

NAPA RIVER SEDIMENT TMDL BASELINE STUDY:

GEOMORPHIC PROCESSES AND HABITAT FORM AND FUNCTION IN SODA CREEK

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Final Report

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EXECUTIVE SUMMARY

During the Fall 2002 and Spring 2003 empirical observational data were collected in Soda Creek pertaining to geomorphic behavior, current channel condition and function, and change over time. Soda Creek, a tributary to the Napa River, is mostly open space, with small areas of vineyard, grazing and rural residential housing. Soda Creek historically and currently supports salmonid spawning and rearing, and also provides habitat for other aquatic species. Data collected included 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, man-made structures, and indicators and volume of bank erosion. In addition to physical data collection, an assessment and analysis of historical data pertinent to the geomorphic analysis of Soda Creek was completed using SFEI's historical ecology methodology. Many sources of historical data were incorporated into the assessment of the Soda Creek watershed, providing context for the channel form and function presently observed, an understanding of the types of valley floor habitat that have slowly diminished over the years, and lastly providing possible management solutions and preservation priorities for enhancing steelhead habitat. This involved a broad-based recruitment of historical data, community participation to incorporate local knowledge, and the use of multiple sources to establish the historical patterns of the landscape.

Surface and subsurface sediment size analyses suggest that Soda Creek has a relatively coarse sediment supply and does not have a significant amount of fine sediment (< 2 mm). Surveyed cross-sections illustrate the wide variety of channel morphologies observed throughout the watershed. Soda Creek has a relatively low number of LWD pieces, with most being live upright trees functioning to stabilize the banks, shade the stream and provide flow roughness. LWD is not a significant cause of pool formation and most pools have a residual depth of 0.6 m or less. Sediment deposits and bars were numerous in all reaches of the creek. Boulders and bedrock outcrops, along with the sediment deposits had a greater influence on channel morphology than LWD. A majority of the sediment deposits measured have been active in the past one to five years. Overall roughly 70% of sediment is stored in about 20% of the number of deposits measured. Bars and sediment deposits are scaled to the size of the bankfull channel; large volumetric bars tend to be fine grained and above the wetted channel, whereas small volumetric bars tend to be coarser, located in the bankfull channel, and represent patches of potential spawning gravel. Sediment size is slightly larger than ideal for steelhead spawning, but suitable spawning gravels appear to be reasonably abundant. Bank erosion was the largest contributor of sediment to the channel, especially in the lowest reaches and the mid to upper reaches. Bank revetment was greatest in the lower reaches, especially in areas with suburban housing bordering the creek.

Salmonid habitat in Soda Creek is acceptable for maintaining a steelhead population. Salmonid success in Soda Creek is limited primarily by lack of perennial flow, and secondarily by the coarse grain sizes available for spawning, quality and quantity of pools, migration barriers, lack of channel complexity and cover, and discontinuous riparian vegetation. Climatic records show that this seasonal flow regime has not significantly changed within the past 50 years, causing the ephemeral flow to be a constant factor in the quality and quantity of steelhead habitat over this time period. Evidence indicates that the lower portion of Soda Creek has been disconnected from its historical drainage system by the removal of an approximately 600 m (2000 ft) section of stream channel, with concomitant effects on flooding potential and reductions in side channel salmonid stream habitat. With the exception of areas of the creek near the

confluence with Napa River, we suggest that the quality and quantity of spawning and rearing habitat for steelhead trout has not changed over the past 50 years, and is sufficient to maintain a viable anadromous population. Future management actions should minimize land use changes that increase the fine sediment supply to the channel (pool filling) or decrease the groundwater levels or the available habitat features, potentially driving the channel to a condition unsuitable for steelhead.

Although the watershed has experienced some recent development, overall land use changes have not caused increased sediment supply to the channel or a greater flood frequency. The primary sources of sediment are bank erosion and the interface between small ephemeral and intermittent channels and hillslopes in the upper reaches of the watershed. Flood hazards are greatest in the lower reaches of Soda Creek due to the local topography and the backwater effects caused by Napa River. It is in these areas that local residents are working hard to maintain the creek banks and their property lines. However, future changes in land use that significantly alter the sediment and discharge supply to the channel could have deleterious effects in the watershed and may cause increased flood risk in the lower portion especially downstream of Silverado Trail.

The removal of riparian vegetation along Soda Creek will affect channel processes and have detrimental effects to the stream function and habitat such as increased water temperatures, reductions in channel complexity, increased bank erosion, and reduced recruitment of LWD. Retaining the riparian vegetation and in-channel LWD in its natural state could both maintain and improve the quality of anadromous fish habitat.

Watershed conditions such as the quality of current anadromous fish habitat, the flood response of the watershed, the sediment production and storage characteristics of the stream, and condition and function of riparian vegetation communities are of particular importance for Soda Creek and other tributaries of the Napa River watershed. There are many management initiatives being implemented by CDFG, the County of Napa, and others to preserve or enhance numbers of steelhead trout. Initiatives for the control of sediment source and transport are being encouraged by the RWQCB through the sediment TMDL processes and by the County through the hillslope ordinance. The Napa flood control project is helping to reduce the risk of flooding. In the context of these ongoing management initiatives, we make the following recommendations for management of Soda Creek and suggest that these are likely to be relevant to other areas of the Napa River watershed:

- a) Further conversion of uplands to vineyard or residential should be carefully planned to reduce possible effects on stream flow and sediment supply.*
- b) Reach specific erosion control solutions that consider local ecology and geomorphology should be encouraged in the lower portions of Soda Creek and these should include consideration of Biotechnical streambank stability techniques.*
- c) LWD removal should be more carefully managed. Education for local residents and County staff regarding LWD removal will have benefits on in-channel salmonid habitat.*
- d) A habitat restoration and enhancement plan focusing on pool habitat, spawning gravel patches and surface flows should be developed.*
- e) The riparian corridor should be maintained in order to maximize LWD recruitment, stream shading, and bank erosion protection.*

ACKNOWLEDGEMENTS

We greatly acknowledge the section 205(j) Water Quality Planning Program and State Water Resources Control Board (SWRCB) for providing the funding for this study. Without funds such as these, the research and planning necessary to maintain the environment for future generations would not be possible.

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We would also like to thank our colleague Elise Brewster for her help in gathering and interpreting historical information.

And most of all, we would like to thank the landowners in the Soda Creek watershed for granting permission to access the creek, and providing the local knowledge and history of the watershed. Their enthusiasm and collective knowledge has greatly enhanced the quality of the project both in terms of helping us to interpret the data and in terms of providing us with an opportunity answer community questions and concerns. It is these kinds of planned or random interactive liaisons that help to fulfill the educational objectives of the Water Quality Planning Program and achieve a better environment for the future.

DISCLOSURES

The report was prepared through an agreement with the State Water Resources Control Board (SWRCB), contract agreement number 00-112-250-0 for the amount \$120,372.00. All work reported herein was carried out by San Francisco Estuary Institute in accordance with State and Federal provisions described in detail within the contract including the use of recycled paper for the reproduction of this report. There were no subcontracts necessary to complete any portion of this work and none were specified in the original scope of work and contractual agreement.

OBJECTIVES

The objective of this project, “*the Napa River Watershed Sediment TMDL Baseline Study*” was to collect empirical observational data in a sub-watershed or sub-watersheds (depending on the outcomes of consultation with the modeling group, University of California at Berkeley [UCB] and Stillwater Sciences Inc. [SSI]) who are carrying out an analysis of limiting factors for steelhead in the Napa River in response to the sediment TMDL on behalf of the Region 2 Regional Water Quality Control Board (RWQCB). The data collected by San Francisco Estuary Institute (SFEI) will be used by the RWQCB to validate the findings generated by UCB and SSI and pertain to geomorphic behavior, channel condition, and function in relation to the beneficial use, anadromous fish, and limiting factors to steelhead success in the Napa River watershed.

BACKGROUND

The Napa River is listed as impaired by sedimentation under section 303(d) of the Clean Water Act. Primary sediment-related concerns include: (1) stream-riparian habitat degradation; and, (2) increased flooding for which streambed aggradations may be a contributing factor. UCB and SSI have been contracted by the RWQCB to characterize stream-riparian habitat suitability at the watershed scale to determine whether excess sediment supply or other factors constitute significant limitations to population sizes of key native stream species. The RWQCB study is being conducted as Phase I of the sediment TMDL study in order to:

1. Confirm, reject, or modify the sedimentation impairment listing;
2. Determine whether other causes exist for habitat impairment; and
3. Set the stage for further investigation(s) in Phase II of the study, should impairment(s) be confirmed, as needed to identify causes and solutions to land-use related impacts.

Findings from Phase I (Stillwater Sciences Inc., 2002) focus on anthropogenic changes in the watershed that have negatively affected the habitat of Chinook salmon, steelhead trout, and California freshwater shrimp. An analysis of the limiting factors for these species found that many changes in the physical habitat were having deleterious effects upon the populations, including: incision of the mainstem Napa River, change in river pattern, decreases in connectivity with the floodplain, decreases in habitat complexity, sediment fining and increased mobility of bed sediments, changes in the seasonal flow patterns, decreases in large woody debris (LWD) and pools, decreases in permeability of spawning gravels, increases in the number of migration barriers, and increases in water temperatures. Recommendations of actions to improve in-channel habitat and areas that need further study in phase II were given. These recommendations include: studying mainstem exotic predator populations and outmigrating Chinook smolt mortality, increasing the number of LWD pieces in tributaries to help in the retention of spawning gravel and the abundance of pools, enhance woody riparian vegetation, conduct additional gravel permeability studies and develop a relation between land use and fine

sediment delivery to channels, document and remediate any migration barriers, increase stream shading through riparian vegetation, reduce inefficient water use to increase summer baseflows, and conduct additional studies on undercut bank habitat for California freshwater shrimp habitat (Stillwater Sciences Inc., 2002).

NAPA VALLEY SETTING

The Napa River valley covers an area of approximately 1100 km² (426 mi²) on the northeastern side of San Pablo Bay and is the third largest watershed in the nine-county Bay Area. The watershed is dendritic and rectangular in overall shape, with a length of approximately 88 km (55 mi) and an average width of 13 km (8 mi) (Figure 1).

Population

The ethnically diverse population of Napa County has increased steadily in the past 150 years, following a pattern similar to other parts of the Bay Area, with the most rapid increase occurring from 1950 to 1980 (Figure 2). Population in the county has grown from 46,603 in 1950, to 99,199 in 1980, and to a population of 124,219 by 2000. Presently about 1% of the population are Native American and about 24% are Hispanic or Latino. The Napa River watershed comprises approximately half of Napa County, however, the majority of the county's population lives within the watershed boundary.

Climate

The people of the Valley enjoy a mild Mediterranean climate with hot dry summers and mild wet winters (Figures 3 and 4) and soils are fertile. Average temperatures range from a maximum of 27.8° C (82° F) in the summer months, to a minimum of 2.8° C (37° F) in the winter months (Napa State Hospital). Rainfall occurs primarily from November to April with the maximum occurring in January. Annual precipitation ranges from 510-890 mm (20-35 inches) near the mouth of the Napa River and the city of Napa, up to 1400-1525 mm (55-60 inches) near Mt. St. Helena (Whyte et al., 1992).

Runoff

Annual runoff for the Napa River averages 322 mm (182 Mm³ or 147,300 acre feet) at the City of Napa gage (USGS gage no 11458000) for the period on record (1929-1932 and 1960-present). The seasonal runoff pattern generally follows the pattern of rainfall. The region has historically experienced severe droughts and floods. For example, during the 1977 water year (the driest year on record), only 1 mm (0.65 Mm³ or 527 acre feet) of runoff occurred. In contrast, during the 1995 water year (the 3rd wettest on record, 868 mm (490 Mm³ or 397,200 acre feet) of runoff occurred.

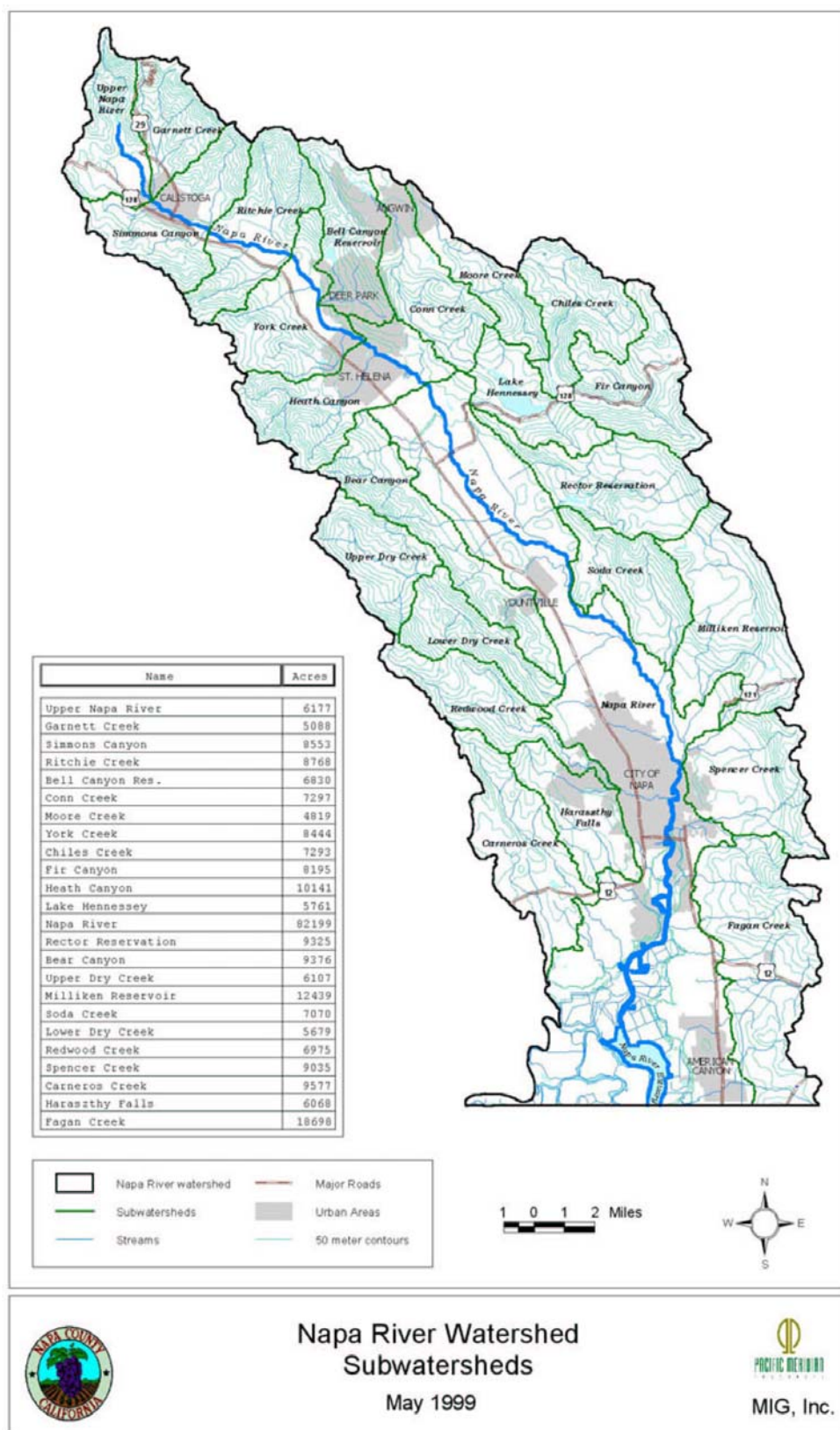


Figure 1. Map of the Napa River watershed (NCCDP, 2002).

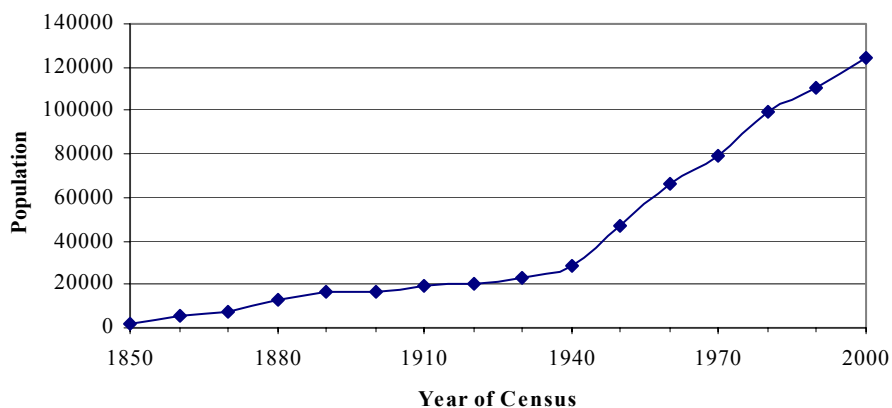


Figure 2. Napa County Population (ABAG 2002, Weber 1998).

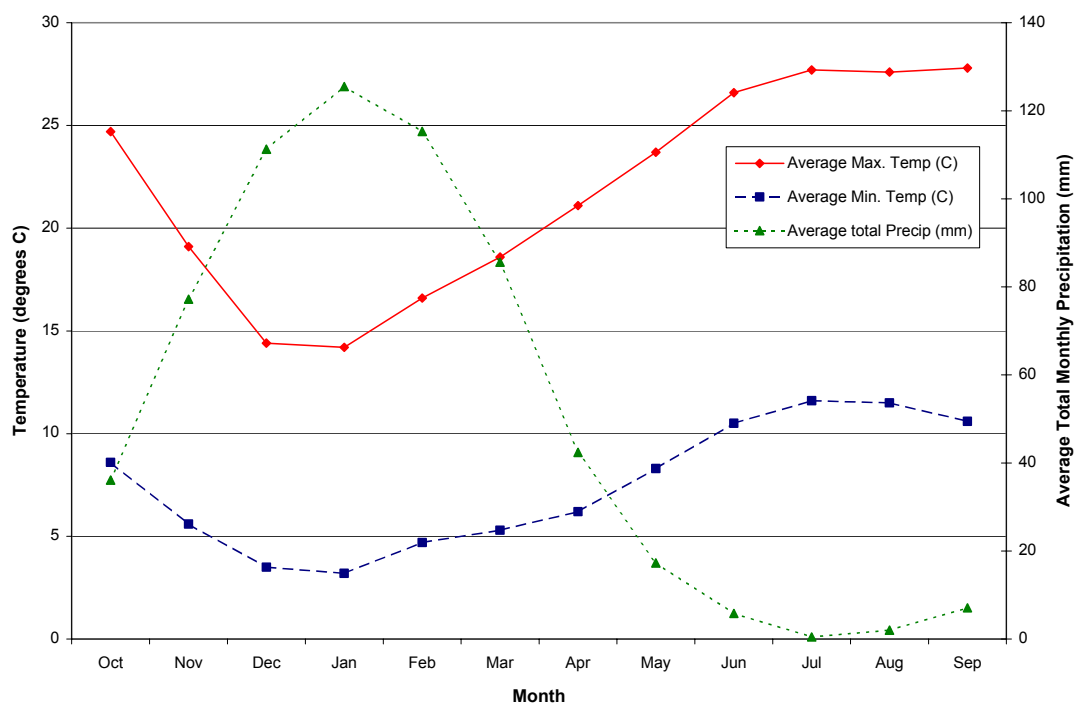


Figure 3. Average maximum and minimum temperatures and average total monthly precipitation recorded at Napa State Hospital, 1917 to 2000 (WRCC, 2002).

