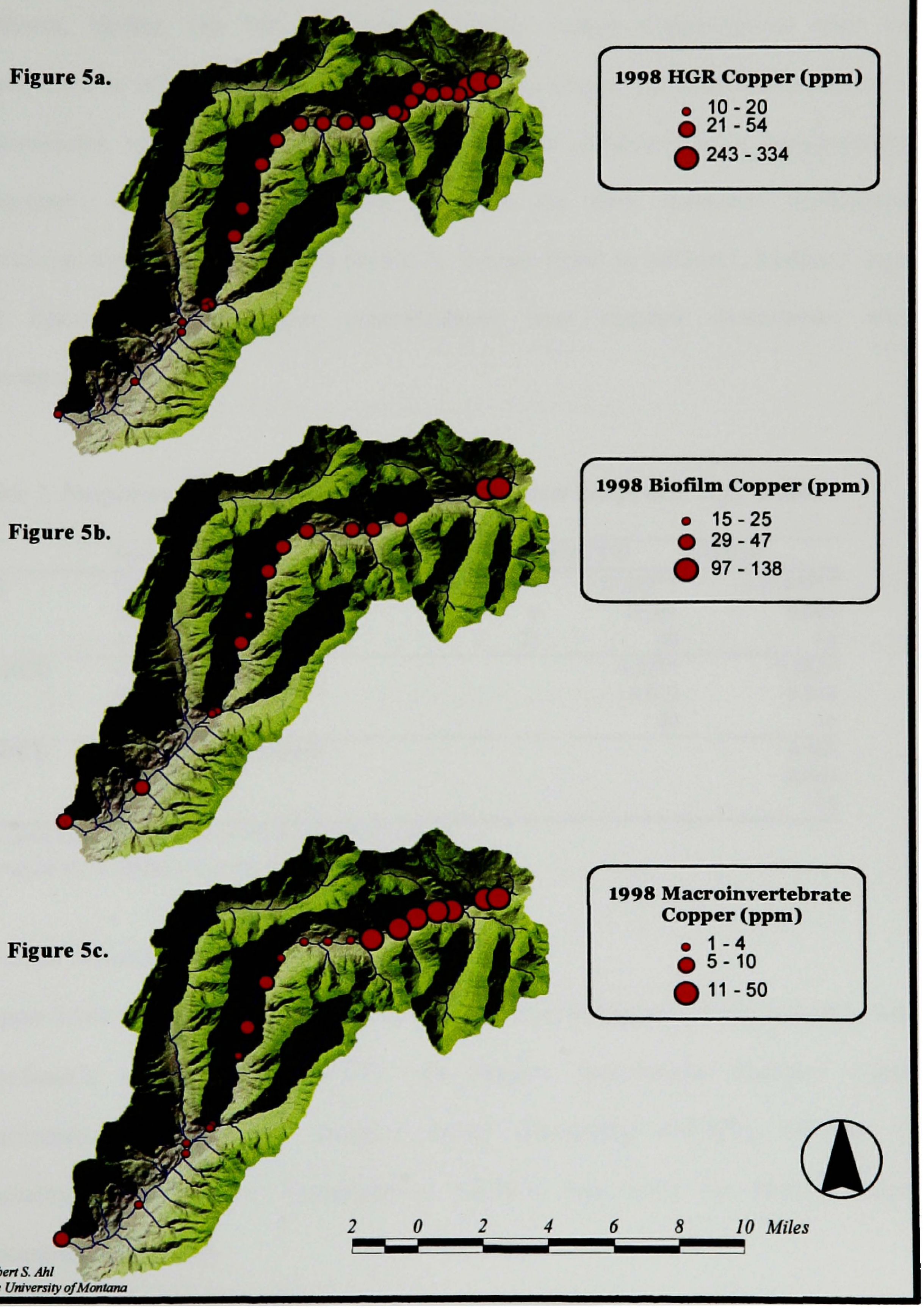


Figure 4c. 1998 Macroinvertebrate Copper Concentrations (ppm)

Note: Error bars indicate 10% lab error for sediment and 15% lab error for biotic samples in reported copper levels. Field variability is estimated at 15% for sediment samples, but no field replication error estimates are available for these data due to small sample size. A minimum of 1.0 gram ash weight sample was required for metal analysis. Where no values are reported for biotic components, insufficient biological material was available to yield metal analysis samples.

Soda Butte Creek: Sediment, Biofilm & Macroinvertebrate Cu Distributions



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Correlations between Copper Levels in HGR Sediment, Biofilm and Macroinvertebrates

Sediment, biofilm and macroinvertebrate sample copper concentrations were log transformed to reduce the skew imparted by the punctuated, elevated concentrations at contaminated sites. The log-transformed data were subjected to a nonparametric Spearman's rho correlation analysis, in which the three ecosystem components containing copper were compared (Table 3). Trends found in sediment, biofilm / algae and macroinvertebrate copper concentrations, over distance downstream were investigated.

Table 3. Nonparametric correlations for 1998 ecosystem component copper data

	Spearman's rho	**HGRCU**	**MACCU**	**ALGCU**
KM	*Correlation Coefficient*	(-)0.727**	(-)0.663**	(-)0.659**
	Sig. (2-tailed)	0	0.001	0.006
	N	25	20	16
HGRCU	*Correlation Coefficient*		0.521*	0.582*
	Sig. (2-tailed)		0.019	0.018
	N		20	16
ALGCU	*Correlation Coefficient*			0.485
	Sig. (2-tailed)			0.067
	N			15

*** correlation is significant at the 0.01 level (2-tailed)*

** correlation is significant at the 0.05 level (2-tailed)*

Distance Downstream

Copper levels found in all ecosystem components, from sediment to biological data, were significantly correlated ($p < 0.01$) with distance downstream. Sediment copper concentrations showed the strongest linear relationship (-0.727), followed by macroinvertebrate copper concentrations (-0.663) and lastly by biofilm copper concentrations (-0.659).

Biofilm Correlation

At the 0.01 level, copper concentrations in biofilm data were most strongly related to distance downstream (-0.659). Biofilm copper concentrations were less strongly, but still significantly ($p<0.05$) correlated to sediment copper concentrations (0.582).

Macroinvertebrate Correlation

Copper macroinvertebrate data were most strongly ($p<0.01$) correlated to distance downstream (-0.663). At the 0.05 level, macroinvertebrate copper concentrations were also strongly related to sediment copper concentrations (0.521).

Correlations between sediment and biotic compartments are probably due to contamination of the biotic samples with sediment. Sediment levels are correlated with distance downstream because clean sediments, transported in from uncontaminated tributaries, most likely help to dilute mainstem sediment copper levels.

Effect of High Flow Events on HGR Sediment Copper Levels

To evaluate the effect of high flow events on the downstream distribution of copper in bed sediments, I compared the distribution pattern over the period of record (1994-1998). Multiple year data exist for only seven of the 25 sample sites along SBC.

The multiple year data are presented in two ways – as a grouped histogram showing each year's data for all the sites and as box plots to facilitate comparing the same variability between sites. The box plots (Fig. 6) show that year-to-year variability generally decreases downstream which is to be expected since extreme "hot spots" are more likely near the contamination source.

The grouped histogram (Fig. 7) reveals that there is no pattern in the year-to year variability that can be easily related to the two recent high flow years (1996 & 1997) during the period of record. The km 1.5 site did show an increase in copper levels following the high flow in 1996, but if this higher level was real, it did not persist.

Figure 6. 1994-1998 HGR Sediment Cu Level Variability by Distance Downstream

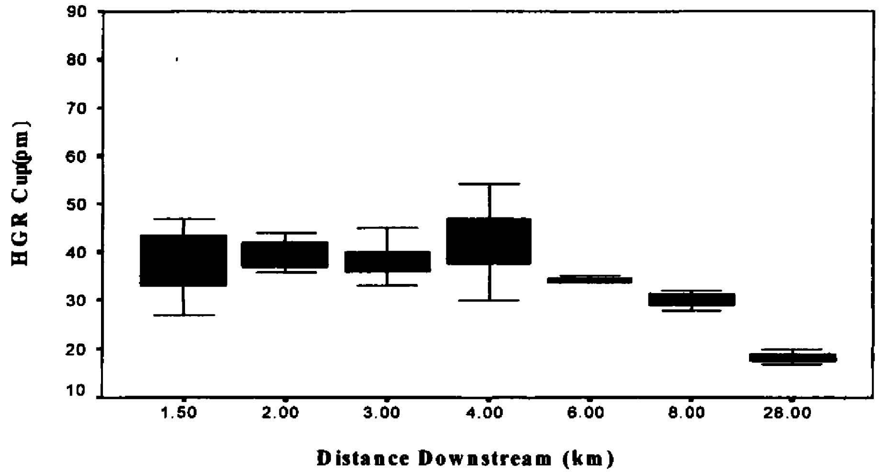
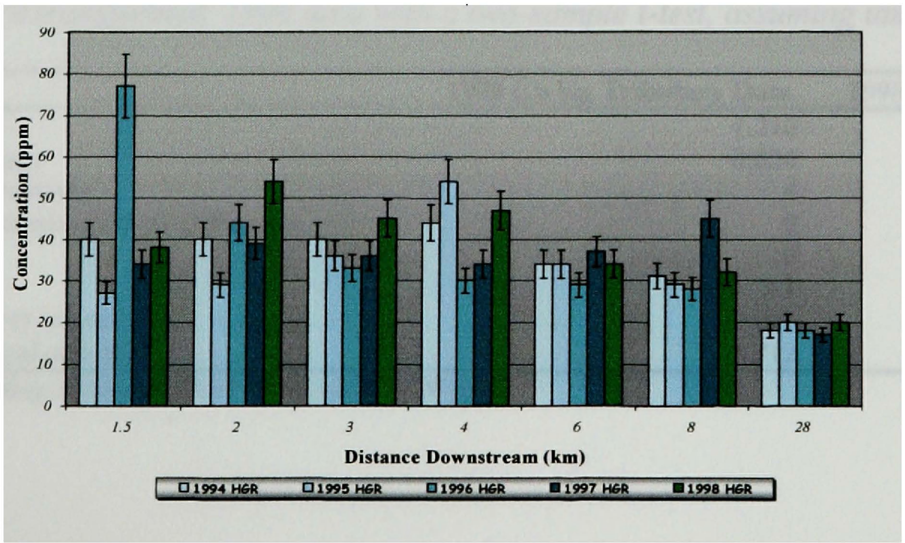


Figure 7. 1994-1998 Year-to-Year HGR Sediment Copper Level Comparison



These data suggest that floods of the magnitude that occurred in 1996 & 1997 have little or no noticeable effect on the sediment distribution, neither raising nor lowering sediment copper levels. It appears that larger floods, probably similar to or greater in magnitude than the 1950 flood, would be needed to change sediment copper distribution noticeably.

