Channel morphology controls on the spatial distribution of trace metals in bed sediments in Soda Butte Creek, Montana
by Scott Christopher Ladd

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Channel morphology controls on the spatial variation of trace metals in bed sediments are examined in a 500 m reach of Soda Butte Creek, Montana. Sampling by a channel morphology classification system is used to determine the variation in trace metals between morphologic units, laterally and longitudinally within units, and to assess whether channel hydraulics and differential transport of sediments control trace metal distributions. The types of morphologic units sampled are low gradient riffles, high gradient riffles, glides, backwater pools, lateral scour pools, attached bars and detached bars. Ten of each type of morphologic unit were sampled. Three to nine samples were collected from each of these 10 riffles, bars, pools, and glides. Nine of 12 trace metals show significantly different concentrations in sediments smaller than 2 mm when stratified by morphologic units. Backwater pools and attached bars consistently have the highest metal concentrations, while low gradient and high gradient riffles typically have the lowest concentrations. Metals showing the greatest between unit variability are Fe, Cu, Cr, and Al, followed by Ti, Co, Ni, Mg, and V. Lateral and longitudinal variations of metals within units are not significant, and distance downstream does not show a significant linear relationship with metal concentrations. Sediment samples generally contain less than 1% organic matter. Organic content variation between morphologic units is smaller than variability due to analytical error. Higher metal levels in backwater pools and attached bars may be related to the tendency for metals to concentrate in finer sediments, while relatively high levels of some metals in high-gradient riffles may be related to the mineralogy and density of the sediments. Channel bed morphology is a useful scale at which to examine trace metal variation, and is a starting point from which to determine hydraulic parameters which control trace metal concentrations in sediments.

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Scott Christopher Ladd

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ABSTRACT

Channel morphology controls on the spatial variation of trace metals in bed sediments are examined in a 500 m reach of Soda Butte Creek, Montana. Sampling by a channel morphology classification system is used to determine the variation in trace metals between morphologic units, laterally and longitudinally within units, and to assess whether channel hydraulics and differential transport of sediments control trace metal distributions. The types of morphologic units sampled are low gradient riffles, high gradient riffles, glides, backwater pools, lateral scour pools, attached bars and detached bars. Ten of each type of morphologic unit were sampled. Three to nine samples were collected from each of these 10 riffles, bars, pools, and glides. Nine of 12 trace metals show significantly different concentrations in sediments smaller than 2 mm when stratified by morphologic units. Backwater pools and attached bars consistently have the highest metal concentrations, while low gradient and high gradient riffles typically have the lowest concentrations. Metals showing the greatest between unit variability are Fe, Cu, Cr, and Al, followed by Ti, Co, Ni, Mg, and V. Lateral and longitudinal variations of metals within units are not significant, and distance downstream does not show a significant linear relationship with metal concentrations. Sediment samples generally contain less than 1% organic matter. Organic content variation between morphologic units is smaller than variability due to analytical error. Higher metal levels in backwater pools and attached bars may be related to the tendency for metals to concentrate in finer sediments, while relatively high levels of some metals in high-gradient riffles may be related to the mineralogy and density of the sediments. Channel bed morphology is a useful scale at which to examine trace metal variation, and is a starting point from which to determine hydraulic parameters which control trace metal concentrations in sediments.

CHAPTER 1

INTRODUCTION

The contamination of aquatic sediments poses a direct threat to water quality, benthic fauna and flora, and organisms which feed in the aquatic environment (Marcus 1991). Sediments can carry as much as 99% of the contaminant load of a stream, with the remaining 1% carried in solution (Salomons and Forstner 1984). For this reason there is a need to understand the transport and storage of trace metals in stream sediments.

Hydraulic controls on the spatial variability of heavy metals in sediments are one of the least understood mechanisms of concentration. Hydraulic mixing of metals in sediments decreases concentrations downstream from the pollution source at watershed scales, due to dilution from "clean" tributary sediments (e.g., Wolfenden and Lewin 1978; Graf 1985; Marcus 1987). However, bedload transport can sort sediment containing heavy metals by size, shape and density at local scales (Horowitz 1985), creating great variability in bed sediment metal content from site to site (Graf et al. 1991). With the exception of metals in heavy minerals, however, few studies have examined the spatial distribution of trace metals in stream sediments at reach scales over distances of 1 m to 1 km.

The content of organic matter, which often positively correlates with metal levels in stream sediments, is another important but poorly understood factor affecting the spatial variability of metal concentrations. The ability of organic matter to physically and chemically concentrate metals in sediments varies with metal, composition and amount of organic matter (Swanson et al. 1966; Saxby 1969; Rashid 1974) and grain size (Kuenen 1965; Forstner and Wittmann 1979). However, few studies have examined the transport and deposition patterns of Fine Particulate Organic Matter (FPOM < 2 mm) or the degree to which the spatial variation in FPOM controls trace metal concentrations within sediments at the reach scale.

Documenting and understanding metal concentrations in sediments over reach scales is critical for: (1) developing sampling criteria for environmental and geochemical studies; (2) understanding variations in reach scale environmental impacts; and (3) targeting portions of streams for remediation. Likewise, documentation of the spatial variability in FPOM in stream sediments is critical to understand metal distributions and environmental impacts.

The goal of this study is to determine the role of channel morphology in controlling trace metal and FPOM distributions in bed sediments at scales of 1 m to 500 m in Soda Butte Creek, Montana. Bedform scale channel morphology

(e.g., pool or riffle) is largely determined by hydraulic factors (Schumm and Lichty 1965), so hydraulic controls on trace metal distributions are hypothesized to be reflected through a hydraulically-based morphologic classification system. The system used is a modified bedform scale channel morphology classification system based on Bisson et al. (1982) and Church and Jones (1982). This system was tested for its ability to explain the local variations in trace metal and FPOM concentrations. The two objectives of the study are to: (1) document the local spatial variation of trace metal and FPOM concentrations in bed sediments within and between morphology units in a reach; and (2) test the ability of the morphology classification system to portray local variations of trace metal and FPOM concentrations within a reach.

Previous Studies

Previous studies have shown that metal and FPOM concentrations vary spatially as a function of chemistry, grain size, and hydraulics. The following sections discuss previous research, with an emphasis on hydraulic controls on the spatial variability of metal and FPOM distributions at reach scales.

Much research on trace metal distributions in streams has focused on describing downstream dispersion over many kilometers (e.g., Lewin et al. 1977;

Yim 1981; Graf 1985; Higgins et al. 1987; Marcus 1987) to assess watershed-wide response to contaminant input. These studies have typically documented downstream decreases in metal concentrations from a metal source due to dilution mixing from tributaries (Lewin et al. 1977; Wolfenden and Lewin 1978; Yim 1981; Marcus 1987) or from changes in geochemical factors that put metals in solution (Moore et al. 1991). However, few studies have examined the variability in metal concentrations at the reach scale.

The Role of FPOM

Most attention on the controls of metal concentrations has been given to the metal-scavenging ability of organic matter (e.g., Saxby 1969; Gibbs 1973; Stoffers et al. 1977; Singer 1977; Nriagu and Coker 1980). Due to its large surface area, high cation exchange capacity, high negative surface charge, and physical trapping (Horowitz 1985), organic matter can concentrate as much as 10 percent of its dry weight in metals (Swanson et al. 1966).

However, recent studies in estuaries (Marcus et al. 1993) and in coarse-grained rivers (Moriarty et al. 1982; Haschenburger 1989; Graf 1991) have suggested that at lower organic contents (< 3.5%), organic matter may not appreciably affect metal concentrations. The ability of organics to concentrate

metals depends on the metal, type and amount of organic matter, and the level of decomposition (Horowitz 1985; Forstner and Wittmann 1979). Organic matter can act as a diluent in areas highly polluted by metals, such as near tailings heaps and mine adits (Forstner and Wittman 1979). Other studies have found that highly variable geochemical factors near pollution sources can control metal sorption to sediments, while organic matter plays a less important role in concentrating metals (Forstner and Wittman 1979; Salomons and Forstner 1984).

The transport and storage of metal-scavenging FPOM at reach scales has received little attention, although FPOM concentrations in streams have been attributed to hydraulic controls at bed morphology scales (Sedell et al. 1978; Beschta et al. 1981) and to changes in ecosystem metabolism at reach and system scales (Vannote et al. 1980; Minshall et al. 1992). These studies showed that size, shape, and density of particulate organic matter were important variables in entrainment and deposition processes, with FPOM typically deposited along with fine inorganic sediments. Although studies suggest that the deposition of organics at local scales can be related to channel retention characteristics, such as large woody debris, boulders, interstitial space, and bed roughness Sedell et al. 1978; Speaker et al. 1984), there is no previous work that has

quantified the differences in FPOM concentrations between or within depositional environments.

Geochemical Controls on Local Spatial Variability

For the purposes of this study, an important issue is whether geochemical factors can affect the spatial variability in metal concentrations between morphologic units at reach scales. At scales of 1 m to 500 m, most studies have documented closely spaced changes in metal concentrations immediately downstream of tailings and mine adits where rapid changes in pH and dissolved oxygen content occur (Forstner and Wittmann 1979; Salomons and Forstner 1984; Rampe and Runnells 1989). However, at distances greater than 0.5 km from metal sources, the literature does not describe local variability in concentrations due to geochemical factors. Studies have shown that variability in geochemical factors affecting metal concentrations are often related to grain size (Brook and Moore 1988; Moore et al. 1989; Whitney 1975), which can vary between morphologic units. Metal-scavenging Fe and Mn oxides have been shown to positively correlate with grain size in gravel bed streams (Whitney 1975; Moore et al. 1989). In general, however, existing literature suggests that local variability of metal concentrations may be more related to turbulence and local

hydraulics than to geochemistry (Graf et al. 1991; Moriarty et al. 1982).

Grain Size Controls on Metal Concentrations

Increasing trace metal concentrations have often been attributed to decreasing grain size, because smaller particles have a greater surface area per volume of sediment (e.g., Whitney 1975; Gibbs 1977; Forstner and Wittman 1979; Jenne et al. 1980; Ackerman 1980; de Groot et al. 1982; Salomons and Forstner 1984). This accentuates the adsorption process because smaller grains: (1) provide a greater surface area per unit volume to which metals can bond (Jenne 1976); and (2) have a higher cation exchange capacity than larger grains (Horowitz 1985).

Most studies of grain size controls on metals have been conducted in low gradient fluvial environments containing fine sediments. In coarse grained rivers, studies have shown that concentrations of metals sometimes increase with grain size up to the sand and fine gravel fraction. This can be due to the presence of more metal scavenging iron and manganese oxides in these fractions (Whitney 1975; Moore et al. 1989) or because of coarse metal rich mine waste or coarse detrital heavy minerals in the watershed (Wolfenden and Lewin 1977; Moriarty et al. 1982). Conversely, Graf et al. (1991) found that in a coarse grained

ephemeral stream the concentrations of some metals increased with decreasing sediment size due to the fine-grained nature of the tailings metal source. At present, existing literature does not support the concept of a consistent relationship between grain size and metal concentrations in coarse grained streams.

Hydraulic Controls on Metal Concentrations

Channel hydraulics and differential transport of sediments have been identified by many authors as important controls on the spatial variability of trace metal concentrations in streams. Heavy metals in sediments have been shown to vary with fluvial processes, which differentially sort sediments containing metals over distances of 1 m to 100 m (Moriarty et al. 1982; Haschenburger 1989; Graf 1990; Graf et al. 1991). Local variability in metal concentrations in sediments occurs both between depositional environments (Moriarty et al. 1982; Haschenburger 1989; Graf 1991; Moore et al. 1991) and within them (Wolfenden and Lewin 1977; Nimick and Moore 1991).

One reason hydraulics control spatial variability of metals is because metal concentrations vary with sediment size. In active channel sandbed environments, sediment sorting may create metal levels an order of magnitude different between

sites only meters apart (e.g., Wolfenden and Lewin 1977; Nimick and Moore 1991; Graf et al. 1991). Hydraulic factors often control the local scale spatial variability of metals, while geochemical processes play a secondary role by changing metal distributions in emplaced sediments.

Both density and size of sediments play an important role in hydraulic sorting. Spatial variability of heavy mineral ($\geq$ 3.5 g cm^{-3}) concentrations at a local scale in channels was first noted in research on placer development in sand and gravel bed streams. Although not explicitly addressing trace metals, metals are often associated with heavy minerals.

Transport and deposition processes have been shown to concentrate heavy minerals at bed (1 m) scales. The importance of voids in accumulating heavy minerals within framework clasts in gravel beds has been emphasized, as flood waters recede and large pavement clasts trap the dense sediments (Slingerland 1984; Frostick et al. 1984; Kuhnle and Southard 1990; Day and Fletcher 1991; Hattingh and Rust 1993). Zones of flow separation and associated hydraulic conditions are thought to control heavy mineral distributions at scales ranging from individual grains to individual bed forms (Best and Brayshaw 1985) . Spatial variations in heavy minerals have been documented within depositional environments between the trough, topset and the dune face in

sandbed streams (Sayre and Hubbell 1965; Brady and Jobsen 1973).