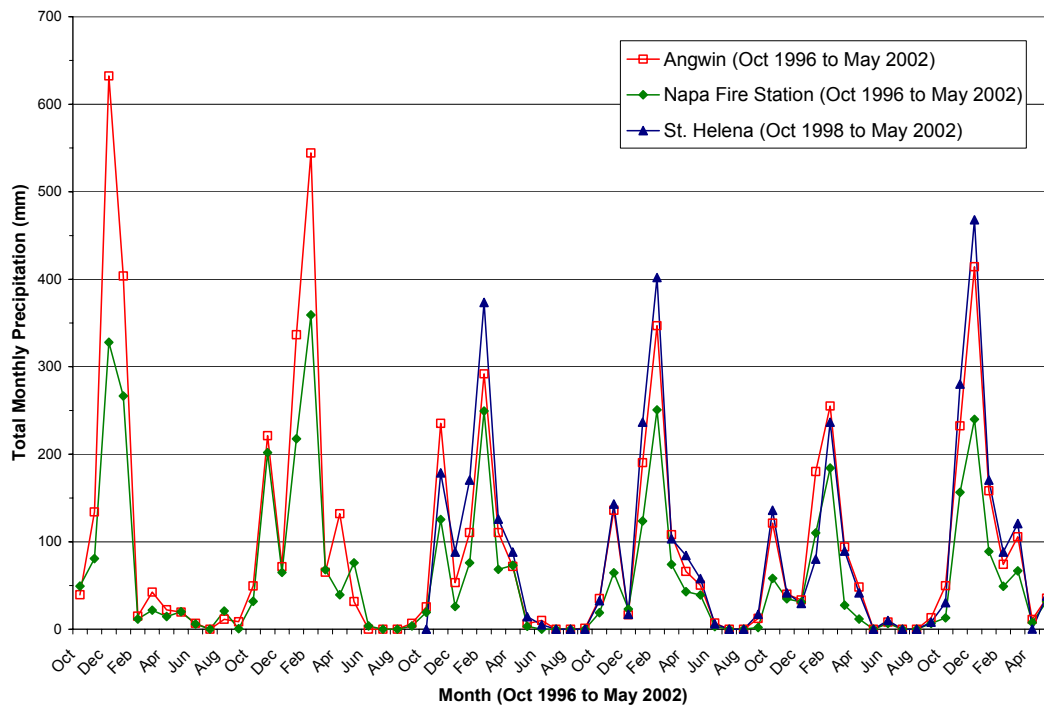


Figure 4. Regional monthly rainfall totals October 1996 to May 2002 (WRCC, 2002).

Land use and Native Species

In the early years (mid 1800's) the watershed was developed for agriculture, including grapes, prunes, pears, apples, walnuts, pasture, hay, grain, cattle, hogs, sheep, poultry, and dairy. Since that time there have been a number of land use and land management changes in response to the demands of rising populations in the Bay Area and changing economic and social pressures. Changes in land use in recent years include the conversion of grazing and open space lands to residential and mainly vineyards (Table 1). Currently 16,736 acres of Napa County is residential (Stillwater Sciences Inc., 2002). These changes in land management are increasing the pressure on water resources for the myriad of beneficial uses including agriculture, urban, recreation, habitat for anadromous fishes and environmental flows. The Napa River watershed is home to a number of threatened and endangered species including steelhead trout (*Oncorhynchus mykiss*), California Freshwater shrimp (*Syncaris pacifica*), Sacramento splittail (*Pogonichthys macrolepidotus*), Delta smelt (*Hypomesus transpacificus*), fall-run Chinook salmon (*Oncorhynchus tshawytscha*), California Red-Legged Frog (*Rana aurora draytonii*), California Clapper Rail (*Rallus longirostris obsoletus*), Salt Marsh Harvest Mouse (*Reithrodontomys raviventris*), and the Northern spotted owl (*Strix occidentalis caurina*).

Table 1. Acreage of wine grapes in Napa County, as reported in Annual Crop Reports (NCAC, 2002).

Year	Crop	Bearing Acreage	Total Tons
1922	Grapes, crushed		30,000 Tons
1930	Grapes		19,000 Tons
1940	Grapes, crushed		32,000 Tons
1950	Grapes		24,421 Tons
1960	Grapes	9,623	23,776 Tons
1970	Grapes	12,254	24,212 Tons
1980	Total Grapes	22,261	80,112 Tons
1990	Total Grapes	28,846	114,303 Tons
2000	Total Grapes	32,365	136,962 Tons

Geology

The Napa Valley is a syncline bounded on the west by the Mayacamas Mountains, to the east by the Howell Mountains, and maintains the general northwest-southeast structural trend of the Coast Ranges. The oldest rocks in the Napa Valley are the accreted Jurassic-Cretaceous (200-67 Million years ago (ma)) Franciscan complex, a sandstone with smaller amounts of shale, chert, limestone and conglomerate. These basement rocks are exposed in outcrop on both the east and west sides of the valley between the towns of Rutherford and St. Helena. Overlying the Franciscan complex is the Great Valley Sequence, a Cretaceous (140-67 ma) forearc basin fill consisting of sandstone, shale and conglomerate. These sedimentary formations originated from erosion in the Sierra and Klamath mountains (Howell and Swinchatt, 1999). The Plio-Pleistocene (5.3-0.01 ma) pyroclastic Sonoma volcanics are exposed along the east side of the Napa Valley between the towns of Napa and St. Helena, in the headwaters of the Napa River near the town of Calistoga, and in smaller amounts along the west side of the valley. The Sonoma volcanics are a thick and highly variable series of andesite, basalt, and minor rhyolite flows with interbedded and discontinuous layers of tuff, tuff breccia, agglomerate, and scoria (Chapman, et al., 1982). The center of the valley is mantled with Quaternary alluvium deposited by the Napa River and its tributaries dating from early Pleistocene (5.3 ma) to the latest Holocene (younger than 10 Thousand years ago (ka)), plus the currently active Napa River alluvium.

The Quaternary deposits can be divided into older alluvium, younger alluvium and alluvial fan deposits (Kunkel and Upson, 1960). The late Pleistocene older alluvium is an unconsolidated stream channel and alluvial fan deposit consisting of reddish-brown cross-bedded poorly sorted clay and silt, with some lenses of sand and gravel. Some of the lenses of gravel are cemented, and thick beds of yellow or gray hard silt and clay are common throughout the deposit. The late Pleistocene older alluvium is exposed where the lowest reaches of Soda Creek have incised through the deposit near the confluence with the Napa River. The late Pleistocene to recent alluvial fan deposits are

unconsolidated, poorly sorted coarse gravel, sand, silt, and clay deposited by the tributaries as they spill from the confinement of the canyon uplands out into the broad valley cut by the Napa River. The recent younger alluvium consists of interbedded unconsolidated gravel, sand, silt, clay and peat that comprise the channel and floodplain of the Napa River and its tributaries. This younger alluvium overlies the older, cemented deposits in lower Soda Creek. Faults in the Napa Valley mapped by Fox et al., 1973 include the Soda Creek Fault, Carneros Fault, St. John Mountain Thrust Fault, as well as many smaller unnamed faults and fault segments. The Soda Creek Fault trends from N10°E to N80°W, is described as “recently active”, and is exposed approximately from Trancas Road to 2 km (1.2 mi) north of the intersection of Silverado Trail and Soda Canyon Road (Fox et al., 1973). Reports generated by independent geotechnical companies for new home construction in the watershed cite evidence that the Soda Creek fault should be considered active, as defined by the California Geological Survey’s Alquist-Priolo Earthquake Fault Zoning Act as showing displacement within the past 11,000 years.

METHODS

Selection of the creek for study (Soda Creek)

The decision to study Soda Creek was made after consultation with the Napa stakeholder groups (Napa Resource Conservation District [RCD], Napa County Soil Survey/ Natural Resource Conservation Service [NRCS]), Michael Napolitano of the San Francisco Regional Water Quality Control Board (RWQCB), and two meetings with Stillwater Sciences Inc. (SSI), and Bill Dietrich, University of California at Berkeley (UCB). There were four criteria that emerged through these discussions and meetings that led to the final decision. The watershed chosen must:

1. Be either a historical or presently viable habitat for anadromous fishes
2. Have a reasonable likelihood of adequate landowner permission for access during the field surveys
3. Have little or no previous data collection so that the pending study would provide new contributions to fluvial geomorphological science in Napa and the Bay Area
4. Have habitat that is reasonably typical of other parts of the larger Napa River watershed so that information learned may be relevant in the wider context of Napa environmental management

Using these criteria a number of candidate creeks emerged including Sulphur Ck., Carneros Ck., Garnet Ck., Dry Ck., Milliken Ck., Redwood Ck., Suscol Ck., and Fagan Ck. Sulphur and Carneros Creeks were discounted as focus watersheds because SFEI and the RCD (at the time) had a study pending on these creeks funded through CALFED.

Garnet, Milliken, Redwood, Suscol, and Fagan Creeks were discounted either because they were not representative, had no known fish habitat, or mainly because access was limited. Dry Creek was a promising alternative but SSI had already done work there and the RCD felt that the local groups would like to have more input in developing their needs in terms of creek preservation before further detailed studies are conducted. The RCD is working with the local groups to develop a study that might include a greater scope than the present grant would allow (i.e. hillslope geomorphology, water quality, ecology, and hydrology). Soda Creek emerged as the only watershed suitable for detailed study following the four criteria. Soda Creek is a known spawning ground for steelhead, had a good likelihood of access to the channel, had little previous data collection, and has habitat that is typical of other eastern Napa Valley tributary streams.

Selection of field locations on Soda Creek

The fluvial geomorphic field survey planned for Soda Creek required access to the stream channel from the confluence with the Napa River upstream to the headwaters. More than 30 private parties own the land on either bank of the creek throughout its length. Because there is no unifying stewardship group in the valley, each of these individual parties was approached by mailing a letter of introduction and a request for access form. In all, there were 18 positive responses, and one party who denied access. The rest of the parties contacted gave no response. The response to the mailing provided access to the majority (approximately 60%) of the mainstem of the creek. Although access was not granted throughout the creek, most of the reaches without access granted were observable from Soda Canyon Road, allowing approximately 80% of the channel to be directly observed.

Physiology of Soda Creek Watershed

Soda Creek is a tributary to the Napa River, located on the east side of the Napa Valley, and flows into the Napa River 7.2 km (4.5 mi) north of the town center of Napa (Figure 5). The channel is a second order stream (Strahler, 1957), with a total channel length of approximately 8.1 km (5.1 mi). Upstream of the confluence with the Napa River, Soda Creek has a drainage basin area of 12.2 km² (4.7 mi²) and a highest elevation of 453 m (1,485 ft) above sea level. At its confluence with the Napa River, Soda Creek has an elevation above mean sea level of 5.5 m (18 ft), and the Napa River at that point has an average gradient of 0.19% (USACE 1963).

Only a subset of the lithologies present in the Napa Valley is present in the Soda Creek sub-watershed. The upper 90% of the watershed is underlain by Sonoma Volcanics, however the lowest mile of Soda Creek flows on an alluvial fan deposited by Soda Creek, and through the older and younger Napa River alluvium. Fox et al., (1973) mapped three main units of the Sonoma Volcanics in the Soda Creek watershed. These

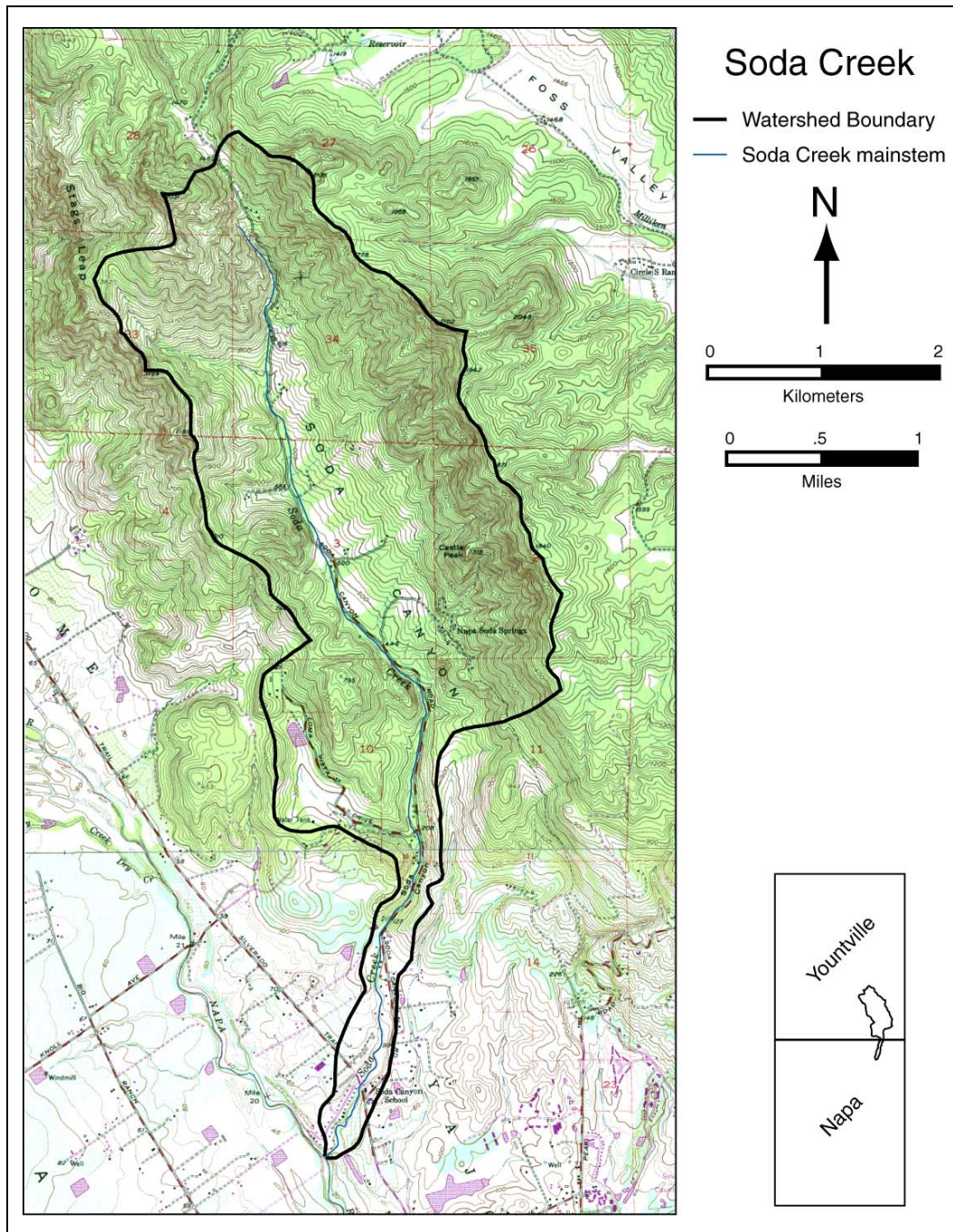


Figure 5. Map of the Soda Creek watershed.

include Tertiary Sonoma andesitic to basaltic lava flows, Tertiary Sonoma rhyolitic lava flows, and Tertiary Sonoma pumicitic ash-flow tuff and agglomerate. The active Soda Creek Fault (Fox et al., 1973) is mainly located south of the Soda Creek watershed boundary, but portions are mapped as uncertain within the watershed. The main orientations of these fault segments are north and northwest, following the same trend as

Soda Creek. However, the location of Soda Creek does not appear to be fault controlled, as the faults are mapped on the eastern hillslopes within the watershed.

Soda Creek, and other tributaries in the area, have response times (the time difference between the center of mass of a rainfall event, and the center of mass of the stream discharge) in the magnitude of fractions of an hour to a couple hours. As these tributaries join the Napa River, the response time of the Napa increases; response time of the Napa River is approximately four hours at St. Helena, 10 hours at Oak Knoll Avenue, and 13-14 hours at downtown Napa (USACE, 1963). From an analysis of measured peak discharge for channels in the Napa Valley (from USGS Gauging Station Peak Discharge data), a 1.5 year return interval flow in a drainage basin the size of Soda Creek will have a bankfull discharge of approximately $8.5 \text{ m}^3\text{s}^{-1}$ (300 cfs) (Figure 6).

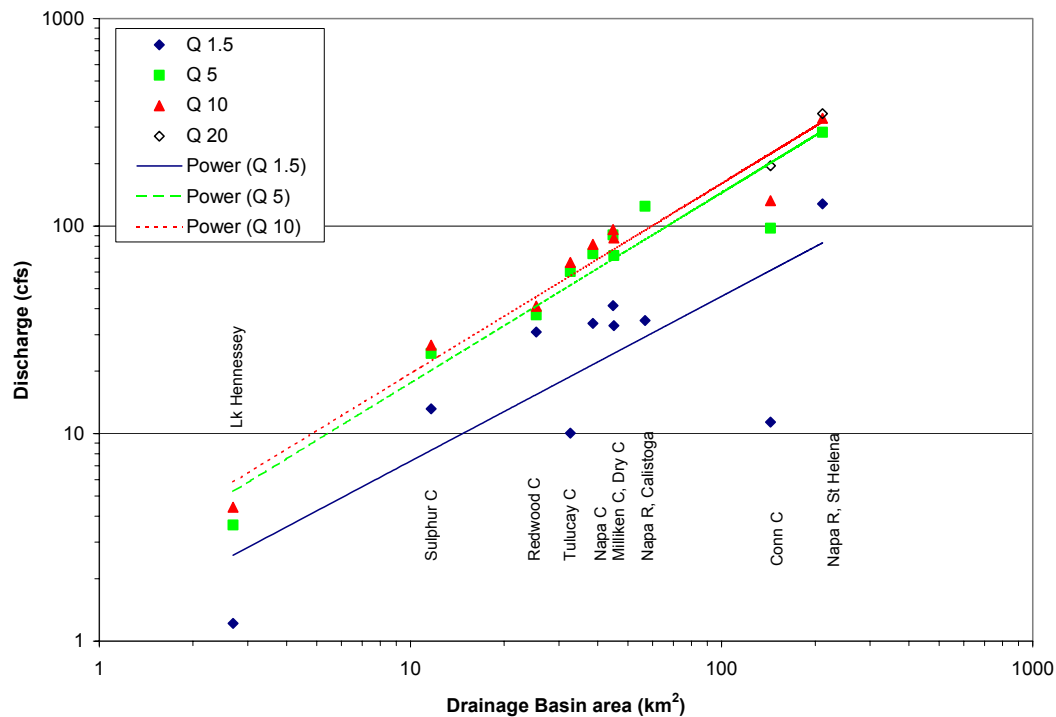


Figure 6. Peak discharge (Q) versus drainage basin area for selected USGS gage sites in the Napa Valley. The recurrence intervals for discharges (Q) of 1.5, 5, 10, and 20 years are plotted with power functions fitted to the data (data from USGS).

Soils of the Soda Creek Watershed

Soil types in the Napa Valley were mapped and described by the US Department of Agriculture Soil Conservation Service (Lambert, 1978). The character of soils mapped within the Soda Creek watershed relate closely to the underlying geology, as well as location in the watershed. The majority of the headwaters are steep hillslopes that range in elevation from approximately 150 to 610 m (500 to 2000 feet) above sea level. These soils are mapped as Rock outcrop-Hambright complex, 50 to 75 percent slopes. Hambright complex soils are described as well drained soils with moderate permeability on uplands formed in material weathered from basic volcanic rock. Vegetation consists of annual grasses and forbs, with oaks on gentler slopes, but most of the area is brushy and rocky.