Comparison of HGR Sediment Copper Levels in Mainstem and Tributaries

A 2-sample t-test of log-transformed high gradient riffle sediment data illustrates that tributary streams have significantly lower ($p < 0.01$) mean HGR sediment concentrations than Soda Butte Creek mainstem HGR sediment values (Table. 4). Although based on only one sampling season, this result suggests that tributary streams may have the potential to slightly depress sediment concentration at nearby downstream sites. However, the data in Table 2 suggest that tributary streams have little influence on regional sediment concentration patterns. Republic Creek was excluded from this analysis because of the proximity of the historic smelter site at its confluence, which therefore disqualifies it as an unaltered tributary.

Table 4. Tributary-mainstem HGR sediment copper level (ppm) comparison using log10 transformed 1998 data with a two-sample t-test, assuming unequal variances

	1998 Cu log Tributary Data	**1998 log Mainstem Data**
Mean	1.210	1.562
Variance	0.024	0.111
Observations	4	20
Hypothesized Mean Difference	0	
df	10	
t Stat	-3.261	
P(T<=t) one-tail	**0.004**	
t Critical one-tail	1.812	

excluding Republic Creek Data, value = 26 ppm

Reference Watershed Identification

States have adopted water quality standards for metals based on ecotoxicological studies, but currently there are no such standards for metals in sediments or biota in the United States. Without such standards, a common approach is to compare metal levels at a contaminated site to those of a physically similar, but uncontaminated, site. Two uncontaminated sub-watersheds of the SBCW appear to be good candidates as reference watersheds to the upper SBCW – these are the Pebble and Amphitheater Creek sub-watersheds. I evaluated their similarity to the SBCW by comparing drainage density, hypsometric, slope, and aspect, as well as landcover characteristics. All of these distributions were derived from an unsupervised classification of 1991 LANDSAT Thematic Mapper multispectral remotely sensed imagery, and the digital elevation and hydrologic models produced for the SBCW. To serve as geochemical reference watersheds to SBC, the Pebble and Amphitheater Creek sub-watersheds must also have similar parent materials. Although geologic characteristics could not be directly evaluated, personal communication with Dr. W. Andrew Marcus (1999), a geomorphologist at Montana State University who has been studying geochemical patterns in SBC since 1994, confirmed that these drainages shared similar geology.

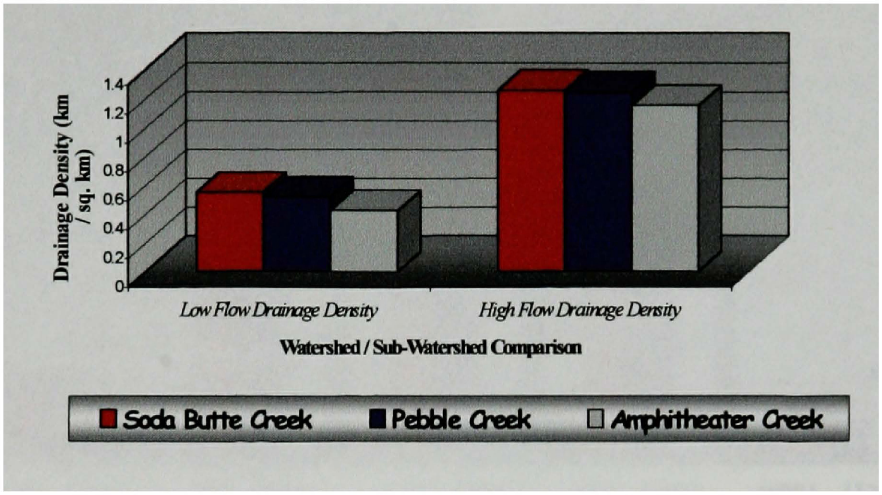
Drainage Density Analysis

Both low flow and high flow stream network models were used to compare drainage density values between the Soda Butte Creek watershed and the Pebble and Amphitheater Creek sub-watersheds (Table 5, Fig. 8). Although remarkably close relative agreement between all three drainages was observed for both low and high flow simulations, drainage density values of Pebble Creek were more similar to Soda Butte Creek than Amphitheater Creek.

Table 5. Drainage density calculation for the Soda Butte, Pebble and Amphitheater Creek watersheds, using both low and high flow hydrologic models

Soda Butte Creek Watershed		
Low Flow Hydrologic Model		
watershed area (sq. km)	*stream network length (km)*	*drainage density (km/sq. km)*
269	148	0.55
High Flow Hydrologic Model		
watershed area (sq. km)	*stream network length (km)*	*drainage density (km/sq. km)*
269	338	1.26
Pebble Creek Sub-Watershed		
Low Flow Hydrologic Model		
watershed area (sq. km)	*stream network length (km)*	*drainage density (km/sq. km)*
65	34	0.51
High Flow Hydrologic Model		
watershed area (sq. km)	*stream network length (km)*	*drainage density (km/sq. km)*
65	81	1.24
Amphitheater Creek Sub-Watershed		
Low Flow Hydrologic Model		
watershed area (sq. km)	*stream network length (km)*	*drainage density (km/sq. km)*
24	10	0.43
High Flow Hydrologic Model		
watershed area (sq. km)	*stream network length (km)*	*drainage density (m/sq. km)*
24	27	1.15

Figure 8. Drainage Density Comparison of the Soda Butte Creek Watershed and its Major Sub-Watersheds

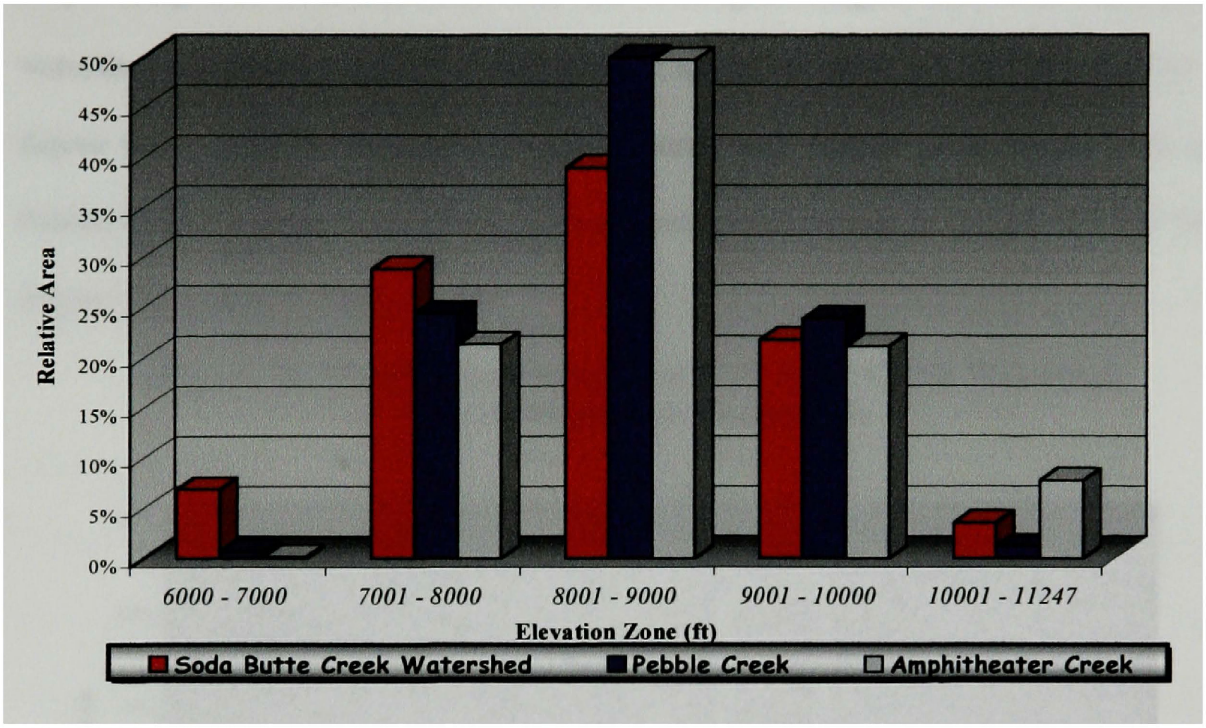


Hypsometric Analysis

The Soda Butte Creek watershed ranged from 6,580 to 11,247 feet in elevation. Hypsometric characteristics of the relative areas between five elevation zones in 1,000-ft increments, were compared for the three watersheds (Figs. 9, 13).

Similar hypsometric patterns were observed in the Soda Butte, Pebble and Amphitheater Creek drainages. Greater than 35% of the area in these watersheds exists in the 8,000 – 9,000 foot elevation zone, while approximately equal area proportions of 20% to 30 were found in both the 7,000 – 8,000 and 9,000 – 10,000 foot ranges. Less than 10% of the total area for any one of the watersheds was located either above 10,000 feet or below 7,000 feet.

Figure 9. Hypsometric Comparison of the Soda Butte Creek Watershed and its Major Sub-Watersheds



A Pearson bivariate correlation analysis revealed that although a significant relationship between Soda Butte, Pebble, and Amphitheater Creek exits, the hypsometric characteristics of Soda Butte Creek watershed and the Pebble Creek sub-watershed were more closely correlated to one another than were those of Soda Butte and Amphitheater Creek (Table 6).

