

**CHANNEL GEOMORPHOLOGY ASSESSMENT:
A COMPONENT OF THE WATERSHED
MANAGEMENT PLAN FOR THE SULPHUR
CREEK WATERSHED, NAPA COUNTY,
CALIFORNIA:**

**PREPARED FOR
STEWARDSHIP SUPPORT AND WATERSHED ASSESSMENT IN
THE NAPA RIVER WATERSHED: A CALFED PROJECT**

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Table of Contents

Executive Summary	iv
Acknowledgements	vi
Introduction	1
Objectives	2
Watershed Characteristics	2
Setting	2
Geology.....	4
Soils.....	4
Climate and runoff.....	5
Land use	6
California Department of Fish and Game Stream Surveys.....	6
Methods.....	8
Startup and review of available data	8
Data collected in channel cross sections	12
<i>Channel geometry</i>	12
<i>Surface sediment size analysis</i>	12
<i>Bank characterization</i>	12
<i>Canopy cover</i>	13
Continuous channel metrics.....	13
<i>Gravel bars and mobile sediment deposits</i>	13
<i>Pool type and size</i>	15
<i>Bank conditions and erosion</i>	16
<i>Large woody debris</i>	16
Additional spot measurements	17
<i>Bulk sediment size analysis</i>	17
<i>Field measurements of slope</i>	18
<i>Hydraulic analyses</i>	18
<i>Bed load transport capacity</i>	19
Results	19
Channel geomorphology.....	19
<i>Surface grain size variation by reach</i>	19
<i>Subsurface grain size variation</i>	23
<i>Stream slope by reach</i>	24
<i>Cross-sections</i>	26
<i>Large woody debris (LWD)</i>	32
<i>Pools</i>	34
<i>Sediment deposits and bars</i>	38
<i>Bank erosion and revetments</i>	44
<i>Bank characterization</i>	48
<i>Channel hydraulic geometry</i>	50
Discussion	52
References	59

EXECUTIVE SUMMARY

The Sulphur Creek Stewardship has a mission to preserve and maintain the watershed for functions that are mutually agreeable among interested local residents. Over the past several years, the group constructed a set of management questions, and helped to instigate a multi-disciplinary science project to help answer these questions. This report is one of five technical reports written to inform the development of a watershed management plan through a participatory process that includes the community, agencies and scientists. It was made possible through funding from a project entitled “Stewardship Support and Watershed Assessment in the Napa River Watershed”. The Napa RCD led CALFED project also provides the same kind of support for the Stewardship of Carneros Creek, which drains to the Napa River adjacent to San Pablo Bay.

During the summer and fall of 2002, empirical observational data was collected to assess the geomorphological condition of Sulphur Creek. This technical report describes the methods, results and conclusions derived from this assessment. This report will be integrated with the other four technical reports by the project partners in close consultation with the Sulphur Creek Stewardship to create a management plan for the local community and the Sulphur Creek watershed.

Sulphur Creek is a western tributary to the Napa River, entering the river in the town of St. Helena. The lower watershed consists primarily of suburban residential area, with some open space and a gravel mining plant. The upper watershed is primarily open space, with some vineyards, grazing, and residential areas. Sulphur Creek historically and currently supports salmonid spawning and rearing, while also providing habitat for other aquatic species. Data collected in this channel geomorphic assessment include surface and subsurface grain size measurements, channel cross-section geometry, channel slope, bank and riparian vegetation characteristics, bank condition, large woody debris (LWD) in the bankfull channel, debris jams, number, type and volume of bars and sediment deposits, number, type and residual depth of pools, indicators and volume of bank erosion, and type and condition of bank revetment.

Surveyed cross-sections illustrate the wide variety of channel morphologies observed throughout the watershed, with the largest contrast between the alluvial fan reaches and the uppermost reaches. Surface and subsurface sediment size analyses suggest that Sulphur Creek has a large sediment supply, yet with low percentages of fine sediment (< 2 mm). Despite the forested upper watershed, and nearly continuous riparian corridor in the upper and middle reaches, Sulphur Creek does not contain many in-channel LWD pieces. Only 15% of all pools measured are formed by or associated with LWD. In addition, the pools measured are relatively shallow, with no pool deeper than 0.7 m (2.3 ft). Sediment deposits and bars are numerous in all reaches of the creek, especially in the alluvial fan reaches, and downstream of large landslides. Approximately 96% of the total volume of measured sediment deposits is stored in 33% of the total number of deposits. These large sediment deposits are generally more important than LWD in shaping the morphology of the channel. Most (90%) sediment deposits have been

active within the past five years, illustrating the ability of Sulphur Creek to rework and modify the sediment that is supplied to the creek. In sampled reaches, subsurface sediment size distributions are slightly finer than ideal for steelhead spawning, but within documented ranges. However, suitable gravel patches and hydraulic locations for spawning are reasonably abundant. Hillslope processes, namely landslides, are the largest contributor of sediment to the channel, especially in the upper reaches. These landslides dominate the local sediment supply and channel morphology. Measured bank erosion is greatest in reaches coinciding with a high incidence of landslides. The downstream reaches, especially in St. Helena, have the largest percentage of bank revetments relative to channel length and modifications to the channel morphology.

The habitat in the channel of Sulphur Creek is currently able to maintain a steelhead population. Salmonid success is primarily limited by the lack of perennial flow, and the resultant barrier to migration, especially through the alluvial fan reaches. Additionally, these reaches lack channel complexity and riparian cover; these issues along with the relatively short windows of flow limit the function of the fan reaches to support a fish migration corridor only. Other secondary limitations to salmonid success include partial physical barriers that limit migration to only the strongest swimmers, spawning gravels that are slightly finer than ideal, shallow pool depths, and lack of LWD cover elements in pools. The middle reaches of the main stem and the majority of the Heath Canyon tributary, provide the best salmonid spawning and rearing habitat. These reaches provide the best combinations of perennial discharge, spawning gravels, pool spacing, pool depth and cover, and riparian shading and channel complexity.

The reaches of Sulphur Creek in the town of St. Helena are not ideal for steelhead spawning or rearing habitat. These reaches are highly impacted by the town; runoff from the streets and residential areas is contributing to the poor water quality, some sections are lacking riparian vegetation, and some sections are dominated by non-native plant species. The cessation of gravel mining in the alluvial fan reaches could cause an increased flood risk to the adjacent neighborhoods and to the town of St. Helena if sediment builds up in the channel to a point where flood capacity is insufficient during heavy rainstorms. Observations suggest that the channel is filling with sediment, decreasing the in-channel volume available to transport floodwaters, but at this time it is uncertain what the equilibrium channel conditions will be.

Throughout Sulphur Creek, LWD does not play an important role in pool formation, despite the nearly continuous riparian canopy in the middle and upper watershed. The best steelhead spawning and rearing habitat is in the middle reaches of the main stem, and the majority of the Heath Canyon tributary, because these reaches contain the best combination of habitat elements. Landslides provide the majority of sediment to the channel, and have a large effect on overall sediment supply, storage, and channel morphology. Besides steelhead spawning and rearing habitat, Sulphur Creek also supplies other resources to watershed residents including flood conveyance, habitat for wildlife and other aquatic species, and an aesthetically pleasing setting to live, work and play.

ACKNOWLEDGEMENTS

We greatly acknowledge the CALFED Science Program for providing the funding for the *Stewardship Support and Watershed Assessment in the Napa River Watershed* project.

We also acknowledge the Sulphur Creek Stewardship group for their participation, enthusiasm, and hard work. This project is a success because the stewardship and landowners have provided access to the creek and local knowledge of the watershed and its history. Special thanks to Phill Blake (Napa County Natural Resources Conservation Service) for providing direction, support and local knowledge of the watershed.

John Emig (California Department of Fish and Game, Yountville) provided historic stream survey data for Sulphur Creek.

We would also like to thank the Napa County Resource Conservation District staff for taking the lead on this project, coordinating with the stewardships, coordinating access to property, providing local knowledge and support, and also providing help during field data collection. Thank you Bob Zlomke, Leigh Sharp, Lara Hadhazy, Blaine Jones, Jonathan Koehler and Michael Champion. Thanks to Eileen Weppner, our project partner from Pacific Watershed Associates for her hard work and collaboration.

INTRODUCTION

The watershed of Sulphur Creek flows west to east entering the mainstem of the Napa River in the town of St. Helena. The watershed sustains a number of land uses including viticulture, range lands, open spaces, rural residential, and urban lands in its lower reaches. The upper watershed is dominated by rolling hills with occasional steep ravines and is generally well vegetated on both hillslopes and in riparian areas as a result of moderate rainfall and perennial stream reaches. The watershed supports a native steelhead population that may be endangered by reductions in summer flow, barriers associated with bridges and grade controls, and increases in fine sediment supply due to land management. All of these factors with the addition of gentle fan topography in the lower watershed provide the backdrop to a tranquil urban setting today and a history of resorts and warm springs over the past 150 years.

In recognition of pressure on the watershed, conflicting social and political interests, concern of unabated influences of regulatory agencies, and the potential decline in community value of the creek and watershed, a group of concerned stakeholders formed the Sulphur Creek Stewardship with the mission to preserve and maintain Sulphur Creek watershed in a natural and beautiful state and to promote both agricultural as well as private recreational usage. There have been a number of successes so far including stream set backs, erosion control of unstable banks, placement of a fish ladder, and plans to improve bridge crossings. Current concerns include fine sediment supply from hillsides, the effects of cessation of gravel mining in the fan reach, and the design of a restored channel after the removal of a grade control in the fan reach.

Quality, defensible science is an important precursor to sound environmental management and restoration decisions. Once the community has constructed a set of management questions or needs, sound science protocol is applied within a framework of continued community involvement to develop appropriate watershed management plans. The assumption is often made that a single science methodology can be used to answer all of a group's management questions, however, the best way to apply environmental science methodologies is to use a variety of protocols that have overlap in the scope of information that they provide. In this way, any conflicting conclusions that are derived from each isolated protocol are reconciled during the planning process increasing the chance of restoration success.

In order to develop and understanding of the spatial and temporal variation of physical, biological and human aspects of the Sulphur Creek watershed at a variety of scales, we carried out the following types of empirical data collection and/ or review of existing information:

1. Historical Ecology
2. Channel geomorphology,
3. Hillslope geomorphology/ sediment budget,
4. Fish and Macroinvertebrates,
5. Water quality.

This technical report describes the methods, results and conclusions derived from the channel geomorphology component and is part of the larger study outlined above. This report will be integrated with other technical reports by the project partners in close consultation with the Sulphur Creek Stewardship to create a management plan for the local community.

Objectives (Channel Geomorphology Component)

To characterize the channel form and function throughout the watershed, focusing on sediment production, transport and storage, and including riparian function and anadromous fish habitat.

WATERSHED CHARACTERISTICS

Setting

Sulphur Creek is a western tributary to the Napa River, which flows into the Napa River at the town of St. Helena, 26 km (16 mi) north of the town center of Napa. Sulphur Creek has a drainage basin area of 24.2 km² (9.3 mi²). The highest elevation in the watershed is 829 m (2,720 ft) above mean sea level, while the confluence with the Napa River is at 61 m (200 ft) above mean sea level. The drainage basin is roughly triangular, with a footprint approximately 6.4 km (4.0 mi) by 7.2 km (4.5 mi). The drainage basin is dendritic, with two main stems: Heath Canyon and the mainstem of Sulphur Creek. The watershed is generally “Y” shaped, with the two branches joining immediately before Sulphur Creek exits the canyon section and begins to flow across the alluvial fan (Table 1). The lowest 2.4 km (1.5 mi) of channel flows through the town of St. Helena. Sulphur Creek is a fourth order stream (Strahler, 1957), with a total channel length of approximately 20.5 km (12.7 mi). From an analysis of measured peak discharge for channels in the Napa Valley (from USGS Gauging Station Peak Discharge data, Pearce et al., 2002), a drainage basin the size of Sulphur Creek can expect a peak discharge of 15 m³/s (530 ft³/s) corresponding to a recurrence interval of 1.5 years.

Table 1. Drainage basin areas of Sulphur Creek sub-basins

Sub-basin	Drainage Basin area (km ²)	Drainage Basin area (mi ²)
Heath Canyon	7.0	2.7
Canyon, North and South Branches	11.6	4.5
Alluvial Fan	5.6	2.1
Total	24.2	9.3

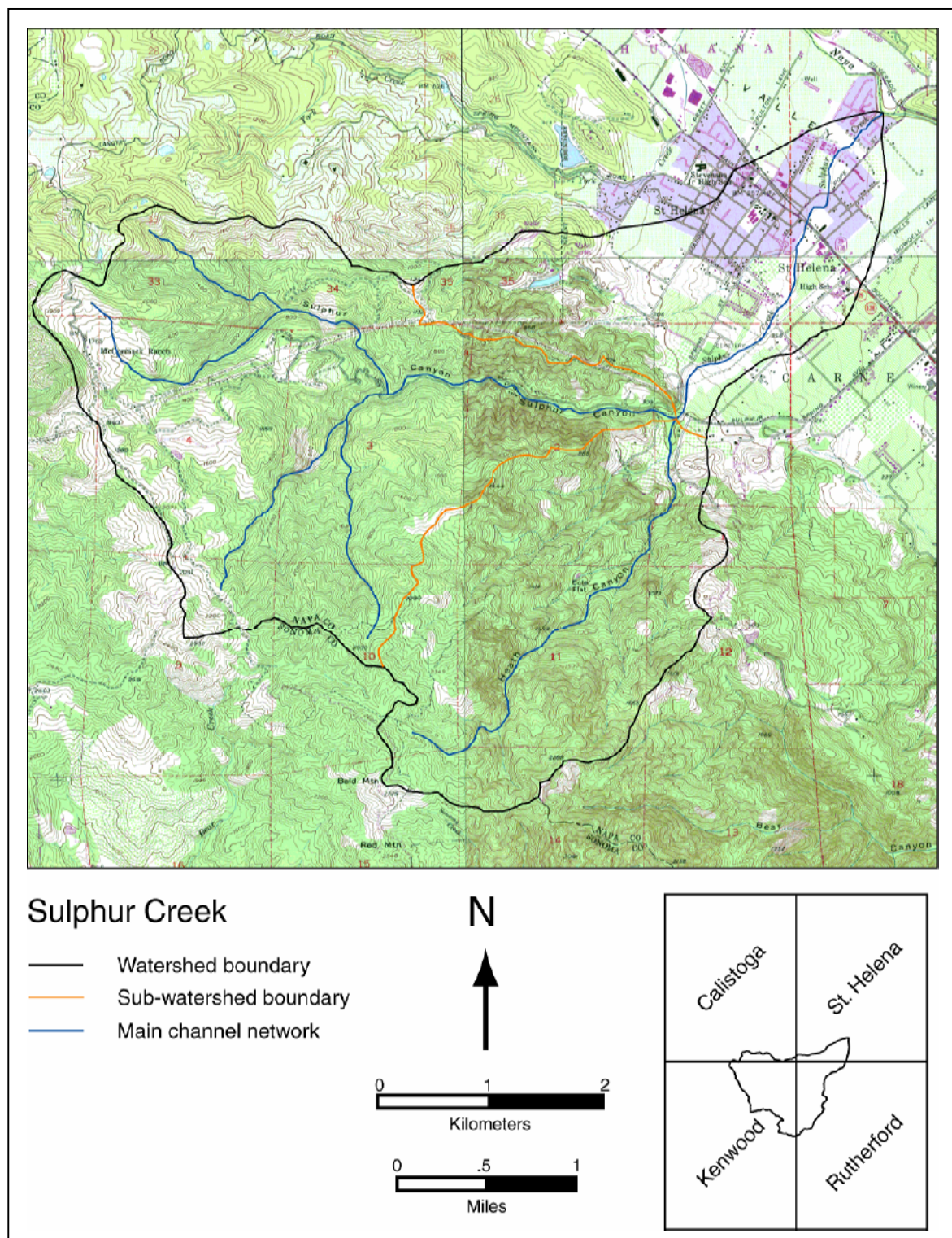


Figure 1. Map of the Sulphur Creek watershed.

Geology

The geology of the region was mapped by Fox et al., 1973. The Sulphur Creek watershed is underlain primarily by the Late Cretaceous to Early Jurassic Franciscan assemblage, with smaller isolated outcrops of Tertiary Sonoma rhyolitic lava flows. The Franciscan assemblage includes a mélange of sheared shale and sandstone with some chert, high-grade metamorphic rocks, shattered sandstones and greenstones, and serpentinite. The Franciscan assemblage supports high topography and steep hillslopes, and is notorious for its erosion potential. After Sulphur Creek exits the uplands, it flows across a Quaternary old fan, and inset Quaternary young fan. The old alluvial fan consists of deeply weathered, poorly sorted coarse sand and gravel, whereas the young alluvial fan consists of moderately sorted fine sand and silt, with gravel more abundant toward the fan head, or upstream portion.

Landslides and other mass movement events are important geomorphic agents in this watershed. Many landslides were observed in Heath Canyon, along the main stem, and along the north and south branches of the creek. The underlying geology is prone to failure; the Franciscan formation is highly fractured and sheared, thus providing a source of fine sediment to the channel when failures occur. Katzel and Larsen (1999) documented some inactive shallow landslides and two deep-seated active landslides on the hillslopes of the North Branch. They estimated that the oldest slide has contributed 46,000 yds³ (35,115 m³) of sediment to the channel since the slide occurred sometime before 1942. A second, and larger slide on the North Branch is named Devil's Slide by the locals, was active by at least the 1860's (Historical Ecology), and was reactivated during the wet season of 1982/1983 (Phill Blake, pers. comm.).

Soils

The soils mapped by Lambert and Kashiwagi (1978) can be generalized and divided into three main reaches of the Sulphur Creek watershed: the alluvial fan, Heath Canyon, and the Main stem/North Branch. The lowest reaches of the alluvial fan have gravelly loam soils formed on alluvium and floodplains, which outside of St. Helena, are used for vineyards. Upstream of Highway 29 (Main Street), the channel flows through riverwash, a unit defined as sand, gravel and cobbles of the active stream channel and floodplains. This reach has a constant deposition and removal of material, and has historically been the site of gravel mining. In the uplands of Heath Canyon, the soils that have developed on slopes between 30 and 75%, are characterized by rapid runoff and high rates of erosion, and are primarily used as range and watershed lands. In the Main stem/North Branch, the soil types are more diverse. They include soil series on slopes from 30 to 75% formed on convex sandstone and shale hillslopes, characterized by rapid runoff, high rates of erosion, and a primary landuse of range, watershed or limited timber harvesting. Also found are rock outcrops with slopes between 30 and 75%, and other soil types on slopes between 5 and 30%, medium runoff, slight to moderate rates of erosion, and are used for grazing, vineyards, and timber harvesting.

Climate and runoff

Precipitation is measured at the California Department of Water Resources St. Helena 4WSW gauge in the upper portions of the watershed, at an elevation of 543 m (1780 ft). Based upon incremental precipitation data collected from January 1984 to the present, the average annual precipitation is 886 mm (34.88 in) (www.whr.noaa.gov/Monterey/cpm/seasontotals.htm), however the total is quite variable as demonstrated by the total for water year 2000 of 1101 mm (43.36 in) and the water year 2001 total of 674 mm (26.52 in). Also, a significant amount of daily data was missing from the record between 1984 and 1997, affecting the calculated annual average. The town of St. Helena receives less rainfall than the higher elevations of the watershed.

The USGS maintained a gage site on the main stem of Sulphur Creek, just upstream from the confluence with Heath Canyon that recorded daily discharge from February 1, 1966 to September 30, 1967 (Figure 2). During this time, the average discharge was 0.17 m³/s (6.0 ft³/s), and the peak discharge was 8.50 m³/s (300 ft³/s) for this 11.65 km² (4.5 mi²) drainage sub-basin. Katzel and Larsen (1999) report that bankfull discharge (recurrence interval of 1.5 years) is 14.2 m³/s (500 ft³/s) for this sub-basin. Peak discharges were recorded for the period between 1956 and 1973, with a maximum discharge of 27.8 m³/s (980 ft³/s) in December of 1964.

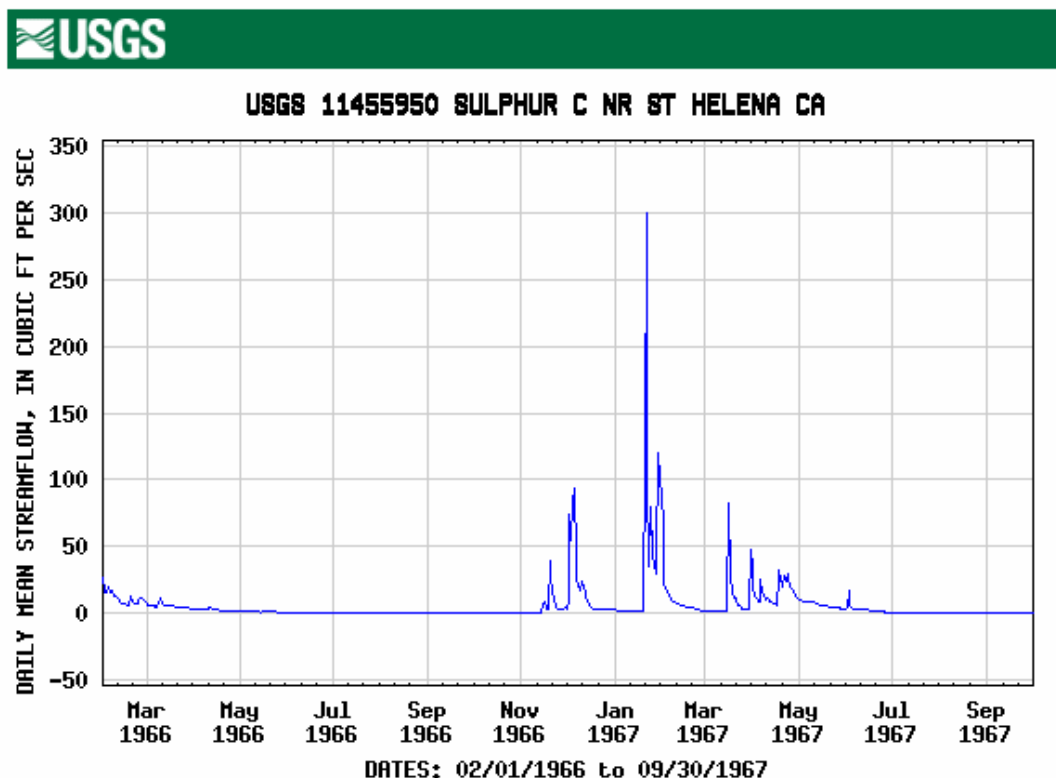


Figure 2. USGS gage data for Sulphur Creek near St. Helena (gage number 11455950). The data is from February 1966 to September 1967.