A small area of Aiken loam ranging from 15 to 50 percent slopes exists adjacent to the channel in the upper watershed. Aiken loams are described as well-drained soils with moderately slow permeability that formed on uplands of basic volcanic rock. Natural vegetation consists of oaks, ponderosa pine, annual grasses and brush, but a few areas that are gently sloping have been cleared and used for vineyards and orchards. Runoff from these soils is moderate on 15 to 30 percent slopes, and rapid on slopes of 30 to 50 percent, with a moderate hazard of erosion in both slope classes. This area of Soda Creek currently contains minor residential and vineyard developments.

Downstream from the Aiken loams, a broad, gently sloping hillslope exists along the east side of the valley. The soil in this area is described as Boomer-Forward-Felta complex, with 5 to 30 percent slopes. This complex has a mix of 40% Boomer soil, 35% Forward soil, and 20% Felta soil. This complex is described as a well-drained soil formed on uplands with medium runoff and a slight to moderate hazard of erosion. The eastern hillslope of sample Strata III is mapped as Sobrante loam, 30 to 50 percent slope. This loam is described as well drained soils with annual grasses, scattered oaks and a few digger pine, with most Sobrante soil areas used for grazing. This soil has rapid runoff and moderate to high hazard of erosion.

On terrace and floodplain deposits along Soda Creek upstream of Silverado Trail, the soils are mapped as Cortina very gravelly loam, 0 to 5 percent slopes. This complex is described as excessively drained soils on flood plains, with rapid permeability, slow runoff and a slight hazard of erosion. The natural vegetation includes willows and water grasses, but most areas of these Cortina soils are now used for residential areas, with some pastures, vineyards and orchards.

As the channel exits Soda Canyon, and spills into the valley formed by the Napa River, a rough alluvial fan is visible in the topography, and has been mapped as early to middle Pleistocene alluvium (Sowers, et al., 1998). The soils mapped on this fan are Coombs gravelly loam, 2 to 5 percent slope, formed from mixed alluvium derived from igneous and sedimentary rock. This unit is described as a well-drained soil on old terraces and old alluvial fans, with slow runoff and a slight hazard of erosion.

Climate and land use of the Soda Creek Watershed

The climate of Soda Creek is typical of the Napa Valley. The majority (89% at Napa State Hospital, 90% at Angwin, 91% at St. Helena) of annual precipitation occurs between November and April. Altitude has a strong local influence on precipitation in the Napa Valley, with higher elevations receiving more precipitation than the low-lying valleys (Rantz, 1971). Soda Creek rainfall averages approximately 914 mm (36 inches) up on the ridges (Milliken Reservoir Gage) and decreases to about 610 mm (24 inches) near the confluence with the Napa River (Napa Fire Department Gage).

Land use in the Soda Creek watershed is generally less intense than in other areas of the Napa Valley largely as a result of thin and less fertile soils. From a visual analysis of aerial photographs flown in 1999 (1:24,000 natural color, stereo overlap, WAC Corporation, 1999), the Soda Creek watershed is mostly open space and low land use intensity on hillslopes, with some of this area used for grazing. Vineyards and orchards only comprise approximately 5% of the watershed, while rural residential areas comprise approximately 3% of the watershed. Currently, a suburban residential area, pastureland, and a vineyard border the lowest several kilometers of the channel. Current influences to the channel from residents and the County include: stabilization efforts on the banks for flood protection and road protection, installation of rock gabions, diversion from a secondary channel to the main channel, and removal of woody debris and riparian vegetation.

Vegetation and native species habitat of the Soda Creek Watershed

Vegetation communities in the Soda Creek sub-watershed are comprised primarily of oak savanna and woodlands, however the highest elevations of the watershed are chaparral and shrubs. Bay, alder and willow are found adjacent to the channel. Other plant species observed in and along the stream in the watershed include: Valley Oak (*Quercus lobata*), Live Oak (*Q. agrifolia*), Blackberry (*Rubus spp.*), Poison Oak (*Rhus diversiloba*), California Buckeye (*Aesculus californica*), Black Walnut (*Juglans hindsii*), Wild Grape (*Vitis californica*), periwinkle (*Vinca spp.*), Giant Reed (*Arundo donax*), Wild rose (*Rosa californica*), Manzanita (*Arctostaphylos spp.*), *Ceanothus spp.*, and Cottonwood (*Populus spp.*).

Soda Creek provides spawning and rearing habitat for steelhead trout and other aquatic species from November to May when the stream length has contiguous discharge. However, this habitat becomes isolated from the Napa River when surface flows cease in the lowest 3 km (2 miles) of the channel during late spring or early summer. On May 16, 2002 flowing water was observed in the canyon portion and the upper alluvial fan of Soda Creek, but the channel was dry in the lower alluvial fan portion, near Silverado Trail. The pools had sufficient water depths, however other portions of the creek only had approximately 10 cm (4 in) of water, and the velocity was slow, most likely less than $0.03 \text{ m}^3\text{s}^{-1}$ (1 cfs). On July 25th, 2002 the stream just below and above Soda Canyon Falls

had pools containing rearing steelhead/ rainbow trout. Other reaches of the creek were dry.

Hypotheses

After an initial field reconnaissance, working hypotheses were generated regarding the condition and function of Soda Creek, in part to help guide data collection:

- a) Because Soda Creek currently has minimal areas of intensive land use within its watershed, the current condition and functioning of the channel is not substantially affected by intensive anthropogenic land use, and represents a condition that has not significantly changed from its natural form.
- b) Soda Creek provides quality spawning and rearing habitat for steelhead trout (*Oncorhynchus mykiss*) because the ideal grain sizes for spawning are present, the channel does not contain large amounts of fine sediment, the majority of the channel is shaded by riparian vegetation, and the channel contains pool and riffle morphology necessary for habitat complexity that is favorable for salmonid fishes.
- c) Habitat for anadromous steelhead trout in Soda Creek is limited to the lower portions of the watershed by the Soda Canyon Falls migration barrier, and the lack of perennial flow in the lower half of the watershed decreases the quality of habitat while significantly reducing the probability of downstream migration.
- d) Previous land uses and channel modifications in Soda Creek do have some effect on the current form and function of the channel. Understanding the land use history will help in assessing the current condition of Soda Creek, and will help us make predictions of how the watershed will react to future changes in land use.

Field Methods

Watershed Science Approach

This field-based fluvial geomorphic study of Soda Creek was designed and implemented using the Bay Area Watershed Science Approach (WSA) (Collins and Collins, 1998) as a reference methodology. The intention of the project partners is to have it be comparable to other watershed studies that have followed the methods outlined by the WSA, while focusing upon specific types of data collection that would allow the greatest understanding of the watershed. Therefore, the study followed most of the methodologies laid out in the WSA, but with some modifications. For example, this study followed the steps of Phase 1 and 2 of the WSA: the compilation of all available relevant maps, aerial photographs, plant species maps, rainfall and stream flow data for the region, the creation of a regional flood frequency curve to help describe the basin, the study of historical flood effects, plotting the longitudinal profile of the channel from the blue line on 1:24000 USGS quadrangle sheets, compilation of a list of landowners in the watershed, establishment and survey of channel cross-sections, use of photographs to document the channel, field collection of channel bed, bank and terrace conditions and erosion, the comparison of bankfull width and depth to published regional curves, incorporation of a historical ecology project in the watershed, description of channel morphological and sediment supply changes, and the preparation of a public report to

discuss the study and its results. Other methods, such as the inventory of channel features and erosion were modified slightly from the WSA; instead of continuous inventory of these aspects over the entire stream length, a continuous inventory was conducted in 10 sample reaches as access allowed and this sample used to characterize the entire stream. Some aspects of the WSA, such as mapping the active and inactive landslides in the watershed, were not completed as a part of this study because they were not needed to calibrate or verify the modeling efforts associated with the sediment TMDL.

To assist in the selection of representative study reaches, the Watershed Science Approach (Collins and Collins, 1998) suggests the use of a longitudinal profile. The longitudinal profile of Soda Creek was plotted using the Napa and Yountville USGS 7.5 minute quadrangles (Figure 7). A visual inspection of the longitudinal profile revealed five reaches, each identified by a characteristic slope. Because channel slope is a good predictor of channel morphology (e.g. Montgomery and Buffington, 1997), the five reaches defined by their characteristic slope were used to define five sampling Strata for Soda Creek (Table 2). 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 Soda Creek. Strata I and II are also distinguished by relatively broad alluvial terraces and floodplains and correspond to the reaches that first go dry in the late spring. The channel in Strata III, IV and V is frequently confined by bedrock and valley walls, and surface water is persistent perennially in Stratum IV and the uppermost reaches in Stratum III. The sampling strategy allowed detailed characterization of representative reaches of each stratum in spite of minor access limitations. Two sample reaches per stratum were characterized in the field (e.g. sample reach IA (1A), sample reach IB (1B), sample reach IIA (2A), sample reach IIB (2B), and so on.) for a total of 10 sample reaches (Figure 8).

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. From a benchmark location such as a bridge, a property boundary, or the confluence with the Napa River, we would walk up the channel to the randomly selected point, and flag the downstream limit of the sample reach. In only one case (stratum II) did access restrict random selection of the starting point for a sample reach; in this case the two sample reaches were contiguous with one another. At the randomly selected starting point for each sample reach, 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. These spatial intervals provided a systematic random sampling frame for selected field data summarized in Table 3.

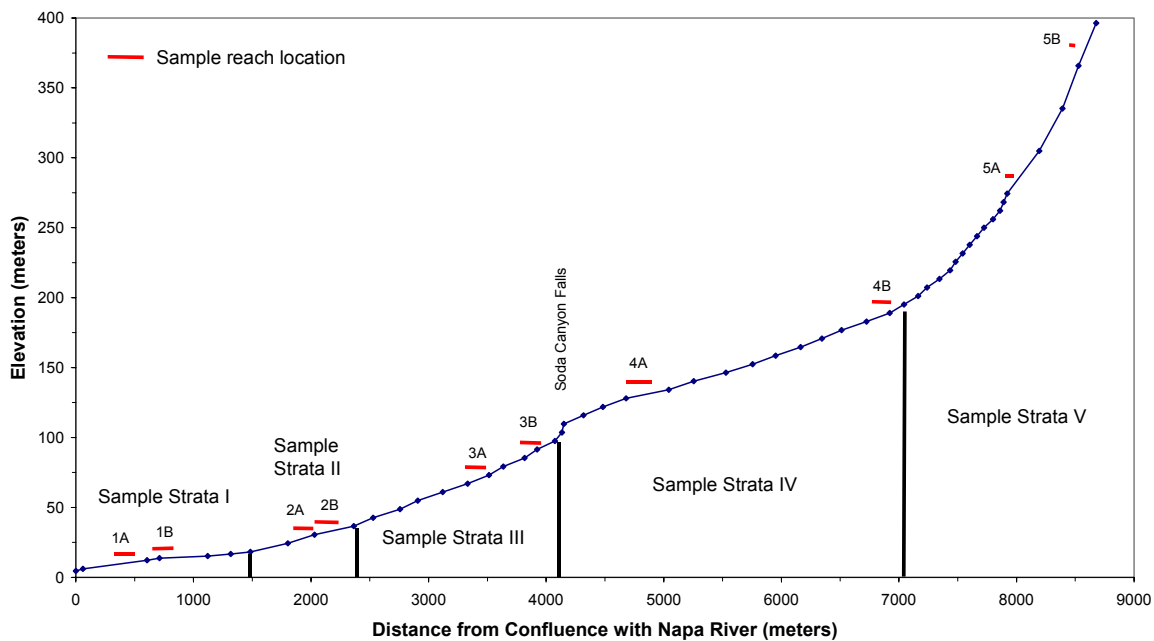


Figure 7. Soda Creek Longitudinal Profile.

Table 2. Soda Creek Reach Geomorphic Characteristics.

Sample Strata	Sample Strata % slope (USGS map) [mean slope from field surveys]	Cumulative drainage basin area (km ²)	Sample reach	Drainage Basin Area above Sample Reach (km ²)	Sample Reach Length (m)
I	0.85	12.38	1A	12.30	170
	[1.2]		1B	12.12	260
II	2.08	11.94	2A	11.88	180
	[2.4]		2B	11.78	186
III	3.56	11.68	3A	10.44	130
	[3.4]		3B	9.84	160
IV	2.95	9.35	4A	7.95	128
	[2.9]		4B	4.17	120
V	12.30	3.99	5A	1.24	72
	[12.2]		5B	0.70	68

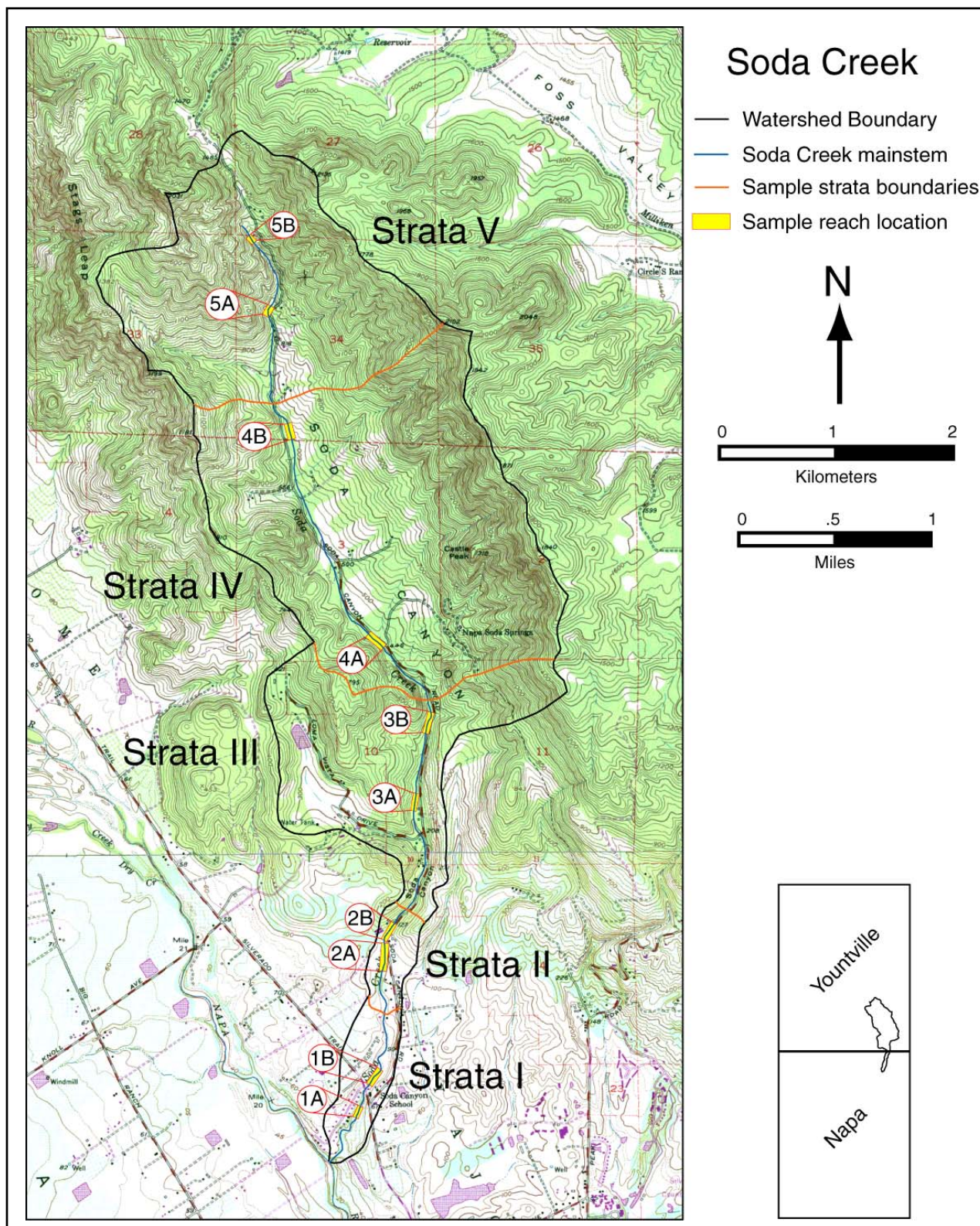


Figure 8. Map of the Soda Creek watershed, sample Strata and sample reach locations.

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 hip chain (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 +/- 2% (determined using one field test consisting of running the hip chain twice along with a metric cloth tape, and based upon previous experience). After the sample reach had been subdivided as described above, channel cross-sections, grain size measurements, bank characteristics and channel slope were measured at the systematic sample points. In addition, a set of observations and measurements of continuous geomorphic characteristics of the channel, such as large woody debris in the bankfull channel, debris jams, bars and sediment deposits, pools, man-made structures, and indicators and volume of bank erosion were recorded (WSA, Collins and Collins, 1998). These data were keyed to the distance on the hipchain, beginning at the downstream edge of the sample reach.

Channel Cross Sections

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. A photographic slide of most locations (taken looking upstream) is on file at SFEI.

Surface Sediment Size Analysis

In each sample reach, pebble counts at five locations were performed following methods proposed by Bunte and Abt (2001), to characterize the surface sediment size distribution in the reach. A systematic random sampling approach was chosen wherein 80 clasts were measured in a grid pattern centered on the five cross section locations in each

sample reach. 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). A patch mapping approach was considered, but because an understanding of stream hydraulics was part of the intended final product and patch mapping is less robust for this purpose, the cross section method, which is suitable for both habitat analysis and hydraulics, was chosen.

The pebble counts were collected along a systematic grid scaled to the local bankfull width and maximum particle size, with the grid centered on a location equal to 5, 10, 15, 20, and 25 times the bankfull width upstream from the start of the sample reach. A 100 m cloth measuring tape was strung from bank to bank, with zero always on the left bank. At locations where a cross-section was also measured, the measuring tape was not moved. A visual inspection of the largest clasts in the channel at that location determined the spacing that measurements would be taken. In most cases, 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. Using the cloth measuring tape to define the spacing of transects perpendicular to the axis of the channel, the telescoping survey rod was placed parallel to the axis of the channel to define the spacing of clasts to be measured. Measurements taken along each transect represent grain size present across the entire channel bed and on active bars within the bankfull channel. 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.

Subsurface Sediment Size Analysis

Near the completion of field data collection and preliminary data analysis, it was determined that the remaining project resources for the field data collection phase would be best devoted to analysis of subsurface streambed sediment size distributions 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 bed material is considered with respect to whether spawning fish are likely to be able to move these “framework” clasts during redd construction. Second, 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.

Reconnaissance sampling sediment size distribution at likely spawning sites was conducted with a 35 cm diameter McNeil streambed sampler at locations distributed

across sample reaches accessible to anadromous fish. The intent was to collect one sample in each of the six sample reaches in strata I, II and III. Potential spawning sites were defined as pool tail outs or the upstream edge of a riffle located between upstream and downstream pools. The field procedure for locating sample sites was to start at the downstream end of a sample reach and walk upstream to the first well-defined potential spawning site. Sample sites were often dry at the time of sample collection.

The sample collection procedure was as follows. The McNeil sampler was inserted into the bed by simultaneously twisting and applying downward pressure on the sample barrel. Downward advancement of the barrel was frequently inhibited by gravel and cobble clasts. Periodic excavation on the outer edge of the sampler reduced friction and allowed manipulation of larger clasts that were blocking downward progress. When the sampler was inserted as far as possible in the bed, generally 15 cm or more, the bed material enclosed within the sample barrel was excavated. The coarser layer on the surface of the streambed was included in the sample, however, the bulk 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.

