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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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 5/17/95

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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

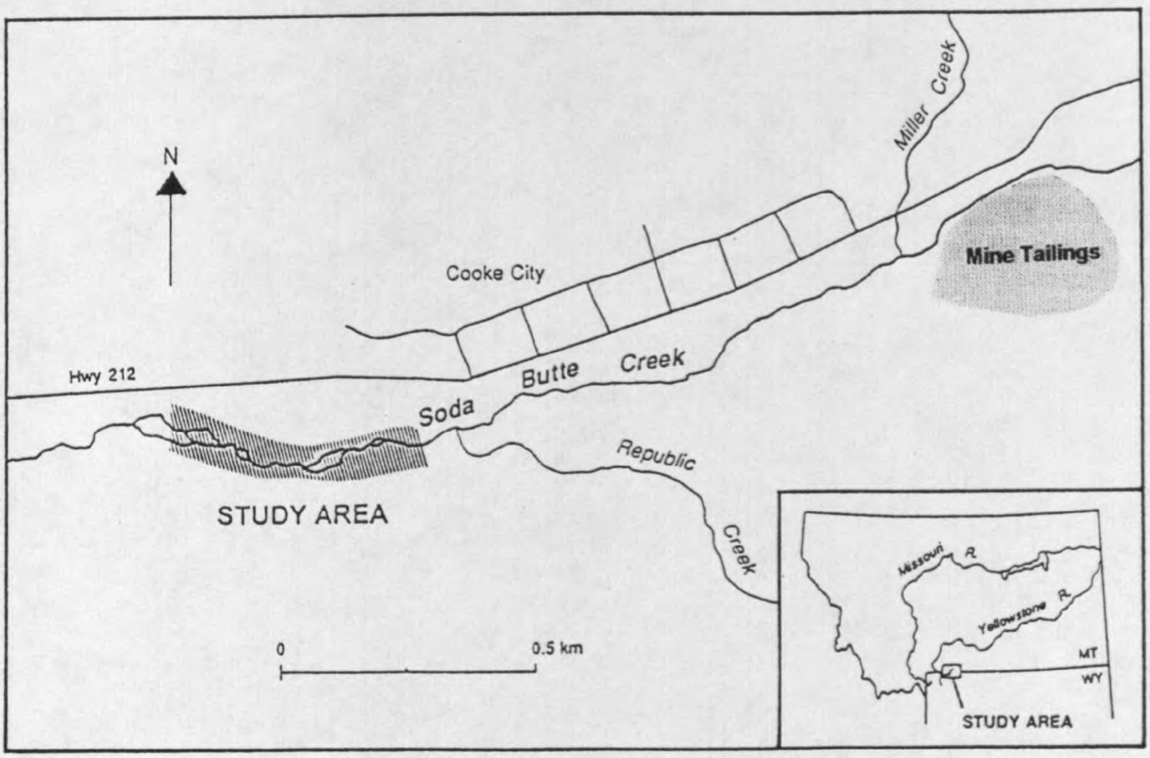
Study Area

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)