Land use

The alluvial fan portion of the watershed is primarily urban, including the city of St. Helena, and also includes a historic gravel mining operation, and some vineyards. The Heath Canyon sub-basin is primarily undisturbed forested watershed, with some limited grazing. The Main stem/North Branch sub-basin is also primarily undisturbed forested watershed, but also includes vineyards, rural residential housing, and evidence of past grazing and logging. Based upon the Calveg primary vegetation type, the Main stem/North Branch and Heath Canyon sub-basins of Sulphur Creek support mixed hardwoods, annual grasses and forbs, Pacific Douglas Fir, Coast Live Oak, and Redwoods, with smaller patches of Douglas Fir Pine and Northern Mixed Chaparral (NCCDP, 2002). Along the channel, young alders and willows are found (Katzel and Larsen, 1999).

Prior to 1999, an approximately 1219 m (4,000 ft) reach of Sulphur Creek from the Crane Valley Road/Valley View bridge to the Heath Canyon confluence was historically mined for gravel for well over a century (Historical Ecology). The mining process significantly modified the channel, including the removal of riparian vegetation and a yearly modification of the channel morphology and location as the channel was excavated. These conditions likely created a partial migration barrier for salmonids, or at least provided a stressor during migration. Despite the modifications in channel form caused by gravel mining, the channel was most likely wide and lacking significant riparian vegetation before any gravel mining began. Both historically and currently, salmonids have been observed upstream of this reach, suggesting that the salmonid population is able to overcome the less than ideal conditions.

California Department of Fish and Game Stream Surveys

Historic stream surveys were completed by the California Department of Fish and Game (CDFG) in 1941, 1958, and 1980. Other documents describing either fish population studies, or fish rescues from 1969, 1981, and 1989 also exist for Sulphur Creek. The August 23, 1941 stream survey by Brian Curtis of the CDFG described Sulphur Creek on McLure Kelly Ranch. The average stream width was two feet (0.6 m), average depth was two inches (5 cm), with a boulder and bedrock bed, dense arboreal shading, a few pools and occasional three ft (0.9 m) falls. Trout (Rainbow trout? [sic]) were reported although the stream was described as having few spawning areas. Also noted were reports of steelhead runs in this section of the stream, and the drying up of Sulphur Creek in July before it reaches the Napa River, but the persistence of water in the upper Redwoods section.

The October 28, 1958 stream survey by Elwell and Jones described Sulphur Creek as having an average width of 3.5 ft (1.1 m), and an average depth of four inches (10 cm). The channel bed was predominantly rubble and gravel, with the exception of the Northwest tributary which had a large amount of silt from landslides. The headwaters had perennial flow, however, the lower portion (through an area of vineyards and orchards) of the stream was dry during the summer. The canyon reach and the headwaters had ample

shading from conifer, bay and alder trees. Pools were abundant except in the lower dry section, and a 200 yd (183 m) dry section above the Methodist Camp [White Sulphur Springs Resort], with an average pool geometry of 6 ft x 4 ft x 10 in (1.8 m x 1.2 m x 25 cm). Ample rock and overhanging bank shelter was noted, along with an earthslide on the northwest tributary, which acted as a complete migration barrier. Spawning gravel was described as very good in the lower and midsections of the creek, with poor to fair gravels in the headwaters. RT-SH (Rainbow Trout-Steelhead) were reported as common in the lower section, scarce in the upper 1/8 mi (200 m), and few in the lower northwest tributary. No fish were reported upstream of the earthslide. Elwell and Jones concluded that Sulphur Creek was very good spawning and nursery habitat, with the exception of the earthslide area, and overall hampered by the drying up of the lower sections in the summer.

The May 23, 1980 survey by Ellison and Hobson described Sulphur Creek as having an average width of 3.5 ft (1.1 m) and an average depth of 6 in (15 cm). The upper 2/3 of the stream had a rubble and gravel bed, while the lower reach had a fine to moderate gravel bed, with patches of mud near the mouth. On this survey date, flow was contiguous, however it was noted that the lower reach goes dry in the summer. Riparian shading was well developed in the canyon reaches, consisting of conifers, alders and bay trees, however from the mouth of the canyon to the Highway 29 bridge, the channel and its riparian vegetation was described as being severely degraded from gravel removal operations. Downstream of the Highway 29 bridge, the channel had fair to good riparian shading from riparian alder and oak trees. This reach of channel flows through a highly urbanized area, is confined, and had portions lined with concrete and riprap. Spawning gravels were described as very good in the mid and upper portions of the stream, however the reach along the valley floor was lightly to heavily silted. Shelter in the form of large rocks and undercut banks was fair, and the only potential migration barrier noted was the summer crossing culverts under Sulphur Springs Avenue. Pools were fair in the upper 1/3 of the watershed, typically 20 or 25 ft x 4 to 10 ft x 1.5 to 2 ft (6.1 to 7.6 m x 1.2 to 3.0 m x 0.6 m), but the pools diminished in length and depth in the lower sections. An electrofishing survey of four stations found five steelhead, and some roach, stickleback, and lamprey at a station near the mouth, one steelhead, roach and some fry downstream of the Highway 29 bridge, two steelhead, roach and sculpin on the mainstem of Sulphur immediately upstream of the canyon mouth, and 17 steelhead and some sculpin at the confluence of the Northwest branch and the mainstem. Overall, Sulphur Creek was classified as having good spawning and nursery habitat for steelhead, but the limiting factors included the stream and riparian degradation in the gravel extraction reach, and moderately developed pools and shelter in the upper sections. Ellison and Hobson recommended stricter standards in the gravel extraction reach to allow for the return of riparian vegetation.

Other documents on file at the CDFG offices include fish population sampling in 1969 and 1989, and a fish rescue in 1981. The August 12, 1969 fish population survey used electrofishing techniques at a single location near the confluence of the Northwest branch and the mainstem. A total of 164 steelhead and 58 sculpin were measured, giving an estimate of approximately 170 fish per 100 ft (30 m) of stream. At this location, the

mean width was 6.2 ft (1.9 m), the mean depth was 0.5 ft (0.15 m), and discharge was measured as 0.04 ft³/s (0.001 m³/s). The July 14, 1989 fish survey sampled the mainstem of Sulphur Creek in three locations, all upstream of the White Sulphur Springs Resort, finding western roach, sculpin, and juvenile steelhead. The June 16, 1981 fish rescue removed approximately 700 young of the year steelhead from Sulphur Creek, downstream of a concrete sill associated with a bridge abutment. Fish were removed because the water temperature was 69° F (20.5 ° C), the sill acted as a migration barrier, and the downstream reach was drying up.

In addition to the historic surveys, a survey of the number of steelhead trout in the Napa River and its tributaries was completed by Ecotrust, Friends of the Napa River and the Napa County Resource Conservation District (RCD) in 2001. Steelhead were observed primarily in the foothill tributaries, especially along the west side of the valley, and were absent from the alluvial fan reaches of tributaries as well as from the mainstem of the Napa River. A majority of the surveyed reaches of the Sulphur Creek watershed had at least 0.5 steelhead/m², with some reaches having >1 steelhead/ m².

METHODS

This field-based fluvial geomorphic study of Sulphur Creek was designed and implemented using the Bay Area Watershed Science Approach (WSA, Collins and Collins, 1998) as a reference methodology. The methods described here were used in a previous study, the Napa River Sediment TMDL Baseline Study: Geomorphic Processes and Habitat Form and Function in Soda Creek (Pearce et al., 2002). The methodologies have been refined slightly to suit the needs of the Sulphur Creek stewardship.

Startup and review of available data

All available relevant maps, aerial photographs, plant species maps, rainfall and stream flow data for the region was compiled. These were used to:

1. Develop a regional flood frequency curve to help describe the basin,
2. Plot the longitudinal profile of the channel from the blue line on 1:24,000 USGS quadrangle sheets,
3. Establish the locations for the survey of channel cross-sections, field collection of channel bed, bank and terrace conditions and erosion,
4. Develop a comparison of bankfull width and depth to published regional curves.

Five segments, or strata, each identified by a characteristic slope were revealed by a visual inspection of the longitudinal profile. Because channel slope is a good predictor of channel morphology (e.g. Montgomery and Buffington, 1997), these five strata were used to organize the sampling strategy in Sulphur Creek. The sample strata were numbered I through V, with Stratum I being the furthest downstream near the confluence with the Napa River, and Stratum V being the furthest upstream in the headwaters of

Sulphur Creek. Two sample reaches in Stratum I, II and III were characterized in the field (e.g. sample reach 1A, sample reach 1B, sample reach 2A, sample reach 2B, and so on). One sample reach in Stratum IV and V was sampled for each sub-basin: Heath Canyon, Southwest Branch and the Northwest Branch. The South Branch was not sampled due to the similar slope to the Southwest Branch, and also for logistical issues. Data was collected from a total of 12 sample reaches to characterize Sulphur Creek (Figure 3).

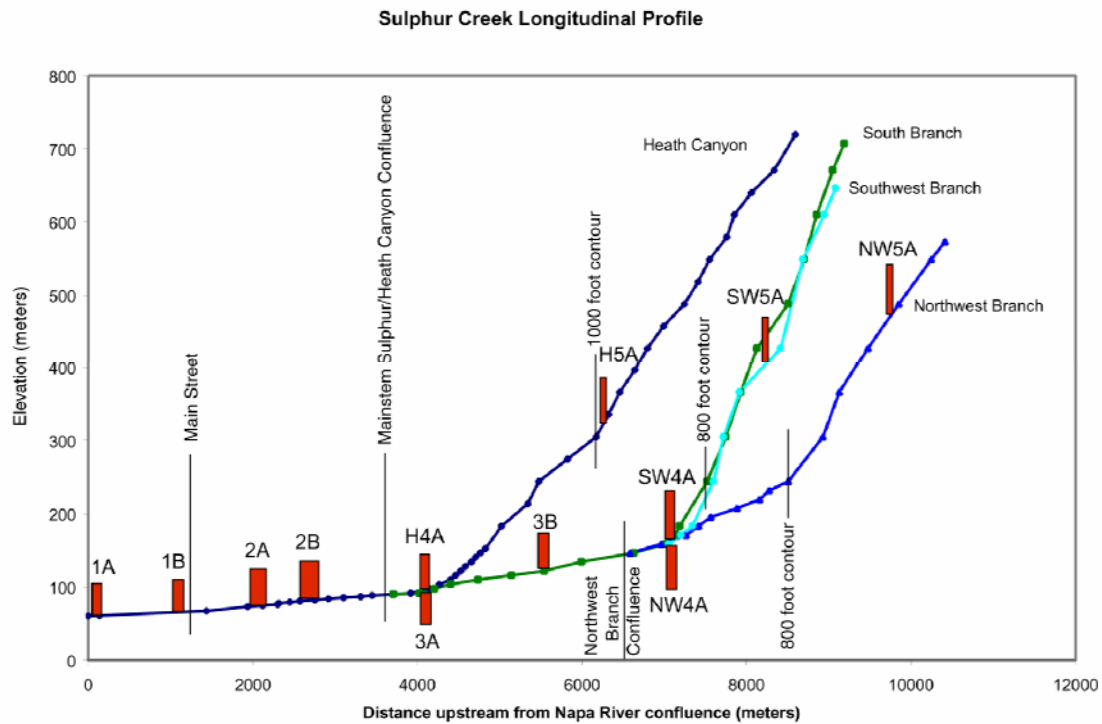


Figure 3. Longitudinal profile of Sulphur Creek. Red rectangles represent sample reach locations, while vertical thin lines represent Strata boundaries.

Table 2. Sulphur Creek Reach Geomorphic Characteristics.

Sample Strata	Sample Strata % slope (USGS map)	Cumulative drainage basin area (km ²)	Sample Reach	Drainage Basin Area above Sample Reach (km ²)	Sample Reach length (m)
I	0.47	24.19	1A	24.19	175
			1B	23.10	200
II	1.00	23.05	2A	19.11	275
			2B	18.90	300
III	1.93	18.62	3A	11.42	150
			3B	10.00	150
IV	9.47	6.99	Heath 4A	4.68	100
	10.93	4.46	Southwest 4A	4.25	62.5
	10.07	4.92	Northwest 4A	4.37	150

V	17.12	1.99	Heath 5A	1.99	67.5
	27.13	1.86	Southwest 5A	1.86	75
	17.27	0.58	Northwest 5A	0.58	87.5

The length of each sample reach was 25 times the measured bankfull width. A sample reach of this length is necessary to capture in-channel features such as pool-riffle sequences, which develop in natural streams with coarse sand or larger bed material (Leopold, 1994). An adequate sample of potential pools, which tend to have a spacing of 5 to 7 bankfull widths in meandering alluvial streams (Leopold et al., 1964; Dunne and Leopold, 1978), is assured by imposing a minimum survey length of 25 bankfull widths. Sample reaches within each stratum were selected by a comparison between the longitudinal profile and the map of property access.

A simple field protocol was used to randomize the start point for the sample reach. A random number was generated, representing the location where the sample reach would begin within the accessible area. The distance to the randomly selected point was measured from a mapped benchmark location such as a bridge, a property boundary, or a confluence. This point was flagged and the bankfull width was measured based on visual field indicators (e.g. Harrelson, et al., 1994) along the channel banks in the vicinity.

Indicators of bankfull include, but are not limited to: the break in slope between the bank and the floodplain, a small break in slope of the bank, a change in vegetation type or density, the top of a bar surface, or the change from absence to presence of leaf litter. Based on this measurement, field flagging was placed at intervals of five times the bankfull width until a total of 25 bankfull widths of channel had been flagged. The spatial intervals provided a systematic random sampling frame for selected field data summarized in Table 3.

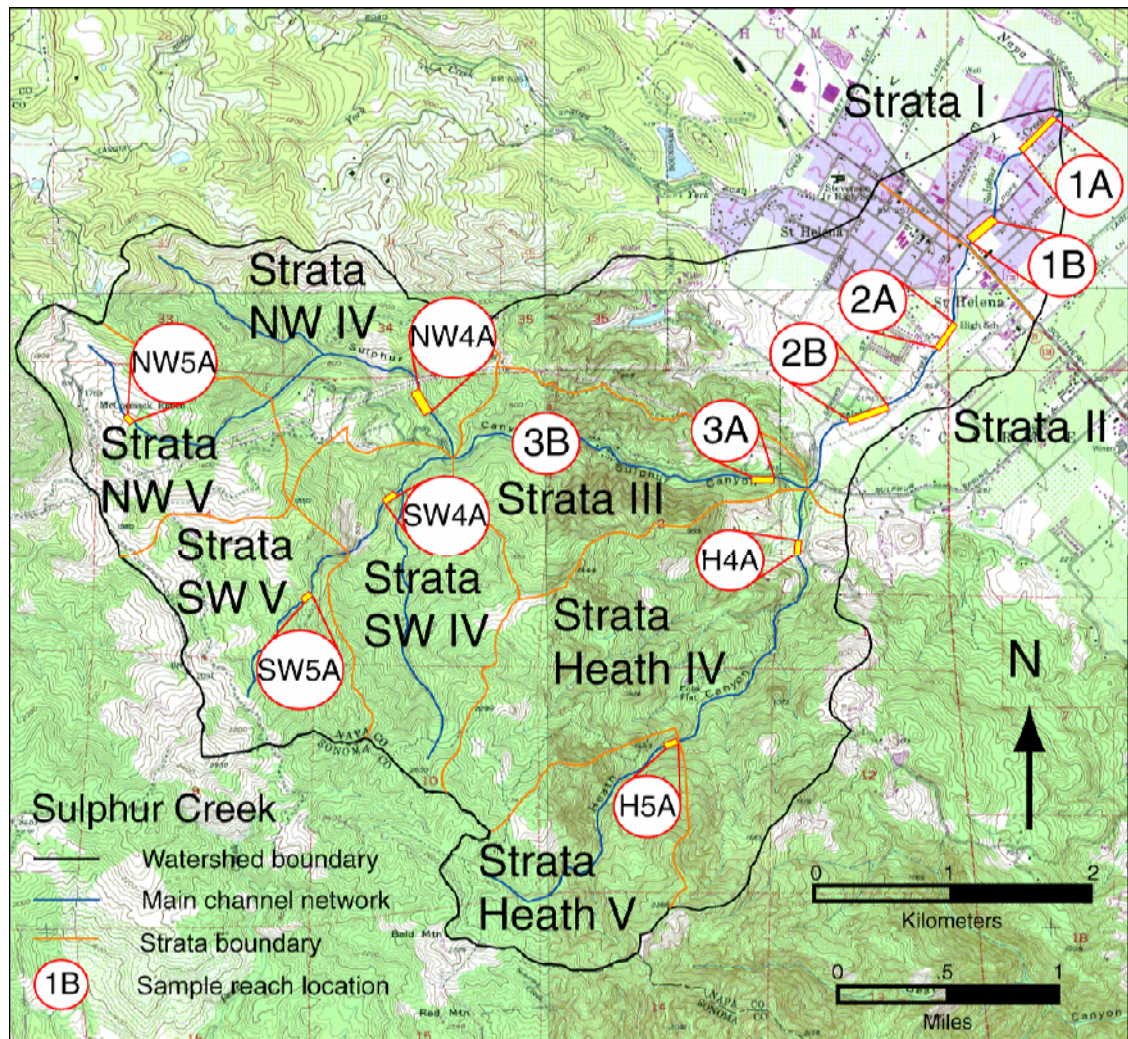


Figure 4. Map of the Sulphur Creek watershed, sample Strata, and sample reach locations.

Table 3. Field measurements in each sample reach.

Distance (in bankfull widths)	Slope (rise/run)	Cross-section	Pebble count	Bank characterization
0 (downstream)	X			
5	X	X	X	X
10	X		X	
15	X	X	X	X
20	X		X	
25 (upstream)	X	X	X	X

All distances in the field were measured using a Forestry Suppliers model metric hipchain (calibrated to 0.1 m). Field notes were indexed by the distance on the hipchain, but were not geo-rectified. Over a distance of 200 meters the accuracy of the hipchain was approximately $\pm 2\%$ (determined by using one field test consisting of running the hip chain twice along with a metric cloth tape, and also based upon previous experience). After the sample reach had been subdivided as described above, data were collected systematically in 1. Channel cross sections, 2. Continuously along the channel length and 3. At spot locations (for a minority of data).

Data collected in channel cross sections

Channel geometry

In each sample reach, three channel cross-sections were measured to explicitly incorporate in the data the variability in channel geometry both along the sample reach, and between sample reaches. The cross-sections were measured at a distance equal to 5, 15, and 25 times the bankfull width upstream from the start of the sample reach. A 100 m cloth measuring tape was strung between the ends of the cross-section, perpendicular to the channel axis, with zero always on the left bank. A telescoping survey rod and an optical hand level were used to measure the depth in the cross-section relative to the surveyor's eye. Field notes describe channel forms and the location of visual indicators of bankfull height. Cross-section surveys were not tied into a geodetic survey point.

Surface sediment size analysis

In each sample reach, pebble counts at five cross section locations were performed following methods proposed by Bunte and Abt (2001). A systematic random sampling approach was chosen wherein 80 clasts were measured in a grid pattern scaled to the local bankfull width and maximum particle size and centered on the five cross section locations in each sample reach. In most cases, 0.25 to 0.5 m spacing between measures was adequate to avoid double counting a single clast. However, if a single clast was large enough to be counted twice, one measurement and one "no count" was recorded. Clasts were selected by a finger touch guided to a location in the grid, but with eyes averted to retain random selection. Clasts were measured with a ruler and reported as the $\frac{1}{2}$ phi sieve mesh on which the particle would be caught (i.e., 2, 4, 5.6, 8, 11, 16, 22 mm etc.). Clasts finer than 2 mm were reported as < 2 mm. Although it is difficult to select and manipulate the smallest diameter sizes, care was taken to minimize observer bias and measurement error for the finer grain sizes. A total of 400 clasts per sample reach were measured to produce a statistically robust estimate of surface sediment size distribution for the sample reach (Bunte and Abt, 2001).

Bank Characterization

Data were collected on the bank and terrace condition and erosion, the extent of riparian forest, and field observations of plant and wildlife species at three out of the five cross-sections in each sample reach. The three "spot measurements" within a sample

reach allow comparisons of the bank composition and vegetation to be made between sample reaches, highlighting areas that are potentially more susceptible to erosion, and allowing an analysis of the interaction of the riparian vegetation with the channel. A description of the riparian zone vegetation and management on the terrace or hillslope adjacent to the stream were also included.

Canopy Cover

The percent canopy cover was estimated at all five cross section locations in each study reach. While standing in line with the cross-section, and in the middle of the channel, the sky was visually divided into quadrants, with the divisions being parallel and perpendicular to the channel. Each quadrant was classified as “shaded” or “open” with respect to overhead vegetative canopy. The percent canopy cover is the percentage of quadrants that are classified as “shaded”. Although this is a relatively crude measurement of canopy, the intent was to distinguish open sites from shaded sites in the context of the riparian vegetation providing shade to maintain a water temperature appropriate for fish habitat.

Continuous channel metrics

Along the entire length of each sample reach (25 bankfull widths), data were collected on type and volume of gravel bars and other deposits of mobile sediment, pool type and size, bank conditions including erosion, and large woody debris (LWD) characteristics and abundance.

Gravel bars and mobile sediment deposits

The objective of this survey protocol is to quantify the volume of the active portion of the streambed, which is conceived to be the portion of the stream that is ordinarily entrained as bedload and can be routed through the entire channel network in a period of decades. The definition of “active” is potentially subjective, and the surface size distribution of individual bars and other deposits of sediment are compared against the size distribution of more stable, coarse-textured reaches to identify active sediment deposits and bars. In general, gravel and sands are regarded as mobile in ordinary peak stream flow events (i.e. extreme floods are not required), cobbles may be regarded as mobile depending on circumstances, and boulders are regarded as essentially immobile with respect to downstream sediment routing. Consequently, point bars are considered active, as are relatively fine textured deposits of sand and fine gravel in pools. Plane bed reaches with abundant cobbles and sometimes boulders are considered to be marginally active because a high proportion of the bed surface is comprised of sediment clasts with low mobility. Plane bed reaches, and streams with a high proportion of cobble and boulder in the bed, may have substantial storage of gravel and sand in pockets formed between the larger clasts.

The average depth, width, and length of individual bars and sediment deposits were measured to the nearest 0.1 m. Width and length of deposits are relatively easily

identified, however, depth frequently requires consideration of field evidence of likely depth of the deposit, including likely depth of scour. Depth of larger bars is typically determined as a function of the average bar height relative to the thalweg elevation measured adjacent to the bar and/or in pools upstream and downstream. A shape factor (adjustment of deposit depth) is typically included where the bar cross-section geometry is regarded as triangular, with the maximum bar height and the thalweg depth defining the hypotenuse of a right triangle; for a smoothly sloping bar, the shape factor is 0.5, and the average depth of the deposit is estimated as one-half of the maximum bar height above the thalweg. In other words, in order to accurately portray the true thickness of a deposit, an adjustment of the deposit depth is made for deposits that are not rectangular in shape. The shape factor is adjusted on a case-by-case basis to best represent more complex bar geometry for purposes of estimating sediment volume. For some other general types of sediment deposits, depth of the active layer of sediment was estimated according to the following methods.