Bank Characterization

The WSA (Collins and Collins, 1998) suggests that data be collected on the bank and terrace condition and erosion, the extent of riparian forest, and field observations of plant and wildlife species. At the three locations where cross-sections were measured in each sample reach, the bank and its vegetation were characterized. The observations were limited to the area of the bank and terrace immediately adjacent to the cross-section. 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. The percent canopy cover was also estimated at these locations. 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.

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.

Hydraulic analyses

Field data were used to evaluate likely bankfull discharge values and relative bedload sediment transport capacity among reaches. Field observations of bankfull stream stage, reach average slope, and cross section geometry were used as inputs to WinXSPRO (USDA, 1998), a program developed for the U.S. Forest Service to estimate stream discharge and stream velocity based on cross section data in streams with slopes of about 1% or greater. The program requires the user to select a method for determining flow resistance; an empirical formulation based on gauging data (Jarrett, 1984) was used that predicts Manning's n as a function of water surface slope and hydraulic radius. Reach average bed slope was used to approximate water surface slope. Only a limited analysis was intended for general interpretive value.

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 as described by the WSA (Collins and Collins, 1998).

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 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. The shape factor is adjusted on a case-by-case basis to best represent complex bar geometry for purposes of estimating sediment volume. For 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 Soda 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 discreet 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 Soda 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.

Soda 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 (WSA, Collins and Collins, 1998). 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.

Large woody debris

Data on large woody debris (LWD) were collected as a part of the methodologies outlined by the WSA (Collins and Collins, 1998), however, the LWD characteristics in this study were measured according to a modified version of 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 = surface extensively rotted 7 = surface 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

Historical Research Methods

Compared to other parts of the Napa River watershed, the Soda Creek sub-watershed has experienced relatively less intensive Euro-American land use. A full analysis of historical impacts and changes within the Soda Creek watershed was therefore not budgeted as part of this project. However, the ongoing effort by SFEI and other partners to map Napa Watershed conditions at the time of European contact (the Napa Watershed Historical Ecology Project), combined with focused historical research through this effort, made an initial assessment and analysis of historical data pertinent to Soda Creek possible.

This assessment used SFEI's historical ecology methodology, a companion methodology that was developed along side the Watershed Science Approach to help

interpret geomorphic data. The historical ecology methodology involves a broad-based recruitment of historical data, community participation to incorporate local knowledge, and the use of multiple sources of different origin to establish historical patterns of the landscape (Grossinger, 2001). SFEI evaluated numerous local and regional archives for pertinent information about early conditions in the watershed and subsequent land uses with potentially significant impacts. Interviews were also conducted with longtime local residents. The historical record for the Soda Creek watershed is substantial, including a variety of documents produced for a wide range of purposes. Much of this information is associated with ownership, and the land's classification for the purpose of designating private property.

Training of volunteers and staff from local stakeholder groups

Public education is one of the important methods of reducing, eliminating or preventing water pollution and enhancing water quality. As part of this project, one of our aims was to transfer some of SFEI's technical knowledge on watershed processes, science protocols, data collection methods, and watershed management philosophies to local groups. The best way to do this is to solicit local interested people who live in the watershed to come and work with us in the "watershed classroom" during field data collection. As outlined above, field data included physical geomorphological data as well as collection historical documents, maps, photographs and oral histories.

We conducted a number of interviews with local residents and "old-timers" to help us to understand longer-term watershed processes and human impacts and to pass on our own experiences. These interviews represent one of the ways that we "train" local volunteers to think about the watershed as a whole and how positive or negative actions in the watershed are transmitted downstream via the processes of water and sediment transport.

In the latter stages of the project we trained one Napa RCD staff member in the methods of physical data collection in the field. That person worked with us extensively during the collection of field data in Sulphur and Carneros Creeks, the two creeks that we chose for collecting a data set for comparative purposes. The training occurred in the field using "hands on" experience. SFEI staff oversees all fieldwork and data collected by volunteers and quality is maintained through intimate supervision and quality control processes both in the field and in the office during data interpretation and reporting.

RESULTS

Landscape History

In the centuries prior to European contact, Soda Creek was part of the territory of what is now known as the Wappo Tribe. Calling themselves the "Mishwal", this cultural group occupied Napa Valley and some nearby valleys up until heavy colonization began

in the early 1800's. The first recorded contact with the Mishwal was in 1823 by a group of 20 Spanish soldiers, led by Ensign José Sanchez, and accompanied by Father Altimira, a Spanish priest whose duty it was to locate a site for a new mission. The Mishwal likely had some unrecorded contact with Russians, who had established a presence at Fort Ross, some 80 km (50 miles) west of the Valley, and maintained peaceful relations with the Coast Miwok and other neighboring Tribes. The relationship between the Mishwal and early Spanish could be characterized as much more violent than that of other nearby Tribes. It was due to this that they were dubbed "Guapo" – Spanish for "brave"- which was later anglicized to "Wappo." The modern Tribe still refers to themselves as Mishwal (Earl Couey, pers. comm., 2001, Heizer 1953).

Violence escalated over numerous battles to the point that in 1836, General Mariano Guadalupe Vallejo made what is thought to be the only treaty between California Indians and the Spanish government. The treaty described agreements regarding ending hostilities, exchanges of gifts, rights of passage and land ownership, but also had passages about burning. The Mishwal periodically conducted controlled burns for a great many reasons including maintenance of botanical communities for food and medicinal plants, hunting drives, fuels management, to name just a few. As part of this treaty, the Mishwal agreed to restrict their burning in years of drought, but retained that right in all other years. However, the treaty was short-lived. Violence again escalated and the Mishwal eventually fled north into Alexander Valley and other, largely Pomoan and Yuki areas. In 1828-29, and then again in 1838-39, much of the north part of state experienced severe smallpox epidemics that resulted in significant indigenous mortalities, opening much land to the now-secularized Spanish mission inhabitants (Driver 1936, Heizer 1953).

In 1841, the lower portion of the Soda Creek watershed was deeded to Damaso Antonio Rodriguez as part of the Yajome Mexican land grant (Heizer 1953). The grant boundaries were later ratified by the U.S. government in 1864 as encompassing 6,652.58 acres (State Lands Commission, 1982). As a U.S. territory, the upper part of the Soda Creek watershed was classified as part of the rectangular coordinate system of the General Land Office, comprising all or part of Townships 6N and 7N, 4W.

Each of these new designations resulted in substantial documentation about the basic features of the landscape, including the original Spanish diseños depicting land grant requests (Anonymous 1839), the written transcripts of the American court proceedings to determine Spanish/ Mexican land grant claim ownership (District Court of the United States, Northern District of California 1852-1861), the final confirmation surveys for the land grant legal process (District Court of the United States, Northern District of California 1852-1861), and the General Land Office surveys to establish the Township and Range divisions outside of land grant boundaries (Department of the Interior 1859).

Important federal surveys depicting the watershed were conducted in 1933 by the USDA (USDA 1938), the US Army (Corps of Engineers, 1919, 1933; Army Map Service 1947), and the USGS (eg. USGS 1902, 1951, 1958, 1968, 1978, 1980). The USGS

conducted plane table surveys of the area in 1896/ 1899 (with the United States Coast Survey) and 1915, used plane table techniques in conjunction with aerial photography in 1951, and carried out photography-based revisions ("photorevisions")--mostly new roads, agricultural ponds, or channels-- in 1958, 1968 and 1973. "Photoinspection" was carried out in 1978 with "no major culture or drainage changes observed." Different editions of these surveys were published in the interim periods, generally without revisions, leading to potential confusion. For example, the 1933 Corps of Engineers Sonoma 15' quadrangle map shows Soda Creek as of 1915.

Local surveys depicting the creek were produced in association with the construction of county roads and bridges (Napa County Public Works ca. 1865). Proximity to UC Berkeley is probably responsible for the relative abundance of early botanical data, including the Weislander surveys (1932) and the local botanizing of Willis Jepson (Jepson 1910). The popularity of Soda Springs as an early resort center generated substantial amount of relatively early written and photographic materials (e.g., Photograph of Napa Soda Springs, Anonymous, n.d.). Surveys focused specifically on stream condition related to fisheries support were conducted on Soda Creek by the California Department of Fish and Game beginning in 1958.

Changes in Soda Creek's Connection to the Main Stem of Napa River

Historical research focused largely upon elucidating the history of changes to the form and function of the Soda Creek channel at and just upstream from the confluence with the Napa River. The historical record suggests that the interaction between Soda and Napa River has been highly dynamic, probably both as a result of natural process and human activity. In general the trend in the past 60 years in this system has been one of channel simplification. Evidence suggests that Soda Creek has been disconnected from its historical drainage system by the removal of an approximately 600 m (2000 ft) section of stream channel, with concomitant effects on flooding potential and backwater stream habitat.

The earliest available map of the area, a Spanish *diseño* associated with the Yajome land claim (Anonymous, 1839), shows the Napa River, Sarco Creek, and Soda Creek (Figure 9A), with a substantially different tributary pattern from present-day condition. The interpretation of this map rests on several related pieces of information. Later testimony over the ownership of the Yajome grant, recorded by the U.S. courts, confirms that Arroyo de las Trancas is Napa River, and discussion of Arroyo Seco's (Dry Creek) geographic orientation (running nearly south) and relationship to other streams indicate that it is what is now called Soda Creek (District Court of the United States, Northern District of California, 1852-1861).

This earliest picture of Soda Creek shows it running parallel to the Napa River and joining Sarco Creek prior to their intersection with the Napa. The juncture of Soda Creek with Napa River is shown over two miles further downstream along Napa River than the current juncture. Subsequent maps reaffirm the existence of an interconnected

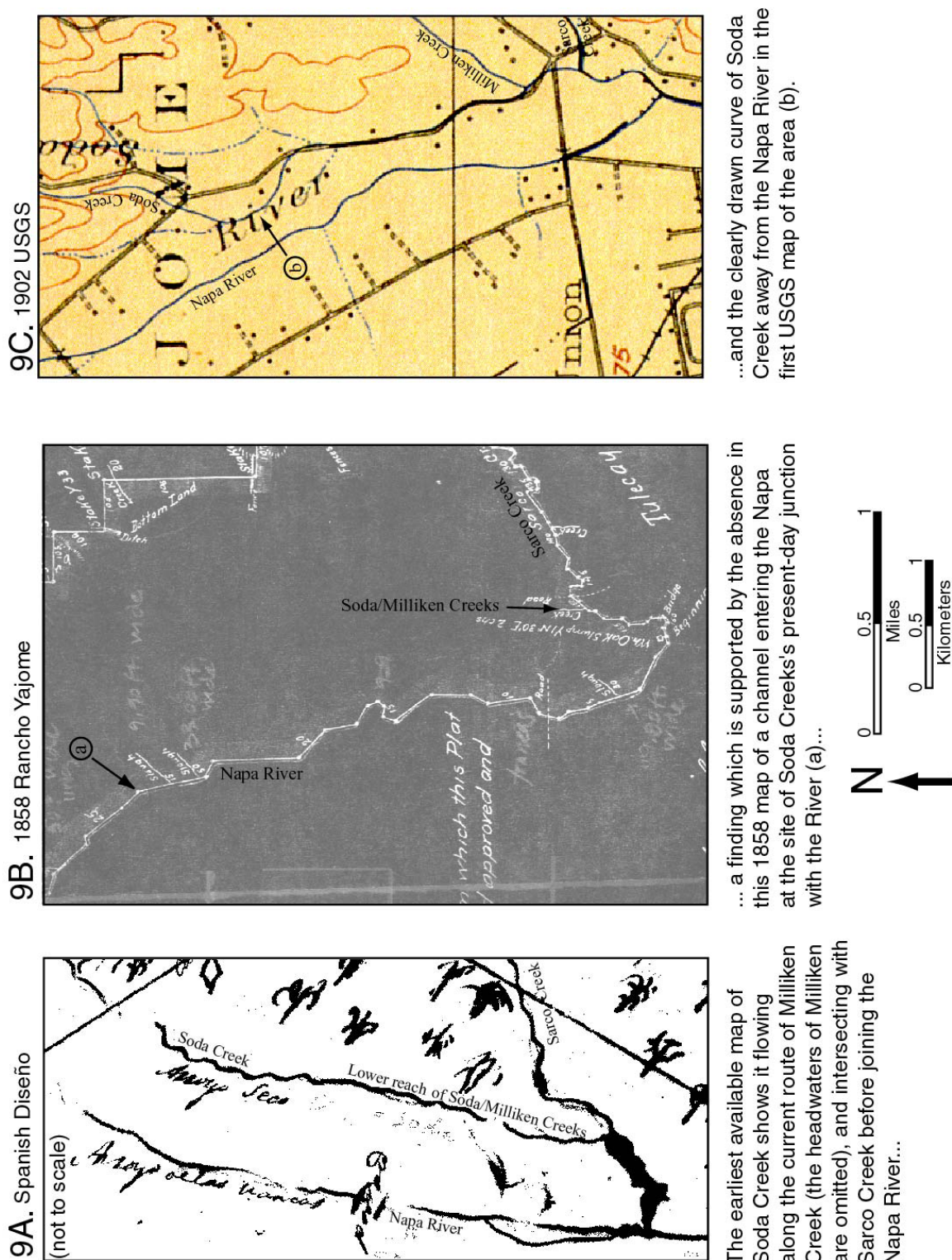


Figure 9. A) 1839 Spanish Diseño; B) 1858 Map of Rancho Yajome boundary; C) 1902 USGS.

tributary system joining Soda, Milliken, and Sarco Creeks prior to their confluence with the Napa. These include both the final map associated with the Yajome land grant case (which was surveyed by Tracy in 1858), and the first USGS survey of the area (1902).

The 1858 Rancho Yajome (Tracy, 1858; Figure 9B) is a boundary survey, showing features only as they intersect with the outer boundary of the grant. The Napa River marked the grant boundary, so only the confluence of tributary junctures were mapped, not the entire tributary watershed. Note that the survey distinguishes "creeks" from "sloughs". The creeks shown correspond with present-day tributary channels, while the sloughs probably indicate anastomosing or secondary channels of Napa River. Since neither a creek nor slough is shown at the position where Soda Creek would be expected (Figure 9B (a)), this map suggests that Soda entered Napa through Sarco Creek rather than independently, by providing negative evidence for the juncture of Soda Creek in its current location. It seems unlikely that the surveyor missed or misplaced such a feature given the number and accuracy of measurements recorded on the Napa upstream and downstream.

The USGS map was produced at a much coarser scale than Rancho Yajome, yet clearly shows Soda's curve away from Napa River (Figure 9C (b)). This map was surveyed from the ground, so there must have been fairly clear evidence to cause this less intuitive route to be shown, rather than the more direct continuation into the Napa. It suggests that the riparian corridor was more notable along the course shown, and that any connecting channel appeared less permanent and less well developed. However, there are also contradictory sources. Local surveyors Dewoody and Quibb each seem to indicate in land grant case testimony that Dry Creek (Soda) "now" empties directly into Napa River, suggesting that that is a recent change at that time, 1861 (District Court of the United States, Northern District of California, 1852-1861). It is possible that both conditions predominated at different times under natural controls.

The next significant document, the 1938 USDA Soil Survey, which was produced independently from the USGS maps, shows a secondary channel intersecting near the current confluence of Soda Creek with the Napa River (Figure 10 A). The alignment suggests that Soda Creek discharge continues along the earlier documented route, rather than making a sharp bend and flowing up-gradient to enter into the mainstem Napa.

The first aerial photography available for Napa was produced in the early 1940s (COF, 1942) and shows further evidence of a direct connection between Soda Creek and the Napa River (Figure 11A). It is a fairly straight connection, with a riparian overstory substantially narrower than the route to the southeast. The route to the southeast has been substantially reduced or eliminated near Silverado Trail, suggesting that human efforts to remove flow from this direction had started at least several years earlier. The relatively uniform and narrow riparian corridor between "old" Soda and the Napa River would be explained by its youth.

Also in the 1940s, the U.S. Army surveyed the area (Figure 10B). Details unique to this map, such as the braided channel (at upper left) and substantial detail in riparian

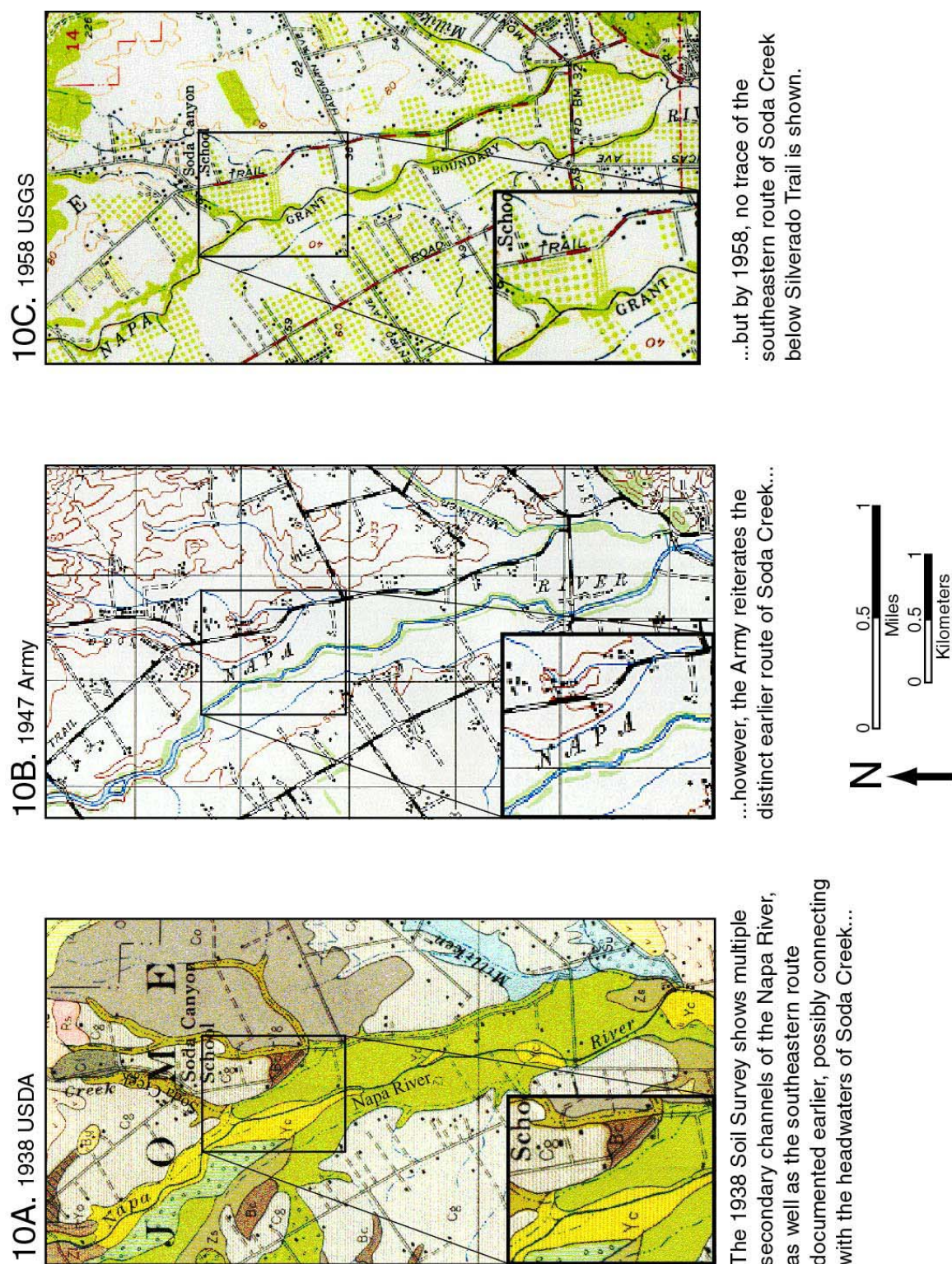


Figure 10. A) 1938 USDA soil map; B) 1947 Army map; C) 1958 USGS.