Table 6. Hypsometric correlations between the SBCW and its major sub-watersheds

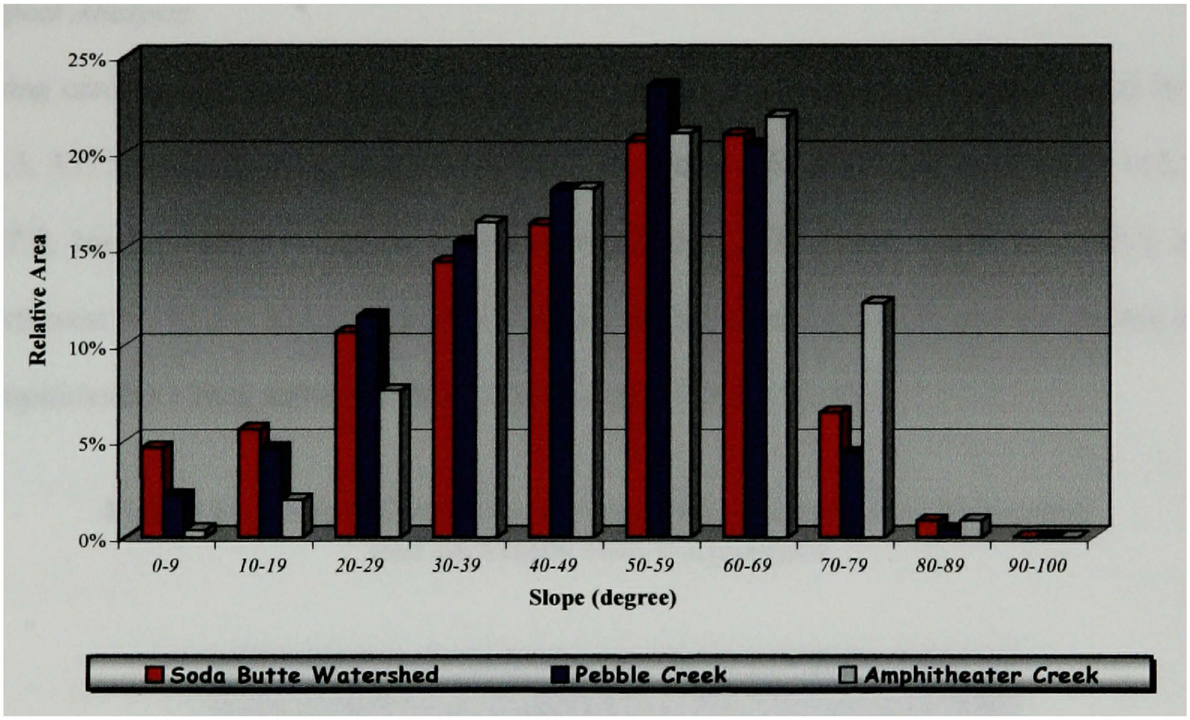
		Soda Butte Creek	Pebble Creek	Amphitheater Creek
Soda Butte Creek	*Pearson Correlation*	1.000	0.972**	0.924*
	Sig. (2-tailed)	.	0.006	0.025
	N	5	5	5
Pebble Creek	*Pearson Correlation*		1.000	0.983**
	Sig. (2-tailed)		.	0.003
	N		5	5
Amphitheater Creek	*Pearson Correlation*			1.000
	Sig. (2-tailed)			.
	N			5

** *Correlation is significant at the 0.01 level (2-tailed).*
* *Correlation is significant at the 0.05 level (2-tailed).*

Slope Analysis

Slope categories were classified into ten 10-degree ranges. The Soda Butte Creek watershed contained a greater distribution of slopes in the 0 –9, 10 – 19 and 70 – 79 degree range than Pebble Creek. Amphitheater Creek tended to be steeper than either Pebble Creek or Soda Butte Creek, with a greater relative area in the 60 –69 and 70 –79 degree slope classes (Figs. 10, 14).

Figure 10. Slope Comparison of the Soda Butte Creek Watershed and its Major Sub-Watersheds



The majority of the Soda Butte Creek watershed and its sub-watersheds were contained in the 50 – 59 degree and 60 – 69 degree slope classes. Overall, the Pebble Creek and Soda Butte Creek drainages contained the most similar slope class distribution characteristics, and the correlation between them was higher than that between the Soda Butte and the Amphitheater Creek drainage (Table 7).

Table 7. Slope correlations between the SBCW and its major sub-watersheds

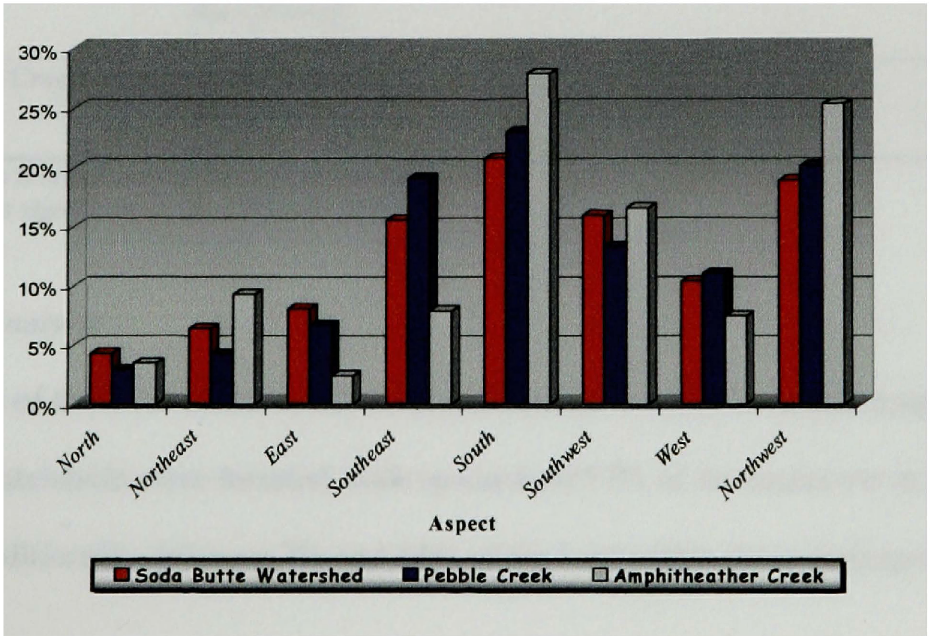
		Soda Butte Creek	**Pebble Creek**	**Amphitheater Creek**
Soda Butte Creek	*Pearson Correlation*	1.000	0.988**	0.936**
	Sig. (2-tailed)	.	.000	.000
	N	9	9	9
Pebble Creek	*Pearson Correlation*		1.000	0.920**
	Sig. (2-tailed)		.	.000
	N		9	9
Amphitheater Creek	*Pearson Correlation*			1.000
	Sig. (2-tailed)			.
	N			9

** *Correlation is significant at the 0.01 level (2-tailed).*

Aspect Analysis

Using cardinal and sub-cardinal classification categories, where north is represented by 0-22.5, 337.5 - 360 degrees, northeast = 22.5 - 67.5, east = 67.5 - 112.5, southeast = 112.5 – 157.5, south = 157.5 – 202.5, southwest = 202.5 – 247.5, west = 247.5 – 292.5, and northwest = 292.5 – 337.5, an aspect comparison between the SBCW and the Pebble and Amphitheater Creek sub-watersheds was computed (Figs 11, 15).

Figure 11. Aspect Comparison of the Soda Butte Creek Watershed and its Major Sub-Watersheds



Soda Butte Creek and Pebble Creek were more similar to one another than either was to Amphitheater Creek. Amphitheater Creek has a greater distribution of north, northwest, northeastern and southern aspect ranges than either Soda Butte Creek or Pebble Creek, and a substantially lower distribution of eastern and southeastern aspect ranges.

Pebble Creek has a slightly greater distribution of southern and southeastern aspect ranges and a slightly lower northern, northeastern, eastern and southwestern aspect range distribution than Soda Butte Creek. Despite statistically similar ($p<0.01$) aspect distributions within the Soda Butte, Pebble and Amphitheater Creek drainages, a stronger linear relationship existed between aspect values in the Soda Butte Creek and Pebble Creek drainages (Table 8).

Table 8. Aspect correlations between the SBCW and its major sub-watersheds

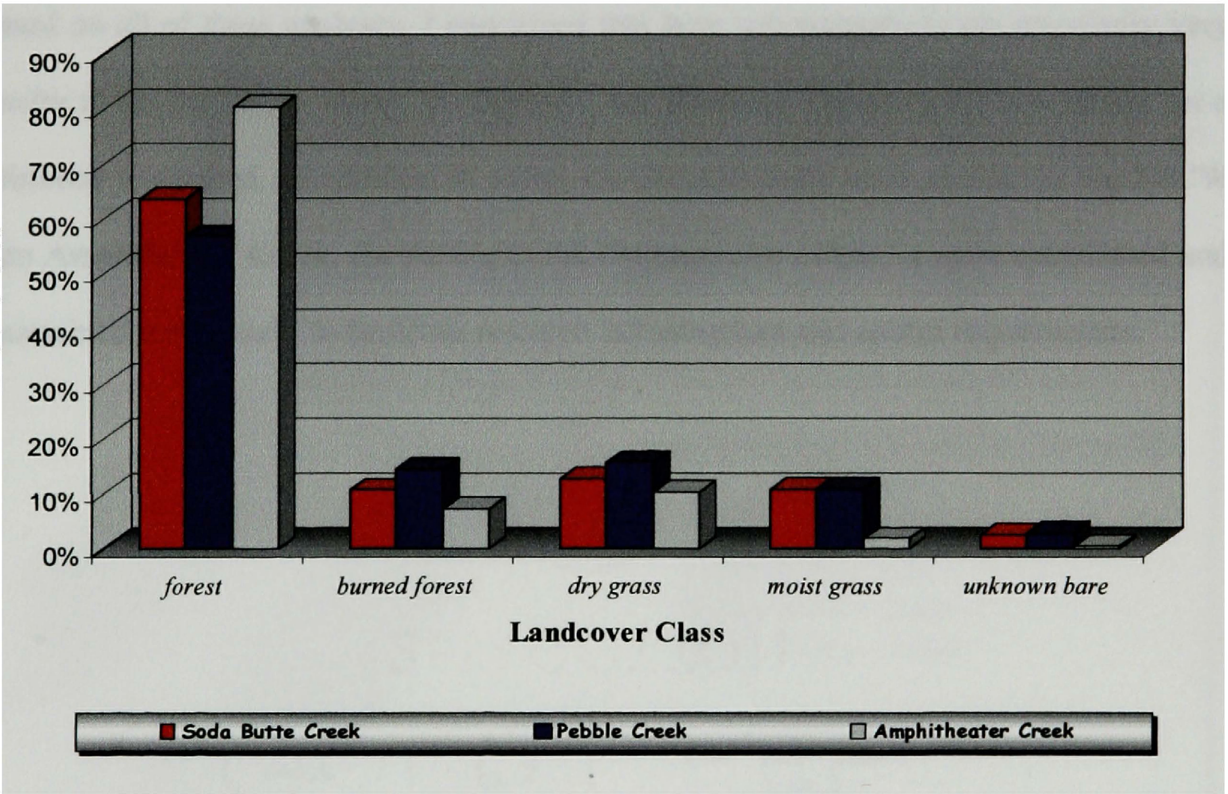
		Soda Butte Creek	**Pebble Creek**	**Amphitheater Creek**
Soda Butte Creek	*Pearson Correlation*	1.000	0.972**	0.868**
	Sig. (2-tailed)	.	.000	.005
	N	8	8	8
Pebble Creek	*Pearson Correlation*		1.000	0.794*
	Sig. (2-tailed)		.	.019
	N		8	8
Amphitheater Creek	*Pearson Correlation*			1.000
	Sig. (2-tailed)			.
	N			8