For fine textured deposits, the depth can often be probed with a metal rod, or estimated by digging with the heel of a boot. In pools, the maximum pool depth can be compared with the water depth over fine-textured pool deposits, and an estimate of the depth can be made by subtraction. More detailed methods described by Lisle and Hilton (1999) are relatively accurate, but require more time than feasible for this more generalized protocol.

In coarse textured channel segments with relatively shallow and uniform depth, the typical depth of scour determines the depth of the active layer during peak flows. The scour depth is thought to be controlled by the size of the larger sediment clasts on the bed. DeVries et al., (2001) suggested that D₈₄ (the diameter for which 84% of sediment is finer) is an approximate predictor of the depth of scour in ordinary peak flow events in reaches dominated by cobble size clasts. In practice, particularly in coarse bedded channels such as the upper reaches of Sulphur Creek where boulders are not uncommon, the estimated depth of the active bed for purposes of estimating active sediment storage rarely exceeds 0.1 m.

The minimum size criteria for surveyed gravel bars were length or width larger than 1 m. Although a wide range of bars were measured, calculations show that the larger bars dominate the reach total volume of sediment storage, and thus, measuring bars near the nominal 1 m threshold will not significantly alter the reach total sediment storage calculations. Hence, the overall interpretation of data is not very sensitive to the minimum bar size used in this investigation.

Bars and sediment deposits were categorized according to the following classifications: alternate, active channel, pool deposit, forced, point, secondary channel, medial and lateral bars. Classification of bars and deposits is of secondary importance to measurement of dimensions for volume estimates. This style of bar classification is similar to that used in the Stream Channel Assessment of the Washington DNR Watershed Analysis Methodology (Washington Forest Practices Board, 1997). Alternate bars are formed in relatively straight channels with moderate gradients and are somewhat

analogous to point bars in meandering streams (Lisle et al., 1991). Active channel deposits include mobile bed material deposited on the channel bed, but not in the form of a bar; this category may include patches of sand and fine gravel dispersed in pockets of relatively immobile boulder and cobble clasts. Pool deposits are similar to active channel deposits, but are located in pool bottoms or pool tails. Forced bars are formed in the lee of flow obstruction such as woody debris or live vegetation, boulder clusters or bedrock outcrops. Point bars are formed opposite pools in meander bends. Secondary channel deposits are similar to active channel deposits, but occur in a discrete overflow or backwater channel. Medial bars occur in the center of a channel where a channel diverges into multiple threads, and are typically associated with localized zones of accelerated bed load deposition. Lateral bars are found on channel margins and are presumably formed in areas of local deposition associated with flow divergence or bank roughness, but lack any discrete roughness element as for forced bars.

In portions of Sulphur Creek, a substantial portion of the mobile sediment consists of coarse sand and fine gravel deposited in small pockets formed by the relatively immobile cobble-boulder bed. The patches of relatively fine, mobile sediment are conceptually similar to sediment deposits in pools described by Lisle and Hilton (1999). For measurement, these “active channel” deposits were often aggregated over larger channel lengths than individual gravel bars. The stability of the bars and sediment deposits were estimated based upon the age of vegetation growing on the deposit, the type of deposit, as well as the dominant grain size of the deposit. The age estimates were categorized as approximate age class intervals of deposit mobility: < 1 yr, 1-5 yr, 6-19 yr, and 20 yr +.

Pool type and size

The surface dimensions (average length and width) and residual depth (maximum pool depth minus tail-out depth) of significant pools were measured to the nearest 0.1 m (Lisle, 1999). The minimum size criteria for measured pools was length or width larger than 1/4 the bankfull width, with all pools at least 1 m in width or length. Minimum pool size for inventory purposes was defined as residual depth > 0.2 m. The length and width measurements in the field were adjusted for fluctuation of water elevation, and were intended to capture the pool dimensions for the pool defined by the residual depth. Pool classification was accomplished with a modified version of fish habitat inventory methods (Flosi, 1998). An index of pool volume was computed as the product of pool length, width and residual depth; actual pool volumes were not measured. Classification of pools focused on apparent mechanism of formation and secondarily on descriptive morphology. Pools were categorized according to the following classifications: step-pool, plunge pool, dammed pool, main channel/bedrock trench pool, and lateral scour pool (Table 4).

Table 4. California Department of Fish and Game Level III and Level IV Habitat Types, 1998.

Sulphur Creek Pool Classes	Cal. Dept. of Fish and Game Classifications 1998
Step-pool	Step pool (STP) [4.4]
Plunge pool	Plunge pool (PLP) [5.6]
Dammed pool	Dammed pool (DPL) [6.5]
Main channel/Bedrock trench pool	Mid-Channel pool (MCP) [4.2], and Trench pool (TRP) [4.1]
Lateral scour pool	Level III, Scour pool. Includes: (LSL) [5.2], (LSR) [5.3], (LSBk) [5.4], (LSBo) [5.5]

Bank conditions and erosion

The presence and location of man-made structures including revetments, grade control, bridges, and culverts were recorded. Two measurements were taken in regard to indicators of bank erosion: an average distance of retreat and an average height over which erosion was evident. These measures, when combined with the length of bank that was eroding, gave an average volume of erosion. Indicators of erosion include exposed roots of trees, overhanging vegetation, bank undercut, and undercut bank revetments or bridge pilings. When possible, an estimate of the age of the vegetation or structure was noted, to allow estimation of the rate of erosion. The type, condition, and a general estimate of age of revetment were recorded along with its location along the bank.

Large woody debris

Data on large woody debris (LWD) characteristics in this study were measured according to the methodology developed by O'Connor Environmental, Inc. for the Garcia River TMDL Instream Monitoring Program and for Watershed Analysis in Humboldt County for the Pacific Lumber Company (Table 5) (Forest, Soil and Water, Inc., O'Connor Environmental, Inc., and East-West Forestry, 1998). Data collected on LWD and living trees only included pieces larger than 20 cm (8 in) in diameter and 1.8 m (6 ft) in length. Other data collected for LWD and live trees in the bankfull channel included the position of the piece relative to the bankfull channel, the species if known, the decay class, if the piece was associated with a pool, the entry process for the piece if known, if the piece was a part of a debris jam, and if it was a key piece in the debris jam. These data allow for assessment of the role of LWD in channel morphology, including formation of pools, sediment storage sites, and the effects on flow hydraulics and roughness.

Table 5. Large woody debris (LWD) field survey abbreviation key.

LWD Survey Abbreviation Key		
Minimum LWD Dimensions = > 20 cm diameter and 1.8 m length		
Mid-point diameter	Length	Distance fell from
Position 1 = in low-flow channel (LF) 2 = portions in both LF & BF 3 = in bankfull channel (BF) 4 = portions in both BF & above BF 5 = above the BF channel 6 = portions in LF, BF & above BF	Type 1 = log 2 = snag 4 = live log up 5 = Rootwad 6 = live log down 7 = log with rootwad	Species 4 = Alder 6 = Willow 7 = Oak 8 = Bay Laurel 9 = Unknown Hardwood 10 = Ash
Decay Class 1 = bark intact, limbs, twigs, and needles present 2 = bark intact, limbs and twigs present 3 = bark intact, limbs absent 4 = bark loose or absent 5 = bark absent, surface slightly rotted 6 = sruface extensively rotted 7 = sruface completely rotted, center solid 8 = surface and center completely rotted	Pools (2 letter code) First letter a = LWD associated f = formed by LWD nn = no pool Second letter s = shallow, depth < 1 m d = deep, depth > 1 m	
Entry Process if logging debris (sawmark) add 0.5 1 = bank erosion 2 = windthrow 3 = mortality 4 = landslide 5 = enhancement structure 6 = unknown	Key Piece independently stable and in bankfull width or is retaining other pieces of organic debris Debris Jam (must satisfy 3 criteria below) 1 = contains at least one key piece 2 = spans at least half the bankfull channel 3 = contains 10 or more LWD pieces	

Additional spot measurements*Bulk sediment size analysis*

Spot sampling sediment size distribution at likely spawning sites was conducted with a 35 cm diameter McNeil streambed sampler at locations distributed across sample reaches that were accessible to anadromous fish. Potential spawning sites were located by reconnoitering study reaches and locating the first well-defined pool tail out or the upstream edge of a riffle located between upstream and downstream pools. Sample sites were often dry at the time of sample collection. The McNeil sampler was inserted into the

bed to a depth of >15 cm by simultaneously twisting and applying downward pressure on the sample barrel. Bed material enclosed within the sample barrel was then excavated. The coarser layer on the surface of the streambed was included in the sample; however, the majority of the sample was subsurface material. The three largest clasts were measured and weighed in order to determine the proportion of the sample represented by the largest clast; this provides perspective on how representative the sample is with respect to the full size distribution of the streambed. All clasts coarser than 50 mm were removed from the sample during excavation, sorted according to 50 mm, 64 mm and 90 mm median diameter, and weighed in the field to the nearest 0.1 lb (45 g) using an electronic fish scale. Material finer than 50 mm was collected in buckets and transported to a contract geotechnical lab for size analysis according to ASTM C-136.

An analysis of subsurface streambed sediment size distributions was completed to provide quantitative data on spawning habitat quality. The approach described by Kondolf (2000) provided the guiding principles for assessing habitat quality with respect to sediment size distributions. Three sediment size criteria were evaluated in relation to critical biological aspects of spawning. First, the 50th percentile (D50) and 84th percentile (D84) of the bed material is considered with respect to whether spawning fish are likely to be able to move these “framework” clasts during construction of the redd. Second, the percentage of bed material finer than 1 mm was considered with respect to whether fine sediment will affect incubation of eggs in redds. Finally, the percentage of bed material finer than 6.35 mm was considered with respect to whether fine gravel will affect emergence of fry from the redd.

Field measurements of slope

Stream slope measurements were made using a telescoping survey rod and a hand level. The relative height of the thalweg was recorded every five bankfull widths. Slope was calculated as rise in elevation over horizontal run (approximately the same as channel slope distance), and is reported in percent slope. The average reach slope reported for each sample reach is the total elevation change divided by the total distance.

Bed shear stress

The bankfull width and depth measurements taken along the entire length of the channel in each study reach help to assess relative bed load sediment transport capacity at different locations in the stream channel network. Bed load sediment transport is generally a function of bed shear stress. To provide an index value of shear stress that is likely to be significant with respect to bed load transport rates, reach average bed shear stress has been computed for bankfull flow conditions (roughly the 1.5 to 2 yr recurrence interval flood). Only a limited analysis is intended for general interpretive value.

Reach average shear stress was computed as the product of the hydraulic radius (channel cross-section area divided by channel wetted perimeter) at each of three cross-sections measured in each reach, reach average channel slope (assumed to be the best estimator for water surface slope at bankfull flow), and constants for gravitational

acceleration and the density of water. The steeper or deeper a channel is, the more bankfull shear stress it will have, allowing it to transport larger grain sizes.

Bed load transport capacity

An assessment of relative bed load sediment transport capacity is provided for each reach by comparing bankfull bed load shear stress estimates with a theoretical bed load transport threshold shear stress. This is accomplished by computing the shear stress necessary to mobilize the stream bed using D50 of the bed surface from surface sediment size distribution data obtained in the field for each reach. Threshold shear stress is computed as the product of critical dimension Shield's stress (0.052), the immersed density of sediment (density of sediment minus density of water, with sediment density assumed to be 2.65 g/cm³), gravitational acceleration (a constant), and reach D50. This quantity should be interpreted as the shear stress required to mobilize the majority of the stream bed; initial motion of the stream bed, or minor, local bed load transport would potentially occur at lower bed shear stress.

Relative bed load transport capacity among reaches was then assessed by forming the ratio of estimated bankfull bed shear stress to estimated critical bed shear stress (the "bankfull shear stress ratio"). When this ratio is greater than or equal to one, bed load transport is expected; when this value is less than one, significant bed load transport is not expected. However, the estimated bed shear stress for bankfull flow conditions is relatively crude, and does not account for flow resistance differences in the channels and consequent extraction of momentum from the flow which is not applied to the grains on the stream bed. The estimated bed shear stress is thus likely to overestimate the actual shear stress available for bed load sediment transport. Nevertheless, the ratio of total shear stress to critical shear stress provides a quantitative assessment of relative bed load transport capacity for comparisons among reaches within the watershed.

RESULTS

Channel Geomorphology

Fieldwork on Sulphur Creek was led by SFEI during the summer and fall of 2002. The data collected included a survey of grain size distributions, channel slope, channel cross-sections, large woody debris, pools, sediment deposits and bars, bank erosion, bank characterization, and channel hydraulic geometry. All numerical quantities are rounded to the nearest whole number unless additional accuracy is certain or relevant.

Surface grain size variation by reach

Surface grain size distributions in the lower reaches of Sulphur Creek are generally finer and much more variable from reach to reach, when compared with

distributions from the upper reaches (Figures 5 and 6, Table 6). In the lower reaches, median grain size (D50) ranges from 8 mm in reach 1B up to 31 mm in reach 3A. In the upper reaches, D50 ranges from 29 mm in H4A up to 48 mm in NW5A. Generally, the median grain size decreases downstream, a pattern typical of alluvial channels.

The percentage of fines (grain sizes finer than 2 mm) measured in the surface sediment ranges from 32% in reach 1B to 0% in reach 2B, with most near 7%. The very low percentage of fines (0% included) do not always accurately portray the amount of fine sediment present, but instead serves as an estimate. For example, in some stream systems, surface fines are winnowed, or selectively removed from the spaces between larger clasts. Bulk sediment samples provide a better measure of the proportion of fine sediment present in the subsurface. However, these surface fine sediment estimates do allow us to compare reaches within the watershed, and also to compare statistics derived using the same methodology among other watersheds. Based upon surface sediment measures, Sulphur Creek generally has relatively low amounts of fine sediment in storage. Reach 1B is an exception because it has the highest amount of surface fine sediment, the lowest D16 (the particle size for which 16% of the sample is finer than), the lowest D50, the lowest slope, and is highly affected by an invasive plant species (*Arundo donax*) and the town of St. Helena. The majority of fine sediment stored in this reach is in the form of pool deposits and large fine-textured bars that are armored with dense patches of shrubs and blackberry bushes.

The upper sample reaches, especially H5A, have many large cobbles and boulders. Although these boulders are only potentially mobile during the highest discharges, they have important effects on channel processes. These boulders increase hydraulic roughness, dissipate energy, help sort and store gravels, and provide a velocity shelter for fish habitat. The boulders also have morphologic influence in the channel, commonly forming step-pools in the upper reaches.

Nearly half of the sample reaches in Sulphur Creek have some in-channel bedrock outcrop. Sample reach SW4A has the largest percentage (19%) of bedrock outcrop, followed by H5A, SW5A, NW5A, and H4A. Sample reach 2A has an area of poured concrete in-channel that effectively acts as bedrock, limiting scour, and serving as a local baselevel control. In some reaches, the exposed bedrock is highly fractured and weathered, providing an easily erodable source of fine sediment to the channel, while in other reaches, the bedrock is massive and provides almost no sediment to the channel.

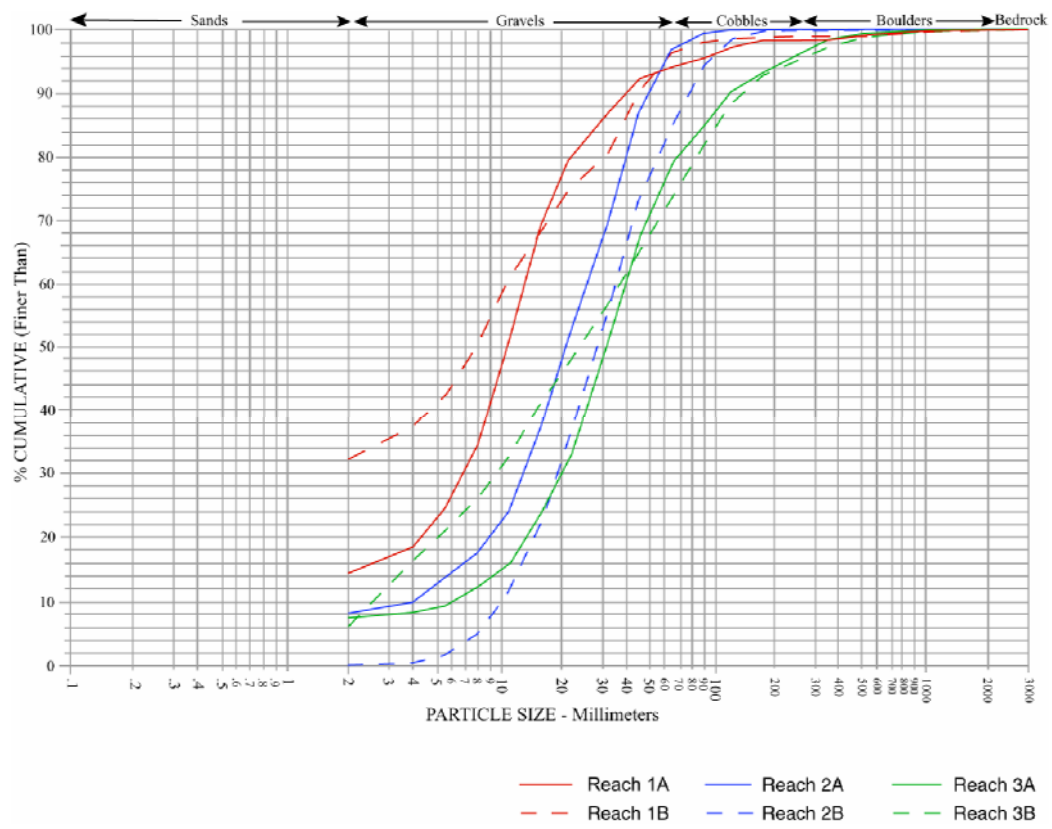


Figure 5. Particle size distribution curves showing the surface grain size distribution for sample reaches 1A through 3B.

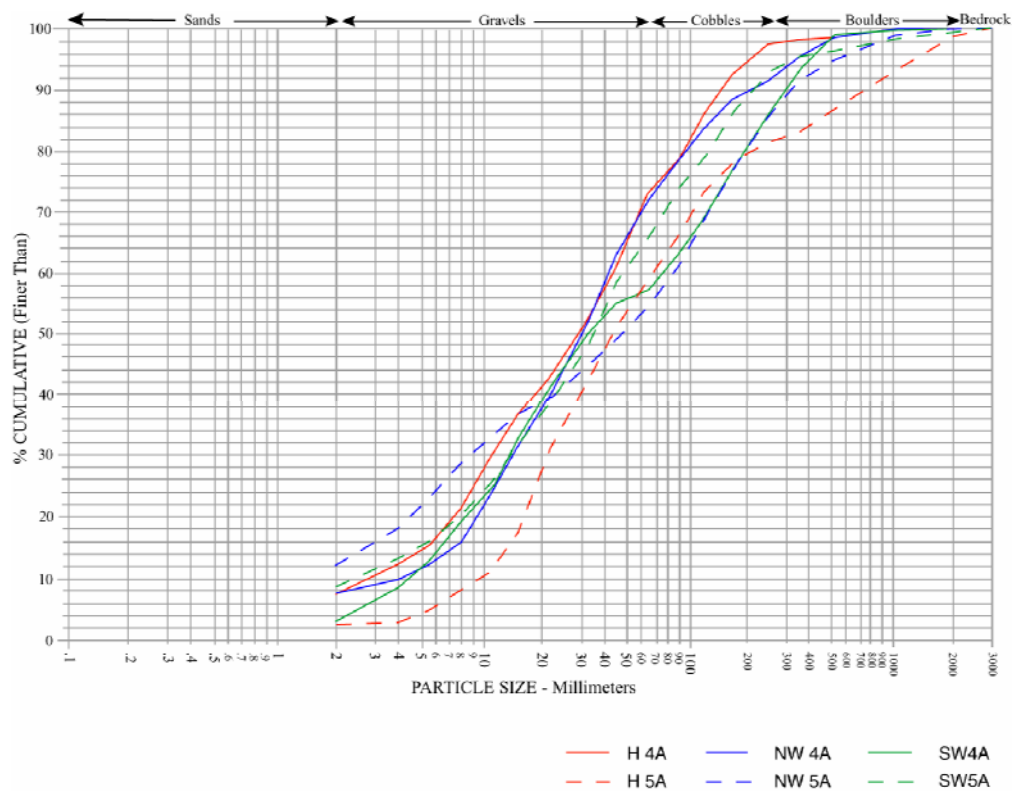


Figure 6. Particle size distribution curves showing the surface grain size distribution for sample reaches Heath (H) 4A and 5A, Northwest Branch (NW) 4A and 5A, and Southwest Branch (SW) 4A and 5A.

Table 6. Surface grain size data for each sample reach. * denotes poured concrete in channel bed.

Reach	% <2 mm	D16 (mm)	D50 (mm)	D84 (mm)	% Bedrock
1A	14	3	11	27	0
1B	32	<2	8	36	0
2A	7	7	21	43	8.7*
2B	0	14	28	62	0
3A	7	11	31	85	1
3B	6	4	24	95	0
Heath 4A	8	6	29	110	2
Southwest 4A	4	7	32	230	19
Northwest 4A	7	8	30	130	0
Heath 5A	2	15	44	400	9
Southwest 5A	9	5	34	155	5
Northwest 5A	12	3	48	230	3

Subsurface grain size variation

Bulk sediment samples were collected using a McNeil sampler at four sites; one each in sample reaches 1A, 1B, 2B and NW4A. These locations were chosen because they represented potential salmonid spawning locations. Sample data are summarized in Table 7. Sample volumes range from about 7.5 l to 12.4 l (2.0 to 3.3 gallons); bulk density of samples averages about 2.2 t/m³ (140 lb/ft³). The largest sediment clast in each sample ranged from 1.3 % to 2.9 % of the total sample mass. Ideally, samples would be sufficiently large to reduce the weight of the largest grain to not more than 1% of the sample mass. If the four samples are bulked together and treated as one sample, the largest clast weight is less than 1.0 % of the sample mass. Hence, interpretation of these data with respect to spawning suitability should consider the mean for the selected parameters as well as the individual samples for a more robust evaluation.

Table 7. Summary of subsurface sediment size distributions.