Other studies indicate channel hydraulics cause heavy minerals to concentrate differently at channel morphology scales. Variability in heavy minerals has also been documented in channel bends, scoured pools, and wide channel sections (Crampton 1937), between erosion areas and sedimentation zones (Wertz 1949), between active channel, bedrock bar, alluvial islands, alluvial fill and bedrock terraces (Adams et al. 1978); and between riffles and pools in meandering channels (Sayre et al. 1963; Schumm et al. 1987). Work by Schumm et al. (1987) shows that hydraulic variations concentrate heavy minerals in: (1) scour holes at channel confluences; and (2) bars and channel breaks.

Studies on placer development have also documented heavy mineral variability at system-wide scales. In general, heavy minerals are often deposited where tractive force and fluid velocities decrease due to abrupt changes in channel geometry, such as at channel junctions and areas of valley widening (Wertz 1949; Mosley and Schumm 1977; Slingerland 1984; Best and Brayshaw 1985; Slingerland and Smith 1986; Schumm et al. 1987).

Compared to research on heavy minerals in sand and gravel bed streams, little work has focused on characterizing differences in trace metal accumulation between channel morphologic units in cobble bed streams. Local scale

variability in metal concentrations has been documented between bars, sloughs, and main channel deposits in ephemeral streams (Graf et al. 1991), between riffle environments (Moriarty et al. 1982), and between topographic features such as point bars, channel fills, ridges and swales (Wolfenden and Lewin 1977). These studies typically attribute metal segregation at scales of 1 m (Wolfenden and Lewin 1977; Graf et al. 1991) to 1000 m (Wolfenden and Lewin 1978; Moriarty et al. 1982) to the effects of variations in channel hydraulics and tractive force on grain sorting.

Studies on the variability in metal levels within depositional units in cobble bed streams is even more sparse, although Moriarty et al. (1982) found that metal levels across channel transects within riffles were not significantly different. Wolfenden and Lewin (1977) showed that metal concentrations within a single floodplain sedimentary unit ranged up to 3 times the level of adjacent sites 1 m apart within a 5 by 5 m grid. Moore et al. (1989) showed that metal concentrations within equal aged floodplain deposits vary by up to 3 orders of magnitude at sites several kilometers apart. However, neither of these studies addressed representative sampling issues. Although little work has addressed within-depositional unit variability in channels, investigations on placers and

floodplain deposition suggest that variations caused by hydraulics are likely substantial.

Gaps in Understanding

Research on metal distributions in stream sediments has documented the presence of local scale variability, but with the exception of heavy mineral transport, work has not quantified the degree of variability within and between morphologic units or depositional environments at the scale of 1 m to 100 m. Likewise, the spatial variability of FPOM in coarse streambeds has not been well established. Investigators have avoided attempts to characterize metal variations within a stream reach, partly due to the time and cost necessary for a dense sampling effort and partly due to the emphasis on watershed-wide dispersion of metal contaminants. Quantification of trace metal variability at the scale of the individual depositional unit is needed to adequately portray and sample metal concentrations in a stream reach and evaluate their environmental impacts.

CHAPTER 2

STUDY AREA AND METHODS

Study Area

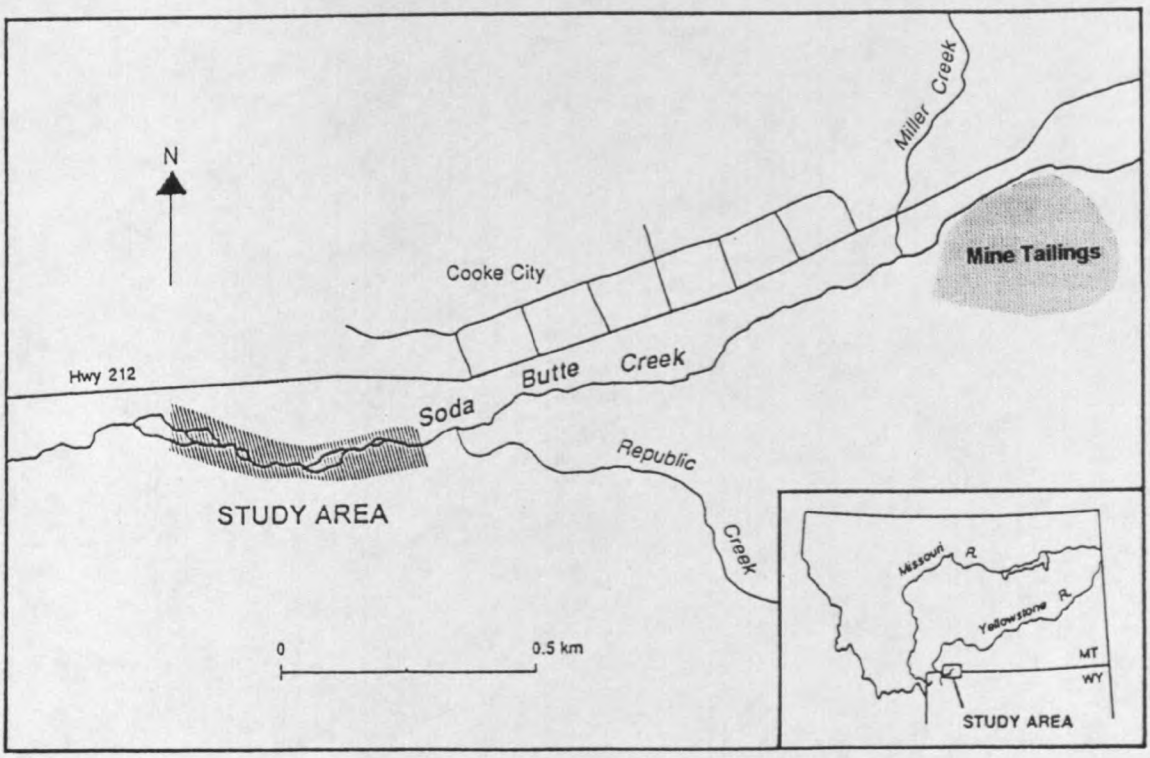
The study area is on Soda Butte Creek, a third order cobble and gravel bed stream 0.5 km southwest of Cooke City, Montana (Figure 1). Soda Butte is a tributary of the Yellowstone River system, draining the Beartooth and Absaroka Mountains. The New World Mining District at the headwaters of Soda Butte Creek contributes trace metals to the stream (Meyer 1993).

A 500 m reach (Figure 1) was selected for sampling based on a survey of aerial photographs, topographic maps and field reconnaissance. The study reach had a complex hydrology where a maximum number of different morphology units could be sampled and had no tributaries which could alter metal concentrations. The reach was also close to a metals source (a tailings pile), where morphologic controls could be analyzed with a strong metal signal.

Soda Butte's channel has a laterally unstable "wandering" bed in the study reach. The channel is sometimes irregularly sinuous and sometimes split with channel islands and braids (Plate 1). The width of the active channel ranges from

approximately 7 m where confined, to 150 m in braided sections. Bed sediment size varies with morphology, ranging from loose deposits of clay, silt, and sand to well-armored gravel and cobble deposits. Bed gradients range from 0 to 4% and vary with morphology. Coarse woody debris is present in the channel, altering sediment deposition patterns and morphology. The upstream portion of the study reach is approximately 300 m downstream from the confluence of Republic Creek, and is approximately 1 km downstream from a tailings pile.

Figure 1. Map of the study area on Soda Butte Creek in southwestern Montana.



Elevations in the watershed range from 1671 m to 3569 m, while the study area is at 2370 m. The upper part of the basin, which includes the study area, lies in a subalpine forest within the Gallatin National Forest, while the lower part of the basin lies within Yellowstone National Park. Total precipitation in the study area averages 64 cm annually (SCS 1994), with more than 180 cm received at higher elevations (Pierce 1979). Much of Soda Butte's flow originates from spring and summer melt of the 400 cm plus of average annual snowfall (Pierce 1979). Sampling was conducted in late August at low flow when the discharge was approximately 1.5 m^3s^{-1}.

Soda Butte's Holocene alluvial deposits are underlain by Pleistocene glacial till, which overlies heavily mineralized Paleocene plutonic rock and Precambrian granitic gneiss, schist, amphibolite and quartzite (Elliot 1979). Upland bedrock contributing sediments to the study area consist primarily of complex Eocene volcanics (Elliot 1979), with occasional clasts from upstream metamorphic and sedimentary rocks.

The headwaters of Soda Butte Creek have been heavily mined since gold was discovered in the Cooke City area in 1869. From 1870 to 1967 approximately 150,000 cubic meters of waste material was deposited 1 km upstream from the study area at the McLaren tailings pile in the Soda Butte valley

(Figure 1), which was also the site of an ore processing smelter for gold, lead, silver and zinc during that time (EPA 1994). Although stabilization of the tailings site was attempted in the 1960s and from 1988 to 1991 (EPA 1994), the tailings continue to contribute trace metals to the stream (Meyer 1993). Other historic mining operations in the headwaters of Soda Butte Creek potentially contribute metals to the stream, including the Republic Smelter adjacent to Republic Creek. In addition, visible fine grained tailings accumulations exist in the floodplain, which may be re-entrained by the stream at high flow.

Portions of the watershed have also been disturbed by forest fire, most recently in 1988. Initial evidence from the adjacent Cache Creek watershed (Minshall et al. 1989) suggests that Soda Butte may be experiencing an influx of particulate organic matter from the flushing of resultant burned and decaying woody debris.

Methods

Morphology Classification System

Samples were collected within seven different types of morphologic units to document metal and FPOM distributions at the reach scale. This sampling

strategy allowed an assessment of within-unit and between-unit variability.

The seven types of morphologic units, modified from systems proposed by Bisson et al. (1982) and Church and Jones (1982), were identified and sampled in the study reach (Plate 1). The modified habitat classification proposed by Bisson et al. (1982) was used because: (1) units represent clearly different and identifiable hydraulic and sediment depositional environments; (2) the classification was developed for small (third order or smaller) forested mountain streams (Bisson et al. 1982; Frissell et al. 1986); and (3) it is widely used by the U.S. Fish and Wildlife Service and U.S. Forest Service for habitat classification in streams. Inspection of the study area showed that five Bisson-defined morphologic units were present: lateral scour pools, backwater pools, glides, low gradient riffles (< 1% slope), and high gradient riffles (1-4% slope).

In addition, samples were collected from two types of bars as defined by Church and Jones (1982). Bars are not incorporated in the standard Bisson et al. classification. The system proposed by Church and Jones (1982) includes two broad categories of depositional zones for gravel bed channels: (1) bank-attached bars (i.e., point, diagonal, lateral); and (2) detached island bars (i.e. crescentic, longitudinal, transverse, medial). More complex bar forms (ASCE 1966; Allen 1968; Church and Jones 1982) are poorly developed in the study

area and thus were not delineated.

Description of Classification Units

Although any one type of morphologic unit varies in appearance, units are relatively easy to visually identify in the field at low flow based on shape, size, and water surface characteristics. Examples of morphologic units are illustrated in Figure 2.

Lateral scour pools are identified by bed and bank scour created by flow that is diverted against a stable bank (Figure 2a). Although they often have the highest velocity, deepest water and contain the thalweg, these units normally span only a portion of the channel width. Lateral scour pools tend to have a great deal of lateral variability in sediment size.

There is typically a transition from the tails of lateral scour pools into shallow, fast flowing, low turbulence glides. Glides are most easily identified by the smooth, "glassy" appearance of the water surface (Figure 2b).

Flow in the lee of an obstruction, such as large woody debris, boulders, or bank outcrops, often form a backwater pool (Figure 2c). A slow eddy current typifies this unit, which characteristically contains fine particles. An arbitrary minimum size of 4 m^2 was used to classify backwater pools, to distinguish them

Figure 2. Photographs illustrating examples of morphologic units in Soda Butte Creek. (a) Lateral scour pool. (b) Glide. (c) Backwater pool. (d) Low gradient riffle. (e) High gradient riffle. (f) Attached bar. (g) Detached bar.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

from micro scale "pocket pools," formed by smaller eddy currents. These pocket pools were not sampled because they reflect hydraulic conditions at scales less than 1 m and there were too many to sample given the research budget.

Low gradient riffles are the largest units, normally spanning the entire width of the channel and often extending for tens of meters. They usually have turbulent flow and sediments up to cobble size (Figure 2d). A survey of 15 sites indicates that low gradient riffles typically have bed gradients less than 1%.

High gradient riffles usually occur at the tail of sediment accumulations, contain emergent cobbles, and exhibit shallow and turbulent flow (Figure 2e). High gradient riffles typically have bed gradients between 1 and 4% and are

dominated by gravels and cobbles. An arbitrary minimum length of 5 m was employed to distinguish high gradient riffles from shorter riffles, which were not sampled because they reflect hydraulic variations at scales less than 1 m and because of budget limitations.

Attached bars were defined as active depositional zones (areas above water lacking vegetation) where at least one side of the unit was attached to the bank (Figure 2f). Detached bars were islands of active alluvium with channel flow around them (2g).