*** Correlation is significant at the 0.01 level (2-tailed).*
** Correlation is significant at the 0.05 level (2-tailed).*

Landcover Analysis

The majority of the Soda Butte Creek watershed and its Pebble Creek and Amphitheater Creek sub-watersheds were forested, with upwards of 57% of the landcover in this category. Additionally, between 7% and 14% of the land within these drainages was occupied by burned forest. The Soda Butte and Pebble Creek drainages both contained roughly 10% mesic and 10% xeric landcover, and less than 3% undefined bare ground. A similar pattern was observed within Amphitheater Creek, where, however, 80% of the drainage was forested and 3% of the land area contains mesic landcover (Figs. 12, 16).

Figure 12. Landcover Comparison of the Soda Butte Creek Watershed and its Major Sub-Watersheds



Although landcover characteristics for both Amphitheater and Pebble Creek were significantly correlated ($p<0.01$) to those of the Soda Butte Creek watershed, a slightly greater correlation coefficient was observed between Soda Butte and Pebble Creek than between Soda Butte and Amphitheater Creek (Table 9).

Table 9. Landcover correlations between the SBCW and its major sub-watersheds

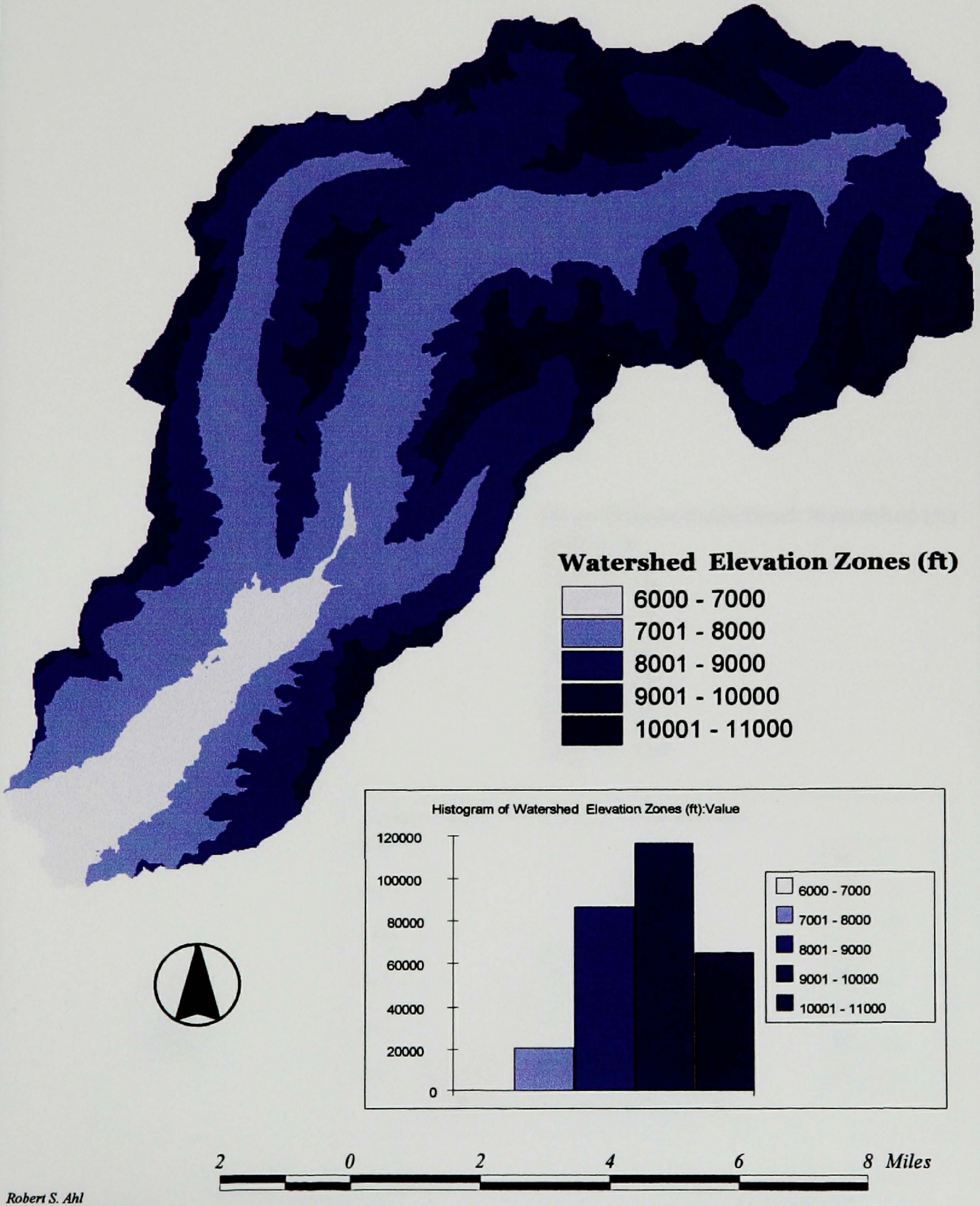
		Soda Butte Creek	Pebble Creek	Amphitheater Creek
Soda Butte Creek	*Pearson Correlation*	1.000	.995**	0.994**
	Sig. (2-tailed)	.	.000	.001
	N	5	5	5
Pebble Creek	*Pearson Correlation*		1.000	0.989**
	Sig. (2-tailed)		.	.001
	N		5	5
Amphitheater Creek	*Pearson Correlation*			1.000
	Sig. (2-tailed)			.
	N			5

** *Correlation is significant at the 0.01 level (2-tailed).*

Based on all of these analyses, I concluded that both sub-watersheds are physically very similar to the SBCW, however, the Pebble Creek drainage represents the best choice for a reference watershed. In addition to being morphometrically more similar to the SBCW than Amphitheater Creek, the Pebble Creek drainage also offered a more established and maintained trail system to facilitate research infrastructure and access requirements.

Figure 9.

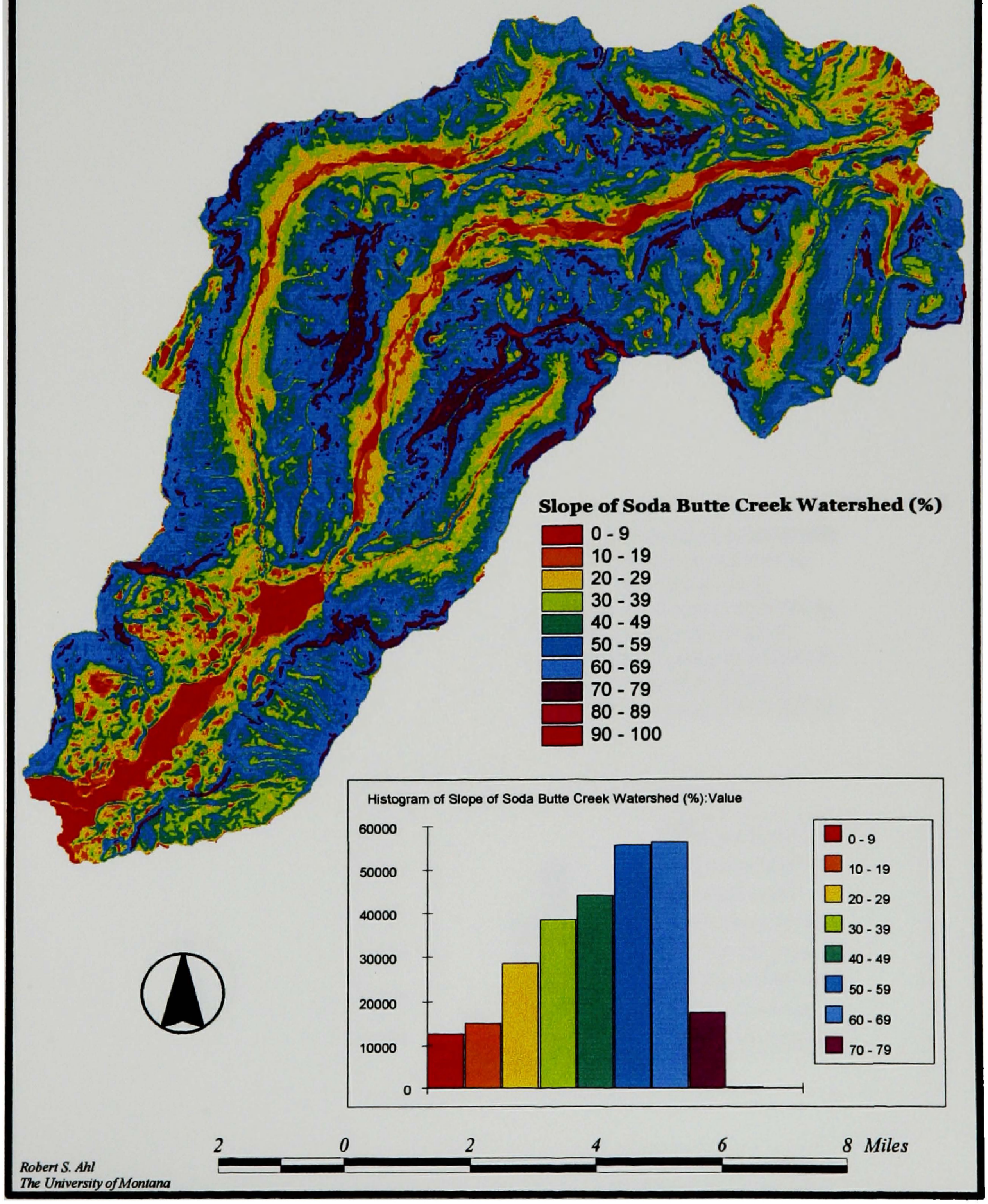
Soda Butte Creek Watershed: Hypsometric Analysis



Robert S. Ahl
The University of Montana

Figure 10.