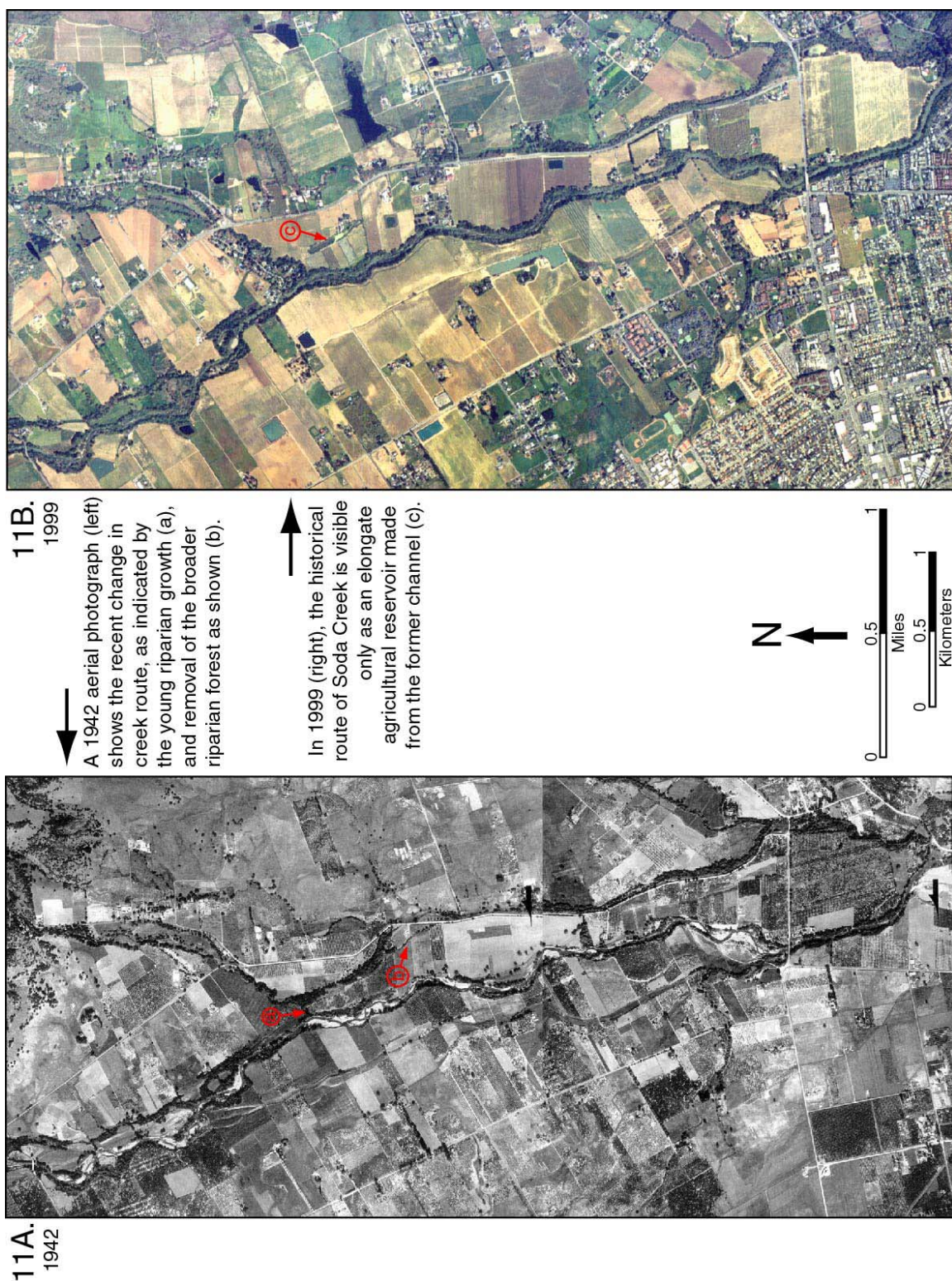


Figure 11. A) 1942 aerial photograph of the Soda Creek confluence with the Napa River (COF, 1942); B) 1999 aerial photograph of the same location (WAC Corp, 1999).

habitat along Napa River, suggest that it was produced independently from the USGS and other previous maps, although likely in a relatively cursory fashion. Surprisingly, the Army map shows only the less direct, parallel route for Soda Creek, despite the photographic evidence for a straight connection by this time, suggesting that the less direct route is still the more prominent visual feature.

Currently, as illustrated by a 1999 aerial photograph (WAC Corp., 1999) (Figure 11B), the former route of Soda Creek below the Silverado Trail is barely visible, except for an elongate agricultural reservoir made from the former channel. Effects of this change are still present, however. Evidence for flooding over the Soda Creek banks towards its former route is provided by local recollections (Wilma and Robert Keig, pers. comm.) and the recent placement of riprap to prevent the creek from taking the former route. On the eastern side of the Silverado Trail, the old channel still serves local runoff and joins Milliken and Sarco Creeks, but is probably substantially oversized for the amount of water delivery since the disconnection of Soda Creek from the system. Other ramifications, such as the reduction in low gradient stream channel fish habitat, and the potential downcutting effect on Soda Creek's gradient above this site make the historical change in Soda Creek's path important for understanding the current form and function of Soda Creek and the Napa River watershed as a whole.

Changes at Silverado Trail

Also in the lower reaches of the watershed, there has been substantial redirection of the Soda Creek channel at its junction with Silverado Trail. The location of the present day Silverado Trail bridge over Soda Creek has undergone many changes in the past 135 years. In fact, the 1865 crossing of Soda Creek may not have even utilized a bridge spanning the creek. But, as traffic grew in the valley, the building of a bridge was necessitated.

The stone masonry bridge was constructed in approximately 1906 (Lance Heide, pers. comm.) later to be abandoned, but not demolished, in 1947 when a larger bridge was built. After many fatalities at the intersection of Silverado Trail and Soda Canyon Road, Caltrans and Napa County redesigned the intersection, raising the road surface, smoothing the curve, and constructing a new bridge in 1973 (Figure 12). These changes have altered the channel geometry in the immediate vicinity of the bridge locations and, in 1973, significantly redirected a several hundred foot long section of the creek.

California Department of Fish and Game Stream Surveys

Three California Department of Fish and Game Stream (CDFG) surveys for Soda Creek are on file at the Yountville Department of Fish and Game office. The first survey was conducted November 16, 1958 by R.F. Elwell and included the entire stream length. At the time of this survey, water depth varied between 2 inches (5.1 cm) and 6 inches (15.2 cm) in the upper and middle sections, with the lower section dry. Soda Creek was

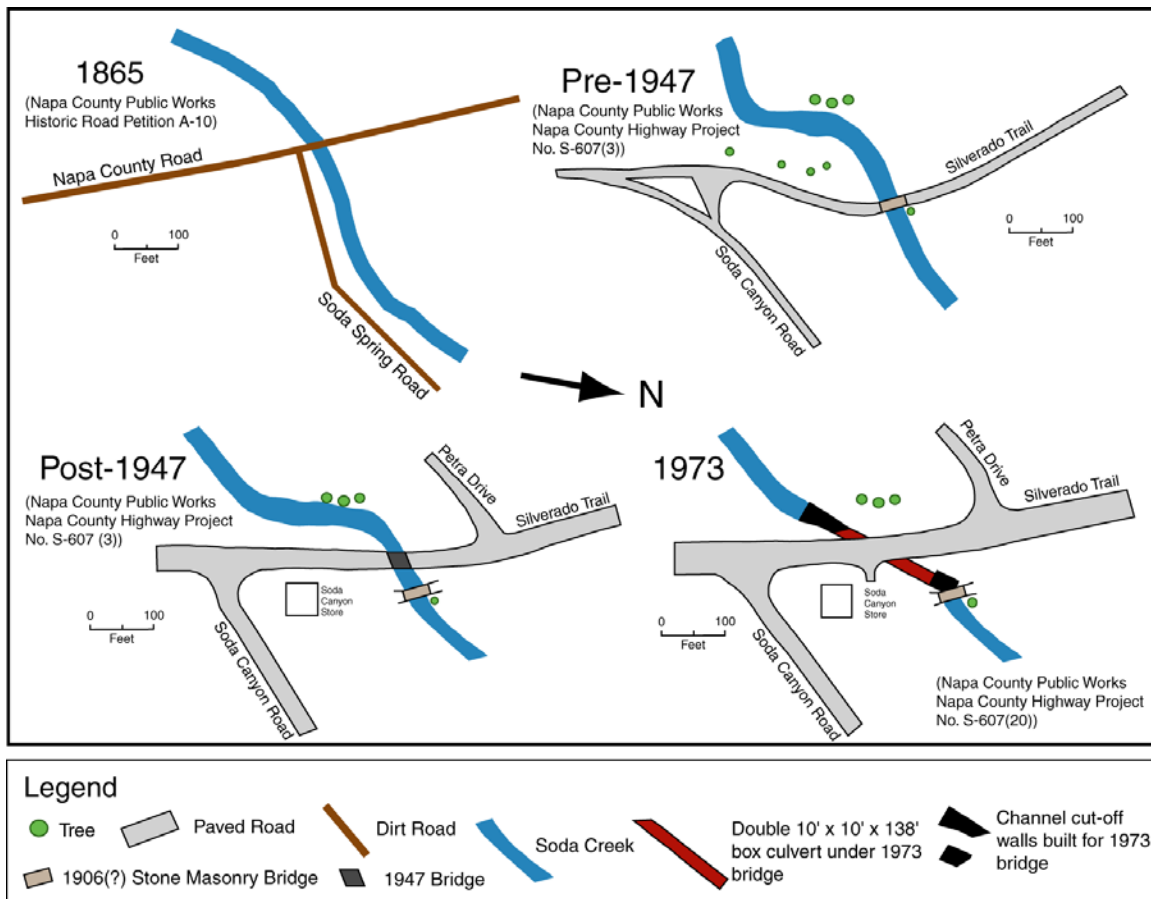


Figure 12. The history of Soda Creek at Silverado Trail. Data gathered from historical documents and construction plans located in the Napa County Public Works office. The anomalous creek shape shown in 1865 was probably sketched rather than surveyed.

described as flowing through densely wooded canyons and open valleys with oak, bay and willow stream shade, with rubble and boulders in the upper 3 miles (4.8 km), and rubble, gravel and sand, with some bedrock, in the lower 3 miles (4.8 km). Wetted channel width is reported as averaging 2 ft (0.6 m) in the headwaters, 6-8 ft (1.8 to 2.4 m) in the upper drainage, 3-8 ft (0.9 to 2.4 m) in the middle drainage, and 12 ft (3.6 m) in the lowermost reaches. Two barriers to migration were noted; a three-foot (0.9 m) barrier at the old stone masonry bridge just upstream of Silverado Trail, and a 14-15 foot (4.2 to 4.5 m) rock barrier at the Soda Canyon Falls. Generally, Soda Creek did not appear to have outstanding spawning area, but was reported as having good steelhead runs each year, second only to Dry and Redwood Creeks and was one of the better steelhead spawning streams in the lower portion of the Napa River drainage.

The reach downstream of Silverado Trail was noted as having excellent (large and deep) pool development, good nursery area, good but limited spawning area, and most

notably reported as dry in the summer. The reach from the stone bridge to Loma Vista Drive was described as dry in the summer, but as having good nursery and trout area, fair steelhead spawning area, and fair (fair sized and scattered) pool development. The reach between Loma Vista Drive and the 15 ft (4.5 m) Soda Canyon Falls barrier was described as having very good nursery area, good trout area, and fair but limited steelhead spawning area. The local warden stated that adult steelhead have difficulty ascending the bedrock stepped barrier (Soda Canyon Falls). Streamflow was augmented by the fairly good spring development in the mid-section of the creek, and affected by a few domestic diversions in the lower reaches. Scarce rainbow trout/ steelhead trout 3-4 inches (76-102 mm) in length were observed in the mid-sections of the creek. Elwell noted that the success of steelhead is limited by the drying of the stream each year in the extreme upper and extreme lower sections.

John Ellison and Tobi Carnine conducted a second stream survey from the headwaters to Silverado Trail on May 21, 1980. On this date, the upper third of the stream was dry, the mid-portion had water 6 inches (15.2 cm) deep flowing less than 0.5 cfs ($0.014 \text{ m}^3\text{s}^{-1}$), and the lower third of the stream was dry. The bed in the upper third was again described as composed of rubble and boulders, the middle third was rubble and boulders with pockets of gravel and occasional bedrock outcroppings, and the lower third had some rubble and gravel grading down to sand. They noted that a fair abundance of spawning gravels suitable for steelhead trout was present, and associated with good riparian cover. The pools in the middle third were characterized as fair, typically less than 15 ft (4.6 m) long, 4-6 ft (1.2-1.8 m) wide, and 1.5 ft (0.5 m) deep. Two additional migration barriers were described, including a fish ladder under the Silverado Trail bridge, and an undercut box culvert 1 mile (1.6 km) upstream of Silverado Trail. The fish ladder is reported as having chronic problems with riprap material sloughing off the banks and blocking the ladder. An electrofishing survey found a total of 50 steelhead/ rainbow trout ranging in size from 52 to 279 mm (2.0-11.0 inches) in three sites in Soda Creek. The third site, in which they found the most and the largest fish, was located immediately downstream of Soda Canyon Falls. They summarized their findings by stating that Soda Creek sustains a major steelhead spawning run, and the limited spawning habitat appears to be more than sufficient to saturate what nursery habitat is available during the summer. Ellison and Carnine suggested that regular cleaning and maintenance of the fish ladder and regulation of water diversions would ensure future viability of habitat for anadromous fishes in Soda Creek.

A third fish survey was conducted between December 1985 and April 1986 by the Yountville Department of Fish and Game (CDFG), however this survey focused on fish survival from a steelhead planting in the creek. On December 6, 1985 approximately 400 steelhead trout were planted in Soda Creek. Electrofishing surveys were conducted on December 12th and 19th, January 3rd, February 7th, and April 23rd to estimate the number of fish that survived, the distance traveled from the planting site, and the food habits of the juvenile steelhead. The December 12th survey found that many of the fish had survived, and most were still within 200 feet (61 m) of the planting site. However, the CDFG was concerned with depth of water in Soda Creek; a minimum depth of 0.3 feet (9 cm) is necessary for downstream migration of smolts. They observed that many locations

barely satisfied this criterion, potentially preventing the planted fish from outward migration. On February 7th, 106 of the 400 planted steelhead were caught. The fish were vulnerable to illegal fishing and predation, and few are believed to have outwardly migrated. On April 23rd, seven planted steelhead were captured, however Soda Creek was dry at Silverado Trail, preventing the outmigration of these smolts.

Interviews with Local Residents

Interviews with long-term watershed residents provided much anecdotal evidence suggesting similar current and historic channel conditions with respect to seasonal flow and fish habitat. All (ten) the long-term watershed residents interviewed remember the channel always drying up in the summer, with the lower reaches completely dry by May or June. The channel flows again after two or three rains, or after approximately an inch (25 mm) of rain, usually in November. A few residents reported that the channel gains some discharge in late September when the trees stop pulling water. The discharge is usually “dirty” due to sediment and oak tannins on the rising limb of the hydrograph, but it quickly clears up. According to some reports, the stream used to clear up more quickly than it currently does, but the water quality is good, especially in comparison to Redwood and Rector Creeks (Brian Hunter, Retired CDFG, pers. comm.). Some residents provided evidence of shifts in the channel location, including the deposition of bars that have shifted the channel location, or filled in pools. Other anthropogenic changes reported in the watershed that may be affecting the channel include: a reduction in the number of cattle grazing in the upper and middle watershed (Clint Smith, pers. comm.), stopping the practice of vegetation removal from the mainstem Napa River channel (Robert Keig, pers. comm.), and the installation of new hillside vineyards in the past 10 years (Penny Mallen, pers. comm.).

Channel Geomorphology

This section reports data that was collected on Soda Creek by SFEI during the fall of 2001 and follow up surveys during the spring of 2002. The data collected includes 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.

Surface grain size variation by reach

Median grain size (D50) for Soda Creek ranged from 95 mm in reach 4A to 32 mm in reach 1A (Figures 13 and 14, Table 6). D50 in reaches 3A and 4B (50 mm and 70 mm, respectively) were slightly lower than the reaches immediately downstream; reach 3A was dominated by bedrock, and reach 4B was strongly influenced by living trees along both banks. In reach 5B, relatively fine grain sizes are attributed to a high degree of

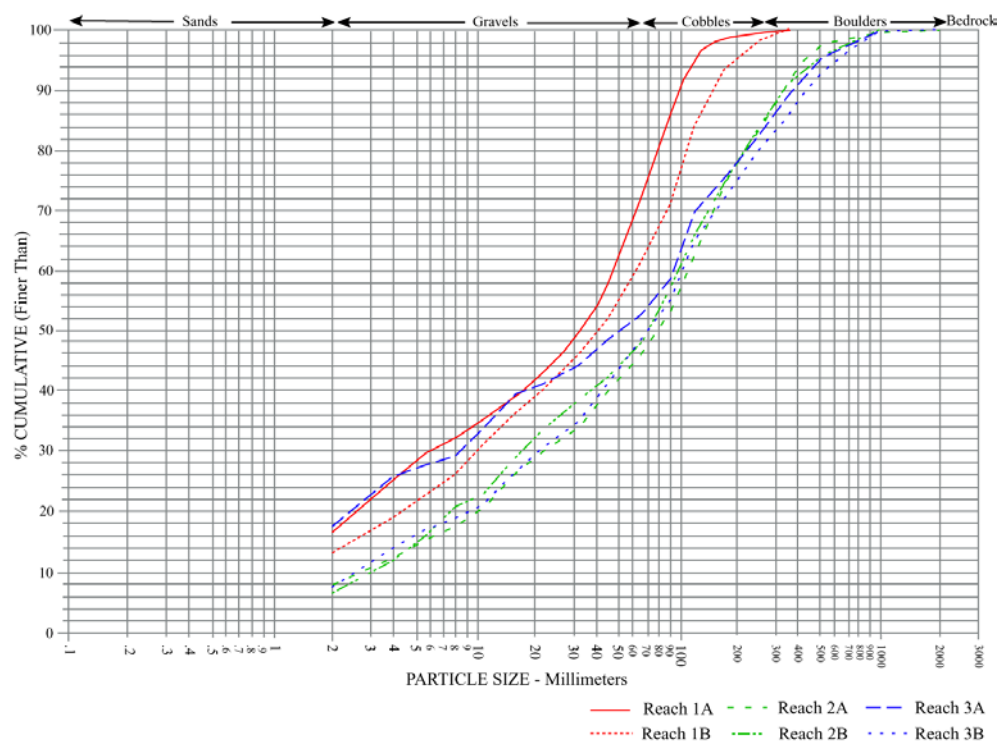


Figure 13. S-curves showing the grain size distribution for sample reaches 1A through 3B.