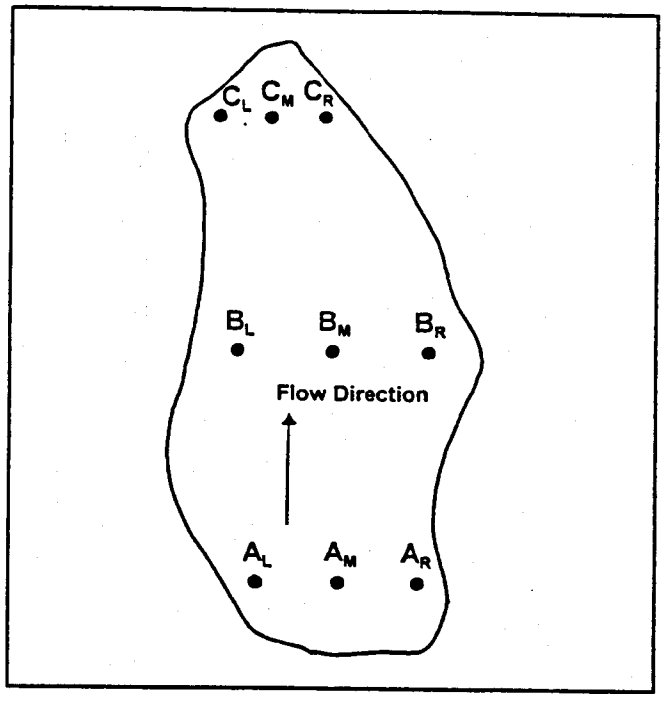
Field Sampling

The effects of geochemical factors were excluded from the study through site selection and timing of sample collection. The study area chosen is: (1) far enough from the tailings so that there is a relatively constant geochemical environment; and is (2) approximately 150 m downstream of the nearest tributary, to avoid changing pH and dilution effects due to tributary influences. Samples were taken at low flow within a period of one month to avoid major temporal changes in water and sediment chemistry. A preliminary survey suggests that changes in pH and temperature did not occur in the study reach during the sampling period (Marcus pers. comm. 1995).

Sample locations were first stratified by morphologic unit. Ten of each type of morphologic unit (e.g., 10 glides, 10 backwater pools, etc.) were sampled to determine variations in trace metals and FPOM in bed sediments within units and between units (Plate 1). Three composite samples were obtained from 7 of each type of unit (e.g., from 7 backwater pools) to determine the variability of trace metal and FPOM concentrations in the downstream direction within each type of unit and the variability between units. The composite samples were taken systematically from three transects at the head of the unit, in the middle of the unit, and at the tail of the unit (Figure 3). Each of the transects ran perpendicular to the dominant streamflow. Each composite consisted of a sediment scoop taken at the two ends of the transect and one scoop from the middle.

In addition, nine uncomposited samples were taken from three of each type of unit (e.g., from 3 backwater pools), to determine the variability of trace metal concentrations perpendicular to the stream flow (laterally) within each unit. The approximate location of sample sites were chosen so that equal spacing was maintained between the three transects and between sample points within each transect (Figure 3). The ends of the transects were located as close as possible to the edge of units without inadvertently sampling other units.

Figure 3. Sample collection points within a morphologic unit.



The exact position of sample points along each transect was chosen by setting the sampling cylinder on the bed while looking to the side. This approach avoided biasing the samples by sampling areas where fines accumulated locally. Average longitudinal distances between samples transects (e.g., between A and B, and between B and C) range from 1.4 m in backwater pools to 12.9 m in low gradient riffles (Table 1). Average lateral distances between sample points (e.g., between C_r and C_m in Figure 3) within transects ranged from 0.4 m in lateral scour pools to 2.1 m in low gradient riffles (Table 1).

Table 1. Sample spacing.

	Longitudinal Distance (m) Between Sample Transects in Each Type of Unit		*Lateral Distance (m) Between Sample Transects in Each Type of Unit*	
	Average	Range	Average	Range
LGR	12.9	4.0 - 35.0	2.1	0.9 - 4.1
AB	6.5	1.2 - 17.7	1.2	0.4 - 3.2
HGR	5.0	2.3 - 10.5	1.7	0.6 - 3.2
DB	4.3	1.2 - 10.0	1.3	0.6 - 3.2
LSP	3.4	1.3 - 7.2	0.4	0.3 - 0.6
G	2.4	1.0 - 5.4	1.4	0.7 - 2.3
BP	1.4	0.6 - 2.2	1.0	0.5 - 1.6
	n = 19	*n = 19*	*n = 16*	*n = 16*

Sediment was sampled through a 20 liter bucket with the bottom removed. The bucket was driven by hand into the bed and protected the sediments from being washed away by the current when scooping out sediments.

A 125 ml plastic scoop was used to obtain bed sediment samples from within the cylinder. After removing the surface armor of cobbles and gravels, approximately 375 ml of sand size and smaller sediments were removed at each sample site from the top 5 to 10 cm of the bed. Sampling these surface sediments allowed for analysis of metal and FPOM concentrations of recent fluvial deposits. After scooping, the sediments were placed in a plastic bowl and held still for 10 to 20 seconds so suspended particles could settle before excess

water was decanted from the bowl. Sediment samples were stored in plastic bags and kept frozen at -20°C until dried.

Despite the carefully designed sampling strategy, some fine grained sediments were washed away during sampling. To estimate sediment disturbance and possible differential loss of fine particles and the effects of loss on metal concentrations, ten 500 ml water samples were taken from inside the cylinder after bed sediments were sampled at one high gradient riffle and one backwater pool. These units were chosen because they represented worst cases for fine grained sediment loss. Suspended sediment loss was then calculated based on the volume of water in the bucket at the time of the sampling (Table 2). Sediment loss as a percent of the total sample weight averaged 0.86%, with the exception of one unusually turbulent and high velocity site which was not representative of any of the other 630 sample sites. Preliminary analysis of metals within size fractions in the study area indicate that the silt-clay fractions never contain more than 1.32 times the metal level of other fractions (Marcus pers. comm. 1995). Ignoring the one extreme example of sediment loss, the worst case scenario is a sediment loss of 2.14%, with silt-clay containing 1.32 times the metal concentration of other size fractions. This is not likely to have changed overall metal concentrations in the bulk sample by more than 0.68%.

Therefore, it is very unlikely that a differential loss of sediment through suspension resulted in any significant change in metal concentrations.

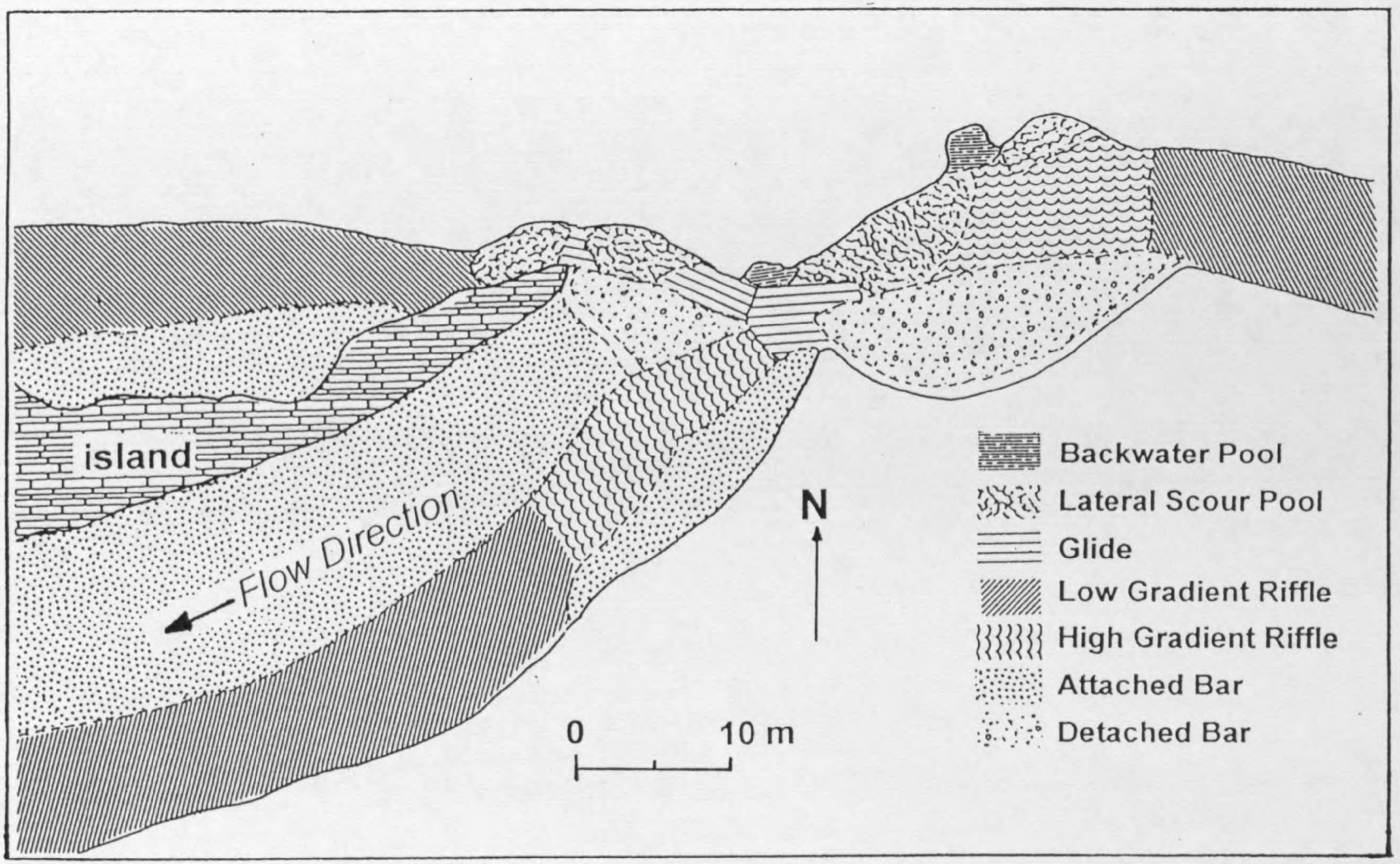
Table 2. Suspended sediment loss from sampling method; 500 ml water samples.

Sample Site	Suspended Sediment, mg/liter	Lost Sediment Weight, g	Sample Lost to Suspension, %
9-HGR-BM	30	0.42	0.12
9-HGR-BR	90	1.35	0.36
9-HGR-CL	90	1.80	0.44
9-HGR-CM	4280	85.60	40.96
22-BP-AM	405	6.08	1.82
22-BP-AR	290	4.35	1.30
22-BP-BL	135	2.30	0.57
22-BP-BR	90	1.53	0.38
22-BP-CM	125	2.00	0.57
Mean*	184	3.10	0.86

*Sample 9-HGR-CM omitted from means because unusually high turbulence and velocity made this site unrepresentative of losses encountered at any other sample site.

Units were mapped with pace and compass techniques. The width of the B transect, the total length, and the distances between the A, B, and C transects were also measured. An azimuth of the dominant direction of stream flow was taken for each site with a Brunton compass with accuracy ± 1 °. These measurements were used to construct Figure 4 and Plate 1, which illustrate the

Figure 4. Map of a 100 m portion of the study area on Soda Butte Creek.



spatial relationships between morphologic units.

Laboratory Methods

Samples were dried at 35°C and then dry sieved through a stainless steel screen. The 2 mm (very coarse sand) and finer fraction was retained for metal analysis. A 1 g subsample was taken from each sample for inductively coupled plasma--optical emission spectrometry (ICP-AES) analysis for 32 elements by Chemex Labs, Inc. (Vancouver, Canada). This procedure used an aqua regia acid (three parts hydrochloric to one part nitric acid) for leaching of metals from particles and provided detection limits to 1 ppm for most elements. Leaching with aqua regia provides a partial extraction of elements from particles, digesting only secondary minerals and sulfur compounds but not silicate structure (Agemian and Chau 1976). Results therefore reflect elemental composition for fine particles and outer surfaces of larger particles, which are the most critical to the environment in terms of availability. Thirty replicate samples (14% of total) were analyzed to test precision, and were generally within $\pm$15% of the original samples for most metals. The importance of variations in replicate samples is discussed in more detail in the following chapter.

In addition to the subsample taken for metal analysis, a 70 g subsample

was taken for FPOM analysis by traditional loss on ignition methods (Ball 1964). The dried subsample was redried at 105°C for 2 hours to evaporate interstitial water, then weighed and placed in a muffle furnace for 3 hours at 550°C. The subsamples were then reweighed, and the percent organic matter computed from the difference between the two weights compared to the initial weight. Eighteen replicate samples (7% of total) were analyzed to test the reproducibility of the organic matter results.