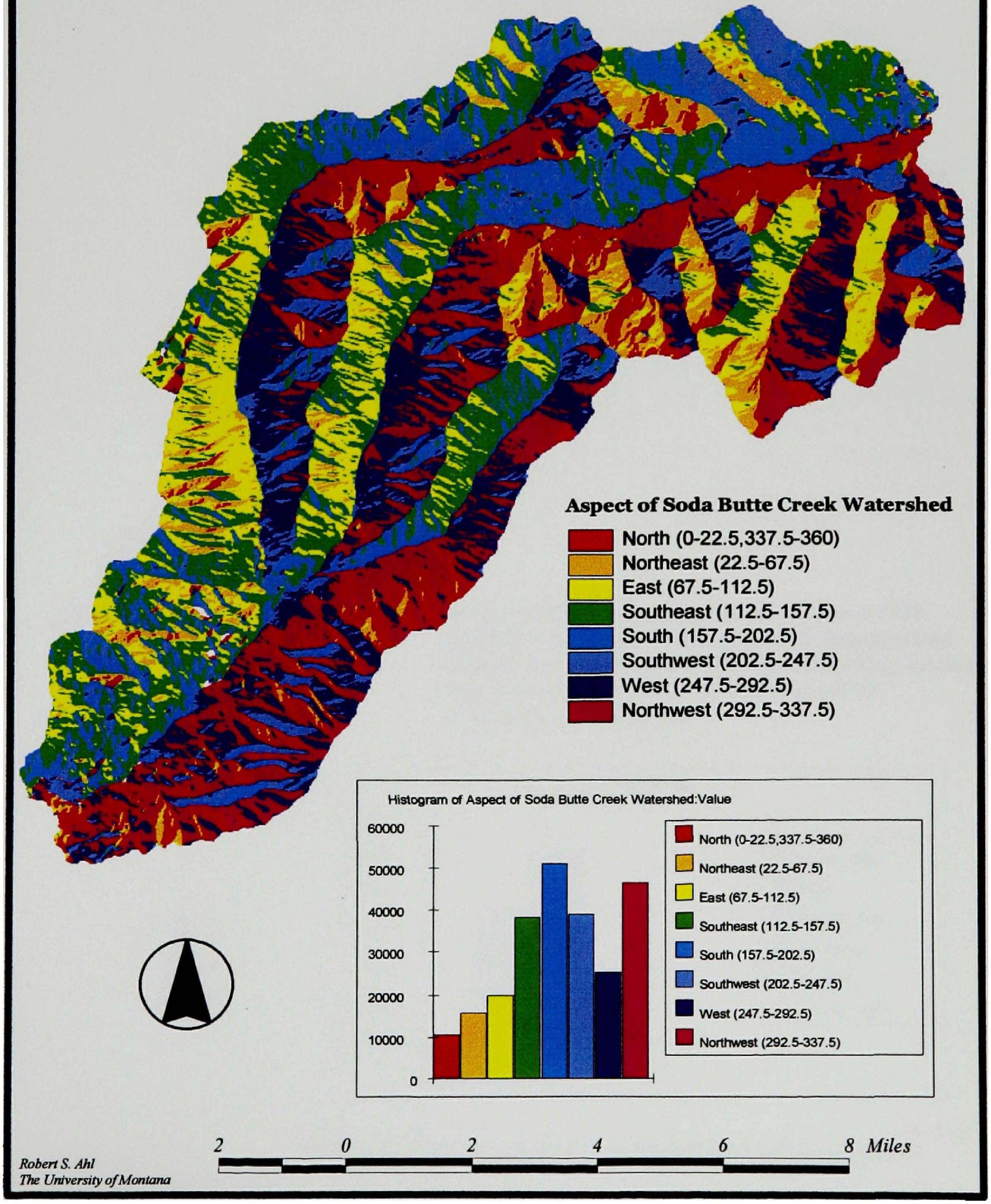
Soda Butte Creek Watershed: Slope Analysis



Robert S. Ahl
The University of Montana

Figure 11.

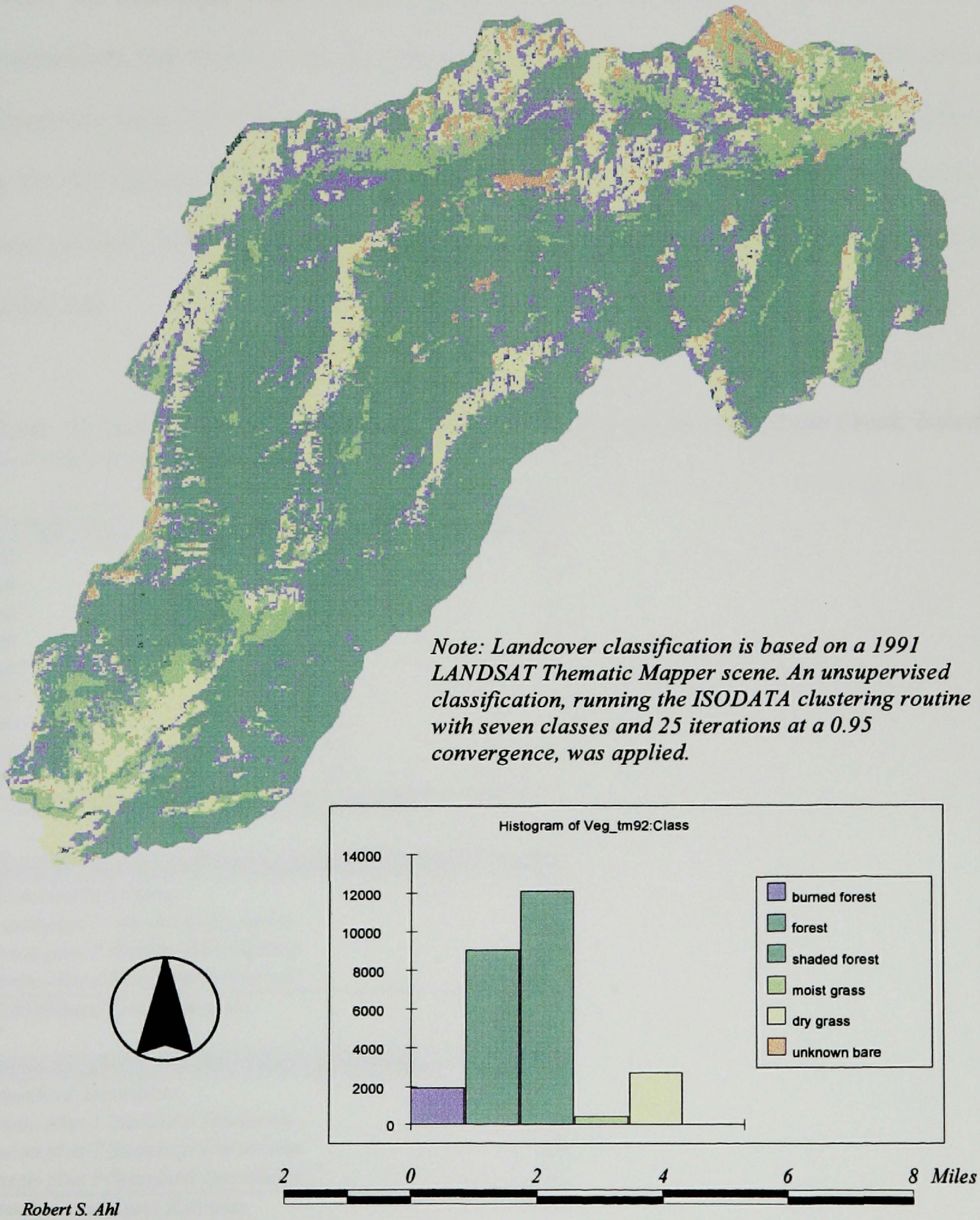
Soda Butte Creek Watershed: Aspect Analysis



Robert S. Ahl
The University of Montana

Figure 12.

Soda Butte Creek Watershed: Landcover Analysis



Note: Landcover classification is based on a 1991 LANDSAT Thematic Mapper scene. An unsupervised classification, running the ISODATA clustering routine with seven classes and 25 iterations at a 0.95 convergence, was applied.

Robert S. Ahl
The University of Montana, 1999

Natural Background Copper Concentrations

Having identified Pebble Creek as a good reference watershed, copper concentrations in sediment and biota from this control system were used to interpret those in Soda Butte Creek. At this point only sediment copper concentration values are available for comparisons, but future work may allow the comparison of copper levels in biological samples as well. These data, along with Data from this study, along with those supplied by Dr. W. Andrew Marcus, from the Department of Earth Sciences at MSU, Bozeman, were used to define a natural background copper concentration for stream sediment (Table 10).