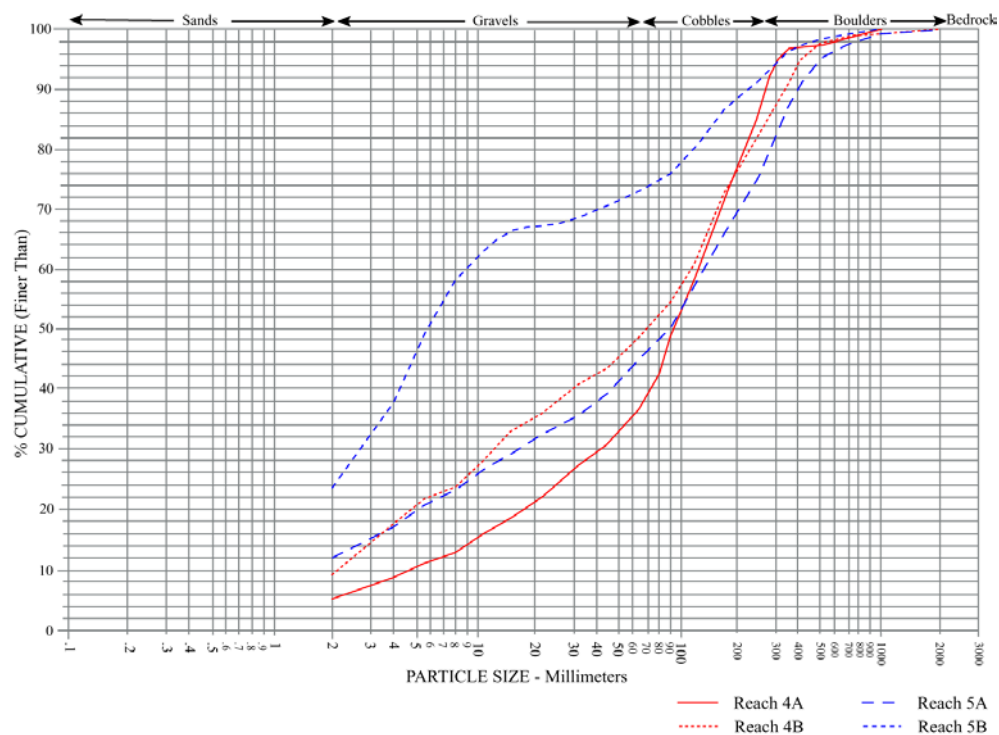


Figure 14. S-curves showing the grain size distribution for sample reaches 4A through 5B.

Table 6. Grain size data for each sample reach.

Reach	% <2 mm	D16 (mm)	D50 (mm)	D84 (mm)	% Bedrock
1A	17	<2	32	84	8
1B	13	3.0	43	130	0
2A	8	6.5	79	256	6
2B	6	5.7	70	256	39
3A	18	<2	50	275	40
3B	8	5.0	70	330	4
4A	5	12.0	95	250	23
4B	9	3.7	70	260	8
5A	12	3.6	90	325	1
5B	23	<2	5.7	150	6

interaction between hillslope materials and fluvial processes common in headwater streams. This was manifested in part by side channels eroded in the valley floor (Reach 5B, Meter 68). Grain size distribution did not follow a pronounced fining downstream trend as is found in many large streams. A marked decline in size relative to upstream reaches occurred only in reach 1A and 1B (Table 6, Figures 13 and 14), with size distributions in Strata II, III and IV generally comparable to one another.

The percentage of fines (grain sizes finer than 2 mm) measured in each pebble count ranged from 5% in 4A to 23% in 5A. Overall, there was no general spatial pattern observed in the watershed with respect to the proportion of <2 mm sediment in sample reaches (Table 6). With respect to reaches most likely to contain spawning habitat, the percentage of fines ranged from 5 to 18%.

Large boulders were common in Soda Creek, especially in the upstream reaches. Of measured clasts in reach 5A, 23% were larger than 256 mm, with 3 clasts larger than 1 meter. These large boulders are only potentially mobile during the highest of discharges, thus making them essentially permanent features in the channel. Boulders are important in all reaches of Soda Creek because of their effects on channel processes (hydraulic roughness and morphologic influence) and fish habitat (velocity shelter, sorting of gravels as indicated by deposits of finer gravel often found downstream of the boulder), particularly in the absence of LWD.

Soda Creek also has bedrock dominated reaches. Reaches 2B and 3A have the highest percentage of bedrock with 39% and 40% respectively. The bedrock dominated reaches are more difficult for the channel to incise and/ or laterally erode, and often have different morphologies compared to alluvial reaches. For example, the bedrock reaches tend to be narrower and deeper with fewer in-channel bars than the alluvial reaches. In reaches 2B and 3A, most of the watershed area is contributing to reaches located in a relatively narrow canyon. Over long periods of time, these maximum stream power conditions have presumably scoured the channel to bedrock in a relatively high proportion of locations. Since stream channel gradients are not markedly different in

these reaches compared to the areas upstream, the high proportion of bedrock may indicate limitations of sediment supply to the channel.

Subsurface grain size variation

McNeil samples were collected at five sites; one each in sample reaches 1A, 1B, 2A, 2B, and 3B. Reach 3A was not sampled owing to logistical constraints. Sample data are summarized in Table 7. Sample volumes ranged from about 10 l to 18 l (2.5 to 4.5 gallons); bulk density of samples averaged about 2.2 t/m³ (140 lb/ft³). Owing to the coarse texture of the stream bed of Soda Creek, the largest sediment clast in each sample ranged from 7% to about 25% of the sample mass. Ideally, samples would be sufficiently large to reduce the largest grain to not more than 1% of the sample mass. If the five samples were bulked together and treated as one sample, the largest clast would be less than about 5% of the sample mass. Hence, interpretation of these data with respect to spawning suitability should consider mean values 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	34.3	4	18	42	90
1B	34.8	7	27	38	110
2A	37.8	5	19	70	185
2B	23.5	5	24	38	130
3B	24.6	3	14	65	130
Composite	155	5	20	52	130

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 (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 Soda Creek indicate framework bed sediment is in the upper end of the range documented for steelhead trout. The bed sediment in Soda Creek is quite coarse, and it appears that appropriate spawning sites for steelhead might be limited to some degree by excessively coarse sediment that cannot be moved by fish attempting to construct redds.

Kondolf (2000) suggests based on a review of prior studies that spawning gravels with less than 12 to 14% sediment finer than 1 mm can be expected to produce about 50% emergence of fry from redds, which is proposed as a reasonable standard for comparison. Kondolf also suggests that a downward adjustment should be applied to bed

samples to account for removal of fine sediment during construction of the redd. An empirical relationship estimates the final percentage of sediment finer than 1 mm as 0.67 times the initial value. Hence, samples with up to 21% sediment finer than 1 mm would be predicted to have levels of about 14% after spawning. Soda Creek clearly has very low levels of sediment finer than 1 mm in the subsurface sediment, suggesting that there would be relatively high survival to emergence of steelhead fry from redds.

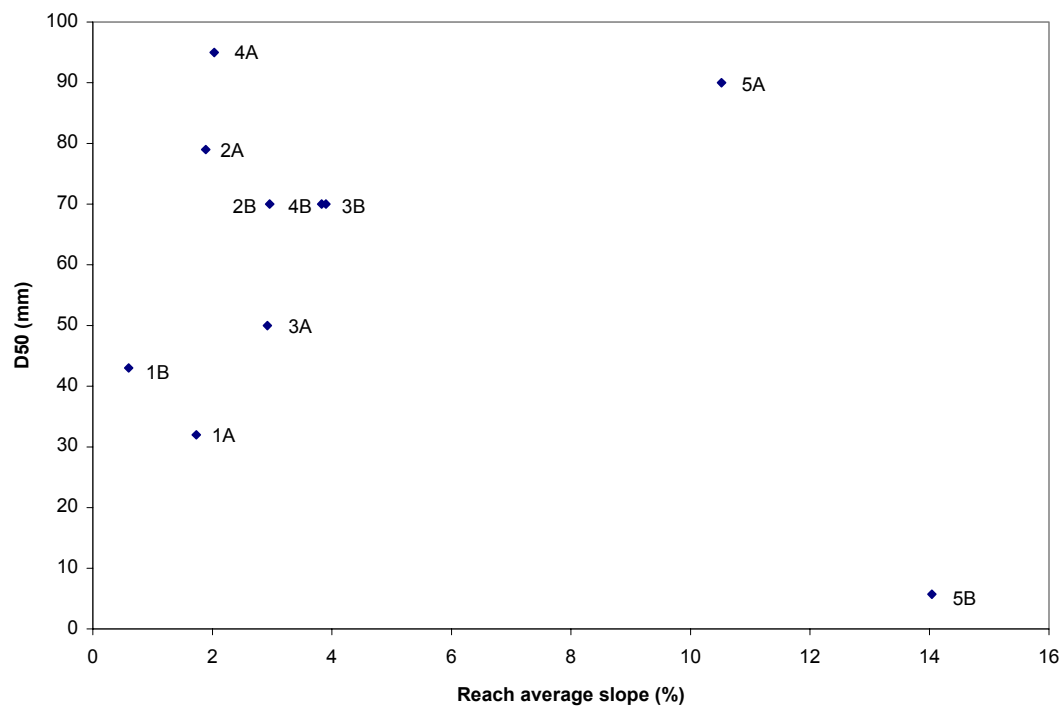
With respect to fine gravel impeding emergence, Kondolf (2000) suggests that previous studies are somewhat variable. However, for steelhead in particular and salmonids in general, the 50% emergence criterion indicates that sediment finer than 6.35 mm should not be greater than about 30%. Again, a correction for removal of fine gravel 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 value. 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 Soda Creek, although three of the five sites had greater than 25% sediment finer than 6.35 mm, even a small reduction accomplished during spawning would be expected to reduce levels below 30%. Hence, the percentage of subsurface sediment sizes finer than 6.35 mm in Soda Creek does not appear to be an impediment to emergence of fry from redds. Overall, spawning conditions in terms of subsurface sediment size distributions in Soda Creek appear to be well within the range of documented conditions suitable for steelhead trout.

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. The reported stream slopes represent reach average slopes; the slopes in each reach varied locally. Reach average slopes increased from 1.7% in reach 1A to 14.0% in reach 5B, with two exceptions in reach 1B and 4A where the slope decreased (Table 8). Reach 1B is wider and shallower than other reaches, and its downstream elevation is controlled by a stone masonry bridge with a concrete and stone footing, whereas reach 4A has underlying bedrock control. Reaches with lower slopes tend to be areas of aggradation, because stream energy tends to decline in areas of lower slope. Increased sediment deposition can affect morphology, sometimes resulting in widening and shallowing of the channel, as well as the filling of pools. In addition to the upstream increase in slope, the standard error reported also increased upstream in response to greater influence of boulder step-pools and bedrock shaping the morphology of the narrower channel. The range of slopes measured illustrates the variability and complexity of the channel morphology within a sample reach. A plot of mean reach slope versus reach D50 (Figure 15) shows a weak relationship that includes two notable outliers in reaches 5A and 5B, where hillslope influences in small steep channels mask fluvial process relationships. In general, reaches in Strata II, III and IV have similar slopes, channel morphology, and grain size distributions.

Table 8. Soda Creek reach average % slope and standard error.

Reach	Reach Average % Slope	Standard Error	Coefficient of variation
1A	1.7	0.69	0.40
1B	0.6	0.12	0.20
2A	1.9	0.05	0.03
2B	3.0	0.29	0.10
3A	2.9	0.33	0.11
3B	3.9	1.15	0.30
4A	2.0	0.92	0.45
4B	3.8	4.78	1.25
5A	10.5	8.40	0.80
5B	14.0	9.71	0.69

**Figure 15.** 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 Soda Creek. Channel width and depth both increase downstream, with increasing discharge. The cross-sections illustrate the channel's width, depth, entrenchment, bank slope, floodplains, and valley confinement. The field interpretation of "bankfull" flow is also shown; this is considered to be the flow level of the 1.5 to 2 yr recurrence interval flood as opposed to the flow level that would fill the channel to the top of its banks. The cross-section for reach 2A, Meter 180, illustrates a morphology observed in many locations along Soda Creek; the channel is confined on one side by a steep bedrock hillslope, and has a high vegetated bar or floodplain on the other side. Some reaches have a secondary "overflow" channel, as is seen in this cross-section. However, given that many different morphologies were observed, it is difficult to choose a single cross-section to typify Soda Creek (Figures 16 through 20). The most notable cross-sections include the high entrenchment of reach 1A, the large vegetated bar in reach 2A, the road revetment (riprap) in reach 2B, the bedrock control of 4A, and the narrow channel in reaches 5A and 5B.

Large Woody Debris (LWD)

A variety of species of LWD and live trees were recorded along the length of Soda Creek, with the species observed varying between reaches (Figure 21). LWD abundance is low compared to most other small coastal streams in the Pacific Northwest that support anadromous salmonids, in part because the vegetation types in Soda Creek do not include coniferous trees. Overall, very few pieces of LWD were present in any reach, and the majority of woody material inventoried was in the form of live standing trees in the channel. Reach 4B had relatively abundant living alder trees growing within the bankfull channel. Reach 3A and 3B have the second and third highest number of LWD pieces, and the greatest variability of species. Reaches 2A and 2B have the lowest number of LWD pieces, with one each. Not all tree species were found in all reaches. Alder only occurred in reaches 3A through 4B (corresponding to the reaches with perennial flow), bay was only recorded in reaches 1A and 3A, and willow was only recorded upstream of reach 2B. Excluding the live upright trees, no single reach would have more than six pieces of LWD (log, snag, or live tree down), and reach 2A would have none (Figure 22).

Typically, LWD pieces provide shade and cover for aquatic species, help shape the morphology of the channel, including pool and bar formation, and rooted LWD pieces help stabilize the banks and bars. These functions are quite limited except in reaches 3A, 3B and 4B; even in these reaches, pool-scour function is quite limited. The dominant function of woody material in Soda Creek is provided by live standing trees in the bankfull channel; the functions of these trees include stabilizing banks, shading the stream, providing leaf litter for aquatic bioenergetics, and providing flow roughness during peak flow periods.

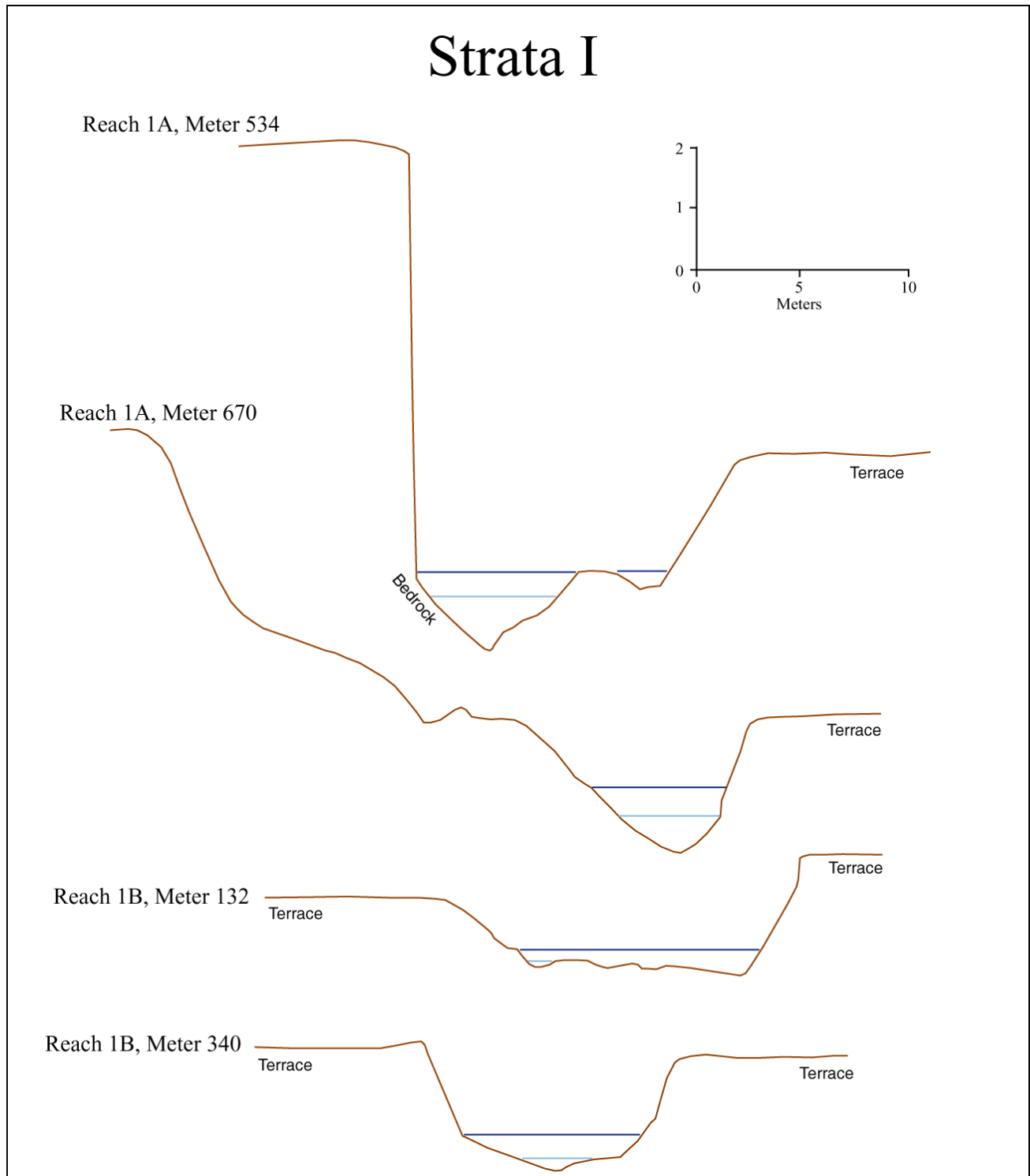


Figure 16. Soda Creek cross-sections for sample Strata I. The lower light blue line represents the water depth on the date the cross-section was surveyed, and the upper dark blue line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side. Areas of in-channel bedrock outcrop are noted.