Reach	Sample Mass (kg)	% < 1 mm	% < 6.35 mm	D50 (mm)	D84 (mm)
1A	17.4	16	41	8	24
1B	16.7	6	21	16	30
2B	19.6	13	29	16	48
NW4A	27.8	15	32	14	30
Composite	81.6	11	30	14	31

Kondolf (2000) suggests that the subsurface D50 and D84 (the framework material) of potential spawning gravel be compared to documented spawning gravel size distributions. Kondolf and Wolman (1993) compiled such data for salmonids, including steelhead trout. The range of D50's from these data for steelhead is about 18 mm to 34 mm; D84's are about 100 mm. The data for Sulphur Creek indicate framework bed sediment is slightly smaller than the range documented as ideal for steelhead trout spawning. The bed sediment in Sulphur Creek is primarily cobble and gravel, however the subsurface sediment is medium to fine gravels. Landslides dominate the sediment supply in Sulphur Creek, thus the subsurface grain size distributions tend to reflect the large amount of gravel and sand sized sediment directly contributed to the channels by these landslides.

Kondolf (2000) suggests based on a review of prior studies that spawning gravels with less than 12 to 14% sediment finer than 1 mm (fines) are correlated with 50% survival to emergence on average. The 50% emergence is an arbitrary cutoff, yet it is widely accepted by biologists as a benchmark for comparison. Kondolf also suggests that a downward adjustment should be applied to bed samples to account for removal of fine sediment during redd construction. An empirical relationship estimates the final percentage of sediment finer than 1 mm as 0.67 times the initial percentage. Hence,

samples with up to 21% sediment finer than 1 mm would be predicted to have levels of about 14% after spawning. However, fines deposited in the redd during the egg incubation period could fill the gravel interstices and ultimately bring fine sediment levels back up to pre-redd construction levels. The levels of sediment finer than 1 mm in the subsurface of Sulphur Creek are within documented ranges that do not excessively impact steelhead egg incubation. This suggests that with only some removal of fines during redd construction, there would be relatively high survival to emergence of steelhead fry from redds.

With respect to fine gravel impeding steelhead fry emergence, Kondolf (2000) suggests that previous studies are somewhat variable. However, for steelhead in particular and salmonids in general, the 50% emergence criterion indicates that sediment finer than 6.35 mm should not be greater than about 30%. Again, a correction for removal of fines during redd construction is recommended. An empirical relationship estimates the final percentage of sediment finer than 6.35 mm as 0.58 times the initial percentage. Hence, samples with up to 52% sediment finer than 6.35 mm would be predicted to have levels of about 30% after spawning. This empirical relationship has a relatively wide scatter, however, and the specific correction should be used with caution. In Sulphur Creek, although sample reach 1A has 41% sediment finer than 6.35 mm, the remaining samples all contain 32% or less, suggesting that even a small reduction accomplished during spawning can be expected to increase the emergence rate. Hence, the percentage of subsurface sediment sizes finer than 6.35 mm in Sulphur Creek does not appear to be an impediment to the emergence of fry from redds. However, additional sampling in the middle reaches and in Heath Canyon would give a more comprehensive picture of spawning sediment quality. Overall, spawning conditions in terms of subsurface sediment size distributions in Sulphur Creek appear to be on the fine end of documented conditions suitable for steelhead trout, but are most likely acceptable.

Stream slope by reach

Channel slope is generally regarded as an important control on channel morphology and sediment grain size in streams, along with sediment supply. In typical alluvial perennial channels, as slope decreases, discharge tends to increase and particle size decreases. The reported stream slopes represent average slopes; the slopes in each reach varied locally. Reach average slopes vary from 0.2% in reach 1B up to 18.1% in reach H5A (Table 8). The range of slopes measured illustrates the variability and complexity of the channel morphology within a sample stratum. In addition to the upstream increase in slope, the standard error reported also increases upstream in response to greater influence of boulder step-pools and greater proportion of exposed bedrock. A plot of mean reach slope versus reach D50 (Figure 7) shows a logarithmic relation, with reaches of low slope having finer grain sizes compared to reaches with higher slopes. Areas of reduced slope, such as reaches 1B and 2B, tend to be areas of aggradation due to reduced stream power. Increased sediment deposition can result in the widening and shallowing of the channel, as well as the filling of pools. Reach 2B is wide and shallow due to high sediment supply, diverging flow, and position on the alluvial fan, whereas reach 1B has a high number of pool and sediment deposits. The morphology of

reach 1B likely will not change significantly in the future because of the entrenchment of the channel, and the amount of bank revetment present as it passes through the town of St. Helena.

Table 8. Sulphur Creek reach average percent slope and standard error.

Reach	Reach average % slope	Standard error	Coefficient of variation
1A	1.1	0.3	0.3
1B	0.2	0.1	0.2
2A	1.0	0.3	0.3
2B	0.8	0.1	0.1
3A	1.6	0.5	0.3
3B	2.0	0.2	0.1
Heath 4A	1.9	0.3	0.2
Southwest 4A	7.1	9.9	1.4
Northwest 4A	4.1	0.2	0.1
Heath 5A	18.1	8.9	0.5
Southwest 5A	3.7	1.6	0.2
Northwest 5A	9.9	1.6	0.2

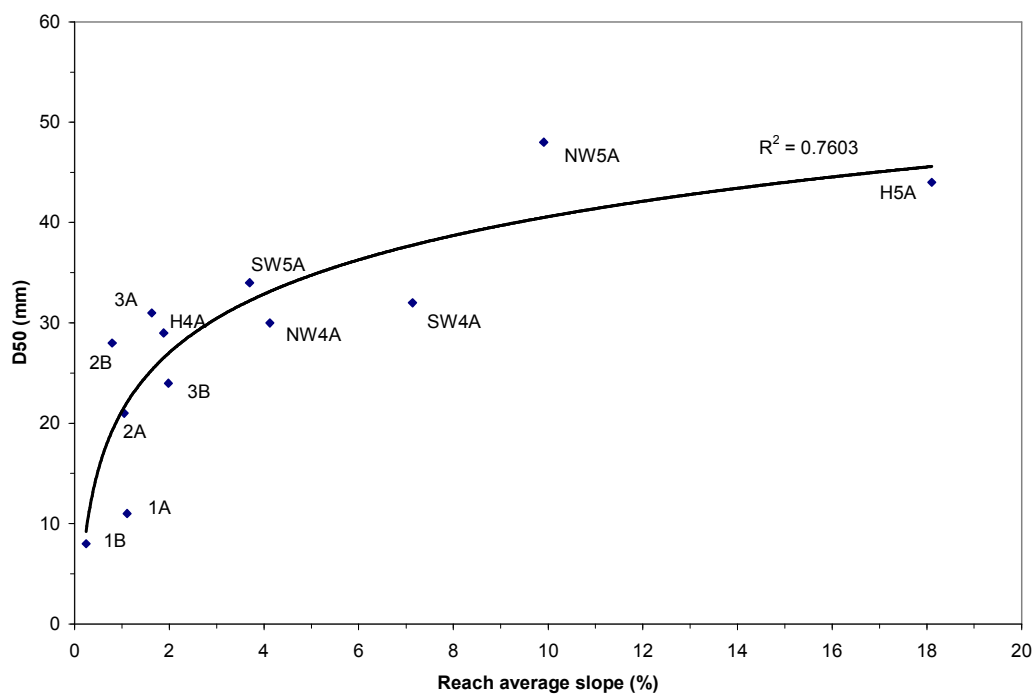


Figure 7. Reach average slope versus mean grain size (D50) for each sample reach.

Cross-sections

Scale drawings of cross-sections generated from field measurements demonstrate the variability of morphologies present in Sulphur Creek (Figures 8 through 12). The cross-sections illustrate the channel's width, depth, entrenchment, bank slope, and floodplains. Where water was present on the date of survey, it is shown on the cross-section. The field interpretation of "bankfull" flow is also shown; this is considered to be the water depth of the 1.5 to 2 year recurrence interval flood, as opposed to the water depth that would fill the channel to the top of its banks. Cross-sections from Stratum I reflect the influence and modification to the channel by the residents and the town of St. Helena, including bank revetments and flood control measures. Reach 1A, Meter 175 is the only cross-section in Stratum I that represents a channel morphology with a low amount of modification. Stratum II cross-sections have been scaled down by 50% to fit the entire section on the page. These reaches are the alluvial fan component of Sulphur Creek, illustrated by the wide and shallow cross-sections. Bankfull widths are much larger in these reaches, averaging 11 m in width.

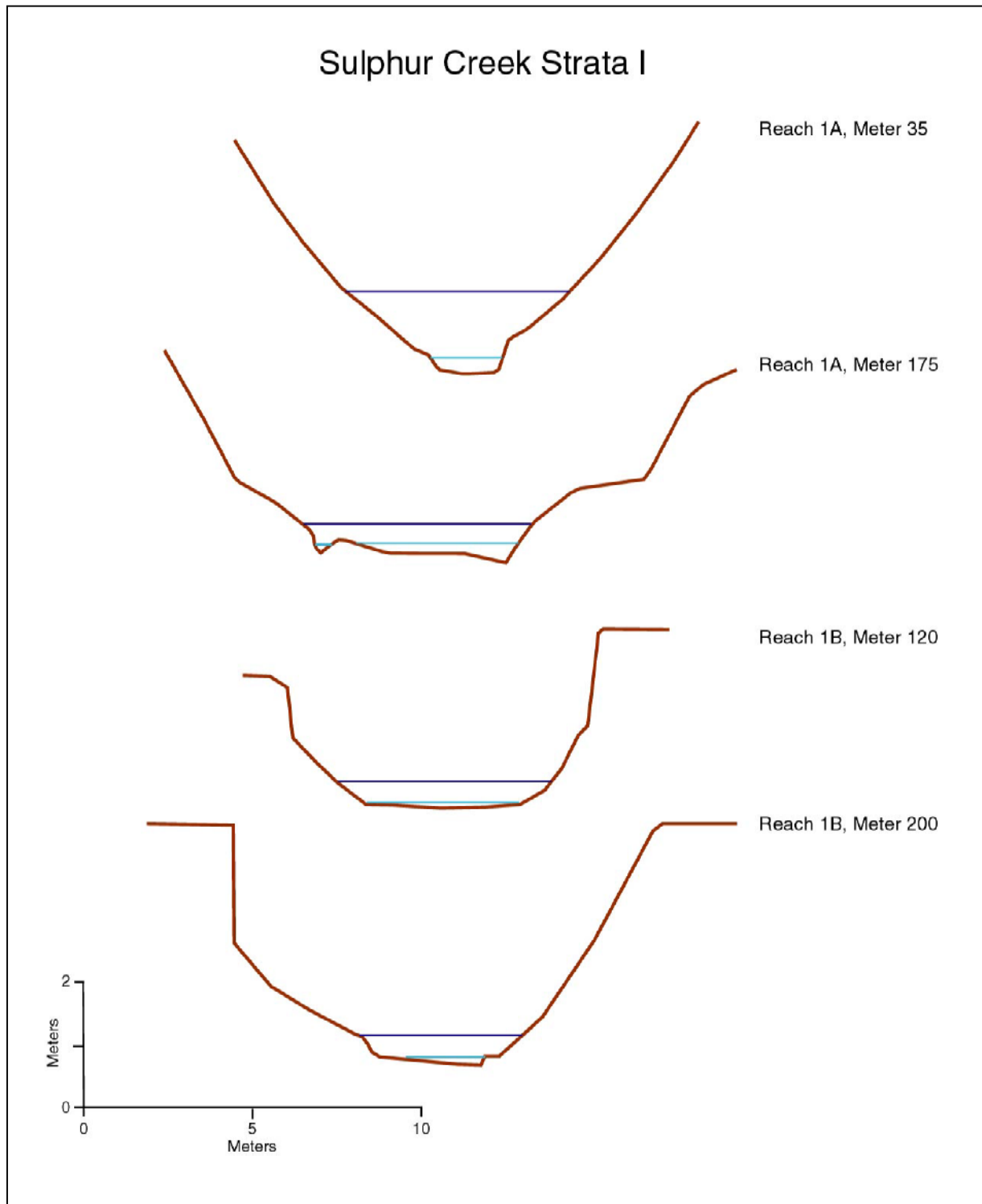


Figure 8. Sulphur Creek cross-sections for sample Strata I. The thick line represents the ground surface, the lower line represents the water depth on the date the cross-section was surveyed, and the upper line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

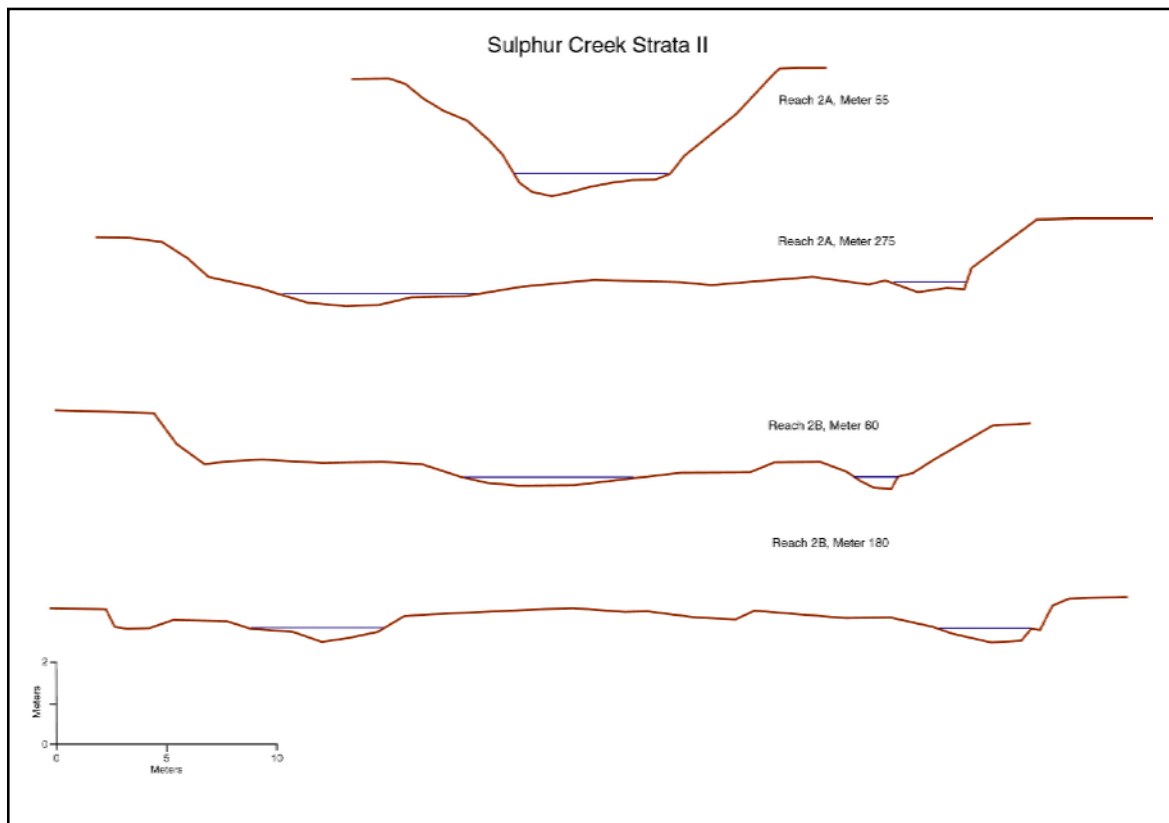


Figure 9. Sulphur Creek cross-sections for sample Strata II. The thick line represents the ground surface, and the thin the line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side. Cross-sections have been scaled down by 50% compared to other Strata.

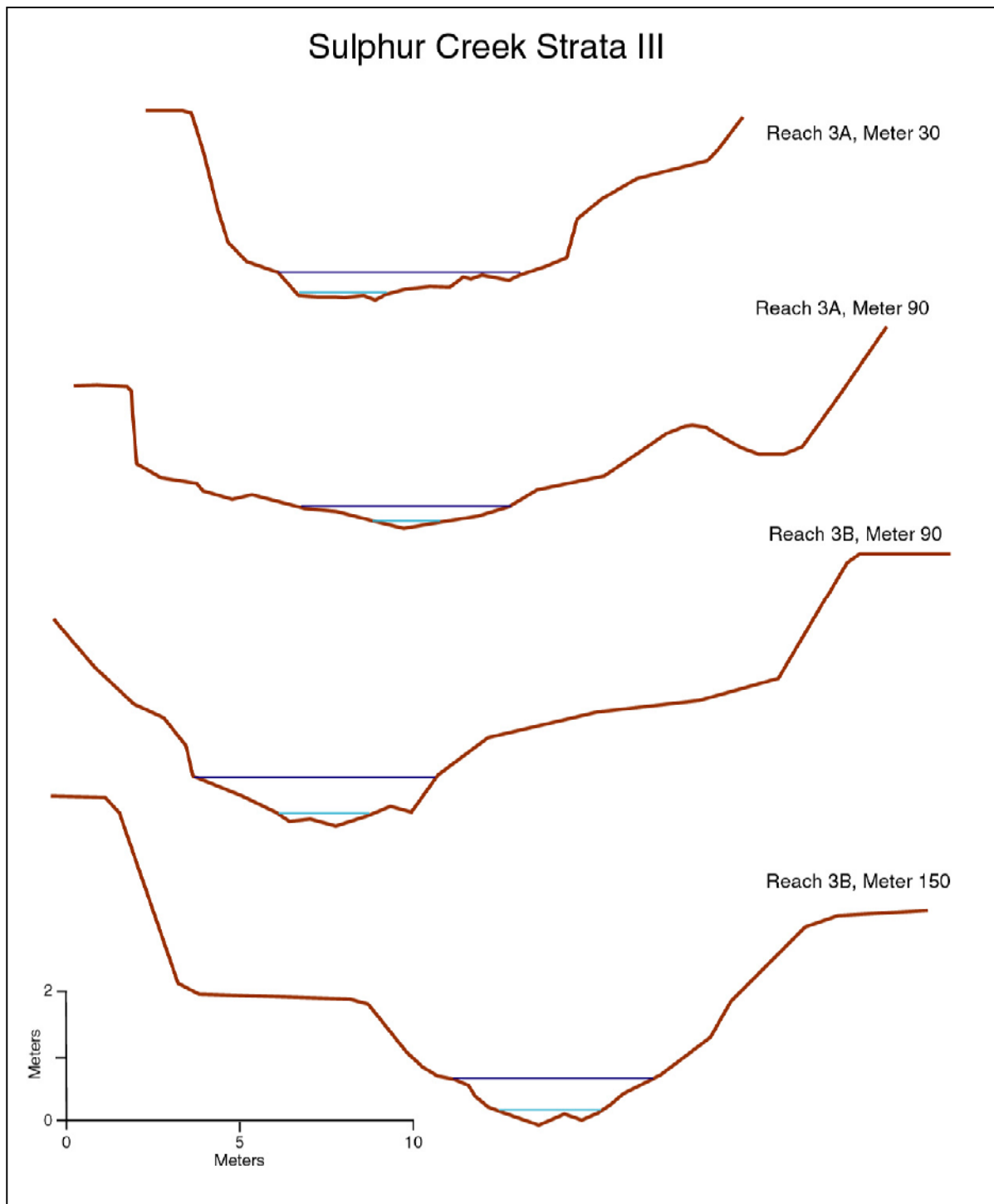


Figure 10. Sulphur Creek cross-sections for sample Strata III. The thick line represents the ground surface, the lower line represents the water depth on the date the cross-section was surveyed, and the upper line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

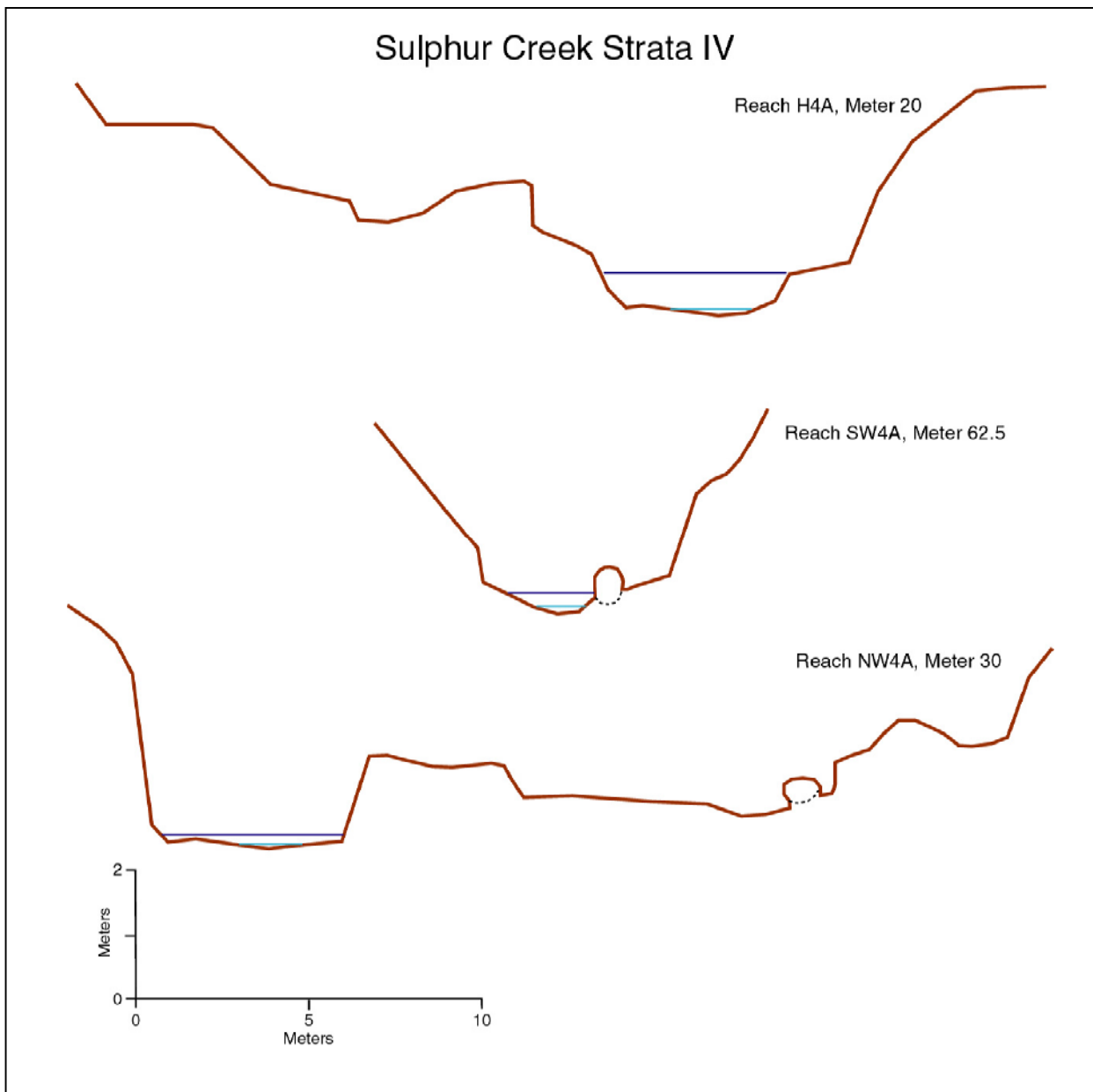


Figure 11. Sulphur Creek cross-sections for sample Strata IV. The thick line represents the ground surface, the lower line represents the water depth on the date the cross-section was surveyed, and the upper line represents the field interpretation of bankfull. Dashed lines represents the inferred extent of logs and boulders in the cross-section. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