Table 10. Natural background sediment copper levels (ppm) for Soda Butte Creek, based on Pebble Creek sediment data.

Sample Unit	Pebble Creek 98	Pebble Creek 95*
hgr	13	*13*
hgr	11	*10*
hgr	11	*12*
hgr		*12*
hgr		*12*
edz	21	
edz	12	
gld	11	
gld	10	

* *1995Pebble Cr. data from Dr. Marcus, MSU*

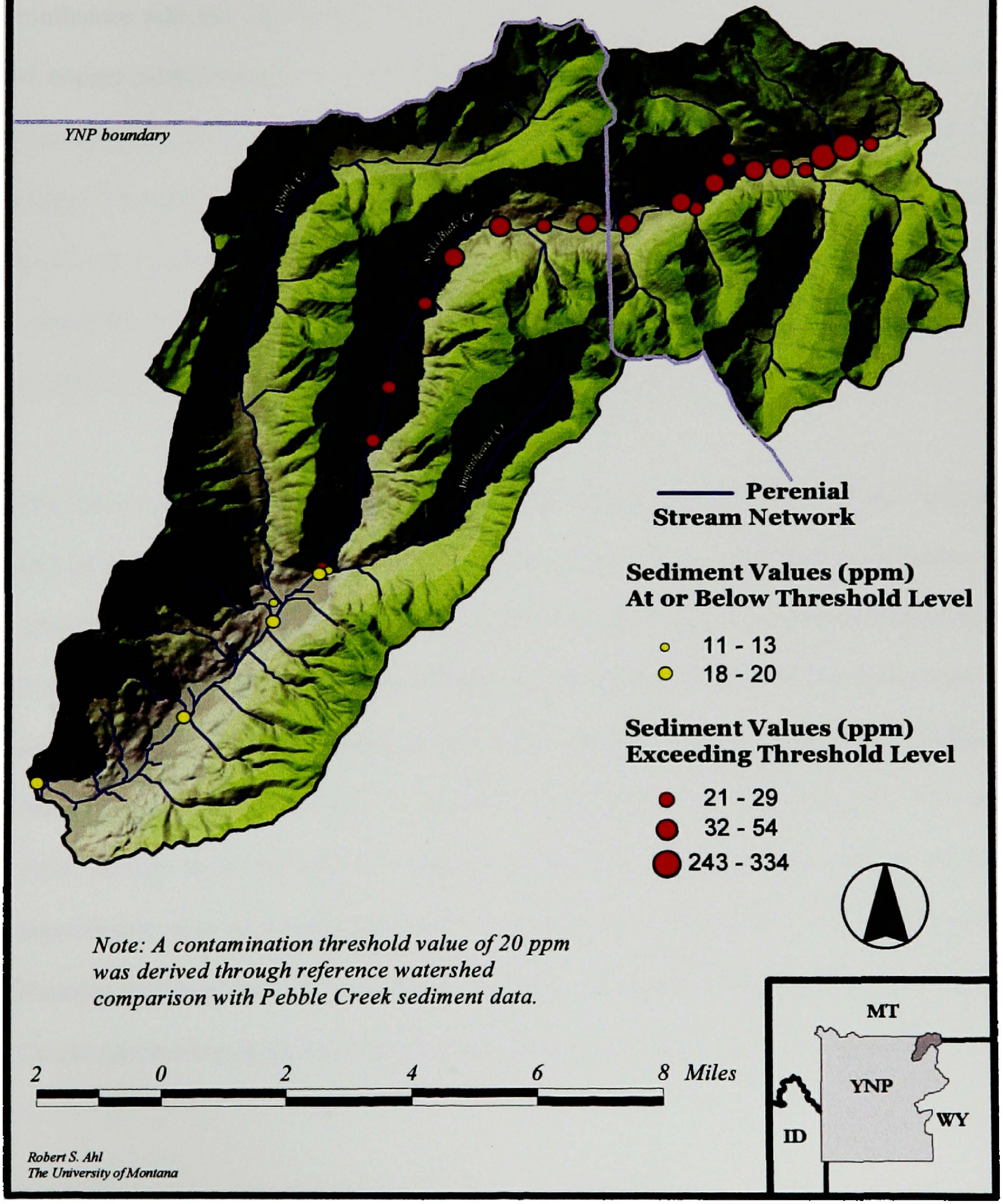
Mean of 1998 & 1995 Pebble Creek HGR data	**12**
Standard Deviation	1
mean plus 1 Standard Deviation	13
mean plus 2 Standard Deviations	14
mean plus 3 Standard Deviations	15
Background Level Estimate	15

Mean of all 1998 & 1995 Pebble Creek data	**12**
Standard Deviation	3
mean plus 1 Standard Deviation	15
mean plus 2 Standard Deviations	18
mean plus 3 Standard Deviations	21
Background Level Estimate	~20

When all sediment data, including EDZ, HGR and GLD, were averaged, the mean Pebble Creek sediment copper concentration was approximately 12 ppm, with a standard deviation of roughly 3 ppm. When only HGR sediment data were considered, the mean was also 12 ppm, but the standard deviation was only 1 ppm. I assumed the background levels could be as high as the mean plus 3 standard deviations. If only HGR sediment copper levels are considered, copper concentrations in excess of 15 ppm probably exceed background levels. This indicates that the entire length of Soda Butte Creek's mainstem, from the headwaters to the confluence with the Lamar River, HGR sediment copper levels exceed background levels. If background copper levels are estimated, based on all sediment values, then sediment copper values greater than 20 ppm exceed background levels. Such values were observed from the Soda Butte Creek headwaters downstream to Amphitheater Creek, nearly 21 kilometers downstream and 14 km into Yellowstone National Park (Fig. 17).

Figure 17.

Spatial Extent of Sediment Copper Contamination in the Soda Butte Creek Watershed, Yellowstone National Park



Note: A contamination threshold value of 20 ppm was derived through reference watershed comparison with Pebble Creek sediment data.

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SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

As part of an ongoing study of the distribution and partitioning of copper and other trace metals in Soda Butte Creek, copper concentrations were determined in stream sediments, epilithic biofilms, and macroinvertebrates collected from the creek's headwaters to its confluence with the Lamar River. In this study, I attempted to evaluate the spatial extent of copper contamination in these aquatic ecosystem components within Yellowstone National Park. The Land and Water Conservation Fund has allocated twenty two million dollars for mine site reclamation projects at the New Wold Gold Mine site. I hope this study will further the understanding of persistent mine waste impacts on high elevation temperate aquatic ecosystems, and prove useful for the identification of stream reaches for future remediation projects within and along Soda Butte Creek.

The Yellowstone ecosystem and surrounding mountains are of violent volcanic origins, and have a geologic constitution that is complex and heavily mineralized. Because of these mineral deposits, resource extraction has focused on this region. Soda Butte Creek, a major tributary of Yellowstone National Park's Lamar River, originates in what is known as the New World mining district. This area had a long mining history and has been mined, primarily for gold, since the 1870's (Marcus, 1996). Between 1933 and 1953, tailings from the McLaren gold mine were placed in an impoundment located immediately east of Cooke City, which is four miles northeast of the Yellowstone National Park boundary, in a relatively level area at the junction of Miller and Soda Butte Creeks. An inadequately constructed impoundment dam failed in late June of 1950 during an intense flood event. It was estimated that 31,000 m^3 of contaminated tailings (copper 841 - 12,600 ppm and lead 71 - 672 ppm) were deposited along the entire length of Soda Butte Creek (Meyer, 1998). Elevated copper and lead concentrations are toxic to many plants and aquatic organisms (Förstner and Wittman, 1981), and are believed to be the most likely cause of degradation of water quality and biodiversity in upper Soda Butte Creek (Meyer, 1998).

The majority of the Soda Butte Creek watershed is located above 8,000 feet. The slopes are generally steep, with greater than half of the slope distribution above a 40 degree incline. Most slope aspects face south or southwest. Abundant snow accumulated on southern aspects melts quickly, and steep slopes facilitate rapid movement of water down to stream channels.

Soda Butte Creek's hydrology is dominated by snowmelt. Peak flow coincides with spring runoff, and diurnal fluctuations are evident during early to mid summer, following mid-day snowmelt. Despite heavily forested slopes, the stream responds quickly to short, high intensity precipitation events during summer months, with rapid increases in runoff and sediment transport.

Fluvial sediment transport mechanisms influence the fate of trace metals in the aquatic environment. Copper concentrations in sediment, biofilm and macroinvertebrates generally decreased downstream from the contamination source in SBC. This downstream trend was highly significant; hence, not surprisingly, the concentrations of copper in all three components were highly correlated (possibly due to sediment contamination of the biotic compartments).

A site-by-site analysis of temporal variability in copper concentrations of HGR sediment samples revealed a decreasing downstream trend, based on data from 1994 to 1998. Sediment copper concentrations were fairly consistent across all years studied, suggesting that flooding events, of the magnitude that occurred in 1996 and 1997, have little influence on the concentration or distribution of copper concentration in HGR sediments in SBC. It appears that it would take a flood as big as the one that occurred in 1950 to change sediment copper distribution noticeably.

When Soda Butte Creek's HGR sediment copper concentrations were compared to those of its major tributary streams, it became evident that copper concentrations in the mainstem of the creek are significantly greater than those of its tributaries, Sheep Creek, No Name Creek, Amphitheater Creek and Pebble Creek. Republic Creek was excluded from this analysis because the former smelter site near its mouth disqualified it as and uncontaminated tributary.

Although it is commonly accepted that underwater sediments act as sinks for trace metals, the extent to which trace metal-contaminated sediments have an impact on aquatic organisms and their uptake and regulation mechanisms is still poorly understood (Timmermans, 1993 In Rainbow and Dallinger, 1993). While standards based on toxicological effects exist for metals in the water column, no such standards exist for metals in stream sediments and biota. The influence of elevated copper concentrations in sediments and biota is difficult to predict and is likely to be site-specific. Without such standards, comparing copper levels in ecosystem components of Soda Butte Creek to an unaltered reference system provides the most meaningful assessment of water quality and depression of biological potential.