CHAPTER 3

RESULTS AND DISCUSSION

The following sections present and discuss the results of statistical analysis of metal and FPOM spatial variability with an emphasis on: (1) analysis of variance (ANOVA) on within-unit variability and between-unit variability in metal concentrations in sediments; and (2) possible reasons for patterns in variability. Three hundred thirty-six sediment samples from 70 morphologic units were collected in 1993, and statistical analysis was conducted on 12 metals: Al, Co, Cr, Cu, Fe, Mg, Mn, Ni, Pb, Ti, V, and Zn. These metals were chosen because their concentrations exceeded the detectable limits from the ICP-AES analysis. All metal concentrations are for the 2 mm and finer sediment fraction. A significance level of 0.05 was used for all statistical tests. Statistical analyses were performed using MSUSTAT 5.22 (Lund 1993) and NCSS (Hintze 1992). Metal data for each unit, including mean concentration, standard deviation, range, and coefficient of variation are summarized in Table 3.

Table 3. Summary statistics for metals. N = 30 for each unit type and metal.

Morphologic Unit		Al %	Co ppm	Cr ppm	Cu ppm	Fe %	Mg %	Mn ppm	Ni ppm	Pb ppm	Ti %	V ppm	Zn ppm
BP	*Mean*	0.882	13.4	52.1	48.1	2.81	1.19	545	33.9	28.6	0.128	88.6	80.1
	Std.Dev.	0.1223	1.6	14.9	9.6	0.19	0.12	161	3.3	33.2	0.014	10.1	48.3
	Range	0.72-1.09	11-17	35-96	36-73	2.43-3.23	1.02-1.57	425-1345	29-41	14-201	0.11-0.17	76-119	54-328
	Coef. of Var.	0.139	0.115	0.286	0.199	0.068	0.103	0.296	0.097	1.162	0.110	0.114	0.601
AB	*Mean*	0.772	12.0	50.5	49.9	2.74	1.12	670	31.3	74.7	0.120	87.6	103.1
	Std.Dev.	0.078	1.3	6.7	9.6	0.14	0.07	389	1.9	159.9	0.009	6.7	75.9
	Range	0.65-0.92	10-16	39-66	35-74	2.48-2.92	0.99-1.27	405-2385	29-36	10-894	0.10-0.14	74-103	56-360
	Coef. of Var.	0.102	0.107	0.132	0.193	0.050	0.061	0.580	0.059	2.142	0.077	0.077	0.736
LSP	*Mean*	0.716	12.6	41.4	42.4	2.63	1.13	561	32.3	29.1	0.113	84.9	80.5
	Std.Dev.	0.057	1.8	5.8	8.2	0.17	0.05	202	2.3	29.4	0.014	5.9	28.1
	Range	0.61-0.83	9-16	32-60	31-59	2.41-3.05	1.01-1.24	360-1097	29-37	4-137	0.08-0.14	72-96	54-189
	Coef. of Var.	0.080	0.142	0.139	0.193	0.065	0.048	0.360	0.071	1.011	0.128	0.069	0.349
DB	*Mean*	0.721	11.4	44.6	41.2	2.60	1.09	520	31.0	30.5	0.115	85.0	76.8
	Std.Dev.	0.072	0.9	7.5	7.2	0.18	0.06	205	2.3	35.3	0.012	4.7	46.7
	Range	0.56-0.88	9-13	31-59	32-62	2.21-2.91	0.92-1.21	350-1410	27-36	4-194	0.09-0.14	75-94	52-296
	Coef. of Var.	0.100	0.075	0.168	0.176	0.070	0.060	0.386	0.075	1.159	0.102	0.055	0.608
G	*Mean*	0.687	11.6	39.0	37.5	2.54	1.15	626	31.5	23.2	0.110	84.0	89.5
	Std.Dev.	0.043	1.1	3.7	6.0	0.10	0.13	691	2.2	25.1	0.011	4.4	66.0
	Range	0.63-0.78	10-14	28-48	31-59	2.31-2.72	1.00-1.53	353-4175	28-39	4-102	0.09-0.13	74-94	54-326
	Coef. of Var.	0.062	0.097	0.095	0.161	0.041	0.115	1.103	0.069	1.085	0.095	0.052	0.737
HGR	*Mean*	0.668	11.8	39.3	43.5	2.49	1.10	802	30.9	41.3	0.105	82.9	100.8
	Std.Dev.	0.046	1.1	3.4	9.3	0.12	0.10	733	2.4	64.3	0.013	5.3	60.5
	Range	0.60-0.75	10-14	33-45	33-71	2.17-2.73	0.95-1.36	315-3498	26-35	4-331	0.08-0.13	70-91	54-260
	Coef. of Var.	0.068	0.097	0.087	0.215	0.046	0.087	0.913	0.079	1.556	0.122	0.064	0.601
LGR	*Mean*	0.678	11.7	39.1	37.5	2.50	1.10	510	30.8	26.2	0.110	82.7	68.7
	Std.Dev.	0.057	1.12	4.2	3.6	0.13	0.07	279	2.1	25.6	0.012	5.0	13.3
	Range	0.58-0.77	9-13	31-47	30-43	2.22-2.78	0.99-1.30	350-1905	28-35	6-130	0.09-0.14	74-93	54-102
	Coef. of Var.	0.083	0.096	0.106	0.095	0.061	0.063	0.546	0.067	0.982	0.110	0.061	0.193

BP=backwater pool, AB=attached bar, LSP=lateral scour pool, DB=detached bar, G=glide, HGR=high gradient riffle, LGR=low gradient riffle.

The Role of Channel Morphology

Analysis of variance (ANOVA) was used to test if metal concentrations varied significantly between morphologic units and within morphologic units. Analysis of variance tests the hypothesis that all group means are equal by comparing the ratio of the between group variation to the within-group variation and a theoretical F-distribution of the same ratio (e.g., Griffith and Amrhein 1991). Analysis of variance: (1) tests the hypothesis that metals in sediments vary with channel morphology; and (2) indicates the spatial scale at which significant variability in metal concentrations exist.

All metals consistently exhibit normal distributions, with the exception of Mn, Pb, and Zn. Normality was tested by the Kolmogorov-Smirnov normality test, which compares the distribution of data to a theoretical normal distribution. The results for Mn, Pb, and Zn may not, however, be appreciably affected by non-normality because of the robust nature of ANOVA for large sample sizes (Wesolowsky 1976). For instance, the number of samples in the between unit ANOVA test is 30 for each type of morphologic unit (e.g., backwater pool), for a total sample size of 210 when all unit types are included.

Between-Unit Spatial Variability

Variability: Table 4 summarizes the ANOVA results for between-unit variation for each metal. Mean metal concentrations for each unit type (e.g., high gradient riffle) were based on three composite samples from 10 of the units, for a total of 30 samples per unit type. The total sample size for the ANOVA was 210 for each metal because there were 7 different types of morphologic units. All metals analyzed except Mn, Pb, and Zn have significant differences in concentrations between some of the morphologic units ($p < 0.05$).

Table 4. Summary of results of ANOVA testing for significant differences in metal concentrations between unit types. Significant p-values in bold ($\alpha = 0.05$). Degrees of freedom = 203, n = 210 for each metal.

Metal	*p-value*	*Metal*	*p-value*
Al	**0.0000**	Mn	0.1255
Co	**0.0000**	Ni	**0.0000**
Cr	**0.0000**	Pb	0.0729
Cu	**0.0000**	Ti	**0.0000**
Fe	**0.0000**	V	**0.0011**
Mg	**0.0006**	Zn	0.1075

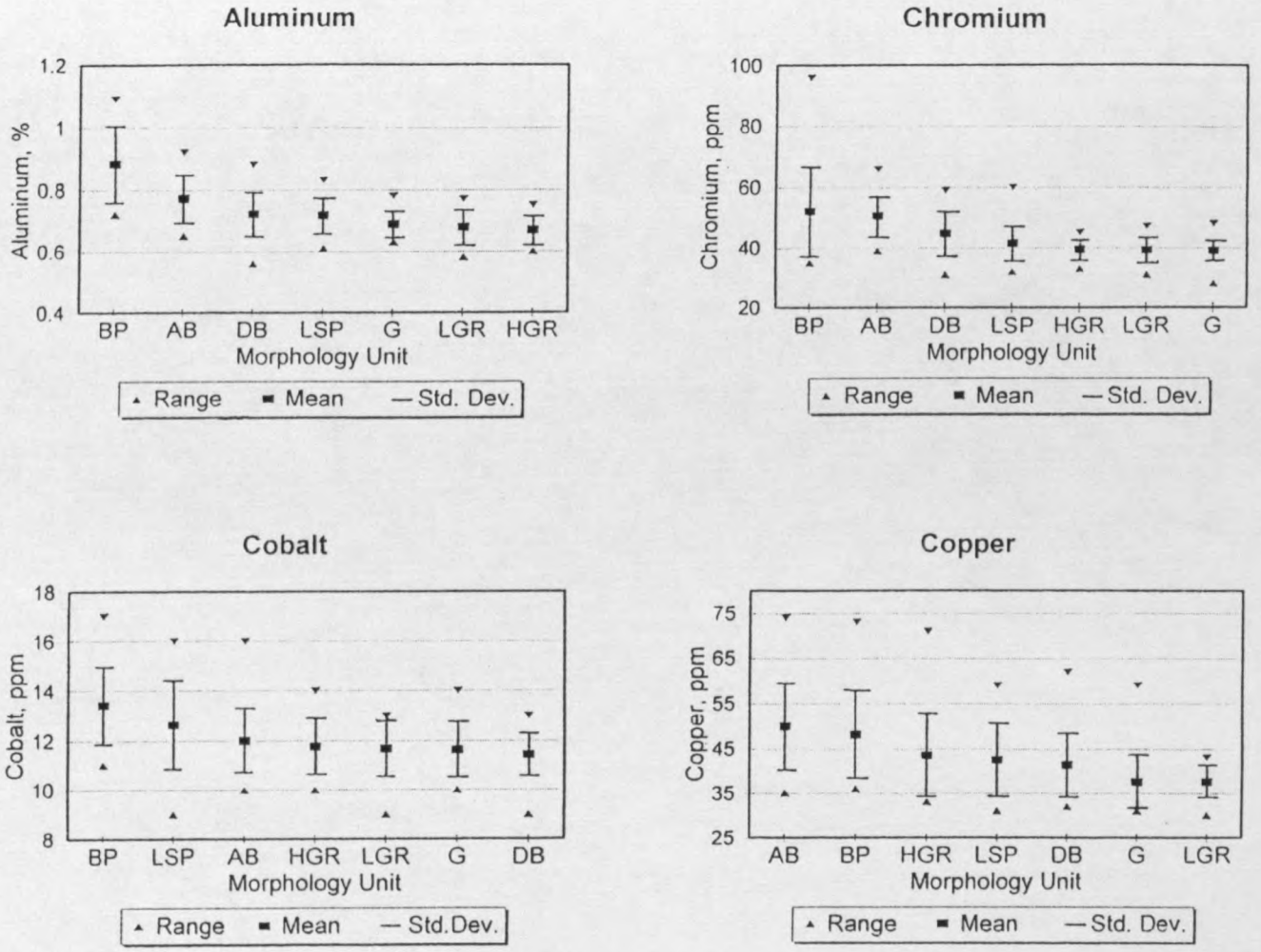
In general, backwater pools and attached bars consistently have the highest concentrations of metals, while low gradient riffles and high gradient riffles

consistently have the lowest metal concentrations (Figure 5). For instance, Al, Ti, and V exhibit typical patterns, with the highest concentrations occurring in backwater pools and the lowest concentrations occurring in high gradient riffles or low gradient riffles. Other metals exhibit somewhat different patterns, such as Mg and Co, where detached bars have the lowest concentrations, and Cr, where glides have the lowest concentrations.

The range and standard deviations of metal concentrations vary with morphologic unit (Figure 5). In general, the greatest range, standard deviation, and coefficient of variation for all metals occur in backwater pools, which also generally have the highest metal levels. Exceptions are Cu, Pb, and Zn which are highest in attached bars, and Mn, which is highest in high gradient riffles. The units in which the smallest range and standard deviation occur varies with metal.