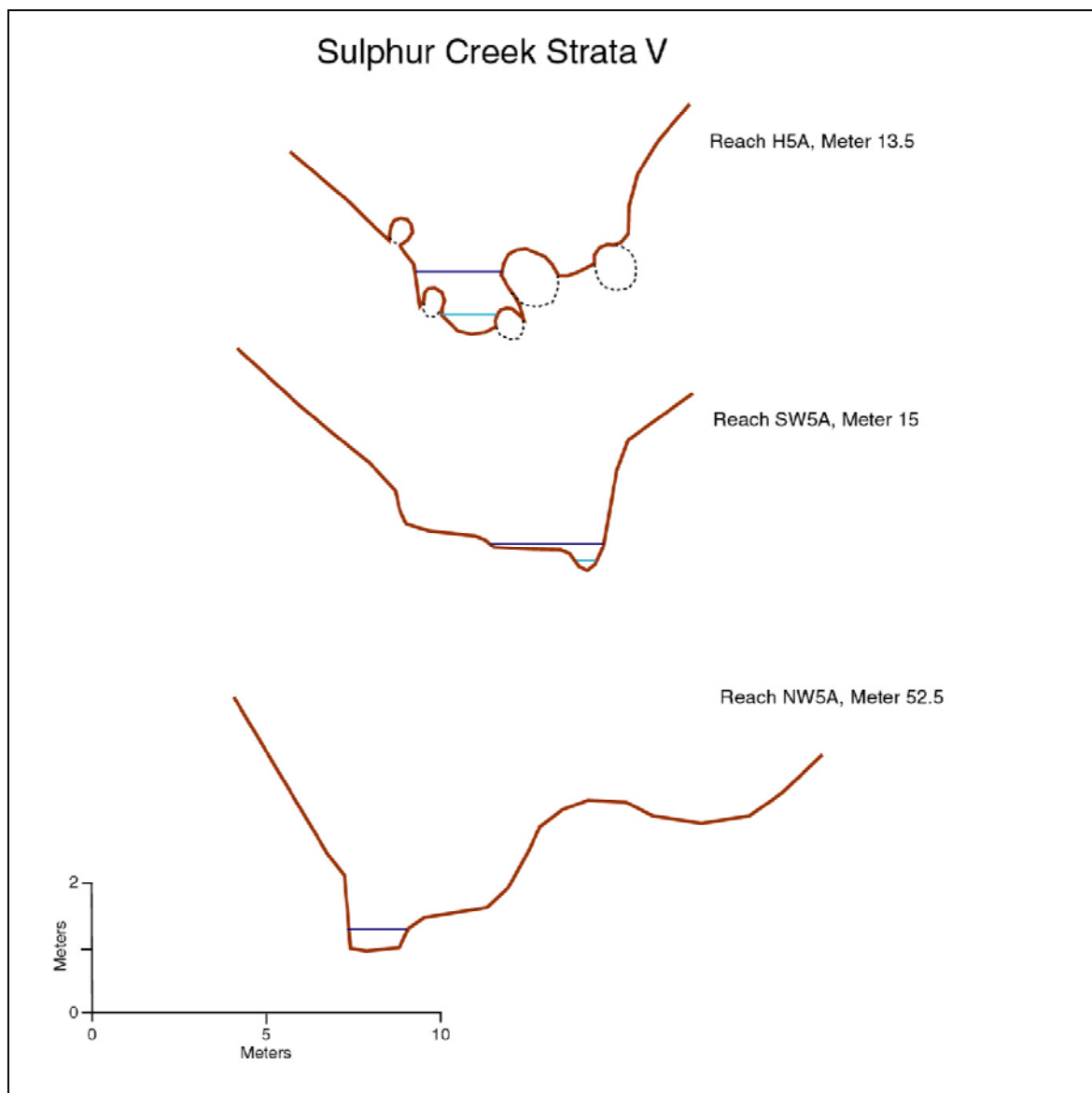


Figure 12. Sulphur Creek cross-sections for sample Strata V. The thick line represents the ground surface, the lower line represents the water depth on the date the cross-section was surveyed, and the upper line represents the field interpretation of bankfull. Dashed lines represent the inferred extent of logs and boulders in the cross-section. In Cross-section NW5A, the thin line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

The morphology of the channel in Stratum II is controlled by the flow dispersal, high sediment supply, and storage occurring in this braided reach. Reach 2A, Meter 55 is narrower than other cross-sections immediately upstream because this portion of the channel has been confined and revetted in association with a historic relocation of the channel (Historical Ecology). The valley width in Stratum III is generally larger than further upstream, allowing the deposition of bars and terraces in these reaches. In this

stratum, the channel displays a pool-riffle morphology, and is influenced by upright tree roots, and landslide-derived boulders in reach 3B. The wide valley width and terraces of reach H4A and NW4A is evident in the cross-sections of Stratum IV. The cross-section from reach SW4A reflects the much narrower canyon, and influence of a single large boulder on the morphology. Stratum V exhibits narrow and steep channels, with terraces in reaches SW5A and NW5A, and the step-pool morphology created by the many large boulders in H5A.

Large woody debris (LWD)

A wide variety of species of live upright trees and LWD pieces were measured along the length of Sulphur Creek (Figure 13). The number of LWD pieces is larger in the upper watershed, reflecting the more continuous riparian corridor. The lower reaches have fewer pieces of LWD, especially in reaches 2A and 2B, the alluvial fan portion of the watershed. Overall LWD abundance is low, especially considering that this watershed has coniferous trees, which are important because of their size and time of residence in-channel. A majority of sample reaches have less than 20 pieces of LWD, and half have less than 10 pieces. Alder and conifers dominate the middle reaches, while bay laurel (bay) and oak dominate the upper reaches. A large number of pieces, especially logs, have decayed beyond identification, most probably being hardwoods. Reach 3A is unique because it only contains alder, with all but one piece being live upright trees. This continuous stretch of alder trees help shape and stabilize the banks in this reach. Reach NW4A contains the largest percentage of conifers, Douglas firs, and Redwood trees, which are likely emplaced in the channel during landslide events. A majority of LWD pieces in the middle watershed are live upright trees, while logs dominate the LWD count in both the upper and lower watershed reaches (Figure 14). If live upright trees are excluded, all of the sample reaches downstream of SW4A would have fewer than 10 pieces of LWD.

LWD pieces provide shade and cover for aquatic species, leaf litter for aquatic bioenergetics, and flow roughness during peak flow periods. Live upright trees help stabilize the banks and bars while also shaping the morphology of the channel. In-channel LWD is also important in pool formation because the pieces provide objects for the channel to scour around and create new pools. The number of live upright trees present in the upper reaches of Sulphur Creek appears to be suitable for the riparian functions, but in-channel LWD is lower than ideal in these reaches. The nearly continuous riparian canopy provides an ample source for the recruitment of LWD pieces, yet the number of in-channel pieces is lower than expected. Active wood removal in the majority of the middle and upper reaches would likely require more effort than the amount of benefit gained. This suggests that the low numbers of LWD are possibly due to overall low recruitment rates, or the inability of the supply to keep pace with the channel's ability to transport pieces. Based upon these observations, it appears that in-stream habitat would improve and become more complex with a greater number of in-channel LWD pieces, especially in the middle and lower reaches.

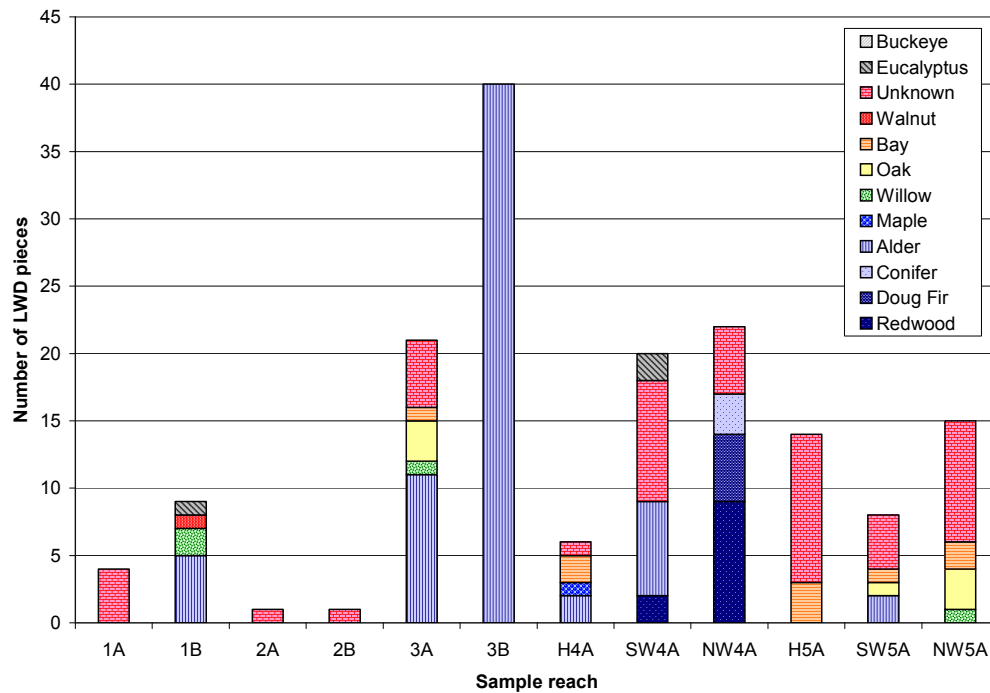


Figure 13. Number and species of woody material (LWD and live trees) per sample reach.

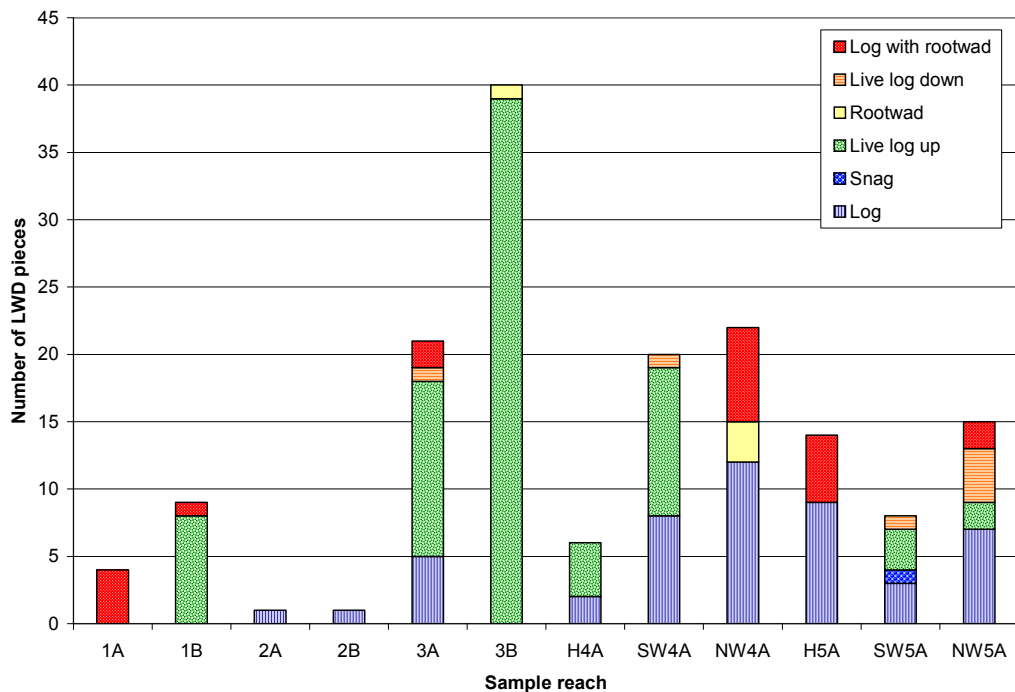


Figure 14. Number, position, and form of large woody debris (LWD) per reach.

Pools

A total of 92 pools were measured in the 12 sample reaches of Sulphur Creek. The causes of pool formation were categorized into five classes (after the California Department of Fish and Game Salmonid Stream Habitat Restoration manual, Flosi et al., 1998): step-pools, plunge pools, dammed pools, main channel/ bedrock trench pools, and lateral scour pools. Lateral scour pools and step-pools comprise 95% of all pools measured (Figure 15).

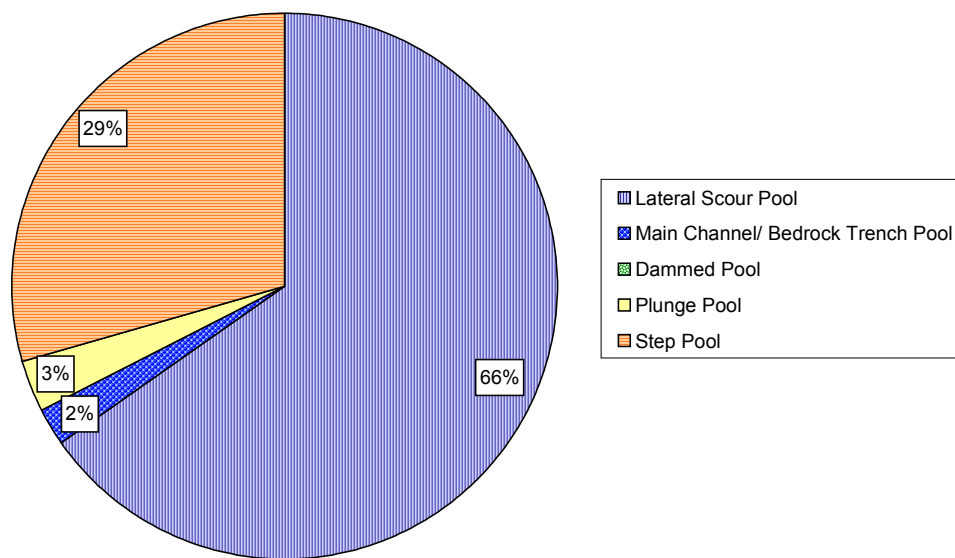


Figure 15. Percentage of each pool class measured in the 12 sample reaches combined.

The types of pool formed appear to follow a spatial pattern along Sulphur Creek related to channel geometry (Figure 16). For example, step-pools, plunge pools and main channel/bedrock trench pools only form in the upper watershed. Reach 2A does have a plunge pool, but it is associated with poured concrete on the bed of the channel, and plans have been developed to remove this concrete as a part of an upcoming restoration project (Fish Habitat Assessment). Also, all reaches except NW4A have four or more pools; NW4A is a reach that is highly impacted by large landslides upstream, causing it to be a transport-limited reach, with simply too much sediment for pools to form and persist. Reach H5A has the highest number of pools (14), all being step-pools, reflecting the many large boulders in this reach, and their influence on channel geometry and pool formation. With the exception of reach NW4A, average pool spacing was less than every seven bankfull widths, with eight of 12 reaches having pools spaced less than every four bankfull widths (Table 9).

Table 9. Sulphur Creek average pool spacing.

Reach	Reach length (m)	Number of pools	Pool spacing (in bankfull widths)
1A	175	7	3.6
1B	200	9	2.8
2A	275	10	2.5
2B	300	7	3.6
3A	150	7	3.6
3B	150	12	2.1
Heath 4A	100	4	6.3
Southwest 4A	62.5	6	4.2
Northwest 4A	150	1	25.0
Heath 5A	67.5	14	1.8
Southwest 5A	75	5	5.0
Northwest 5A	87.5	10	2.5

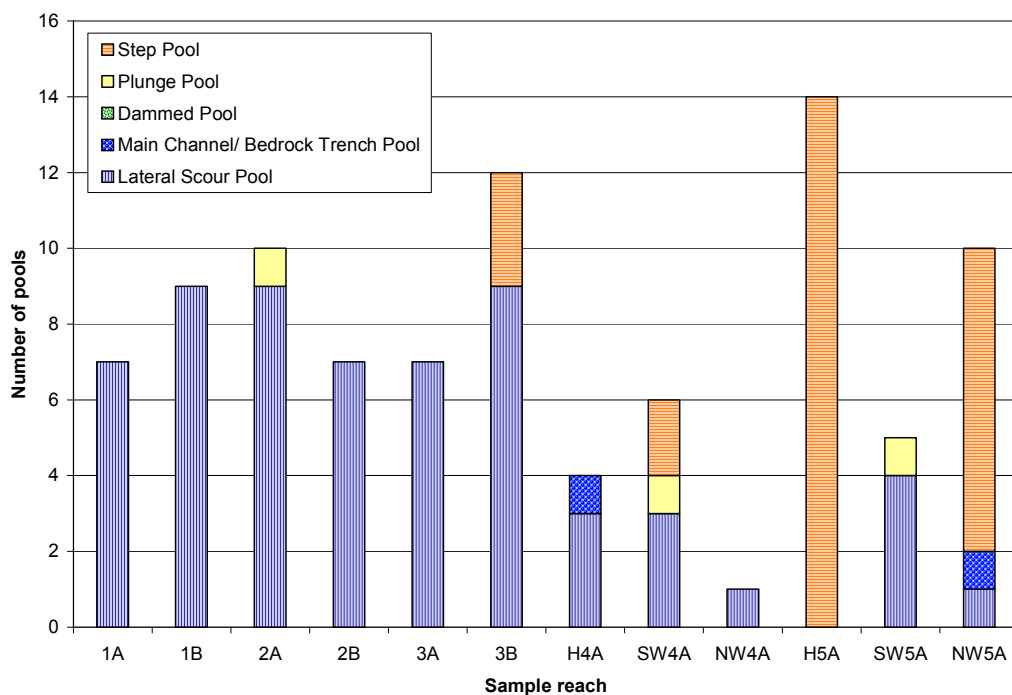


Figure 16. Number and class of pools in each sample reach.

The pools measured in Sulphur Creek are segregated into residual depth size classes, ranging from 0.2 – 0.4 m up to >1 m in depth (Figure 17). Although Sulphur Creek contains a fairly large number of pools, none of the pools measured have a residual depth deeper than 0.8m. Whereas lateral scour pools are present in all three size classes, step-pools and main channel/ bedrock trench pools are only present in the smallest two

size classes. This reflects the influence of bankfull cross-sectional area and pool-formative agent on pool residual depth. For example, step-pools only form in the upper watershed where channel width is small, large sized sediment is fairly immobile, and the boulder size and spacing controls the depth of pools that form. Typically in alluvial channels, pool residual depth is related to channel slope; as channel slope increases, pool residual depth usually decreases, reflecting the smaller bankfull cross-sectional area. In other words, near the headwaters, the narrow channel will typically form small and shallow pools, whereas near the mouth, the wider channel can form larger and deeper pools. However, in Sulphur Creek, this relationship is not well defined (Figure 18). The deepest pools form in reaches with channel slopes between 1 and 4%, as would be expected. Surprisingly, reach H5A, with a slope of approximately 18%, has pools with depths ranging between 0.2 and 0.55m deep, nearly the range of all pools measured.

LWD pieces do not play a large role in pool formation in Sulphur Creek (Figure 19). Only 5% of all pools measured are directly formed by LWD, and an additional 10% are associated with LWD, that is, the piece is present, but is not a primary contributor to the formation of the pool. Although Sulphur Creek has a large number of pools, not many have the benefit of cover and complexity given by LWD. The number and habitat value of pools could potentially increase with an increase of well-placed LWD in-channel.

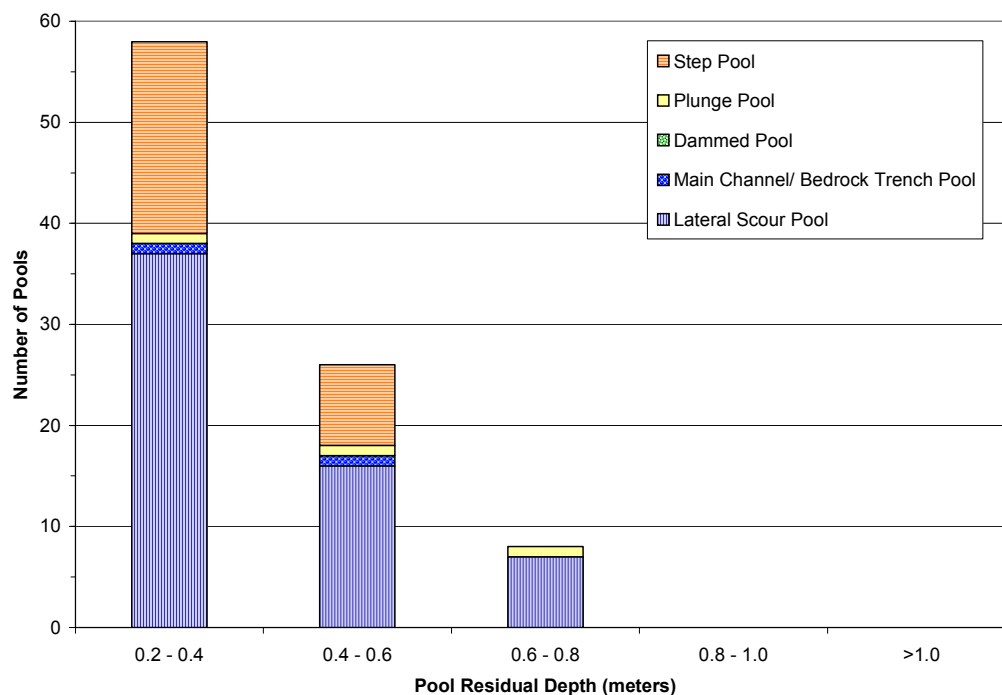


Figure 17. Number of pools per residual depth class and their associated cause for all sampled reaches.