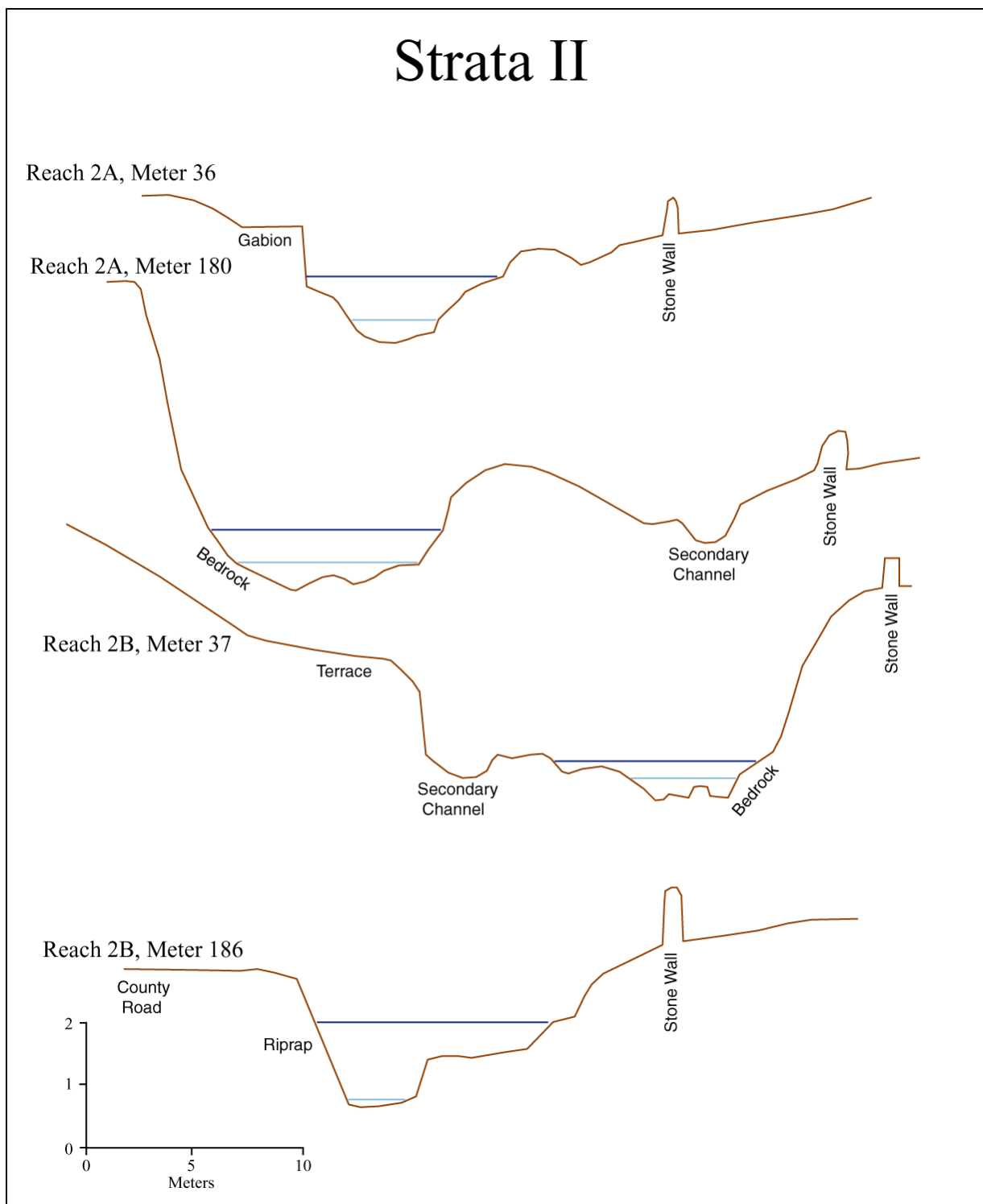


Figure 17. Soda Creek cross-sections for sample Strata II. The lower light blue line represents the water depth on the date the cross-section was surveyed, and the upper dark blue line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side. All four cross sections include a small stone wall adjacent to the channel. Areas of in-channel bedrock outcrop are noted.

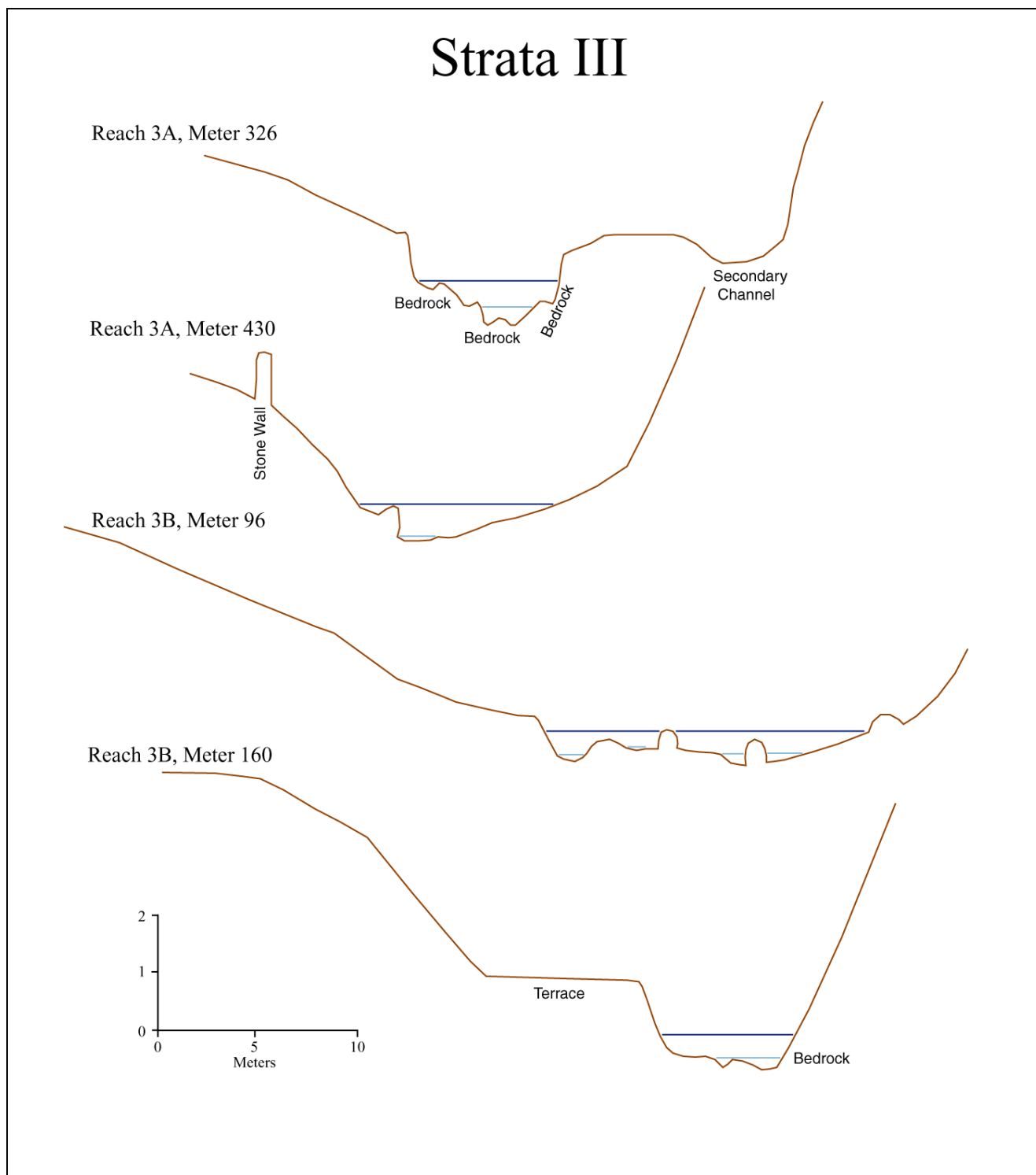


Figure 18. Soda Creek cross-sections for sample Strata III. The lower light blue line represents the water depth on the date the cross-section was surveyed, and the upper dark blue line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side. Reach 3A, Meter 430 includes a small stone wall adjacent to the channel. Areas of in-channel bedrock outcrop are noted.

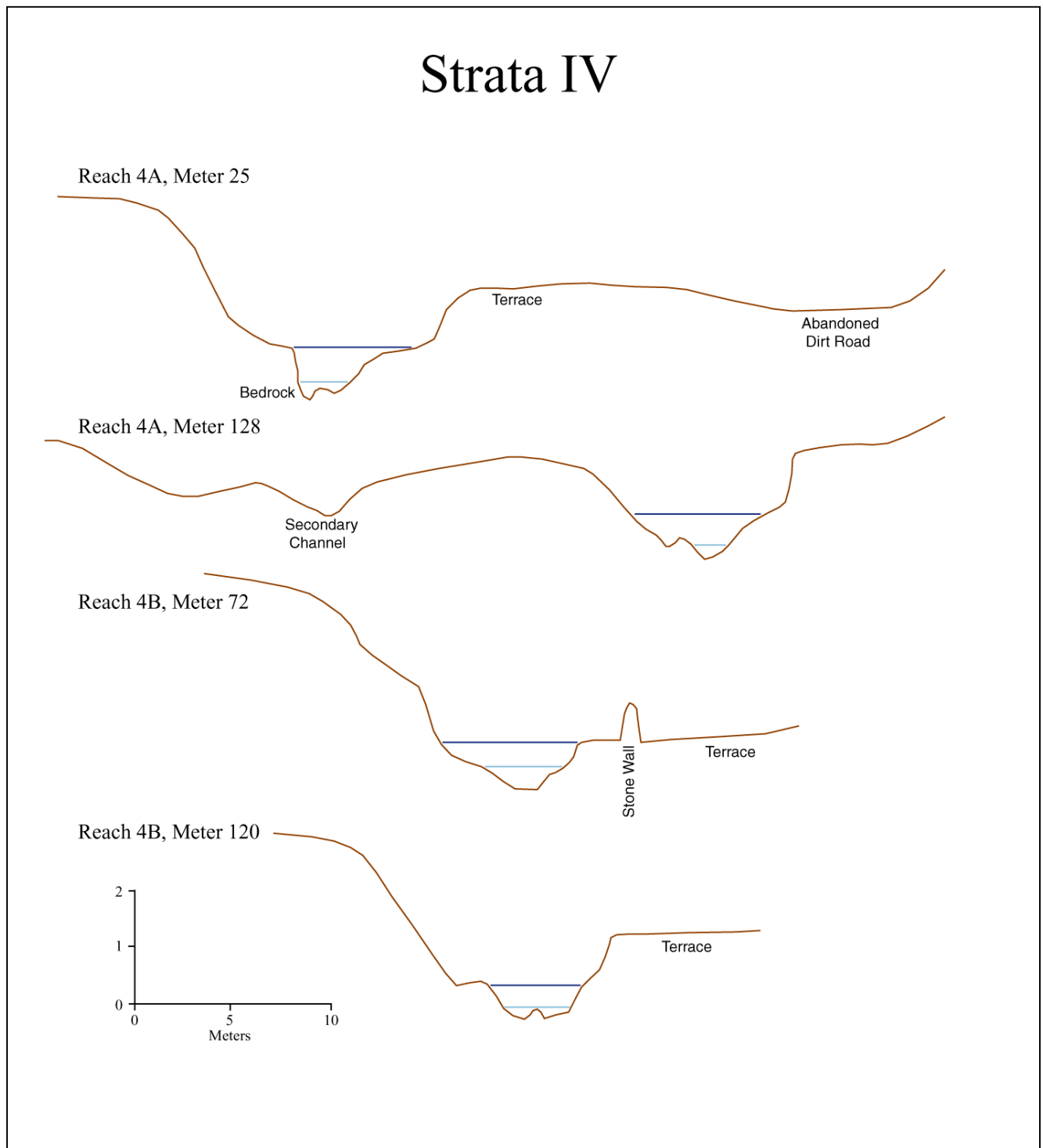


Figure 19. Soda Creek cross-sections for sample Strata IV. The lower light blue line represents the water depth on the date the cross-section was surveyed, and the upper dark blue line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side. Reach 4B, Meter 72 includes a small stone wall adjacent to the channel. Areas of in-channel bedrock outcrop are noted.

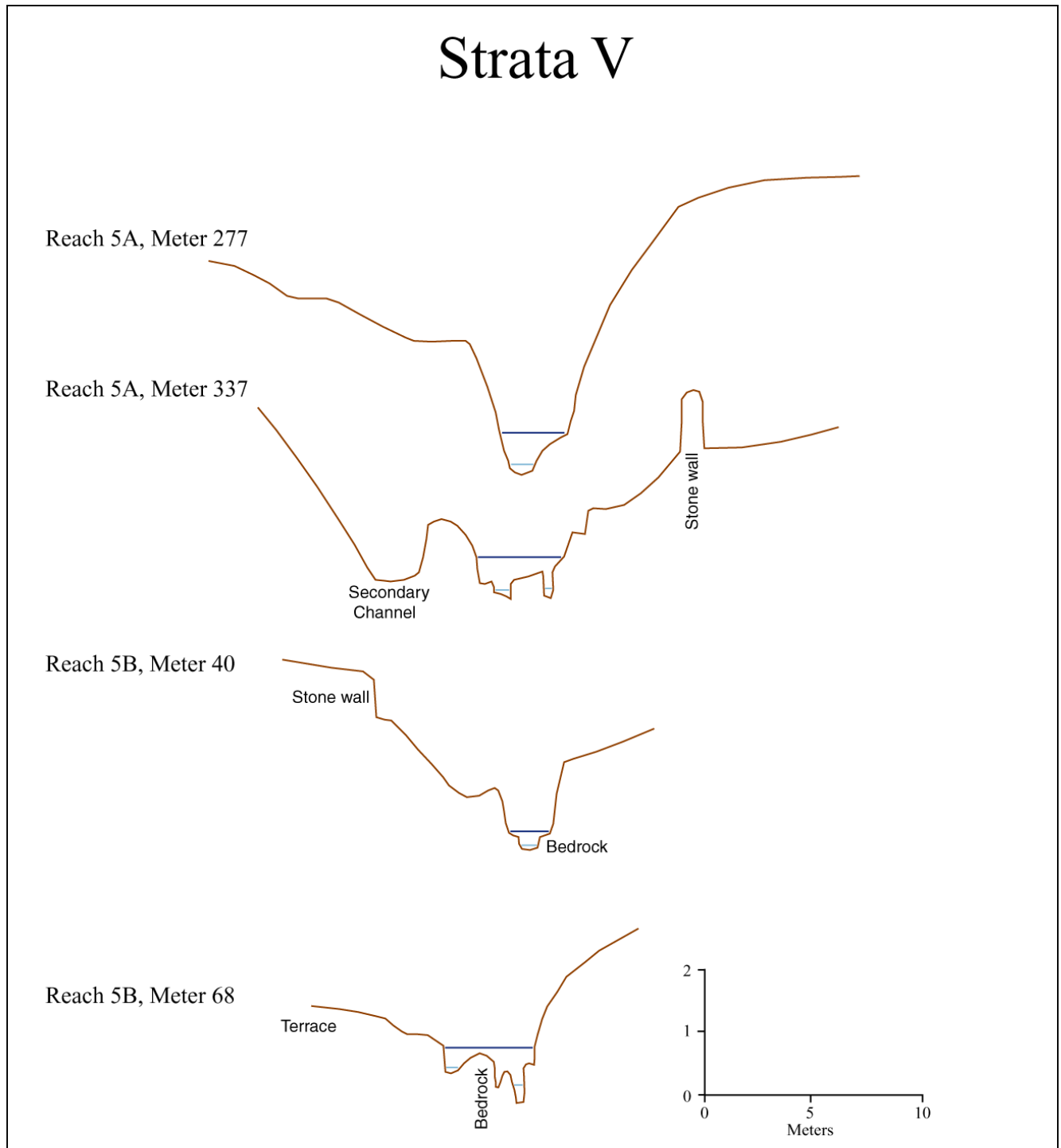


Figure 20. Soda Creek cross-sections for each sample Strata. The lower light blue line represents the water depth on the date the cross-section was surveyed, and the upper dark blue line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side. The cross-section Reach 5A, Meter 337, includes a small stone wall adjacent to the channel.

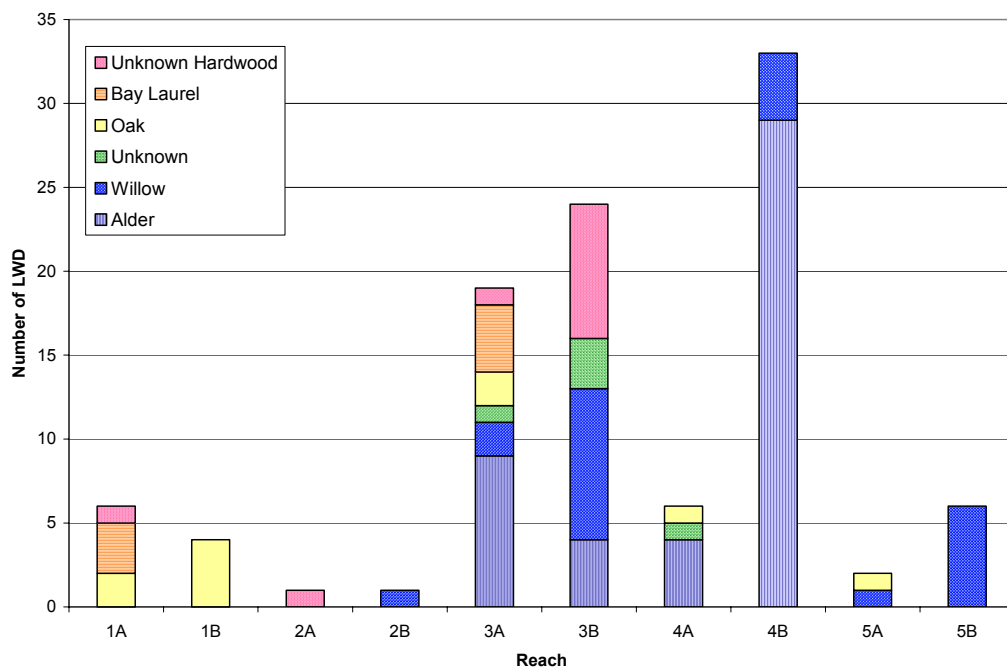


Figure 21. Number and species of woody material (LWD and live trees) per sample reach.

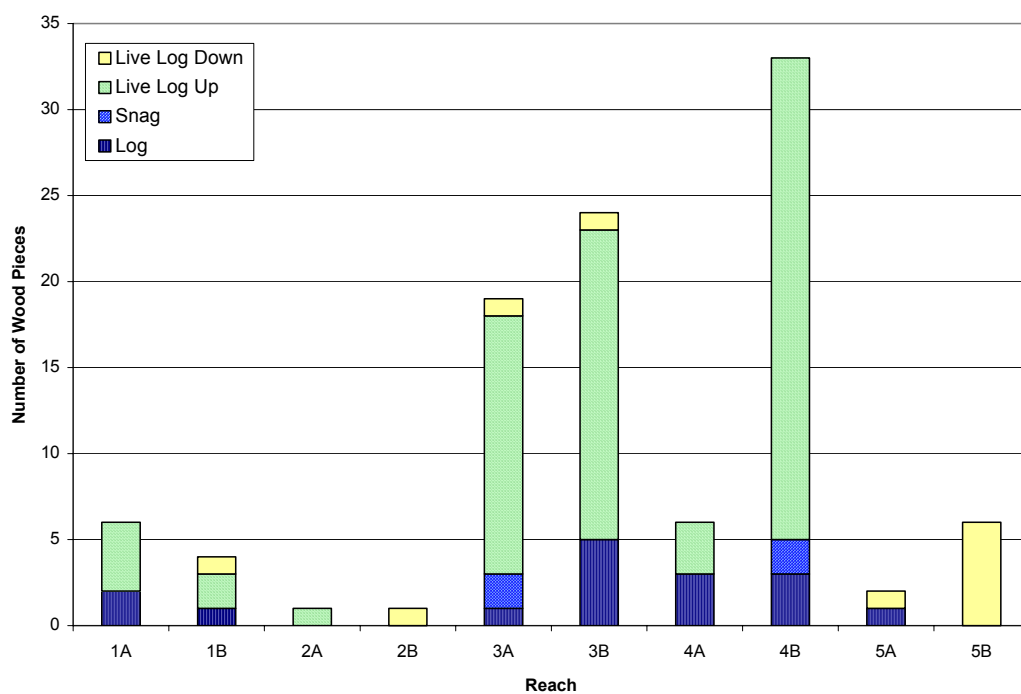


Figure 22. Number, position, and form of large woody debris (LWD) per reach.

Pools

A total of 50 pools were measured in the 10 sample reaches of Soda Creek. In all instances, except one in 2A, pools had a maximum spacing of 5-7 bankfull widths, with most pools spaced more closely (Table 9). The causes of pool formation were categorized into 5 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 (Figure 23). The two categories with the largest number of pools were step-pools and lateral scour pools; together they make up 2/3 of all measured pools.

Table 9. Measured Pool Spacing in each sample reach.