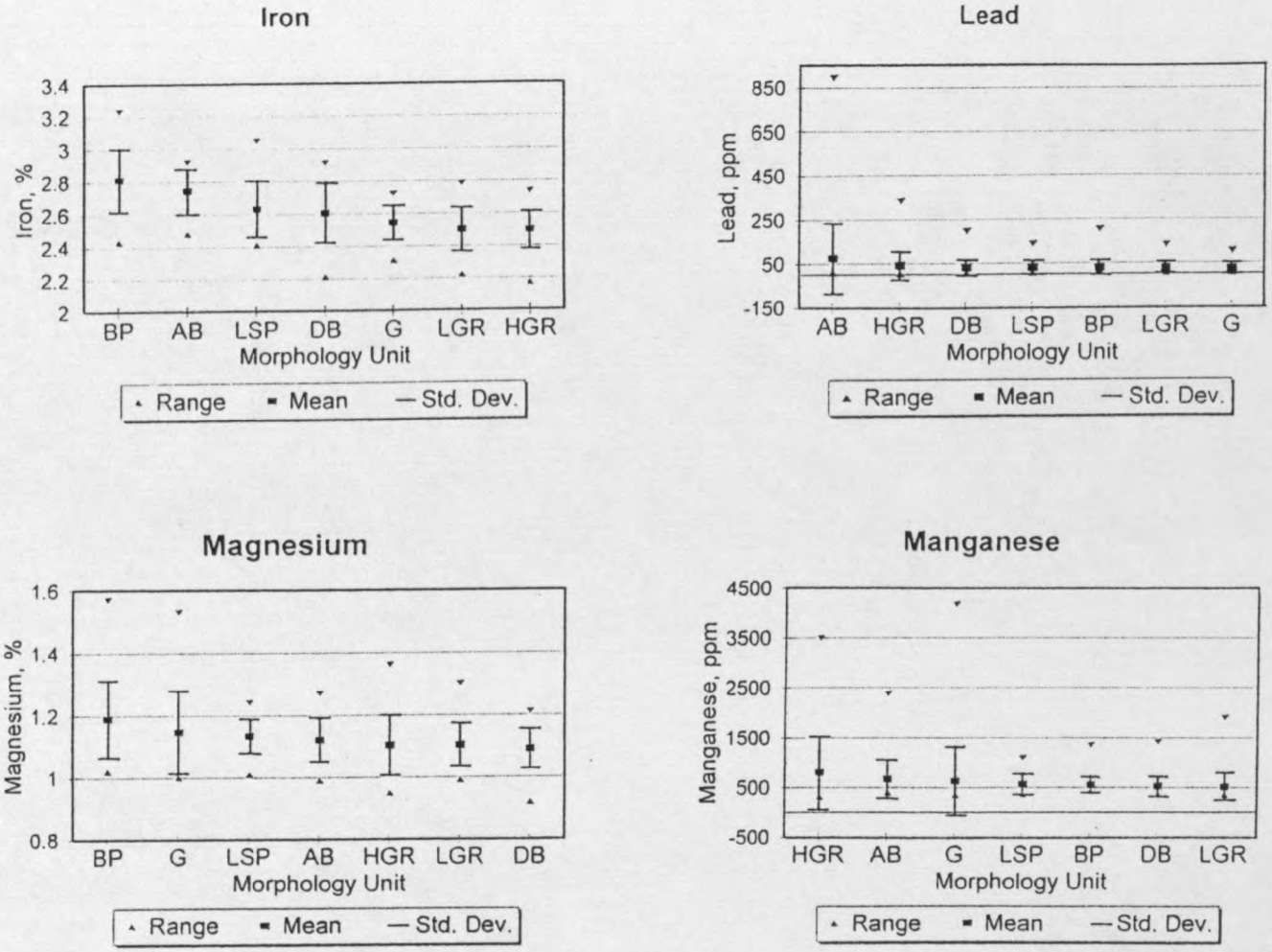
Standard deviations and ranges for the three metals (Mn, Pb, Zn) with no significant differences in concentrations between units vary considerably and inconsistently between units. This variation may reflect the high variability in these metals between samples at a range of scales, as discussed in a following section.

Figure 5. Variations in metal concentrations between morphologic units, including mean, standard deviation, and range. Units in descending order by mean metal concentration.



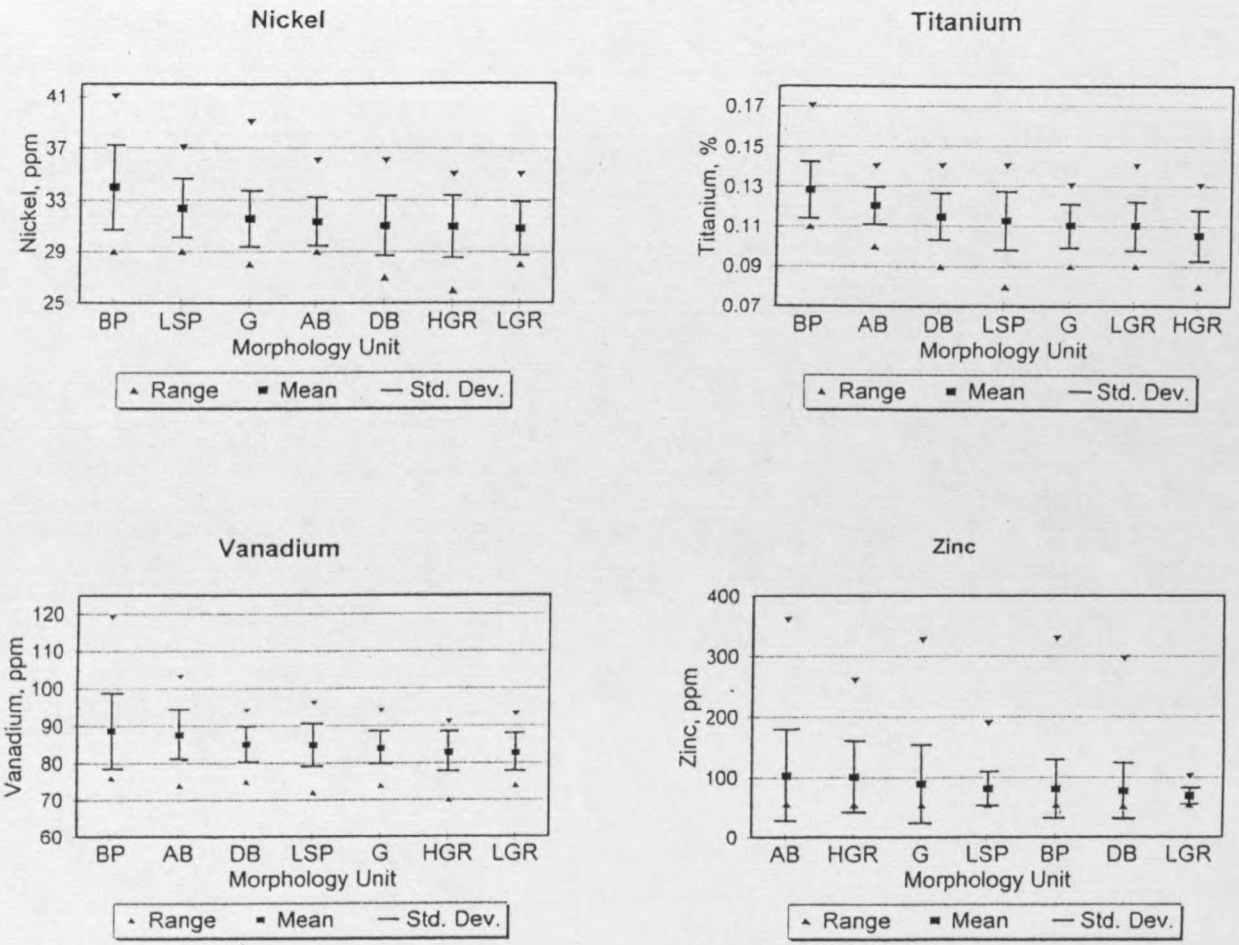
LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detached bar.

Figure 5 continued.



LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detached bar.

Figure 5 continued.



LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detached bar.

Pairwise Unit Comparisons: A Newman-Keuls multiple comparison test was run to determine which pairs of morphologic units differed significantly for each metal (Table 5 and Appendix). Newman-Keuls tests whether significant differences exist between pairs of group means (i.e., morphologic unit type means for a given metal). It compares a theoretical Studentized Range distribution to the ratio of the pairwise difference between means divided by the within-group variance (Toothaker 1993). This test shows that out of 21 possible pairwise comparisons for each metal, the number of significant differences among units ranges from 5 to 14, depending on the metal. The number of significantly different pairs is shown for each metal in the Appendix. The Newman-Keuls test was not applied to Mn, Pb, and Zn because the mean concentration differences between unit types for these metals are not significant.

Table 5 shows the Newman-Keuls groupings for all the units and metals, with units exhibiting the highest concentrations having a grouping, or rank, of A. Some of the morphologic units have the same letter, or grouping, because the measured differences in metal concentrations between these units are not statistically significant. For instance, backwater pools and attached bars are given a rank of A for Cu because both unit types have significantly higher concentrations of Cu than other unit types, but are not significantly different from

one another. Other units with significantly lower Cu concentrations are placed in the B or C group, depending on their rank.

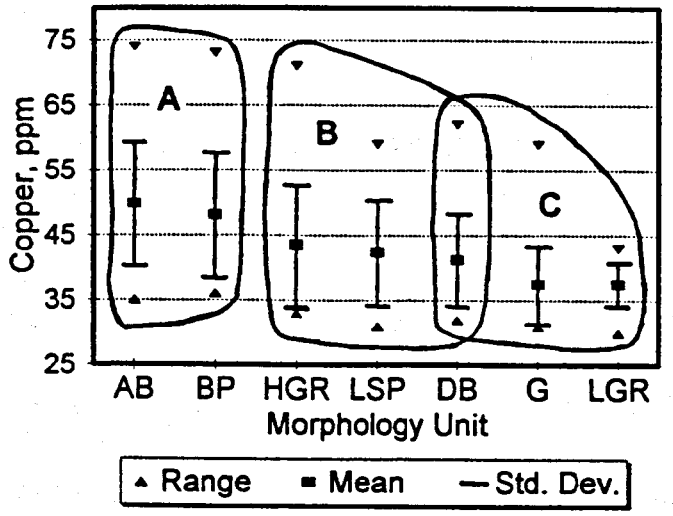
Table 5. Unit type groupings by rank. Number of significantly different pairs using the Newman-Keuls multiple comparison test.

Morphologic Unit	Al	Co	Cr	Cu	Fe	Mg	Mn	Ni	Pb	Ti	V	Zn
Backwater pool	A	A	A	A	A	A	—	A	—	A	A	—
Attached bar	B	BC	A	A	A	B	—	BC	—	AB	AB	—
Lateral scour pool	C	B	BC	B	B	B	—	B	—	BC	ABC	—
Detached bar	C	C	B	BC	B	B	—	C	—	BC	ABC	—
Glide	CD	C	C	C	BC	AB	—	BC	—	C	B	—
High gradient riffle	D	C	C	B	C	B	—	C	—	C	C	—
Low gradient riffle	CD	C	C	C	C	B	—	C	—	C	C	—
No. of significantly different pairs (of 21)	13	10	13	13	14	5	0	6	0	11	5	0

Some unit types have more than one letter rank because they are not significantly different from other groups. Detached bars have the rank of both B and C for Cu, because they have a significantly different mean than the group A unit types, but are not significantly different than the other 4 types of units. Figure 6 illustrates this concept for Cu. Each group that differs significantly from another group is encircled. This figure shows that detached bars do not differ significantly from either high gradient riffles and lateral scour pools or from glides and low gradient riffles because of their intermediate concentrations. High gradient riffles

and lateral scour pools, however, have significantly higher concentrations than glides and low gradient riffles. High gradient riffles and lateral scour pools therefore receive a rank of B because they have the second highest group Cu concentrations, while glides and low gradient riffles receive a rank of C. Detached bars, which are not significantly different than either group, receive both a B and C ranking. The Appendix shows which pairs of unit types contain significantly different means, from which Table 5 was constructed.

Figure 6. Groupings of morphologic unit types for copper by significant and non-significant means.



Several trends in variability and ordering in the between-unit type metals data are illustrated in Table 5. Metals showing the greatest between unit variability are Fe, Cu, Cr, and Al, followed by Ti, Co, Ni, Mg, and V. In addition,

the groupings based on the multiple comparison results reflect the ordering of units in Figure 5 as previously discussed.

Backwater pools and attached bars consistently have the highest concentrations while low gradient and high gradient riffles the lowest. Backwater pools typically have significantly higher metal concentrations than lateral scour pools, and attached bars typically have significantly higher metal concentrations than detached bars. However, low gradient and high gradient riffles tend to concentrate metals relatively similarly. The one exception to the general ranking pattern among units is for Mg in the glide unit, which has a relatively high ranking compared to its ranking for other metals.

Discussion: The spatial distribution of metals in the study reach generally varies in a consistent manner between channel morphology units. Possible explanations for these distributions include vertical stratification of sediments and associated metals, variability in geochemical factors, and grain size. However, causes for the spatial distribution of metals cannot be determined from the data. The data suggest, however, that variations in stream hydraulics may differentially transport and deposit sediment and associated metals, preferentially concentrating some metals in certain types of units.

Differences in the silt and clay content of different morphologic units may partly explain metal distributions in the study reach. Preliminary analysis by Marcus (pers. comm. 1995) suggests that metals in the study area are consistently highest in clay and silt. However, metal concentrations are not consistently higher or lower in other size fractions. Thus backwater pools and attached bars likely have the highest concentrations of metals because they experience deposition of fine-grained sediments as flows recede. Conversely, low gradient and high gradient riffles generally have the lowest concentrations because clay and silt are entrained by turbulence, leaving only coarser materials, which typically sorb metals less readily.

The grain size distribution of one of the primary metal sources may help explain the concentration pattern of certain metals. The McLaren tailings contain high levels of Cu (Meyer 1993). High gradient riffles and lateral scour pools, two of the highest energy types of environments, contain relatively high concentrations of some metals, such as Cu, compared to lower energy units (Table 5). It is thus possible that tailings containing metals are sorted and preferentially deposited in these morphologic units because of their size and density. Because some metals concentrate in certain units while other metals do not, other factors may be important. Further study on the association of metals

with mineral phases and grain size may help to explain their distributions in the study reach.