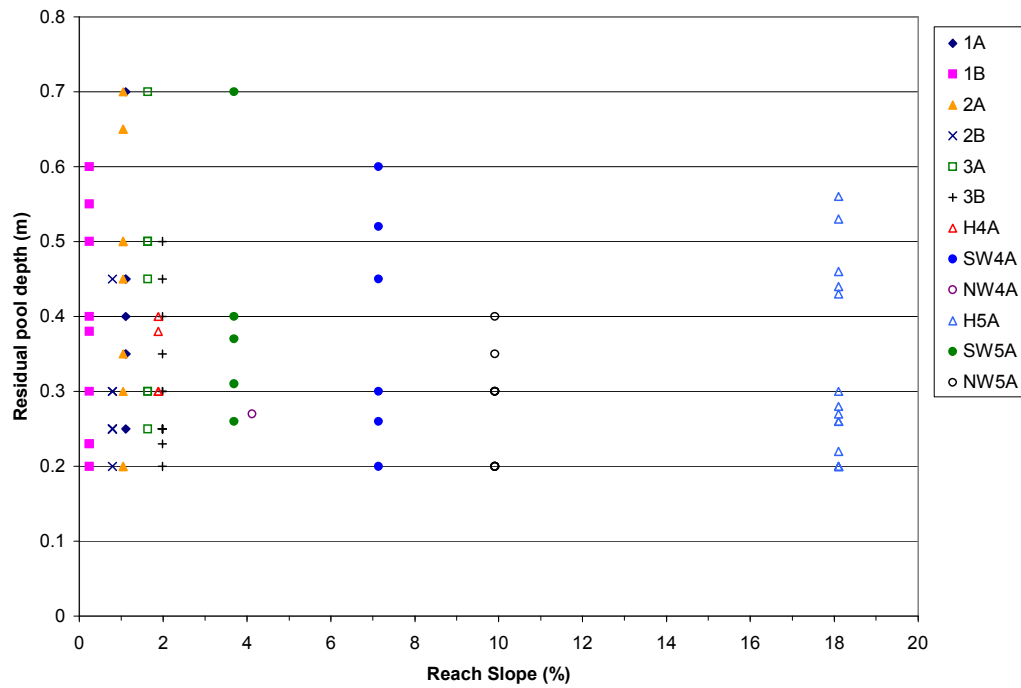


Figure 18. Residual pool depth versus reach average slope.

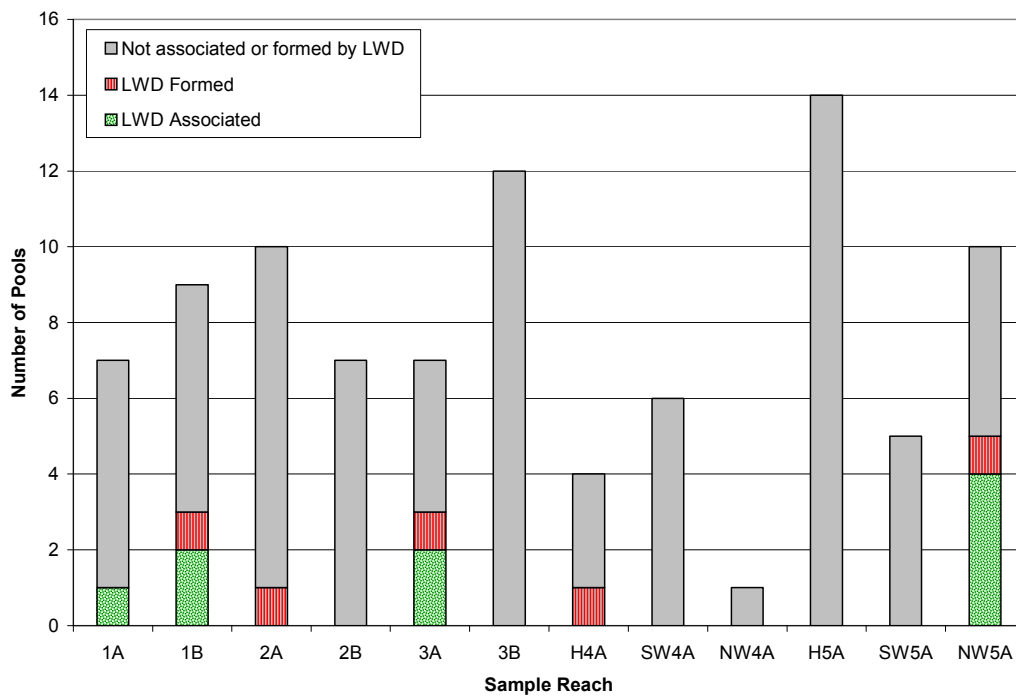


Figure 19. Number of pools formed by or associated with LWD in each sample reach.

Sediment deposits and bars

The number, type, and volume of sediment deposits and bars were measured in each of the 12 sample reaches of Sulphur Creek. The total number of deposits measured varies from 13 in H4A to 38 in NW5A; most reaches have 15-20 deposits. Forced bars comprise the largest number of deposit types measured, followed by active channel deposits and pool deposits. These three types combined make up nearly 75% of all deposits measured (Figure 20). While active channel and pool deposits are found in all reaches, the range of bar types varied spatially relating to bankfull channel cross-sectional area and the dominant fluvial processes at that location in the watershed (Figure 21). For example, medial bars tend to form in reaches with a high sediment supply and a relatively wide cross-sectional area. The upper watershed is dominated by forced bars, or bars that form due to a change in water velocity associated with a protrusion such as a large boulder, a bedrock knob, or a piece of LWD in the channel.

The volume of material stored in each reach was calculated based upon field data. The percentage of sediment stored in each sample reach varies tremendously from reach to reach (Figure 22). Reach 2B dominates, with 44% of the total amount of sediment storage measured being stored in that reach, while NW4A follows with 21%. Although these reaches have similar magnitudes of sediment storage, a distinct geomorphic process controls the storage mechanism in each reach. Reach 2B is a braided stream reach on the alluvial fan. Because of the slope, width to depth ratio of the channel cross-section, the location on the alluvial fan, and the sediment load, this reach is naturally braided. As the stream exits Heath and Sulphur Canyons, the channel is no longer restricted by a narrow valley width or cohesive banks, allowing flow to disperse, the depth to reduce, and inducing the deposition of sediment. This reach is highly dynamic as new bars form and old bars are eroded within the braided pattern, and as the loci of deposition of the alluvial fan shifts. In contrast, the number of bars and volume of sediment in reach NW4A is dominated by hillslope inputs of sediment in the form of large landslides upstream of the sample reach (Sediment Source Assessment, Historical Ecology). Currently, the channel is unable to transport all of the sediment that is supplied, causing the channel to store the excess sediment as a series of bars and active channel deposits.

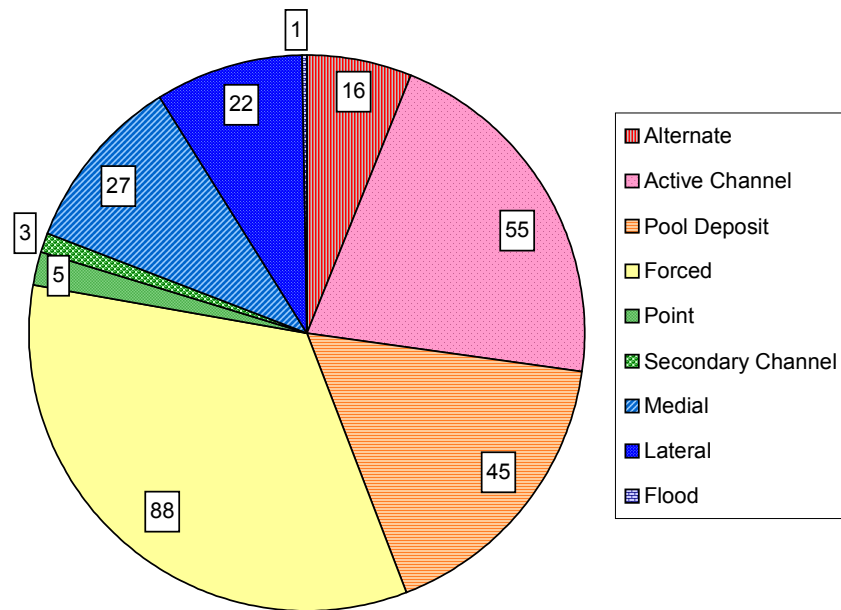


Figure 20. Number and type of bars measured in all 12 sample reaches.

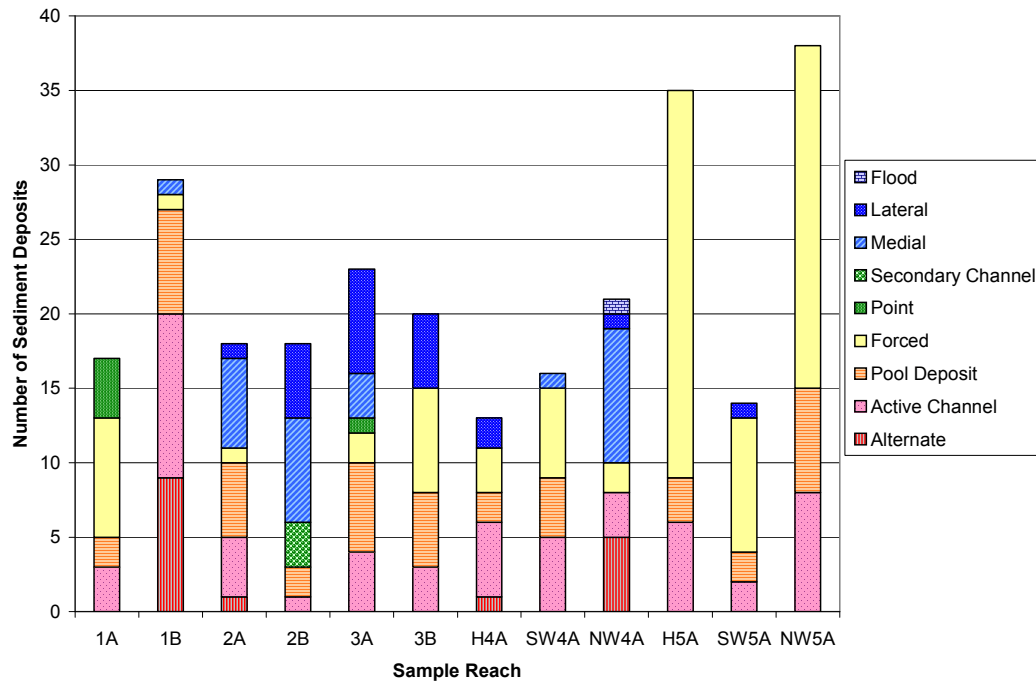


Figure 21. Number and type of bars in each sample reach.

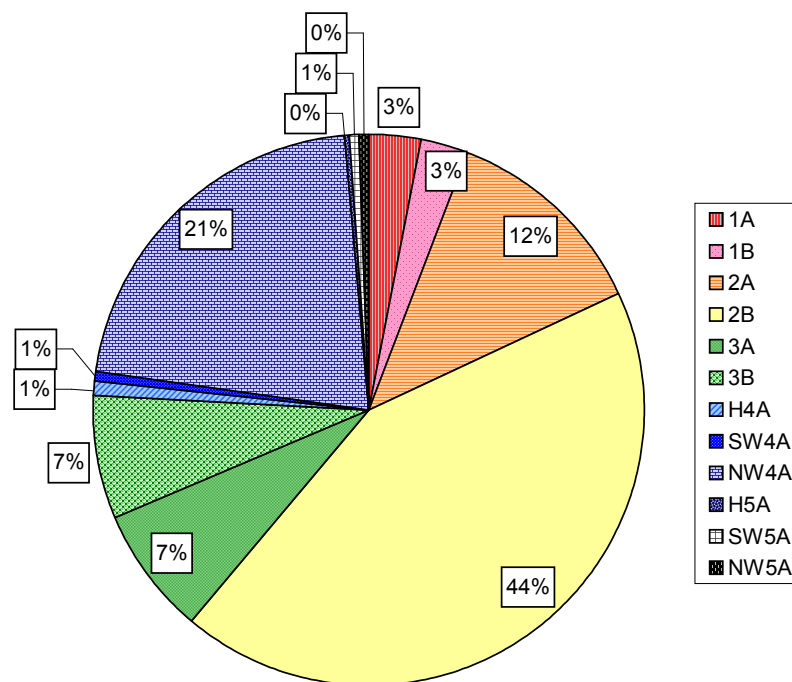


Figure 22. Total volume of bar material measured in each sample reach.

The total volume of material stored in each sample reach is dependant upon the length of the sample reach. To account for the various sample reach lengths, total sediment storage is normalized, giving sediment volume per unit channel length (in m^3/m) allowing the comparison of total storage between reaches (Figure 23). Reaches 2B and NW4A have the largest amount of storage per unit channel length, however, other reaches including 2A, 3A and 3B also have relatively high storage. Large bars account for the high sediment storage volume in Reach 2A, a braided reach on the downstream part of the alluvial fan surface. Reach 3B is significantly affected by a landslide that previously blocked the channel, causing a large bar to form upstream of the blockage. Since the time of the landslide, the channel has incised through a portion of the blockage, returning to its original gradient, and leaving a majority of the bar intact. In addition, this reach has a nearly continuous active channel deposit, indicating a large bedload supply from upstream in this particular setting. Reach 3A is storing a majority of its sediment in many types of bars, some being up to 1 m thick. It also has a large active channel deposit, suggesting a large sediment supply from upstream.

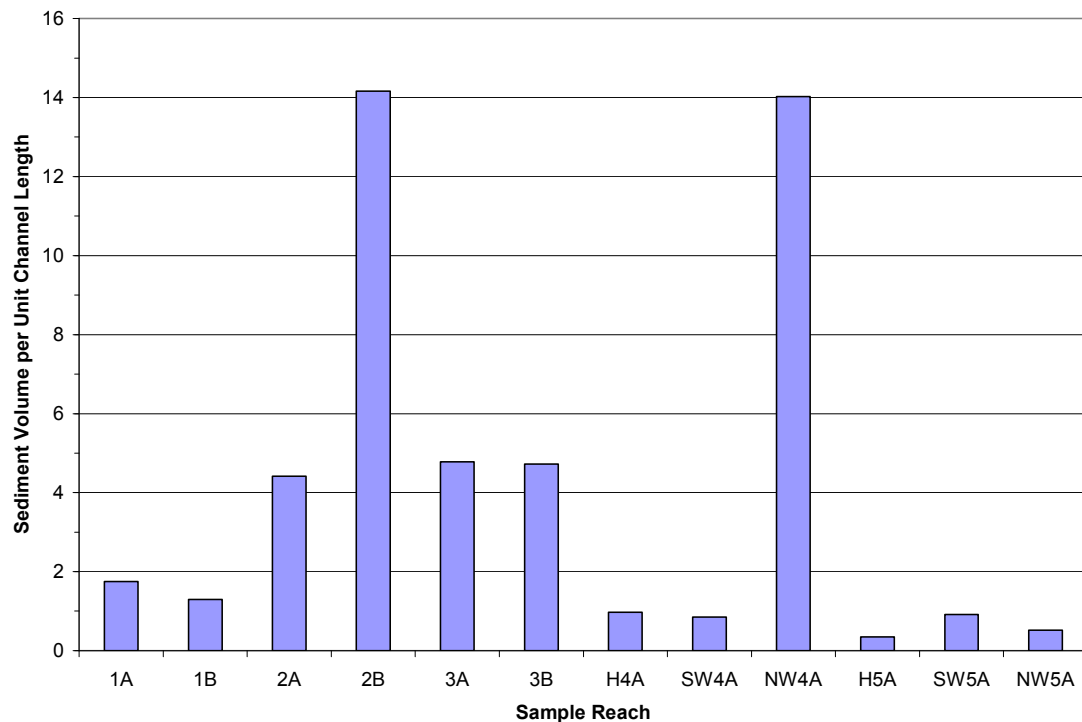


Figure 23. Calculated bar volume per unit channel length in each sample reach.

The volume of material stored in each deposit was calculated based on field data, and later used to segregate individual bars into volume size classes. In Sulphur Creek, an inverse relationship exists between the number of bars measured in a particular size class, and the proportion of total bar material in that size class. For example, deposits with a volume greater than 8 m³ comprise only 33% of the total number of bars measured, but comprise 96% of the total volume of material measured. In other words, the majority of sediment is stored in only a few large deposits and bars. The volume size class of an individual bar relates to the position of the bar in the watershed; generally larger bars are located lower in the watershed, and smaller bars located higher in the watershed. The large volumetric bars tend to have higher elevations above the bed, with the majority of the sediment out of the wetted channel. These large bars reflect the greater sediment mobility in the lower portions of the watershed due to higher discharge (stream power) and the channel's greater ability to scour and transport sediment. In comparison, the smaller volumetric bars tend to have lower elevations above the bed, are usually located in the wetted channel, and are more accessible for spawning habitat. In particular, active channel deposits and small forced bars most likely represent patches of potential spawning gravel if they remain stable and submerged for the duration of a steelhead incubation period (about 60 days).

In alluvial channels, typically as cross-sectional area increases reach-total bar volume will also increase. This relationship is only weakly defined in Sulphur Creek, with reaches NW4A and 2B as outliers (Figure 24). Reach 1A contains less than

predicted sediment deposits and does not fit the trend because it is highly modified by revetments and flood control projects employed by the city of St. Helena. Reaches NW4A and 2B stand out as having much larger sediment deposits than predicted from the cross-sectional area in each reach. The large sediment volumes are easily observed in the channel morphology.

The stability (age) of the deposits is a factor in the availability of sediment for spawning, and in the potential source of sediment for the channel to re-work during floods. The age class of sediment deposits was estimated in the field based on the position of the deposit in the bankfull channel, the size distribution of the deposit, and the approximate age of vegetation on the deposit, if any (Figure 25). The <1 year age class represents fine-grained deposits in pools and in the active channel that would be entrained in high frequency flow events. The 1-5 year class represents deposits with coarser surface textures, young shrubs, and seedlings and herbaceous vegetation, often with upper surfaces above the active channel, but within the bankfull channel. The 6-19 year class and the >20 year class represent deposits at elevations above the bankfull channel, but lower than adjacent terraces, that often have older vegetation and trees colonizing the surface. In Sulphur Creek, 42% of all deposits are in the <1 year age class, 48% are in the 1-5 year class, 8% are in the 6-19 year class, and 2% are in the >20 year class. The recent high magnitude, low frequency floods in 1995 and 1997 are probably responsible for a majority of the 1-5 year deposits. The high flows in 1982-1983 are probably responsible for the >20 year deposits. Overall, Sulphur Creek has a large amount of stored sediment available for transport in a fairly low magnitude flood event.

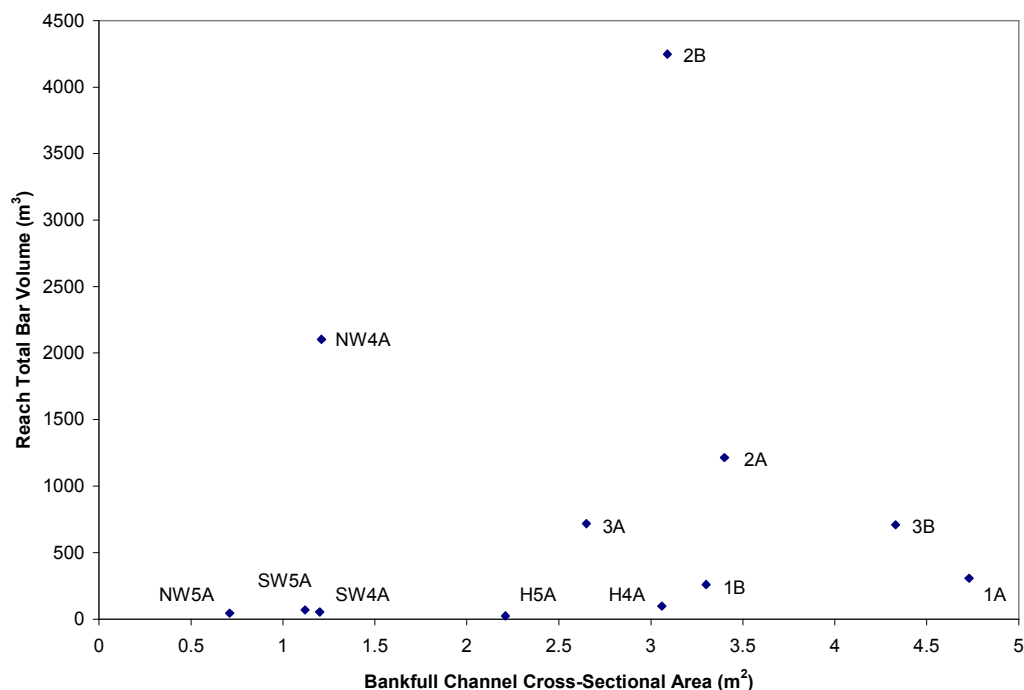


Figure 24. Bankfull channel cross-sectional area versus reach total bar volume.

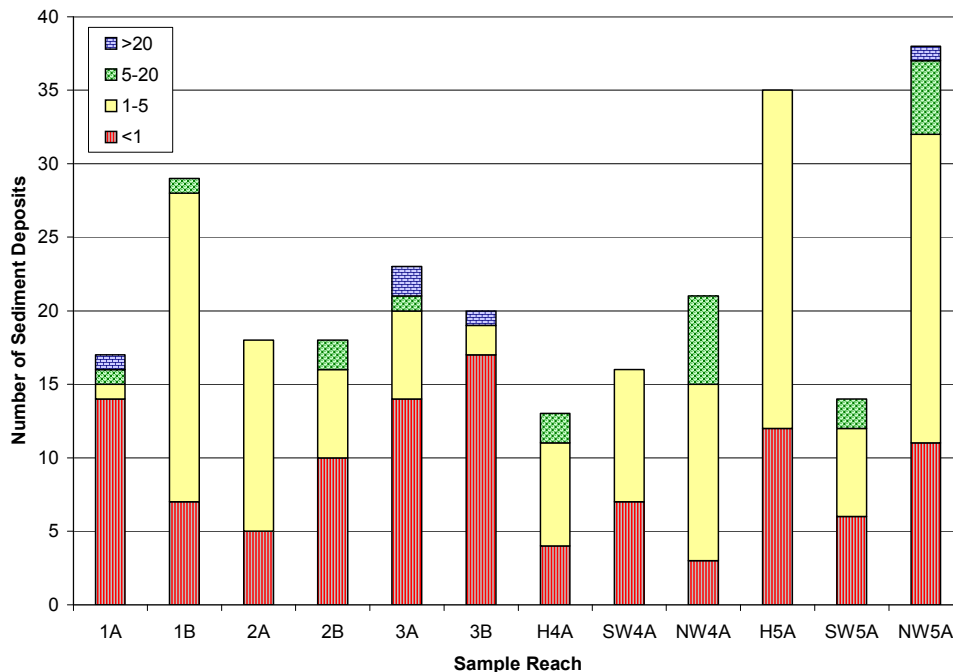


Figure 25. Distribution of estimated age (years) of bars measured in each sample reach.

When the total volume of sediment in each reach is normalized to the reach surface area (sediment volume in m^3 per unit channel surface area in m^2) a simple measure of sediment storage, depth in meters, allows comparison from reach to reach (Figure 26). Sediment deposits are grouped into three general categories: pool deposits, active channel deposits, and bars. A reach average depth of sediment storage is shown for each category. A majority of sediment in Sulphur Creek is stored in the form of bars, with some reaches containing significant active channel deposits. Very few reaches contain pool deposits, especially volumetrically significant deposits. This has implications for salmonid spawning and rearing; pool deposits can decrease the total volume of pools for rearing, while active channel deposits supply a majority of the gravels for spawning. Despite the large input of fine sediment from the hillslope processes, it appears that pool filling is not a significant problem in Sulphur Creek. For example, in reach SW4A, 67% of measured sediment is stored in bars, 31% in active channel deposits, and 2% in pool deposits; overall a good mixture for salmonid habitat. Although pool deposits are not expected to be volumetrically large compared to bar deposits, it appears that an appropriate mixture of sediment storage types is present in Sulphur Creek.