The Soda Butte Creek watershed (SBCW) contains two major sub-watersheds, Pebble and Amphitheater Creeks, that share similar headwater and downstream environments, local geology, natural disturbance histories, landcover characteristics, drainage densities, and climatic conditions. The major difference between these two major sub-watersheds and Soda Butte Creek is that they are wholly within the national park boundary and did not experience large-scale mining, milling and smelting. These two sub-watersheds offer a local, relatively pristine reference for comparison to human-altered Soda Butte Creek.

Previous studies on Soda Butte Creek by Marcus, et al. (1995) used Pebble Creek as a reference watershed, but gave no quantitative justification for such a comparison. This study attempted to determine quantitatively if the Pebble or Amphitheater Creek sub-watersheds are good reference watersheds for Soda Butte Creek.

A comparison of landcover patterns, drainage density, hypsometric, slope and aspect characteristics of Soda Butte with those of the Pebble and Amphitheater Creeks sub-watersheds indicated that either of these drainages could serve as reference watersheds for Soda Butte Creek. When considering all the above variables, comprehensive geospatial and statistical analyses indicated that Pebble Creek is a better reference for Soda Butte Creek than is Amphitheater Creek.

Once Pebble Creek was selected as the best reference watershed, it was possible to use a previously collected longitudinal sediment dataset from Pebble Creek to derive natural background sediment copper concentration estimates standards for Soda Butte Creek.

I assumed that sediment copper levels exceeding 3 standard deviations above mean sediment copper concentrations from Pebble Creek sediment data represented contaminated levels in Soda Butte Creek. The mean plus 3 standard deviations of all existing Pebble Creek sediment data is approximately 20 ppm. However, when only Pebble Creek HGR sediment data are considered, the mean plus three standard deviations is roughly 15 ppm. Using these values as the maximum natural background levels, a geospatial model of sediment concentrations illustrated that the entire length (28 km) of the Soda Butte Creek mainstem had HGR sediment copper levels that exceeded natural background levels. Additionally, sediment copper levels in the upper 21 km of SBC were elevated above background levels estimated using all sediment environments. This contaminated zone includes 14 kilometers of stream within Yellowstone National Park. That is, Soda Butte Creek HGR sediments appear to be elevated well above natural background levels from its headwaters down to its confluence with the Amphitheater and Pebble Creek drainages, 21 kilometers downstream of the McLaren tailing impoundment.

Conclusions and Highlights

- Soda Butte Creek (SBC) is a typical snowmelt-dominated mountain stream.

- From the contamination source in the headwaters to the mouth of SBC (28 km), copper levels in sediment and macroinvertebrates dropped about an order of magnitude while levels in biofilm dropped almost as much.

- Copper levels in high gradient riffle (HGR) sediments, biofilm and macroinvertebrates were all highly correlated ($p < 0.01$) with distance downstream from the tailings impoundment. Biofilm and macroinvertebrate copper concentrations were both correlated ($p<0.05$) with sediment copper concentrations.

- Copper concentrations in HGR sediments were fairly stable over time, and seemed uninfluenced by high water runoff events of the size that occurred in 1996 and 1997. It appears that a flood event greater than these is required to change copper distribution noticeably—perhaps an event as great at the 1950 flood.

- High gradient riffle sediment copper concentrations in the major tributary streams of SBC are significantly lower than those in the mainstem of the creek. Republic Creek was excluded from this analysis because the historic smelting site disqualified it as an uncontaminated tributary.

- Geospatial and statistical analyses indicated that both Amphitheater and Pebble Creek drainages are reasonable reference watersheds for SBC. Based on all factors considered (drainage density, landcover, hypsometric, slopes, aspect, and geology), Pebble Creek is more similar to SBC than is Amphitheater Creek.

- Natural background levels for copper in SBC sediments were estimated by adding three standard deviations to the mean levels in the reference watershed, Pebble Creek. If HGR data only are considered, this yields a background value of 15 ppm. If data from all sediment environments are used, the result is in the range of 20 ppm. Based on the 15 ppm background value, SBC HGR levels are elevated along its entire length. Based on the more conservative 20 ppm value, the creek's sediments are elevated above background levels for 21 kilometers below the tailing impoundment site, including 14 kilometers into Yellowstone National Park.

- Although copper levels are elevated above background in the park, they are below levels associated with noticeable effects on macroinvertebrate communities in the mining-contaminated Clark Fork River of Montana.

Future Research and Management Recommendations

- The Pebble Creek drainage should be used as the primary reference watershed for Soda Butte Creek in future studies.

- Within site replicate samples of sediment, biofilm, and macroinvertebrates should be collected in Pebble Creek and compared to these ecosystem components in Soda Butte Creek to better assess possible biotic contamination and impairment of biotic processes. In order to determine true biotic metal concentrations, a method must be developed for correcting for sediment contamination in biotic samples.

- While contamination extends into the park, severe toxic effects from copper are likely confined to the headwaters outside the park (the potential impacts of other metals should be assessed to determine if this statement holds for them). Hence, there seems little reason to disturb the creek inside the park with removal efforts although removal actions may be reasonable in the first few km of SBC below the contamination source (i.e., outside the park). Simply attempting to seal the contamination source would just put off the problem until a large flood washes the material into the creek. Therefore, I recommend that the contamination associated with the mill and impoundment be removed from the 100 year floodplain, so that the next flood that approaches the 1950 flood could have a beneficial rather than a detrimental effect, diluting and displacing contaminated sediments in Soda Butte Creek. Once the contamination source has been removed, slow, continuous natural recovery of SBC is highly probable.

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APPENDIX I

Geospatial Data Processing

Watershed Delineation

Unrefined DEMs may have numeric errors that can act as "hydrologic sinks" and dilute the precision of delineation procedures. To treat this problem the FILL.GRID request was applied to the DEMs to smooth their exaggerated peaks and valleys. A new, filled, grid is produced. This new, filled grid was then used for subsequent analyses. Using the filled grid, flow direction of each grid cell was calculated using the FLOW DIRECTION.GRID request. A flow accumulation grid was produced. Flow accumulation for each grid cell is then calculated, using the previously created flow direction grid, by applying the FLOW ACCUMULATION.GRID request. At this point a POUR POINT is interactively selected by designating a cell on the flow accumulation grid that represents the endpoint or mouth of the desired watershed. In this particular instance, the confluence of Soda Butte Creek and the Lamar River was selected as the Soda Butte Creek watershed pour point. The WATERSHED.GRID request calculates watershed delineation by selecting all the upstream cells that "flow" into the selected pour point cell by using the slope, aspect, and downslope accumulation values derived from the flow direction and flow accumulation grids. A grid that represents a watershed, based on pour point selection was produced.

Hydrologic Modeling

A specialized Avenue Script was written that utilized the previously derived flow accumulation grid, and a user-specified flow accumulation threshold value to calculate a potential stream network. When specifying an accumulation threshold, a desired number of upslope contributing cells are entered. This implies that a certain number of upslope grid cells (30 meters x 30 meters) are required to produce a grid cell that can be considered a stream cell. For instance, when a threshold value of 100 is designated, 100 30 x 30 cells are required to have geometry (slope and aspect) that points them to a cell that can be considered a stream network cell. Stream networks utilizing 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000 upstream contributing cells were calculated. A raster linear network was produced for each stream network calculation. Using the resulting synthetic stream network grids, the STREAMORDER.GRID request was applied, specifying the Stahler method of stream ordering, where the labeling of a stream reach does not change until a steam of equal or higher order is joined (Strahler, 1957). Based on Horton's laws of fluvial geomorphology and stream bifurcation principles, and observation of the real-world stream network, the 250 (Fig. 18, 20a) contributing grid cells, and 1100 (Fig. 19, 20b) contributing grid cells were selected to represent spring runoff high flow, and late summer low flow SBCW stream networks, respectively (Horton, Geological Society of America, 1945). The raster linear network represented by the 250 and 1100 contributing cell stream network were ordered again using the Arc/Info STREAMORDER command and the Stahler ordering method (Fig 20a,b).

Once stream order was calculated, the resulting raster linear network was further converted to a vector linear network with the Arc/Info 7.2.1 STREAMLINE command. A fuzzy tolerance of 30 meters, representing the dimensions of one grid cell, was applied to the vectorization procedure. The resulting stream network database includes unique stream segment identifications, length (in meters), and stream order designations. The files were stored as Arc/Info coverages and ArcView Shapefiles.

Figure 18. Stream Order as a Function of Upstream Contributing Cells (High Flow)