Within-Unit Spatial Variability

Longitudinal Variability: Composite samples collected from the upstream, middle, and downstream portions of units were compared to determine if there were significant variations within units in the downstream (i.e., longitudinal) direction. Equality of mean metal concentrations was tested with ANOVA for metals data from all units lumped together and for individual units (Table 6). There are no significant longitudinal variations within units for any metal. Figure 7(a) for Cu in lateral scour pools demonstrates the typical pattern in longitudinal concentrations found for all metals.

Lateral Variability: Samples collected from nine locations in three of each type of unit were compared to determine the variability in metal concentrations laterally across units. Equality of mean metal concentrations between the middle and two sides of the units was tested in ANOVA for metals data from all units lumped together and for individual units (Table 7). Concentrations do not vary significantly in the lateral direction, with the exception of Mg in backwater pools. One significant result may not be meaningful, however, since approximately four

significant results out of 84 tests would be expected to occur due to chance at the 0.05 significance level (Table 7). Figure 7(b) for Cu in lateral scour pools demonstrates the typical pattern in lateral concentrations found for all metals.

Table 6. Summary of results of ANOVA testing for significant differences in metal concentrations between the upstream, middle, and downstream portions of units. Significant p-values in bold ($\alpha = 0.05$).

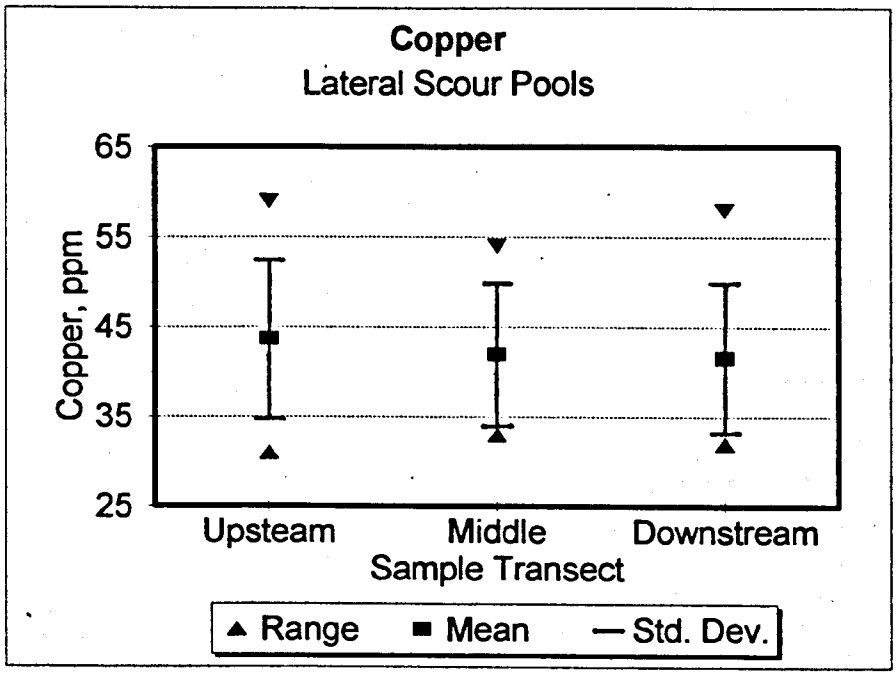
				p-values				**All**
Metal	**LGR**	**HGR**	**G**	**BP**	**LSP**	**AB**	**DB**	**Units**
n =	*30*	*30*	*30*	*30*	*30*	*30*	*30*	*210*
Al	0.757	0.634	0.935	0.951	0.955	0.770	0.583	0.962
Co	0.457	0.908	0.726	0.692	0.934	0.945	0.234	0.754
Cr	0.849	0.367	0.870	0.822	0.367	0.284	0.430	0.427
Cu	0.327	0.339	0.446	0.673	0.841	0.261	0.652	0.668
Fe	0.892	0.678	0.225	0.581	0.807	0.570	0.864	0.690
Mg	0.783	0.769	0.561	0.960	0.445	0.933	0.310	0.814
Mn	0.430	0.617	0.527	0.486	0.344	0.276	0.710	0.635
Ni	0.704	0.257	0.223	0.914	0.744	0.898	0.753	0.717
Pb	0.481	0.835	0.817	0.562	0.944	0.344	0.797	0.292
Ti	0.668	0.548	0.608	0.985	0.369	0.312	0.852	0.295
V	0.955	0.688	0.179	0.905	0.645	0.372	0.808	0.223
Zn	0.533	0.066	0.812	0.499	0.635	0.313	0.213	0.861

LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detached bar.

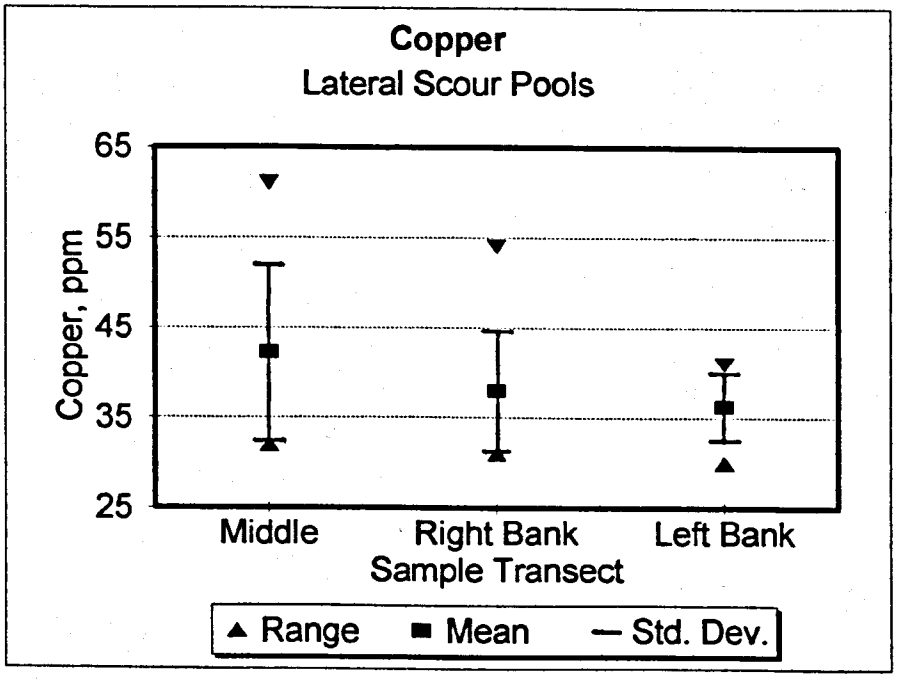
Discussion: The lack of significant within-unit variations means that metal concentrations are relatively homogeneous at the scale of the individual

Figure 7. Variations in copper within lateral scour pools, including mean, standard deviation, and range. Data in descending order by mean metal concentration. (a) Longitudinal variations. (b) Lateral variations.

(a)



(b)



morphologic unit (4 m to 50 m). This is consistent with the hypothesis that hydraulic controls on trace metal distributions are reflected within the morphology classification and that metal concentrations vary significantly between units but not within them.

Table 7. Summary of results of ANOVA testing for significant differences in metal concentrations laterally across units. Significant p-values in bold ($\alpha = 0.05$).

	p-values							All
Metal	**LGR**	**HGR**	**G**	**BP**	**LSP**	**AB**	**DB**	**Units**
n =	*27*	*27*	*27*	*27*	*27*	*27*	*27*	*189*
Al	0.991	0.263	0.813	0.766	0.718	0.201	0.927	0.618
Co	0.963	0.851	0.526	0.618	0.280	0.646	0.392	0.565
Cr	0.275	0.243	0.384	0.645	0.645	0.285	0.632	0.161
Cu	0.871	0.058	0.413	0.807	0.210	0.826	0.896	0.765
Fe	0.754	0.703	0.816	0.678	0.701	0.639	0.488	0.826
Mg	0.210	0.244	0.569	**0.049**	0.681	0.355	0.602	0.523
Mn	0.989	0.532	0.759	0.509	0.792	0.533	0.727	0.660
Ni	0.386	0.399	0.843	0.080	0.427	0.281	0.243	0.835
Pb	0.750	0.682	0.497	0.480	0.748	0.402	0.666	0.736
Ti	0.330	0.471	0.576	0.589	0.944	0.135	0.936	0.256
V	0.376	0.662	0.770	0.800	0.984	0.528	0.132	0.380
Zn	0.933	0.990	0.568	0.566	0.866	0.427	0.728	0.467

LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detached bar.

However, visible differences in grain size distributions at distances less than 1 m suggest that significant differences in metal concentrating factors may

occur at smaller distances. It is possible that these variations are not detected by the sampling network because variations occur at distances much less than 1 m, which are not sampled for in this study. Variations at distances of 0.3 m to 4 m were, however, addressed through sample spacing (Table 1) and found to not be significant. It is possible that the variations in pebble and cobble distributions are due to local scale (< 1 m) boundary roughness, while variations in sand, silt, and clay distributions are controlled primarily by channel roughness at the scale of morphology units.

The Role of Distance Downstream

One of the possible reasons for differences between morphologic units is distance downstream, which may alter metal concentrations due to: (1) settling of metals and resultant lowering of concentrations; or (2) new sources of sediments (e.g., bed or bank erosion) and resultant dilution or enrichment downstream. Regression analysis was thus conducted to determine if the classic distance-decay model for metals may have affected between-unit type variability. Regression analysis tested whether there were significant linear relationships between metal concentrations and distance downstream. Overall, only metals in backwater pools vary with downstream distance (Table 8), with 8 of 12 metals

Table 8. Summary of results of regression analysis of distance downstream and metal concentration. Significant R-squares are in bold. b is the slope of the regression.

Unit	R square	Prob. > F	b	Unit	R square	Prob. > F	b	Unit	R square	Prob. > F	b
	Aluminum				***Chromium***				***Cobalt***		
LGR	0.0677	0.1651	-0.0001	LGR	0.0001	0.9701	0.0003	LGR	0.0115	0.5727	0.0011
HGR	0.0693	0.1598	-0.0001	HGR	0.0670	0.1673	-0.0080	HGR	0.0127	0.5538	-0.0012
G	**0.1312**	**0.0491**	**-0.0002**	G	0.0246	0.4079	0.0060	G	0.0185	0.4731	-0.0016
BP	**0.3694**	**0.0000**	**-0.0004**	BP	**0.4819**	**0.0000**	**-0.0562**	BP	0.0227	0.4270	-0.0013
LSP	0.1094	0.0742	-0.0002	LSP	0.0033	0.7619	-0.0034	LSP	0.0940	0.0993	-0.0056
AB	0.0633	0.1799	-0.0002	AB	0.1111	0.0719	-0.0253	AB	**0.3017**	**0.0017**	**-0.0080**
DB	**0.1865**	**0.0172**	**-0.0003**	DB	0.0130	0.5489	-0.0091	DB	0.0162	0.5028	-0.0012
	Copper				***Iron***				***Lead***		
LGR	0.0154	0.5137	0.0043	LGR	0.0209	0.4462	0.00018	LGR	0.0102	0.5947	0.02425
HGR	0.0195	0.4615	0.0118	HGR	0.0148	0.5224	0.00013	HGR	0.0290	0.3681	-0.0993
G	0.0115	0.5720	0.0069	G	**0.1548**	**0.0315**	**0.00042**	G	0.0110	0.5806	0.02735
BP	**0.1637**	**0.0266**	**0.0446**	BP	**0.2347**	**0.0067**	**-0.0005**	BP	**0.2205**	**0.0102**	**0.01756**
LSP	0.0307	0.3544	0.0145	LSP	0.0497	0.2365	0.00039	LSP	0.0004	0.9129	0.0062
AB	0.0612	0.1876	0.0270	AB	0.0179	0.4813	0.00021	AB	0.0200	0.4644	-0.0647
DB	0.0116	0.5717	0.0083	DB	0.0072	0.6553	0.00017	DB	0.1054	0.0801	-0.1221

LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detached bar.

Table 8 continued.