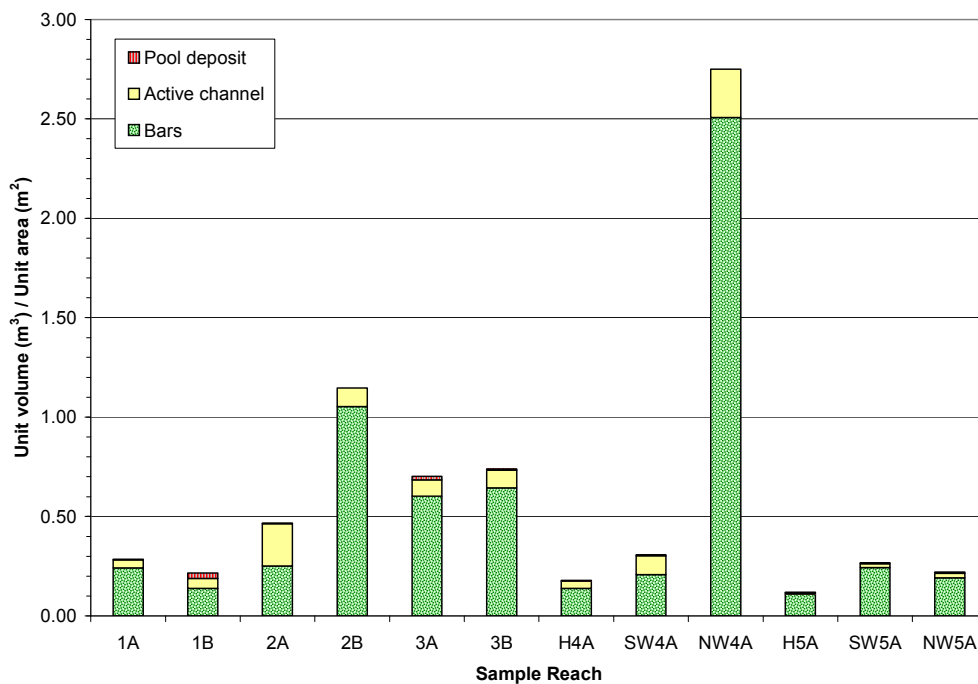


Figure 26. Volumetric percentage of pool deposits, active channel deposits, and all types of bars measured in each sample reach.

Bank erosion and revetments

Bank erosion data collected for the entire length of each sample reach included total volume and average erosion per unit channel length. A total of 4,985 m³ of bank erosion was measured in the 12 sample reaches of Sulphur Creek (Figure 27). Reach 3B has the largest total amount of erosion measured (1,838 m³), followed closely by reach NW5A (1,523 m³), with these two reaches containing 67% of all erosion measured. The average bank erosion per unit channel length was also calculated from this data (Figure 28). Using this measure, reach NW5A has the highest amount of erosion per unit channel length, at 17 m³ per meter of channel length. The age of the indicator places an upper limit on the age of erosion that was measured, allowing the erosion rate to be estimated (Figure 29). It is generally unknown if the visible erosion occurred slowly over several years, or quickly in just a few years. However, these observations do provide a quantitative comparison of the relative age and magnitude of bank erosion, as well as an estimate of approximate minimum erosion rates within each sample reach. A majority of the total volume of erosion measured in Sulphur Creek is based on indicators that are dated at >50 years. This suggests that either erosion has occurred continuously over a long period of time, or recently erosion has just exposed indicators in the 50-year class. However, some reaches such as 3A and NW4A have significant proportions of erosion that has occurred in the past 20 years or less. Although management efforts to control erosion in these locations could control some erosion, the overall amount of erosion in the entire watershed and delivery of sediments from the hillslopes to the stream would

likely overwhelm any localized efforts on the banks. Bank erosion control would most likely be an ineffective method of reducing fine sediment in the channel, but would be an effective method of protecting property and riparian vegetation in discrete reaches.

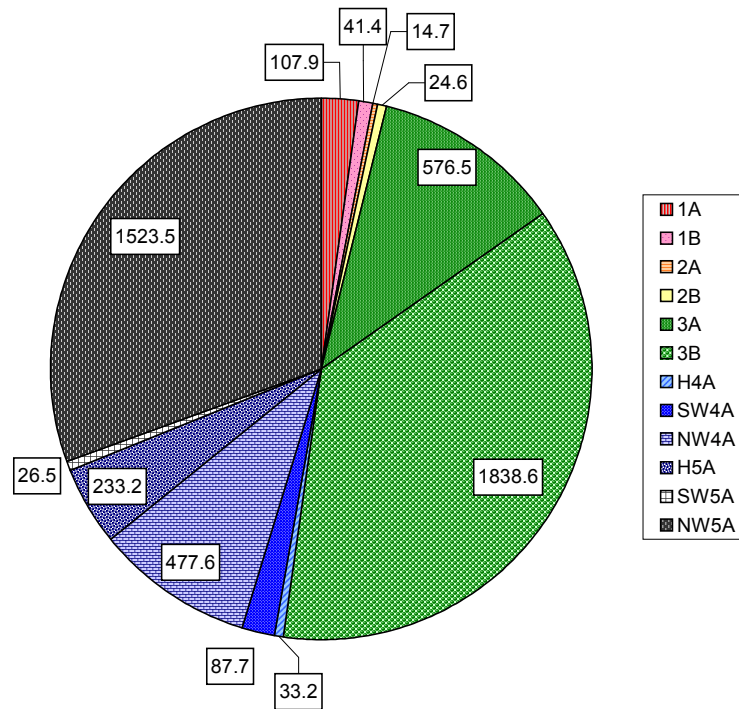


Figure 27. Total volume of measured bank erosion in each sample reach (m³).

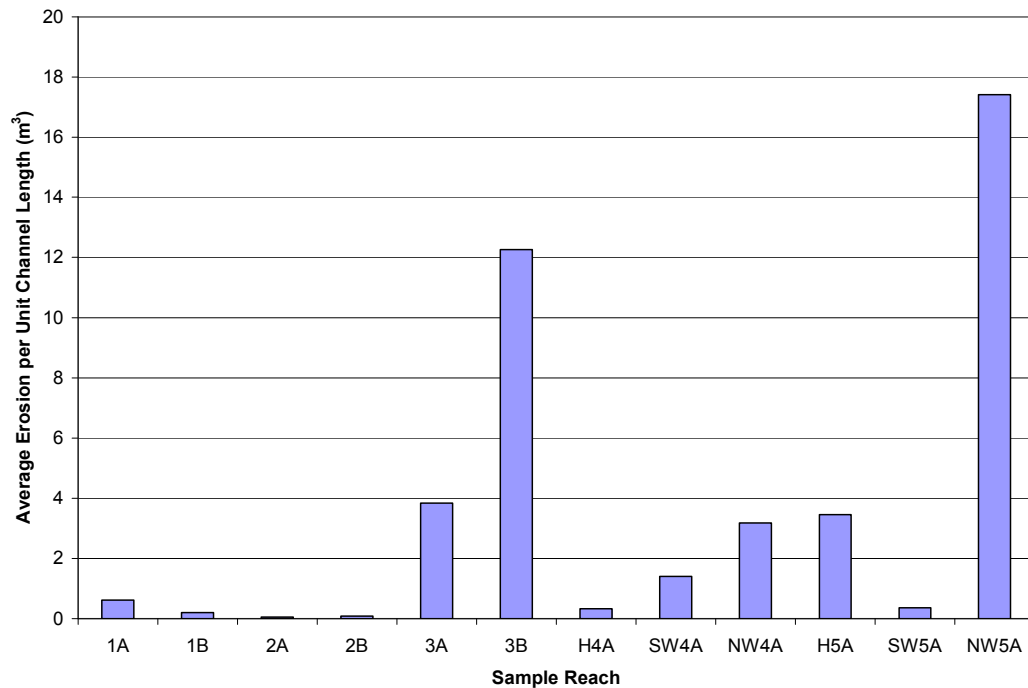


Figure 28. Average bank erosion per unit channel length in each sample reach.

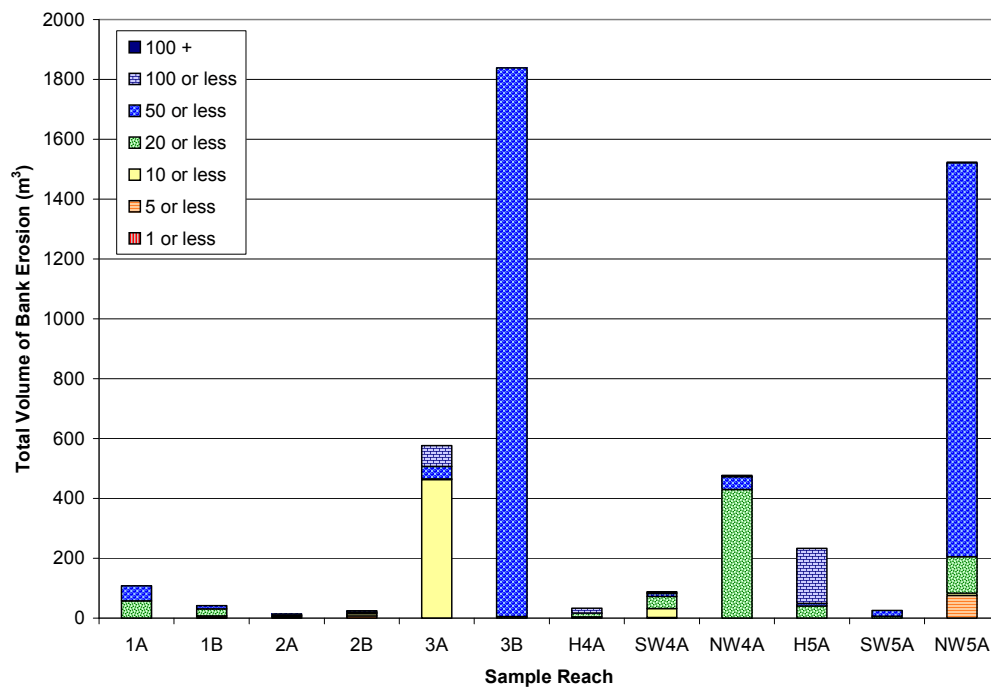


Figure 29. Age estimates associated with measured erosion in each sample reach (years).

Using the amount of lateral bank erosion measured, and associated age class estimates made in the field, an average rate of lateral erosion for each erosion age class in

each sample reach can be calculated (Figure 30). These rates of retreat are for portions of the sample reach that are actively retreating, and thus, represent the highest rates of erosion in each sample reach. In all sample reaches, erosion that is in the 5-year, 10-year and 20-year categories have the highest rates. For example, in seven of the 12 sample reaches, erosion in the 20 years or less age class is equal to, or has the highest average rate. In the reaches where the 20-year age class is not the highest, either the 5-year or 10-year age class has the highest rate. Although a majority of erosion measured was based upon indicators in the 50-year age class, in all reaches, the 100-year and 50-year age class has the lowest and second lowest rates of erosion, respectively. Some reaches have higher rates of erosion, representing bank erosion from active landslides that directly impinge on the creek, as in reaches NW5A, SW4A and 3A. However, the high rate of erosion measured in reach 1A is primarily from localized scour around rootwads that entered the channel during a single bank collapse event. It appears that erosion within the past 10 years has been at a greater rate compared to erosion occurring over longer time periods. This is likely due to the erosion that occurred in the high flow events of 1995 and 1997. The real or perceived higher rates of recent erosion are likely due to the presence of more indicators of erosion that are likely to still exist from erosion that occurred 10 years ago, compared to 100 years ago. For example, exposed tree roots will rot and snap off after a certain length of time, preventing the older erosion from being measured. Also, any recent erosion could completely remove the older indicators, essentially “resetting the clock”. All of these caveats aside, bank erosion is occurring in Sulphur Creek, and regardless of the rates, a majority of the volume of erosion observed is based upon indicators younger than 50 years.

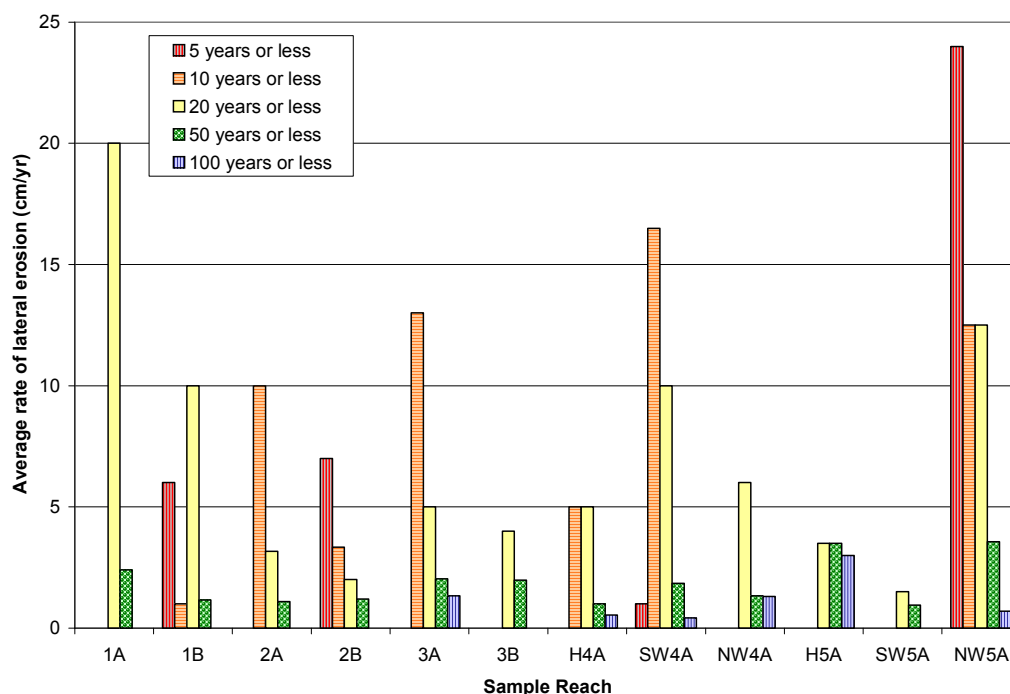


Figure 30. Average rate of lateral bank erosion (cm/yr) in each sample reach.

Modifications made to the banks of the channels, including erosion control measures primarily occur in the lower reaches of the watershed (Figure 31). These bank revetments include riprap, poured concrete slabs, stacked concrete or stone walls, rock gabions, willow wattles, and other styles of revetment. Reaches 1A, 1B and 2A clearly have the longest length of bank with revetments. Reaches 1A and 1B are confined by the entrenchment and revetments in the residential areas of the city of St. Helena; many of the bank revetments in these reaches are efforts by local landowners to prevent the channel from threatening their property or houses. The lower reaches are also the areas that experience the highest levels of flood flow, collecting the drainage from the entire watershed, resulting in the greatest potential for bank erosion. Reach 2A has been modified by historic gravel mining operations, however the bank revetments are set back from the active thalweg to allow some natural modification by the channel. It is important to remember that measurements of erosion in reaches with erosion control devices are minimum measures, because the devices limit the amount of erosion occurring.

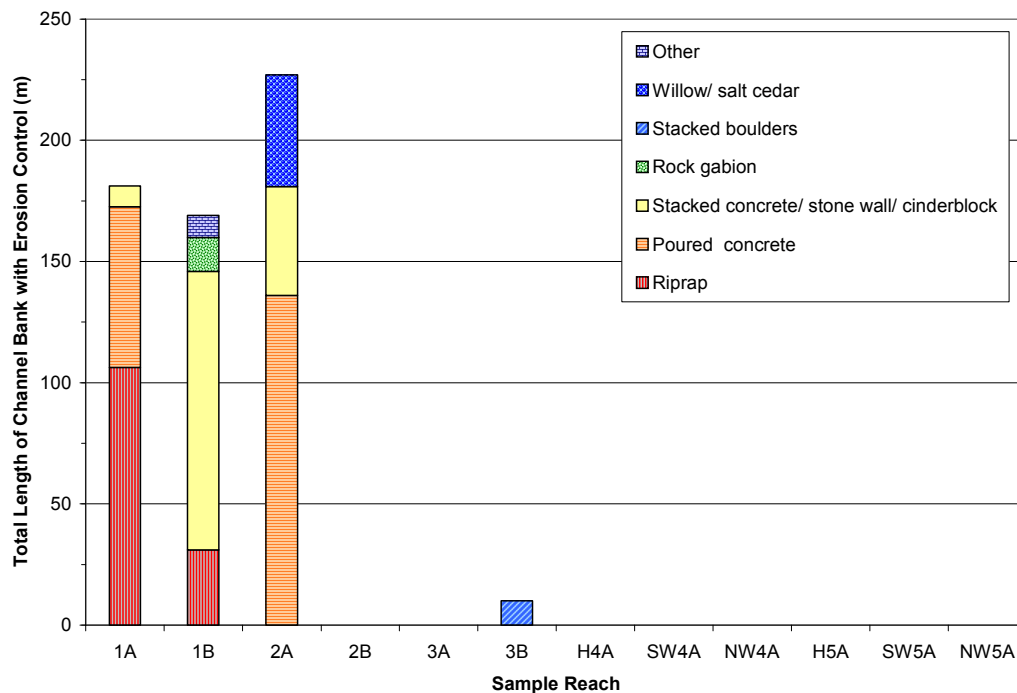


Figure 31. Type and total length of measured channel banks with erosion control revetments.

Bank characterization

At each location where a cross-section was measured, the bank and terrace was characterized for its composition, vegetation, slope, and land use. The compilation of the bank characterization at three locations, both left and right banks, for each sample reach is reported (Table 10). The composition of the bank, as well as the types and age of

vegetation on the banks have a direct correlation to the susceptibility to erosion of the bank because well rooted and established vegetation increases the shear strength of the bank. The combination of bank height and slope reflect the channel morphology of the reach, and also contribute to the bank erosion potential. In addition, the terrace vegetation and land use was also characterized (Table 11). The percent canopy cover refers to the estimated amount of shading the center of the channel would receive on a sunny summer day. Riparian zone vegetation plays a large role in stream health, providing shade for the stream necessary for stable and cool water temperatures, carbon and plant nutrients for fueling the in-stream food web, bank stabilization, as well as providing a source for the recruitment of LWD.

Table 10. Average bank characteristics for each sample reach.

Reach	Bank composition	Bank slope	Bank vegetation type	Bank vegetation age (years)	Bank vegetation condition	Bank height (m)
1A	Concrete, riprap, gravel alluvium	26°-33° (30°)	Blackberry, grasses, alder, willow, vines	<5	Moderate growth	5.0
1B	Gabion, riprap, stone wall, cobble alluvium	22°-79° (49°)	Blackberry, grasses, Arundo, young alder, young willow	10	Dense blackberry, sparse grasses	3.0
2A	Gravel and silty alluvium, concrete	15°-30° (20°)	Annual grasses, weeds, blackberry, willow, shrubs	10	Moderate grasses, dense blackberry and shrubs	2.0
2B	Cobble, gravel and sandy alluvium	15°-80° (45°)	Annual grasses, weeds, willow, tamarisk	<20	Moderate grasses, dense willow	0.7
3A	Cobble and silty alluvium	40°-80° (60°)	Fleshy vines, blackberry, wild grape, alder, willow, sedge	<20	Moderate growth	1.0
3B	Cobble alluvium, with some gravel and boulders	10°-40° (30°)	Alder, blackberry, sedge, grasses, vines	<50	Moderate	1.5
H4A	Cobble alluvium, bedrock	20°-62° (38°)	Roots of alder, bay, oak, maple, wild grape, grasses	>50	Sparse roots, moderate grape and grasses	1.5
SW4 A	Bedrock, sandy soil profile	40°-78° (55°)	Young bay, ferns, moss, poison oak, grasses	<10	Moderate	4.0
NW4 A	Cobble and boulder alluvium, bedrock	10°-90° (40°)	Blackberry, poison oak, alder and bay roots	<50	Sparse	1.0
H5A	Cobble and boulder colluvium, soil profile, some bedrock	40°-65° (53°)	Bay roots, ferns, moss, grasses, snowberry	<50	Sparse	4.0
SW5 A	Cobble and soil colluvium, bedrock	30°-80° (50°)	Bay and oak roots, ferns, grasses	<50	Sparse	2.0
NW5 A	Weathered bedrock, landslide debris	39°-80° (60°)	Grasses, young oak and willow, poison oak, Toya	<20	Sparse	2.5

Table 11. Average riparian characteristics for each sample reach.

Reach	Riparian vegetation type	Riparian vegetation age (years)	Riparian width (m)	Terrace land use	% canopy cover
1A	Alder, Willow, Oak, Walnut, Conifer	<50	10	Mobile home park	25
1B	Alder, Willow, Arundo, Maple, Woody shrubs	<50	8	Residential	75
2A	Willow, Oak	20	5	Gravel mining plant, Landscaping storage	0
2B	Willow, oak, tamarisk	<20	4	Old road, powerline access, open area	0
3A	Bay, Alder, Oak, Willow	<50	7	Horse pasture, natural	50
3B	Alder, Bay, Maple, Oak, Willow, Ash, Buckeye	<50	15	Recreation, county road, landslide toe	100
H4A	Alder, Bay, Maple, Oak, poison oak	<100	20	Old road cut, barn and pasture, natural hillslope	100
SW4A	Bay, Oak, Maple, Ash, Redwood	<100	15	Natural	75
NW4A	Redwood, Bay, Alder, Maple, Oak, Buckeye, Madrone	>100	12	Natural	50
H5A	Bay, Maple, Buckeye	<50	10	Natural	75
SW5A	Bay, Oak, Alder, Conifer	<50	20	Natural	100
NW5A	Bay, Oak, Toyon, Douglas Fir, annual grasses, poison oak	<100	20	Natural, Landslide scars	50

Channel hydraulic geometry

The bankfull width and depth measurements taken in each sample reach of Sulphur Creek help constrain the lower end of a regional relationship between drainage basin area (discharge) and the bankfull channel cross-sectional area. A linear relationship

exists between watershed area and channel cross-sectional area (Figure 32). The D84 of the grain size distribution is strongly correlated with bed shear stress as is usually observed in channel networks. The median grain size, D50, is also correlated with shear stress, reflecting the relatively high degree of mobility of D50 sediment sizes in general and relatively high sediment supply throughout the channel network.