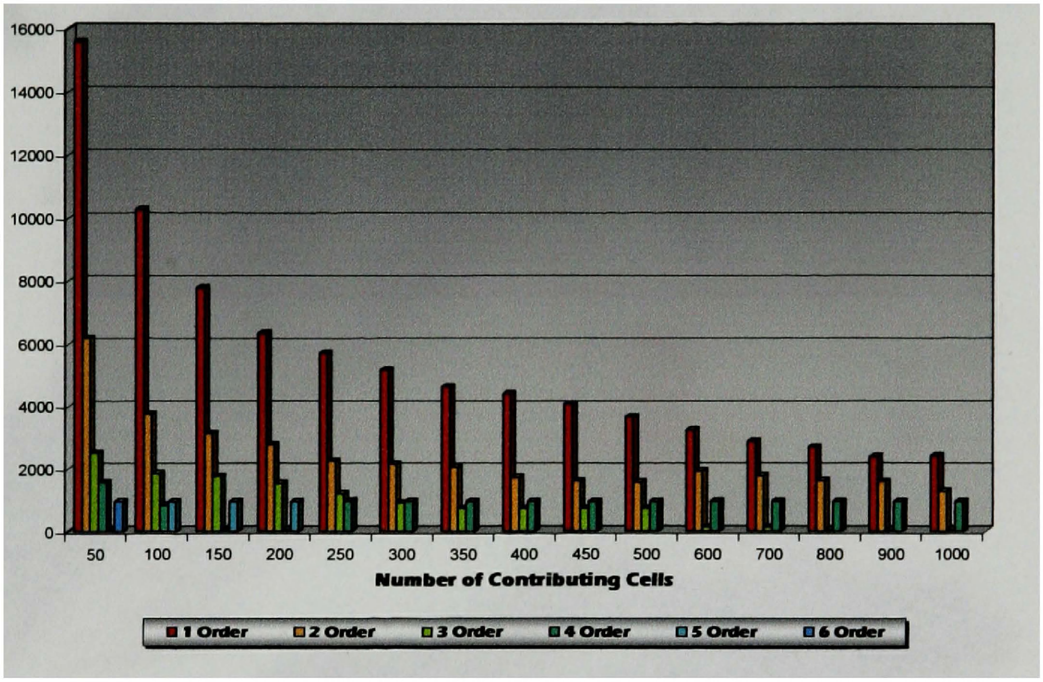
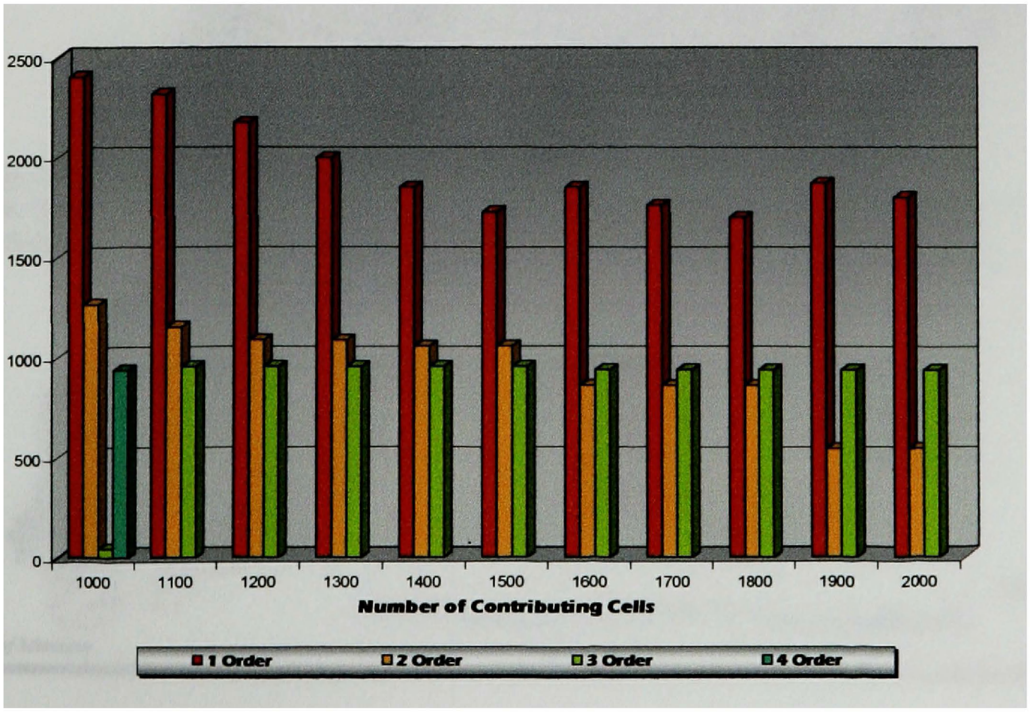


Figure 19. Stream Order as a Function of Upstream Contributing Cells (Low Flow)



Soda Butte Creek Watershed Hydrography

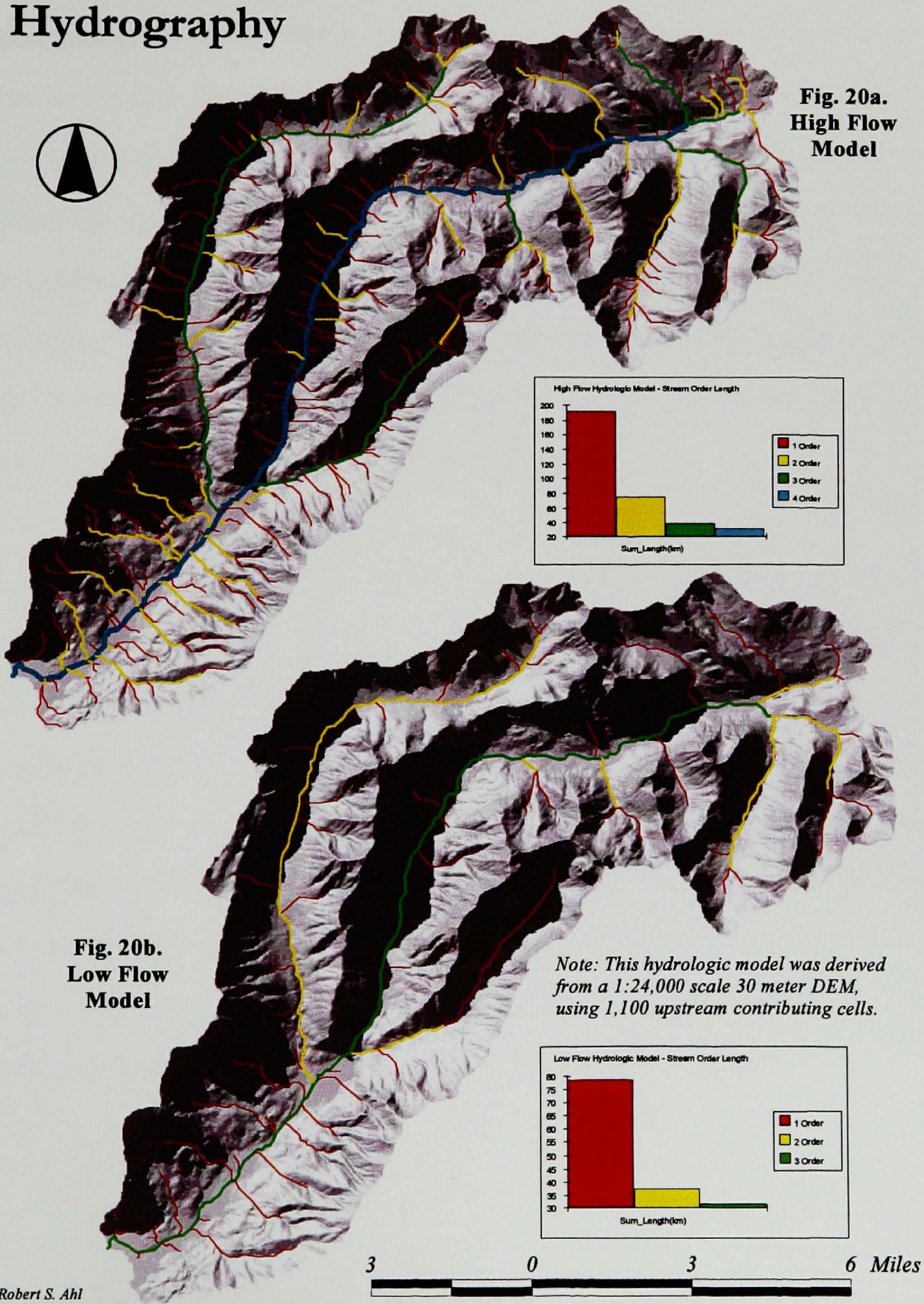


**Fig. 20a.
High Flow
Model**

**Fig. 20b.
Low Flow
Model**

Note: This hydrologic model was derived from a 1:24,000 scale 30 meter DEM, using 1,100 upstream contributing cells.

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Sample Site Point Features

A Trimble Navigation GeoExplorerII Global Positioning System receiver was used to gather point feature data. A PDOP mask of 7 was set, and on average 120 positions were collected for each sample point. The sample site name was entered as an attribute to the point feature during data collection. The resulting GPS files were downloaded from the receiver and data logger to a PC, running the Trimble Pathfinder Office, version 2.02. Uncorrected GPS files were differentially corrected by using the nearest base station data downloaded from the Montana Department of Transportation office located in Helena, MT. The differentially corrected files were converted to ArcView shapefiles, using the planar UTM zone 12, coordinate system and NAD83datum.

A point feature representing the USGS stream gauging station was also added to the geospatial data collection. The USGS web site lists the geographic coordinates of their network of gauging stations. The geographic coordinates of the Soda Butte Creek station were converted to the appropriate UTM zone 12 coordinate system and NAD83 datum, written to a text file, and added to the GIS as a point feature. To facilitate real-time stream flow data for this site, the Internet address for the Soda Butte Creek USGS stream flow web site was linked to this point feature. When this link is initiated, the internal script initiates the operator's default web-browser software, turns on an Internet connection, and opens the Soda Butte Creek USGS stream flow web site.

APPENDIX II

Hydrologic Data

Hydrologic data for Soda Butte Creek were obtained from the United States Geological Survey stream gauging station (number 06187950), located approximately 2 kilometers upstream of the Lamar River confluence. Real-time data (15 minute delay) from this gauging station can be downloaded from the website http://waterdata.usgs.gov/nwis-w/wy/?statnum=06187950. Mean daily values are archived and available at the end of every water year, along with other historic hydrologic data.

This project used data from October 1, 1988 to September 30, 1997, and mean monthly discharge values were calculated as follows:

Table 11. Soda Butte Creek mean monthly discharge values, 1988-1997

Month	1988-89	1989-90	1990-91	1991-92	1992-93	1993-94	1994-95	1995-96	1996-97	POR	SD
Jan	17	26	25	26	25	25	18	28	32	25	5
Feb	17	22	23	26	25	20	17	24	31	23	4
March	20	21	22	31	25	21	21	22	32	24	5
April	81	127	32	100	32	86	37	53	56	67	33
May	454	255	387	538	580	462	217	334	523	417	127
June	727	786	802	491	592	368	815	1249	849	742	251
July	273	330	233	241	285	106	428	447	388	303	107
Aug.	88	104	73	83	134	58	112	115	162	103	32
Sept.	50	58	59	62	63	40	66	61	92	61	14
Oct.	28	45	48	37	44	45	37	49	42	42	7
Nov.	23	33	39	29	38	30	21	40	40	33	7
Dec.	16	26	28	27	26	25	19	31	31	25	5

POR = Period Of Record
SD = 1 Standard Deviation