Unit	R square	Prob. > F	b		R square	Prob. > F	b		R square	Prob. > F	b
	Magnesium				***Manganese***				***Nickel***		
LGR	0.0091	0.6166	0.0001	LGR	0.0468	0.2511	-0.5606	LGR	0.0192	0.4651	0.0027
HGR	0.0179	0.4810	-0.0001	HGR	0.0006	0.8950	0.1671	HGR	0.0038	0.7474	0.0014
G	0.0002	0.9453	0.0000	G	0.0073	0.6538	0.6107	G	0.1024	0.0847	0.0072
BP	0.1293	0.0509	-0.0002	BP	0.0961	0.0954	0.2699	BP	0.0806	0.1283	-0.0050
LSP	0.0390	0.2952	-0.0001	LSP	0.0000	0.9805	0.0093	LSP	0.0485	0.2423	0.0051
AB	0.0018	0.8230	-0.0000	AB	0.0692	0.1600	-1.1619	AB	0.0580	0.1997	0.0051
DB	0.0495	0.2372	0.0002	DB	0.0999	0.0888	-0.6903	DB	0.0150	0.5198	0.0030
	Titanium				***Vanadium***				***Zinc***		
LGR	0.0687	0.1617	0.0000	LGR	0.0237	0.4162	-0.0072	LGR	0.0451	0.2599	0.0262
HGR	0.0634	0.1795	0.0000	HGR	0.0130	0.5488	-0.0054	HGR	0.0088	0.6221	0.0514
G	0.1218	0.0587	0.0000	G	0.0392	0.2946	0.0090	G	0.0097	0.6047	-0.0661
BP	**0.2868**	**0.0023**	**-0.0000**	**BP**	**0.5485**	**0.0000**	**-0.0405**	**BP**	**0.1689**	**0.0241**	**0.1070**
LSP	0.0976	0.0929	0.0000	LSP	0.0029	0.7768	-0.0032	LSP	0.0000	0.9873	-0.0009
AB	0.0570	0.2038	0.0000	AB	0.0370	0.3088	-0.1467	AB	0.0011	0.8599	0.0290
DB	0.0078	0.6423	0.0000	DB	0.0917	0.1038	-0.0150	DB	0.0291	0.3677	-0.0848

LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detached bar.

demonstrating significant increases or decreases with distance. In addition, analysis of the scatterplots for individual unit types for each metal suggest that, with the exception of backwater pools, no linear or non-linear trends with distance exist. The absence of a relationship between metals and downstream distance in most units indicates that variability between units is not appreciably affected by distance.

Discussion

Downstream lowering of metal concentrations is expected if relatively dense metals associated with sediments settle out downstream of the source. The fact that most units do not exhibit decreasing concentrations with distance suggests that the 500 m reach is not long enough to deplete metal concentrations through settling or that metals are not being carried in heavy mineral phases.

Reasons for downstream changes in most metals in backwater pools is unclear. Backwater pools tend to contain largely fine sediment fractions, which are less likely to be sorted by density. Without any major new sources of sediment in the reach except bed and bank deposits, significant metal enrichment or dilution would therefore not be expected on the basis of hydraulics alone. To add to the confusion, some metals in backwater pools experience negative

relationships with distance (Al, Cr, Fe, Ti, V) while others experience positive relationships (Cu, Pb, Zn). The latter patterns suggest that tailings in the floodplain, which have been shown by Meyer (1993) to contain high levels of Cu and Pb, may contribute to metal enrichment downstream as bank deposits are entrained by high flows and redeposited in the channel. Resolving the causes of these patterns requires further research on the mineral phases and sedimentology of these units.

Because backwater pools are evenly distributed throughout the reach, relatively high or low concentrations at one end of the reach do not bias the ANOVA comparison of backwater pools to other unit types by over-representing upstream or downstream units. In addition, scatterplots of distance versus metal concentrations in backwater pools suggest that all sample sites are representative (i.e., no outliers). ANOVA results thus are not appreciably affected by linear downstream patterns in metals for these backwater pools.

The reasons for occasional significant downstream patterns for some metals in units other than backwater pools is unclear. One of the possible reasons that Al and Fe in glides, Co in attached bars, and Al in detached bars show significant relationships with distance is probability. Approximately four "significant" relationships would be expected by chance in 84 tests, using a

significance level of 0.05. No evidence suggests that a consistent relationship exists for any metal or any type of unit, except backwater pools.

Regression analysis was not performed for all units lumped together because many morphologic unit types which contain different metal levels are unevenly distributed throughout the study reach. For instance, the presence of seven high gradient riffles, but only two attached bars in the lower third of the reach would bias the regression because high gradient riffles tend to have the lowest metal concentrations, while attached bars typically have the highest.

Duplicate Sample Variation

One of the important issues with regard to documenting variability between units is whether variability between duplicates affects results. Analysis of 30 duplicates (14% of the sample total) representing all units indicates that the average variability between duplicates differs with metal, and is less than ±15% for most metals (Table 9). The concentration variability for split samples ranges from ±7% for Fe and Mg to ±100% for Pb. The additional variability introduced from duplicate sample variability may increase the within group variance estimates enough to result in non-significance in the ANOVA for metals with poor agreement among duplicate samples. There is thus a chance that false null

hypotheses (i.e., that metal concentrations in units are from equal populations) were retained, and that real differences were not detected for Mn, Pb, and Zn.

Table 9. Mean difference between duplicate subsamples (< 2 mm).

Metal	Mean Difference, ± % *n = 30*
Fe	7
Mg	7
V	8
Ni	9
Al	10
Cr	13
Cu	14
Ti	14
Co	17
Mn	31
Zn	35
Pb	100

The variation between duplicates may reflect differences in split samples as opposed to laboratory errors. One factor causing this high variability could be the occurrence of Mn, Pb, and Zn in discrete mineral grains. Chemex, Inc.'s ICP-AES procedure analyzes just 1 g of sediment. It is possible that the presence of one or more mineral grains in one split but not the other may result in considerable variation among split samples.

The Role of FPOM

The Fine Particulate Organic Matter (FPOM) concentrations of 18 split samples are reported in Table 10. All 250 samples analyzed contained less than 3% FPOM by weight, with the majority containing less than 1%. Error in the 18 replicate (7% of total) samples analyzed ranged from 14% to 271% with an average error of 65% (Table 10). Due to the low overall concentration of FPOM in samples and the great variability between duplicates, an analysis of FPOM variations within and between units was not conducted. Any apparent differences in FPOM between units would be suspect because of the high degree of error in the measurement of low levels of organic matter using the traditional loss-on-ignition method.

Other methods may be more successful in measuring low organic matter levels. Examples of more precise methods include the Walkley-Black method, the Nelson and Sommers method, or combustion with carbon dioxide measurement (e.g., Black 1965; Page et al. 1982; Lewis and McConchie 1994). Because very low amounts of organic matter have been shown to have a negligible effect on concentrating metals (Moriarty et al. 1982; Haschenburger 1989; Graf 1991; Marcus et al. 1993), it is not likely that the low FPOM concentrations in the study reach significantly affected metal concentrations.

Table 10. Comparison of subsample duplicates for FPOM data quality assessment.

Sample #	FPOM 1, %	FPOM 2, %	Difference, %	FPOM1/FPOM2
8-C	0.68	1.17	72	0.58
13-A	0.68	1.18	74	0.58
14-C	0.63	1.35	114	0.47
16-A	0.93	1.58	70	0.59
16-B	0.79	1.39	76	0.57
23-A	0.81	1.39	72	0.58
32-B	1.14	1.62	42	0.70
33-C	0.60	0.34	43	1.76
37-B	0.55	0.24	56	2.29
42-B	0.76	1.35	78	0.56
44-B	0.21	0.78	271	0.27
46-BM	1.72	1.33	23	1.29
47-CL	1.46	2.06	41	0.71
56-BM	1.79	2.13	19	0.84
62-B	2.19	1.41	36	1.55
67-C	0.59	0.76	29	0.78
72-BL	1.85	2.11	14	0.88
76-CL	1.45	0.99	32	1.46
Mean	1.05%	1.29%	65%	---

CHAPTER 4

SUMMARY AND CONCLUSIONS

There is a relationship between channel morphologic units and trace metal concentrations in bed sediments in a 500 m reach of Soda Butte Creek. The seven types of morphologic units sampled were low gradient riffles, high gradient riffles, glides, backwater pools, lateral scour pools, attached bars and detached bars. Ten of each type of morphologic unit were sampled, and three to nine samples were collected from each unit (e.g., from each backwater pool). Statistical analysis was completed on twelve metals detected by aqua regia digestion and analyzed by Inductively Coupled Plasma (ICP) for: Al, Co, Cr, Cu, Fe, Mg, Mn, Ni, Pb, Ti, V, and Zn.

Statistical analysis indicates that concentrations of Al, Co, Cr, Cu, Fe, Mg, Ni, Ti, and V vary significantly between the seven types of morphologic units, while Mn, Pb, and Zn do not vary significantly between unit types. Most metals exhibiting significant between-unit type differences show higher concentrations in backwater pools and attached bars and lower concentrations in high gradient riffles and low gradient riffles. Metals exhibiting the largest number of significant

differences between units are Fe, Cu, Cr, and Al, followed by Ti, Co, Ni, Mg, and V (Table 5).

The three metals (Mn, Pb, Zn) with no significant differences between types of units show large variability between split samples (Table 9). Discrete mineral grains contained in one portion of the split but not the other may explain the variability between duplicates. In turn, this variability between duplicates may increase the within-group variance estimates enough to result in non-significance in the ANOVA for metals with poor agreement among splits.

Metals having the greatest average concentration differences between units are Cr, Cu, and Al, followed by Ti, Co, Fe, Ni, Mg, and V (Table 11). Chromium levels, for example, are 34% higher in backwater pools than in glides on average, while V levels in backwater pools are only 7% higher than in the lowest concentration type of unit on average.

The range of metal concentrations within units varies with type of unit and metal, although the greatest ranges are typically exhibited by backwater pools (Figure 5). ANOVA indicates that no significant lateral or longitudinal within-unit type differences for any metal are present for individual types of units or all types of units lumped together.

The lack of significant within-unit type variations and the presence of

Table 11. Differences in average metal content between units grouped by similar concentrations, as determined from multiple comparison results.

Metal	A Similar Units	B Similar Units	C Similar Units	D Similar Units	A-B Diff., %	B-C Diff., %	C-D Diff., %	*Unit type in which concentrations are:* Highest	Lowest	Diff.,% High-Low
Cr	BP,AB	LSP,DB	G,LGR,HGR	—	16.2	9.1	—	BP	G	34
Cu	BP,AB	LSP,DB,HGR	G,LGR	—	13.5	11.6	—	AB	G,LGR	33
Al	BP	AB	LSP,DB,G,LGR	HGR	12.5	9.3	4.6	BP	HGR	32
Ti	BP	AB,DB	LSP,G,HGR,LGR	—	8.2	6.8	—	BP	LGR	22
Co	BP	AB,LSP	DB,G,HGR,LGR	—	8.2	5.7	—	BP	DB	18
Fe	BP,AB	LSP,DB,G	HGR,LGR	—	6.8	3.5	—	BP	HGR	13
Ni	BP	AB,LSP,DB,G,HGR,LGR	—	—	7.7	—	—	BP	LGR	10
Mg	BP,G	AB,LSP,DB,HGR,LGR	—	—	5.1	—	—	BP	DB	9
V	BP,AB,LSP,DB	G,HGR,LGR	—	—	3.8	—	—	BP	LGR	7
Pb*	—	—	—	—	—	—	—	AB	G	(222)
Mn*	—	—	—	—	—	—	—	HGR	DB	(56)
Zn*	—	—	—	—	—	—	—	AB	LGR	(50)

LGR=low gradient riffle, HGR=high gradient riffle, G=glide, BP=backwater pool, LSP=lateral scour pool, AB=attached bar, DB=detach

* No significant differences in metal concentrations between morphologic units.

between-unit type variations indicates that metal distributions are relatively homogeneous at the scale of the individual morphologic unit (4 m to 50 m). These results suggest that hydraulic controls on sediment and associated metals are reflected within the morphology classification system.

Analysis of Fine Particulate Organic Matter (FPOM) shows that all samples contain less than 3% dry weight organic matter, and the majority of samples contain less than 1%. ANOVA of FPOM within and between types of units was not conducted because of the high variation between duplicates. The results of the duplicate analysis suggest that any significant variability in FPOM between and within types of units would be suspect due to the high degree of error in the measurement of low levels of organic matter using the traditional loss-on-ignition method. Because of the low amounts of organic matter, it is not likely that FPOM significantly affected metal concentrations in the study area.

Applications

The above findings have implications for a variety of applications, including: (1) environmental monitoring and regulation; (2) environmental impact assessment; and (3) environmental remediation. Because most metals concentrate differently between morphologic units, bedform scale channel

morphology aids in developing sampling criteria by providing information on sampling approach and scale, sample locations, and number of samples. In addition to pollution studies, this study confirms that there are links between stream morphology and sediment transport processes.

Sampling Approach and Scale

Statistical analysis shows that there are no significant within-unit type differences in metal concentrations, but there are significant between-unit type differences for all metals except Mn, Pb, and Zn. Therefore, for all metals except Mn, Pb, and Zn, the morphologic unit is an appropriate scale for documenting concentrations.

The stratification of metal concentrations by morphologic unit means that: (1) random sampling may be inefficient because of the large number of samples required to capture the full spectrum of unit types; and (2) systematic sampling of only one type of unit may be inaccurate because the full range of variation in metals in a stream could be missed. Sampling strategies that do not include channel morphology may miss smaller units such as backwater pools, and over-represent larger units such as low gradient riffles and thus inadequately portray metal levels (Figure 4). It is thus critical to stratify sampling schemes by

channel morphology units to accurately and efficiently assess metal concentrations.