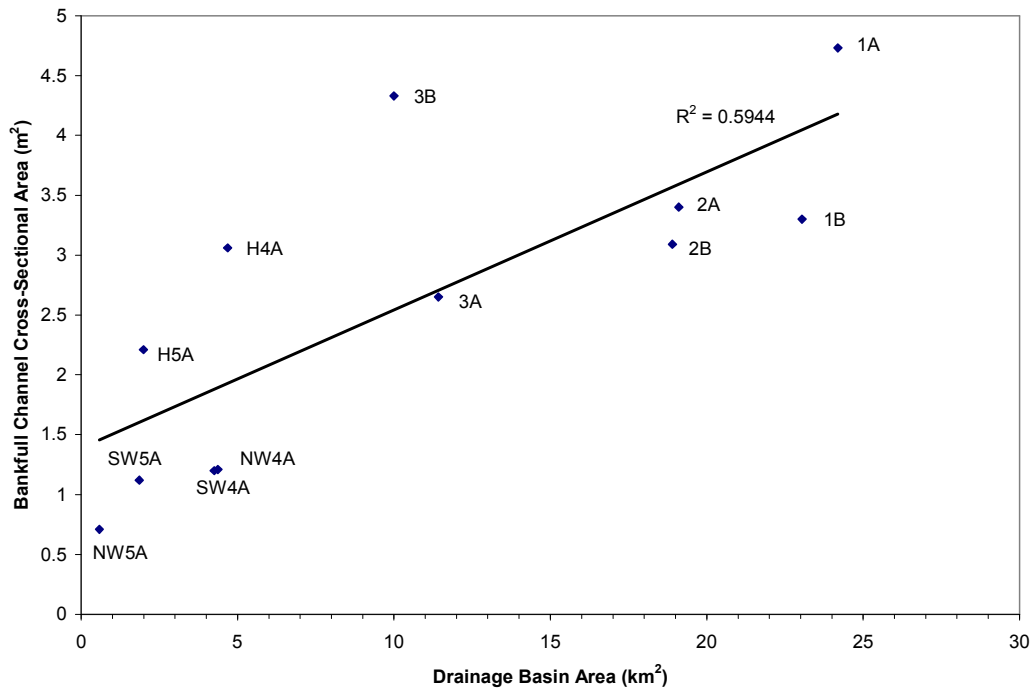


Figure 32. Drainage basin area versus bankfull channel cross-sectional area.

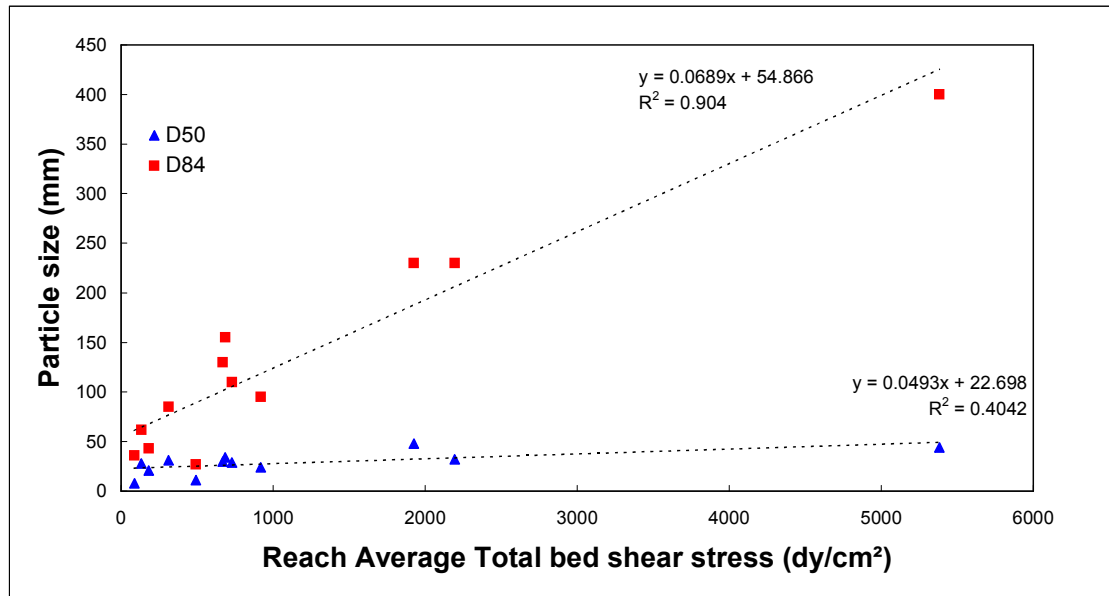


Figure 33. Reach average total bed shear stress versus particle size for each sample reach.

Table 12. Summary of bed shear stress estimates and relative bedload transport capacity in each sample reach.

Reach	Estimated total bed shear stress (dy/cm²)	Estimated threshold shear stress (dy/cm²)	Ratio of total to threshold shear stress
1A	490	93	5.31
1B	90	67	1.31
2A	180	177	1.03
2B	130	236	0.56
3A	310	261	1.20
3B	920	202	4.55
H4A	730	244	2.99
SW4A	2190	269	8.14
NW4A	670	252	2.65
H5A	5380	370	14.53
SW5A	680	286	2.39
NW5A	1930	404	4.77

Bed shear stress in Sulphur Creek generally decreases toward the bottom of the watershed, with the lowest values found in the alluvial fan (reaches 2A and 2B), and increasing again in the relatively confined and incised reaches in St. Helena (1A and 1B). Reaches upstream of, or steeper than 3A generally have high bed shear stress and high sediment transport capacity owing primarily to the steep and confined character of these

channels. The alluvial fan reaches correspond to areas of relatively low channel gradient and a wide, alluvial valley bottom where the channel widens and the channel form becomes braided. Bed shear stress in reaches 1B, 2A and 2B average more than 50% less than upstream and downstream reaches, suggesting the potential for significant sediment deposition.

Threshold shear stress is remarkably uniform throughout Sulphur Creek, reflecting the abundant sediment supply that maintains a gravel texture in most reaches despite high bed shear stress that would otherwise be expected to produce channels armored with cobbles and boulders. Critical shear stress declines substantially beginning in reach 2A and extended to reaches 1A and 1B, reflecting the significant decline in the size of bed sediment below reach 2B.

DISCUSSION

Collecting data on grain size, channel slope, channel morphology, pools, bars, large woody debris, bank composition and vegetation, channel cross-sections, and biotic habitat can help us understand the processes occurring in a watershed, and thus, can tell much about the general health of the watershed in relation to the benefits that the community desires. In addition, the accommodation of new land uses or management practices within the watershed can enhance or subdue the natural response of the channel to climate, tectonics, geology or time. In other words, the natural changes in morphology can be amplified or dampened by human impacts, with either scenario having significant effects on aquatic habitat, and flood and sediment routing. A series of management implications have arisen from consideration of the desires of the community and from the analysis of the geomorphic data collected. These implications focus on different stream morphologies throughout the watershed, migration barriers, riparian vegetation, salmonid spawning and rearing habitat, and whole watershed sediment supply.

The lowest reach of Sulphur Creek does not provide quality habitat for salmonids. Reaches 1A and 1B in the town of St. Helena generally have poor stream health, and do not provide the habitat elements ideal for successful salmonid spawning or rearing. These reaches are heavily influenced by the surrounding city and residential areas of St. Helena. Channel morphology is highly influenced by bank revetments on either bank, with riprap, poured concrete or concrete/stone walls occurring most often (Figure 8, Meters 120 and 200). Because the creek is confined by bank revetments, channel morphology is less able to adjust to the amount of sediment and water supplied by the watershed. In addition, the riparian vegetation in these reaches has been modified, with some portions completely lacking any riparian canopy, and other areas primarily composed of non-native species. The modification is significant because riparian vegetation provides a source of carbon for the in-stream food web, a source for the recruitment of LWD to the channel, and also provides shading for the stream to keep water temperatures cool and less variable, especially during the summer months. The riparian modification is greater in reach 1A, compared to reach 1B, where suburban backyard mature trees compose a portion of the

canopy. Stream temperatures in reaches with no riparian cover are generally warmer, and would favor warm water fish species instead of cool water salmonids (Moyle, 2002). Riparian non-native plant species generally do not have any negative effects on the creek because they provide some of the same ecological functions as native trees and shrubs, such as bank stability and shading. However, some portions of this reach are affected by an in-channel non-native species, the Giant Reed (*Arundo donax*). This species, commonly known as arundo, is able to completely take over the channel, slowing water velocity, trapping sediment, and choking out all other native species. Besides containing non-natives, this reach also appears to have relatively poor water quality, primarily because this reach of the stream receives runoff from the city streets and backyards. The runoff tends to be higher in temperature than discharge in the stream, high in nutrients, and tends to carry excess sediment and trash. Reaches 1A and 1B contain a moderate number of pools (Figure 16), but these pools are typically long, shallow, lateral scour pools. Out of 16 total pools measured in reaches 1A and 1B combined, only 3 have a residual depth greater than 0.5m. These reaches also have a low number of LWD pieces (Figure 19), with only 25% of pools in these two reaches either formed or associated with a LWD piece. The shear stress ratio increases in reach 1A at the mouth of Sulphur Creek owing largely to relatively high channel gradient near the confluence with the Napa River. Despite this increase in shear stress, both reaches 1A and 1B are storing moderate amounts of fine sediment (Tables 6 and 7), which could have negative impacts on spawning success. However, these reaches do contain pool/riffle sequences, with some riparian shading and gravels that are on the fine end of documented spawning gravels. These reaches would not necessarily prevent steelhead success, although these conditions are not ideal. The factors discussed above, especially water quality, appear to limit the quantity and reduce the quality of salmonid habitat available in the lowest reaches of Sulphur Creek.

The alluvial fan reaches of Sulphur Creek act primarily as a migration corridor for salmonids. Sample reaches 2A and 2B on the alluvial fan do not provide adequate spawning or rearing habitat due to channel morphology and processes occurring at this position in the watershed. The creek is braided, displaying a wide and shallow morphology (a high width to depth ratio) (Figure 9), and is storing large volumes of sediment (Figure 22). Relative bed load transport capacity in Sulphur Creek, as described by the bankfull shear stress ratio, is generally > 1 from reach 3B upstream (Table 12). Downstream of 3B, bankfull shear stress declines. The shear stress ratio for reaches 3A, 2A, 2B, and 1B is approximately 1.0, declining to about 0.5 in reach 2B. These areas would be expected to constitute a zone of deposition for bed sediment, and they are in fact an alluvial fan reach with braided channel morphology. Abundant sediment derived from upstream sources has been deposited in this reach, and a gravel mining operation has exploited these geologic conditions for most of the past century. These alluvial fan reaches have moderate numbers of pools, but very low numbers of LWD (each reach only has one piece), and virtually no riparian vegetation of sufficient extent to shade the creek (Table 11). The majority of pools have a residual depth less than 0.4m, and only one pool is formed or associated with LWD (Figure 19). Surface and subsurface grain size analysis reveal these reaches are storing sediment sizes typical of other reaches (Tables 6 and 7), but analysis of sediment storage volumes reveal that these reaches

contain much larger, and highly active deposits (Figure 25). Combined, these two reaches are storing over half of the total amount of sediment measured in the entire channel network (Figure 22). Since gravel mining ceased in 1999, local residents believe that the channel is aggrading, or “filling up” with sediment (Historical Ecology). If this is true, the increased volume of sediment storage in the current channel will decrease the volume available for floodwater, possibly causing an increased flood hazard for the alluvial fan and town of St. Helena. Also, any modification of the channel in this reach should consider the possible increased deposition of sediment, and the implications it will have for the channel modification design and lifespan. But the most important factor limiting the habitat available in these reaches is the lack of perennial flow during the summer and fall. As Sulphur Creek exits its canyon, and begins to flow over the alluvial fan, discharge is lost as the water infiltrates into the fan gravels. During the dry season (approximately May/June to October/November) the stream is completely dry soon after exiting the canyon, and does not transmit surface discharge again until near Main Street. The lack of flow completely eliminates all available salmonid habitat during the summer and fall, and limits both upstream migration of adults and downstream migration of spawned out adults and juveniles to times when these reaches contain discharge. Because these reaches have a relatively low number of pools, low channel complexity, poor cover elements, high sediment storage, and a lack of perennial flow, reaches 2A and 2B act only as a migration corridor for salmonids.

In addition to the lack of perennial flow in the alluvial fan reaches, there are a number of partial physical barriers to salmonid migration on Sulphur Creek. Although these barriers exist, they have not led to the extirpation of salmonids, as fish have been observed upstream of some of these barriers. Some of these barriers most likely act as “obstacles”, that is, limiting migration to periods of higher discharge, and limiting fish passage to only the strongest swimmers (Fish Habitat Assessment). Also, the local community and agencies have identified a number of these barriers previously, and plans have been proposed for their removal. The first barrier is in reach 2A, a section of poured concrete on the channel bed that was initially used for a vehicle crossing location. Currently the concrete forms a grade control with a drop in elevation of approximately 1.5 m over a 20 m channel length. Plans to remove the concrete and restore the site have been developed and should be enacted during the summer of 2003. A series of two barriers in Heath Canyon exist; a double barrel culvert with a drop of approximately 2 m on the downstream edge, and an old summer dam with a concrete apron that limits fish passage. The landowner has been actively working with the appropriate agencies to develop plans for the removal and modification of both barriers. Another partial barrier existed on the mainstem of Sulphur Creek under the Spring Street bridge, just downstream of sample reach 3A. However, in November 2002 a 16 ft (4.9 m) long Alaska Steepass fish ladder was installed to aide fish passage at this location. On the northwest branch, a large landslide, named Devil’s Slide by locals, along with a nearby weir has blocked upstream passage by fish. On the southwest branch, a natural boulder jam in a narrow bedrock canyon has blocked upstream fish passage. Because these boulders are quite large, ranging from 1 to 5 m in diameter, and they represent a “natural” barrier, this barrier will likely remain indefinitely. Barriers to salmonid migration on

Sulphur Creek include both a lack of perennial flow, and physical barriers, however plans exist for the removal or modification of a majority of these physical barriers.

LWD does not play a large role in pool formation and habitat complexity in Sulphur Creek despite a nearly continuous riparian vegetation corridor in the middle and upper reaches, including patches of conifers and redwoods. Conifers and redwoods are important LWD pieces because they decay more slowly than hardwoods, and also because of their large size they tend to have a longer lifespan as LWD pieces in the channel. Median LWD loads per km of stream for second growth redwood forests in northern California are approximately 220 m³/km, whereas loads for old growth forests are approximately 1,200 m³/km (O'Connor Environmental, 2000). Comparatively, Sulphur Creek has fairly low numbers of LWD pieces, although the watershed is composed of both mixed hardwood forests and patches of coniferous forest. LWD loads in Sulphur Creek average 27 m³/km, ranging from 0.3 m³/km to 109 m³/km. The uppermost reaches contain a higher proportion of logs and logs with rootwads than live upright trees, suggesting that pieces are available for pool formation and pool cover. However, upstream of reach 3A, only three pools are directly formed by LWD, and six pools are associated with LWD, with most sample reaches containing pools that are not influenced by LWD (Figure 19). These reaches typically have 50 to 100% canopy cover (Table 11), suggesting a fairly continuous riparian corridor, and a source for the recruitment of LWD. Yet LWD does not appear to be a primary causative agent for pools, or significantly contribute to pool cover and complexity in Sulphur Creek.

The middle reaches of Sulphur Creek provide the best habitat for salmonid spawning. Analyses of surface grain size distributions suggest that the gravels in sample reaches 3A, 3B, H4A, SW4A and H5A are within documented sizes of salmonid spawning. These reaches contain surface framework gravels (D50) between 24 and 44 mm, and also contain less than 8% surface fine sediment less than 2 mm (Table 6). A comparison of size distributions in bulk sediment samples versus surface sediment samples for other reaches in Sulphur Creek shows that the surface grain size is typically 10 to 50% coarser than the subsurface. Sample reach NW4A surface grain size is 60 to 80% coarser than the corresponding subsurface sample, but this likely reflects the large influence of landslides and resulting supply of coarse sediment in this reach. If surface gravels are in fact 10 to 50% coarser than corresponding subsurface gravels in reaches without a bulk sediment sample, it appears that the subsurface gravels in these reaches are also acceptable for spawning. Analyses of the percentage of fines in subsurface sediment samples in the watershed reveal that all samples have between 6 and 16% sediment <1 mm in size (Table 7). Previous studies (Kondolf, 2000) suggest that these percentages of fines would likely not be a limiting factor for survival to emergence of steelhead fry from redds. Also, the percentage of sediment finer than 6.35 mm in these samples ranges from 21% to 41%. These levels are not ideal, but with some coarsening of gravels (removal of fines) during redd construction, these grain size distributions appear to be acceptable. Salmonids tend to spawn in pool tail-outs in gravels primarily classified as active channel deposits in this study. These middle reaches store between 5 and 30% of measured sediment in active channel deposits (Figure 26). In addition to active channel deposits, gravels on the margins of low elevation bars may also be utilized for spawning.

The data suggest that patches of gravel appropriate for spawning exist in these reaches. The number of pools measured in the middle reaches range between 4 and 14, implying that the same number of pool tail-out locations exist in each sample reach, which provide appropriate hydraulic locations for spawning. The combination of appropriately sized and available spawning gravels and a number of appropriate spawning locations suggest that the middle reaches of Sulphur Creek provide the best salmonid spawning habitat.

Besides providing the best spawning habitat, the middle reaches of Sulphur Creek also provide the best salmonid rearing habitat. Reaches 3A, 3B, H4A, SW4A, and H5A appear to have the best combination of habitat elements for summer rearing. Most importantly, these reaches contain perennial discharge, or at least have perennial isolated pools. Continual discharge keeps water temperatures more constant and prevents the drying up of pools. Overall, the pools in Sulphur Creek are fairly shallow, with no pools measured having a residual depth greater than 0.7 m (Figure 18). This shallow depth could potentially be a stressor in the summer due to warmer water temperatures and lack of water depth as a cover element. However, these reaches contain a moderate to large number of pools (Figure 19), and some, especially in reach 3A, with associated LWD cover. While the overall LWD numbers are low, cover is also provided by the fairly continuous riparian corridor, boulders and bedrock outcrops, and undercut banks. These pools have a low proportion of pool in-filling, or pool deposits (Figure 26). Pool deposits comprise only 1 to 3% of all measured sediment deposits in these reaches. A low proportion of pool deposits is beneficial for rearing because pool deposits can decrease the volume of pools, leading to increased water temperatures and decreased amounts of cover for rearing fish. For example, Stillwater Sciences (2002) measured the amount of fine sediment in pools (using a modified V* methodology) in many tributaries throughout the Napa Valley. The measurement taken in Sulphur Creek on the main stem (located in Strata III of this study) showed pool filling of just over 20%, the third highest value measured in the study. Stillwater attributed the high amount of sediment to a large landslide upstream of the sample location. Undoubtedly, the slide Stillwater described is the Devil's Slide area on the northwest branch, which has contributed large volumes of sediment to in-channel storage (Figure 23). Although this study measured large volumes of sediment storage downstream of this area (especially in reach NW4A where the volumes of sediment have decreased the total number of pools present), large volumes of pool deposits were not measured further downstream (Figure 26), and pool in-filling does not appear to be a limiting factor in steelhead success in Strata III (Figure 18). Besides pools with low volumes of sediment storage, a high number of pools, and closely spaced pools are also beneficial for steelhead. Pool spacing in these reaches was less than four bankfull widths, with the exception of reach H4A where pool spacing was approximately every six bankfull widths (Table 9). Based upon the combination of perennial discharge, the number of pools and cover elements, and the low percentage of pool deposits, the middle reaches of Sulphur Creek contain the best salmonid rearing habitat.

The largest source of sediment supplied to Sulphur Creek is hillslope mass-movements, especially landslides that impinge directly on the creek. Reaches with the largest amounts of measured bank erosion are all associated with hillslope mass-movements. For example, the five reaches with the highest values of measured erosion

per unit channel length are all associated with one or more landslides that impinge on the creek. Either the channel is continuously eroding the toe of the slide, as is the case in reaches 3A and NW5A, or the slide deposited a large wedge of sediment in the channel, which is now being eroded through, as in reach 3B. The ages of bank erosion represent a wide range of age classes in the case of 3A and NW5A where sliding is continuously occurring, and a single age class in 3B where a single discrete slide event most likely deposited material in the channel (Figure 29). These landslides are also providing a majority of the sediment that is being stored in the channel. For example, the second largest volume of sediment storage in reach NW4A is due to two large landslides upstream of the sample reach. Overall, the northwest branch appears to be subject to the largest landslide potential (Sediment Source Assessment, Historical Ecology). While reach NW5A is experiencing large volumes of bank erosion due to continuous landsliding impinging on the creek, reach NW4A happens to be downstream of the large landslides, and is storing a large amount of the sediment that has been supplied. The large sediment volume is negatively affecting pool habitat in this reach; only one pool was measured in 150 m of sample reach. Also, the morphology of the channel reflects the large volume of sediment stored (Figure 11). Further downstream, reaches 3B and 3A are also subject to this large input of sediment, with the alluvial fan reaches ultimately storing the majority of the landslide derived material. The sediment storage is observed in channel cross-sections; increased sediment load causes aggradation and an increase in the width of the channel, and the deposition of large bars and terraces (Figure 11). Although large landslides were not recorded in our sample reach in H5A, observations suggest that Heath Canyon is also subject to large deep-seated landslides, potentially contributing large volumes of sediment to the channel. Observations throughout the watershed and geomorphic data collected suggest that the primary source of sediment to Sulphur Creek is derived from hillslope mass-movement processes, especially large landslides.

Besides providing spawning and rearing habitat for steelhead, Sulphur Creek also provides many other resources to residents of the watershed. For example, the town of St. Helena was likely founded in its current location because of the proximity to Sulphur Creek. The creek provides an aesthetically pleasing setting, causing many people to choose to live adjacent to the channel. The enjoyable setting is heightened in the canyon reach, as evidenced by the large number of people that have been drawn to established camps and resorts on the creek over the past 150 years (Historical Ecology). Furthermore, the forests and grasslands of the upper watershed provide habitat for many wildlife species. The wildlife and open areas have both historically and recently drawn recreational hunters to the area. Sulphur Creek itself provides habitat to species other than steelhead, as evidenced by the many species of macroinvertebrates, California roach, sculpin, and stickleback observed (Fish Habitat Assessment). The channel also functions as a corridor to transport water and sediment from the watershed to the Napa River. During the development of St. Helena, the lowest reaches of the creek have been modified to help flood conveyance through the watershed. With the cessation of gravel mining, the alluvial fan reaches are potentially facing the increased risk of flooding, due to sediment deposition in the channel decreasing channel capacity to carry flood waters. Any projects in these reaches should consider the amount of water and sediment that is either transported through or deposited in this reach.

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