Sample Location

Results of this study indicate which types of morphologic units behave in a similar manner and which types of units behave differently for a given metal in Soda Butte Creek (Table 11). For example, backwater pools and attached bars form group A for Cu in Table 11 because they do not contain significantly different Cu concentrations. Likewise, lateral scour pools, detached bars, and high gradient riffles form group B because they have similar Cu concentrations. On average, group B contains Cu concentrations 13.5% lower than group A. Group C is formed by glides and low gradient riffles, which contain significantly lower (11.6% on average) Cu concentrations than group B.

Table 11 also shows which types of units behave similarly for groups of metals. For example, morphologic groupings for Cr and Cu, ranked from highest to lowest concentration, are: (1) backwater pools and attached bars; (2) lateral scour pools and detached bars; and (3) glides and low gradient riffles. In addition, both Cr and Cu exhibit relatively large differences between types of units having the highest concentrations and types of units having the lowest

concentrations. Likewise, types of units in Al, Ti, and Co behave in similar ways. However, Fe, Ni, Mg, and V exhibit unique patterns of unit type groupings. Manganese, Pb, and Zn exhibit large differences between the highest concentrations and the lowest, but since these differences were not found to be significant, grouping of types of units by mean concentrations was not done.

This segregation of metals by types of morphologic unit suggests efficient sampling strategies for documenting peak metal concentrations, averages, and ranges in stream sediments. To compare metal concentrations at different points in a reach or watershed, equivalent morphology must be sampled, since significant differences between types of units are shown to vary by up to 34% on average for some metals (Table 11). Sampling backwater pools and low gradient riffles at each site, for example, can provide quick and inexpensive estimates of the range and average metal concentrations to be expected in the sediments of that stream.

Metal concentrations in morphologic units in Soda Butte Creek may not be the same as in other streams, and therefore cannot be used for direct prediction. However, differential sorting of sediments in streams of similar size and flow regime may create metal distributions similar to those found in Soda Butte Creek, especially in cobble bed mountain streams. Backwater pools and attached bars

in other streams, for example, may exhibit the highest concentrations of metals because they typically are loci for deposition of fine grained sediments, which tend to sorb metals more readily than coarse sediments.

Other types of morphologic units beyond the seven sampled in this study may be present in streams of different size, substrate, and hydrologic regime. Investigators conducting environmental studies in these streams thus should conduct reconnaissance studies to document metal variability between morphologic units before completing more full scale studies of metal distributions and their environmental impacts.

Number of Samples

Results of this study aid in determining the number of samples necessary to adequately represent metal levels in morphologic units. For normally distributed data, the number of samples (n) required to obtain mean metal concentrations for a given metal can be approximated using the sample size estimator:

$$n = [\, z \,(\text{standard deviation} / D \,)]^2$$

where z corresponds to the confidence interval and D equals the level of error (Blalock 1979; Griffith and Amrhein 1991).

Table 12 shows the approximate number of samples required to obtain

Table 12. Approximate number of samples required to obtain mean metal concentrations at given levels of accuracy, at 95% confidence.

	Level of accuracy (from mean)				
Al	**1%**	**5%**	**10%**	**20%**	**30%**
BP	739	30	7	2	1
AB	392	16	4	1	1
LSP	243	10	2	1	1
DB	383	15	4	1	1
G	150	6	2	1	1
HGR	182	7	2	1	1
LGR	272	11	3	1	1
Cr	**1%**	**5%**	**10%**	**20%**	**30%**
BP	3142	126	31	8	3
AB	676	27	7	2	1
LSP	754	30	8	2	1
DB	1086	43	11	3	1
G	346	14	3	1	1
HGR	288	12	3	1	1
LGR	443	18	4	1	1
Fe	**1%**	**5%**	**10%**	**20%**	**30%**
BP	176	7	2	1	1
AB	100	4	1	1	1
LSP	161	6	2	1	1
DB	184	7	2	1	1
G	60	2	1	1	1
HGR	89	4	1	1	1
LGR	104	4	1	1	1
Ni	**1%**	**5%**	**10%**	**20%**	**30%**
BP	364	15	4	1	1
AB	142	6	1	1	1
LSP	195	8	2	1	1
DB	211	8	2	1	1
G	187	7	2	1	1
HGR	232	9	2	1	1
LGR	179	7	2	1	1
V	**1%**	**5%**	**10%**	**20%**	**30%**
BP	499	20	5	1	1
AB	225	9	2	1	1
LSP	186	7	2	1	1
DB	117	5	1	1	1
G	105	4	1	1	1
HGR	157	6	2	1	1
LGR	140	6	1	1	1

	Level of accuracy (from mean)				
Co	**1%**	**5%**	**10%**	**20%**	**30%**
BP	548	22	5	1	1
AB	451	18	5	1	1
LSP	784	31	8	2	1
DB	239	10	2	1	1
G	345	14	3	1	1
HGR	334	13	3	1	1
LGR	352	14	4	1	1
Cu	**1%**	**5%**	**10%**	**20%**	**30%**
BP	1530	61	15	4	2
AB	1422	57	14	4	2
LSP	1437	57	14	4	2
DB	1173	47	12	3	1
G	983	39	10	2	1
HGR	1756	70	18	4	2
LGR	354	14	4	1	1
Mg	**1%**	**5%**	**10%**	**20%**	**30%**
BP	391	16	4	1	1
AB	150	6	2	1	1
LSP	75	3	1	1	1
DB	116	5	1	1	1
G	491	20	5	1	1
HGR	317	13	3	1	1
LGR	156	6	2	1	1
Ti	**1%**	**5%**	**10%**	**20%**	**30%**
BP	460	18	5	1	1
AB	216	9	2	1	1
LSP	590	24	6	1	1
DB	418	17	4	1	1
G	384	15	4	1	1
HGR	589	24	6	1	1
LGR	457	18	5	1	1

BP = backwater pool
AB = attached bar
LSP = lateral scour pool
DB = detached bar
G = glide
HGR = high gradient riffle
LGR = low gradient riffle

mean metal concentrations in each type of unit for levels of accuracy (D) ranging from 1% to 30% deviation from the mean, at the 95% confidence limit ($z = 1.96$). For example, 15 samples must be collected to characterize the mean Cu concentration in backwater pools within 10%, or 4.81 ppm, of the mean (48.1 ppm) (Table 12). The approximate number of samples needed for different levels of accuracy varies by metal and type of unit, but the pattern mirrors Table 11. For example, V, Mg, Ni, and Fe typically have the lowest range of values and therefore generally require fewer samples to obtain mean concentrations within a given level of accuracy. Conversely, metals with a large range of values, such as Cr and Cu (Table 11), generally require a greater number of samples. Backwater pools generally require more samples than other types of units. More than 100 samples are required to obtain better than 1% accuracy for metal concentrations for most types of units. However, fewer than 10 samples are generally required to characterize metal concentrations within 10% of the mean. Estimations of sample sizes needed to characterize Mn, Pb, and Zn were not calculated because the data for these metals were not normally distributed and there were no significant concentration differences between morphologic units for these metals.

Further Research

The above findings show that morphologic units play a major role in segregating metals. However, similar studies in other settings are needed. Studies that sample morphologic units in different stream systems with varying levels of metal contamination are needed to quantify the variations that occur and to determine whether the morphology classification is appropriate for a wide variety of settings. Likewise, further study is needed on the processes that contribute to metal concentration and dispersion at different distances from metal sources, including the relationships between metals and hydraulic parameters, such as shear stress and stream power.

In addition, further research on the temporal variability in metal concentrations is needed. Specifically, documentation of metal variability in morphologic units at a range of time scales and sediment sizes is critical to improve sampling strategies, understand environmental impacts, and effectively regulate and mitigate metal contaminants. Likewise, a better understanding of changes in channel morphology units through time is important for documenting and understanding temporal variability in metals in sediments. This type of information is important for studies that compare metal concentrations over time

for assessing environmental effects and for determining timing of sampling for documenting spatial distributions in metals.

Further study on the relationship between FPOM and metals in morphologic units in a variety of sediment sizes is also important for understanding spatial and temporal variability in metal concentrations and in determining the importance of FPOM documentation in understanding metal concentrations. A better understanding of the role of FPOM in concentrating metals in coarse bed channels will aid in documenting metal concentrations and in understanding the processes that control them.

As discussed previously, the role of mineralogy and sedimentology in contributing to metal segregation by morphology units is unclear and requires further research on the association of metals with mineral phases and sediment size. Determining the sediment sizes that affect aquatic organisms can guide future studies in determining the optimal sediment size for sampling. It is also important to document and understand the spatial variability of geochemical factors that may affect metal concentrations at the scale of channel morphology units.

The results of this study, however, suggest that channel morphology provides a useful sampling framework for documenting metal concentrations in

bed sediments at scales of 1 m to 1 km. The ability to document reach scale metal concentrations is critical for assessing reach scale environmental impacts and for determining sampling approaches necessary to assess watershed wide environmental impacts of trace metal distributions.

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LITERATURE CITED

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APPENDIX

MULTIPLE COMPARISON RESULTS

Table 13. Newman-Keuls multiple comparison results, showing significant differences between pairs of morphologic units. Significant p-values in bold. Last column shows letter ranking of each unit, with "A" indicating the unit(s) with the highest metal concentration. The same ranking indicates no significant difference in metal concentration between the tied pairs.

Aluminum

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	**0.000**	----					B
LSP	**0.000**	**0.008**	----				C
DB	**0.000**	**0.006**	0.803	----			C
G	**0.000**	**0.000**	0.120	0.168	----		CD
HGR	**0.000**	**0.000**	**0.047**	**0.037**	0.554	----	D
LGR	**0.000**	**0.000**	0.100	0.097	0.617	0.592	CD

Chromium

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	0.411	----					A
LSP	**0.000**	**0.000**	----				BC
DB	**0.000**	**0.003**	0.100	----			B
G	**0.000**	**0.000**	0.584	**0.030**	----		C
HGR	**0.000**	**0.000**	0.281	**0.018**	0.981	----	C
LGR	**0.000**	**0.000**	0.465	**0.024**	0.932	0.918	C

Cobalt

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	**0.000**	----					BC
LSP	**0.017**	0.059	----				B
DB	**0.000**	0.441	**0.005**	----			C
G	**0.000**	0.694	**0.024**	0.551	----		C
HGR	**0.000**	0.487	**0.027**	0.753	0.917	----	C
LGR	**0.000**	0.581	**0.021**	0.766	0.921	0.766	C

Copper

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	0.389	----					A
LSP	**0.016**	**0.002**	----				B
DB	**0.004**	**0.000**	0.547	----			BC
G	**0.000**	**0.000**	**0.043**	0.071	----		C
HGR	**0.025**	**0.005**	0.603	0.501	**0.018**	----	B
LGR	**0.000**	**0.000**	0.076	0.168	1.000	**0.028**	C

BP=backwater pool, AB=attached bar, LSP=lateral scour pool, DB=detached bar, G=glide, HGR=high gradient riffle, LGR=low gradient riffle.

Table 13 continued.

Iron

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	0.068	----					A
LSP	**0.000**	**0.005**	----				B
DB	**0.000**	**0.001**	0.485	----			B
G	**0.000**	**0.000**	0.060	0.115	----		BC
HGR	**0.000**	**0.000**	**0.004**	**0.025**	0.427	----	C
LGR	**0.000**	**0.000**	**0.004**	**0.019**	0.257	0.912	C

Magnesium

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	**0.019**	----					B
LSP	**0.044**	0.602	----				B
DB	**0.001**	0.547	0.347	----			B
G	0.065	0.532	0.583	0.158	----		AB
HGR	**0.002**	0.438	0.397	0.847	0.252	----	B
LGR	**0.003**	0.718	0.565	0.583	0.347	1.000	B

Nickel

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	**0.000**	----					BC
LSP	**0.009**	0.213	----				B
DB	**0.000**	0.626	0.132	----			C
G	**0.000**	0.704	0.193	0.661	----		BC
HGR	**0.000**	0.822	0.152	0.914	0.763	----	C
LGR	**0.000**	0.756	0.126	0.943	0.756	0.828	C

Titanium

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	**0.012**	----					AB
LSP	**0.000**	**0.042**	----				BC
DB	**0.000**	0.075	0.529	----			BC
G	**0.000**	**0.009**	0.463	0.361	----		C
HGR	**0.000**	**0.000**	0.097	**0.028**	0.258	----	C
LGR	**0.000**	**0.014**	0.743	0.523	1.000	0.116	C

Vanadium

	BP	AB	LSP	DB	G	HGR	Rank
BP	----						A
AB	0.524	----					AB
LSP	0.093	0.211	----				ABC
DB	0.068	0.113	0.918	----			ABC
G	**0.033**	0.112	0.579	0.788	----		B
HGR	**0.005**	**0.029**	0.433	0.540	0.498	----	C
LGR	**0.005**	**0.032**	0.553	0.616	0.727	0.935	C

BP = backwater pool
AB = attached bar
LSP = lateral scour pool
DB = detached bar
G = glide
HGR = high gradient riffle
LGR = low gradient riffle

Plate 1. Soda Butte Creek study area map showing morphologic units and sample locations.