Sample Reach	Distance between measured pools (in bankfull widths)	Average Pool Spacing (in bankfull widths)
1A	2, 1.5, 1, 3.5, 1.5	1.9
1B	4, 2	3.0
2A	2, 0.5, 3, 10	3.9
2B	1.5, 0.5, 2.5, 0.5, 0.5, 4, 0.5, 2	1.5
3A	7, 6	6.5
3B	1, 0.5, 1, 2, 1.5, 4.5, 1.5	1.7
4A	2, 4, 2	2.7
4B	6, 3	4.5
5A	4.5, 1.5, 4.5	3.5
5B	3.5, 1.5, 1, 0, 7, 1.5	2.4

The types of pool formed appear to follow some spatial pattern along Soda Creek related to channel geometry (Figure 24). Most notable is the typical pool type in the upper watershed (reaches 4A through 5B) relative to typical pool type in the lower watershed (reaches 1A through 3B). Lateral scour pools were only observed downstream of reach 4A, probably because channel depths and widths are large enough to develop a thalweg that concentrates stream energy and enhances scour potential. Step-pools were only measured upstream of reach 3B, which likely results from the abundance of boulders and cobbles in the bed. Main channel/ bedrock trench pools were located in reaches 1B to 3A where the channel was large enough to have a distinct thalweg to scour a channel-width scale pool in alluvium or where bedrock-induced bed variation imposed a pool. LWD pieces were not a significant cause of pool formation, due to the low number of pieces in Soda Creek, suggesting that it is scour induced by resistant channel roughness elements such as banks, bedrock and boulder clusters or steps that accounts for the formation of most pools in this stream system.

Pools measured in Soda Creek were segregated into residual depth size classes, ranging from 0.2 – 0.4 m up to >1m in depth. Generally the larger pools are located in the lower reaches and are either lateral scour pool or main channel/ bedrock pools, and the smaller pools are located in the upper reaches of Soda Creek, reflecting the influence of bankfull cross-sectional area and pool-formative agent upon pool residual depth (Figure 25). Residual pool depths occasionally exceed 1 m, but are typically < 0.6 m. Pool residual depth was inversely related with reach slope; as slope increased, pool residual depth decreased (Figure 26). The exception to this trend was in reaches with < 1% slope, which are uncommon in Soda Creek and in which only two pools occur. Pools were most abundant and had the greatest residual depth in reaches with slopes between 2 and 4%.

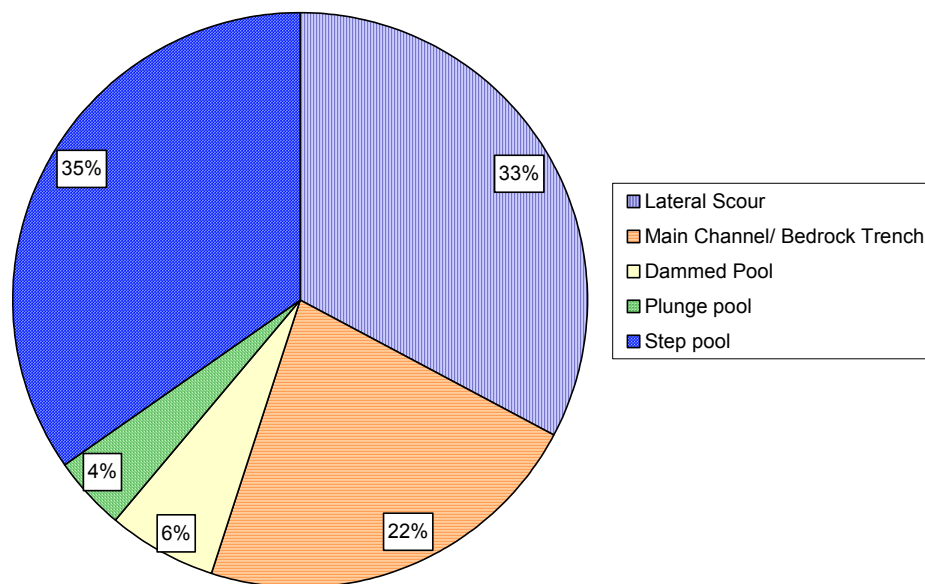


Figure 23. Percentage of each pool class measured in the 10 sample reaches combined.

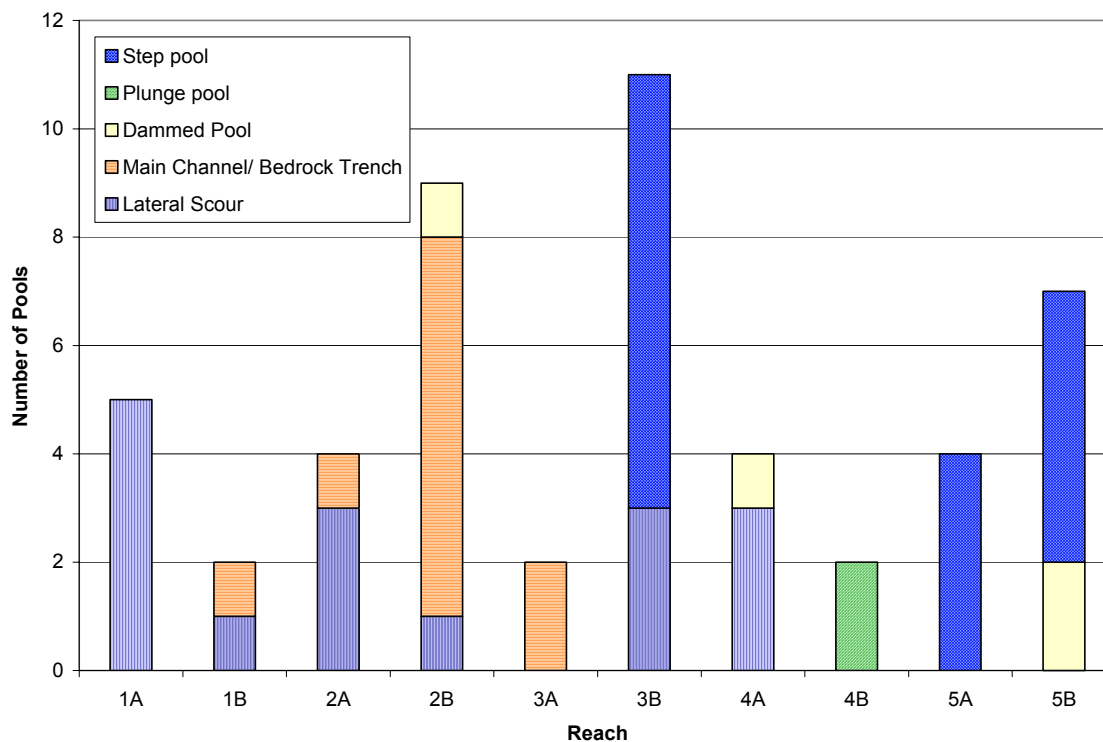


Figure 24. Number and class of pools in each sample reach.

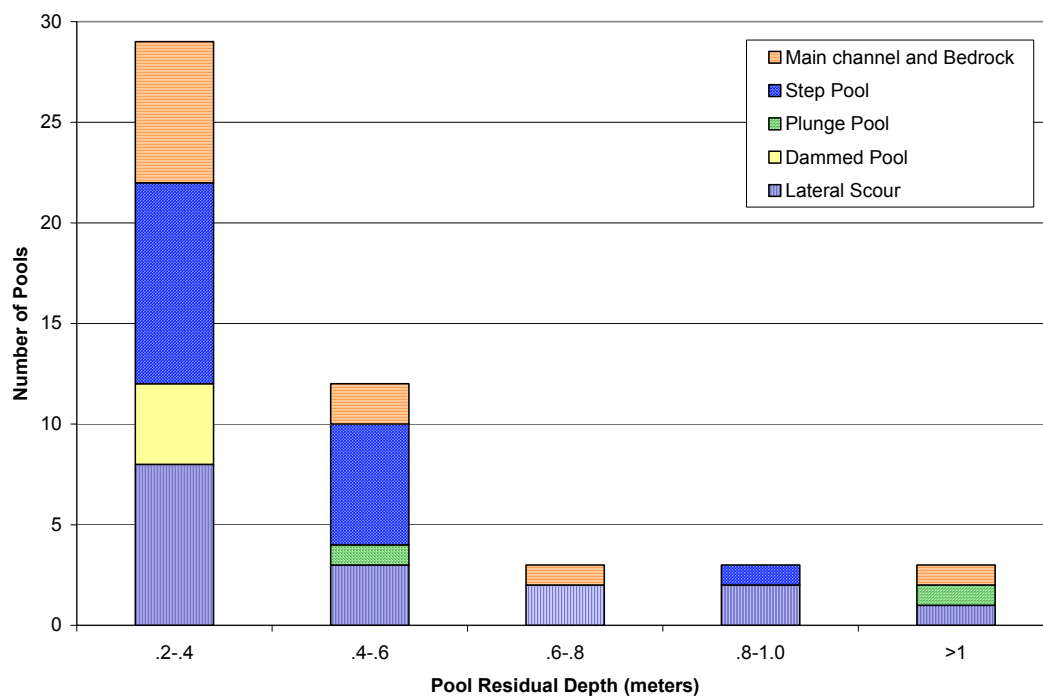


Figure 25. Number of pools per residual depth class and their associated cause for all sampled reaches.

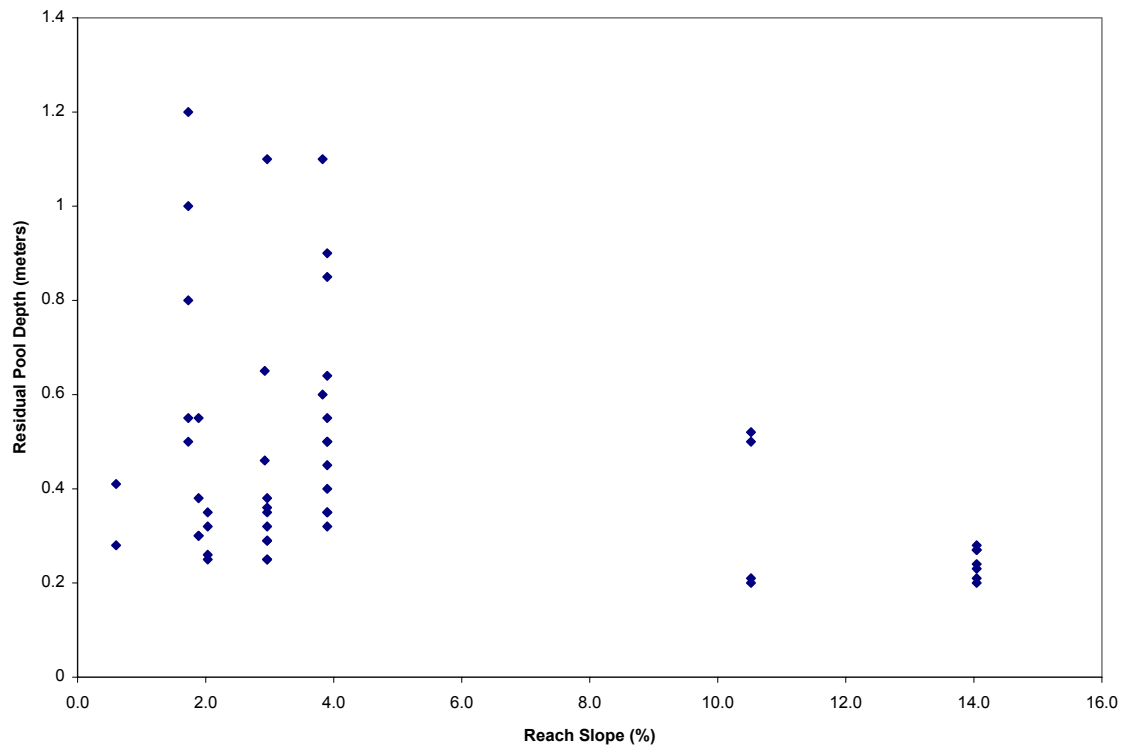


Figure 26. Residual pool depth versus reach average slope.

Sediment Deposits and Bars

In addition to LWD and pools, the number, type, and volume of sediment deposits and bars were also continuously measured in each of the 10 sample reaches. The total number of deposits measured in each section varied from one in reach 5A to 42 deposits in reach 3B, with most reaches ranging between five and 15 bars measured. The three most common types are active channel deposits, forced bars, and pool deposits; together, these three types made up 76% of all sediment deposits measured (Figure 27). Some types, such as alternate bars, forced bars, active channel deposits, and pool deposits, were found in almost all of the 10 sample reaches (Figure 28). However, point bars were only observed in reaches 1A and 1B, reflecting the relatively high sinuosity of this reach relative to most of Soda Creek. Secondary channel bars were only observed in reaches 4B and 5B, and lateral bars were only observed in reach 2A.

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. There was not always a relationship observed between bar type and volume size class (Figure 29). However, an inverse relation was found between the number of bars measured in a particular size class, and the proportion of total bar material in that size class (Figure 30A and B). For example, throughout Soda Creek, 54 bars in the $<1 \text{ m}^3$ size class were measured, however

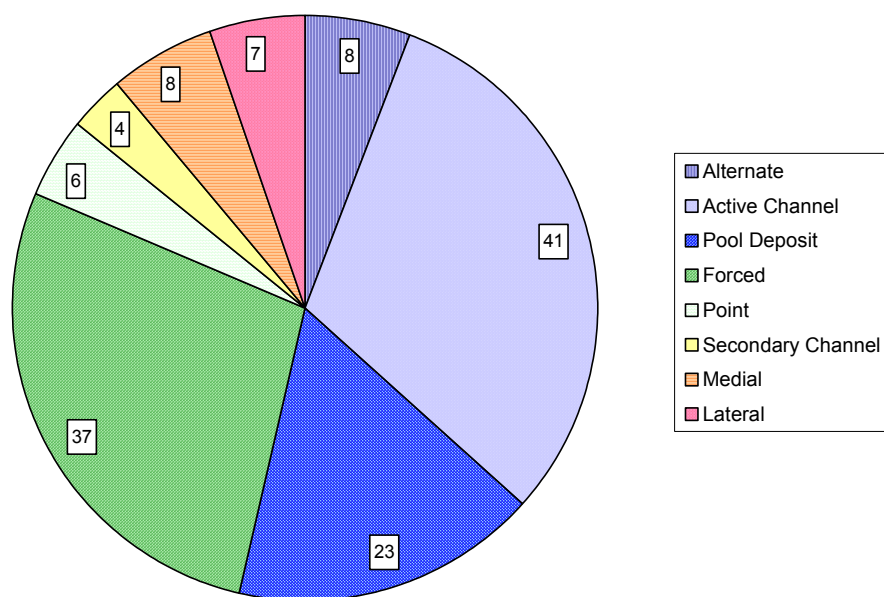


Figure 27. Number and type of bars measured in all 10 sample reaches.

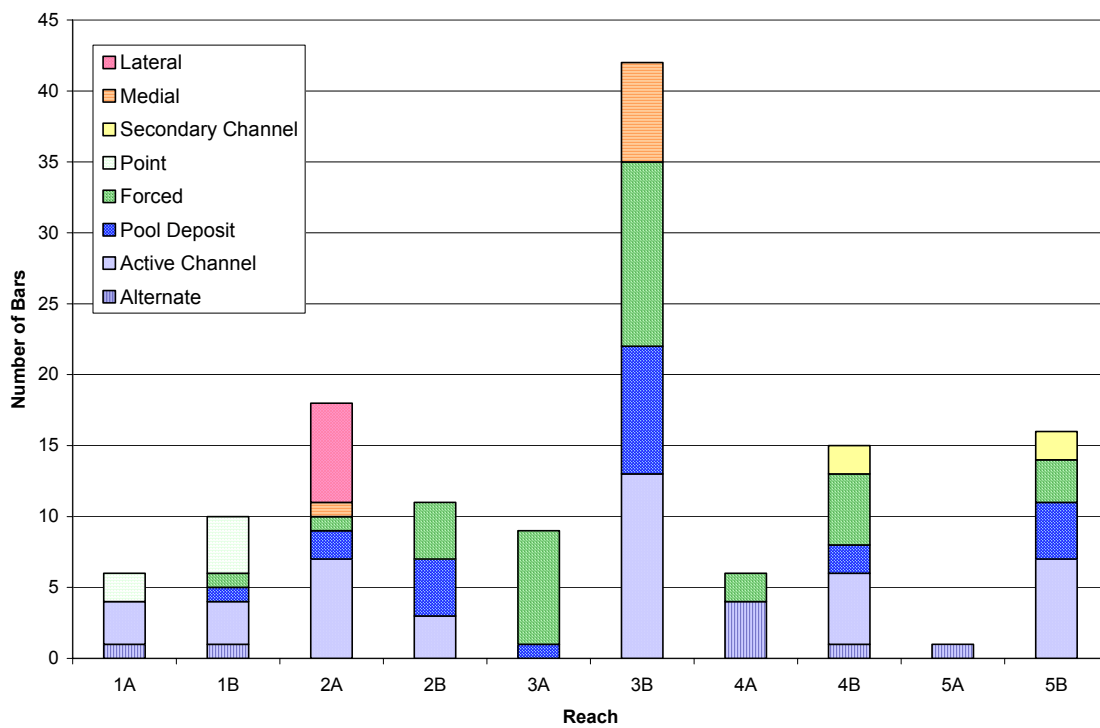


Figure 28. Number and type of bars in each sample reach.

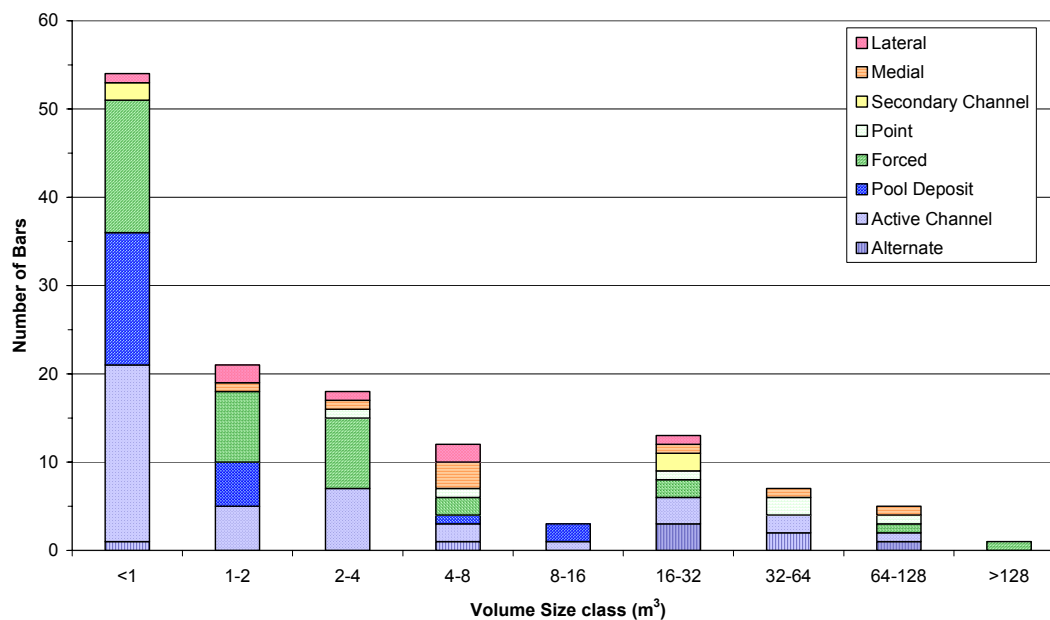


Figure 29. Number of bars per volume size class and their cause.

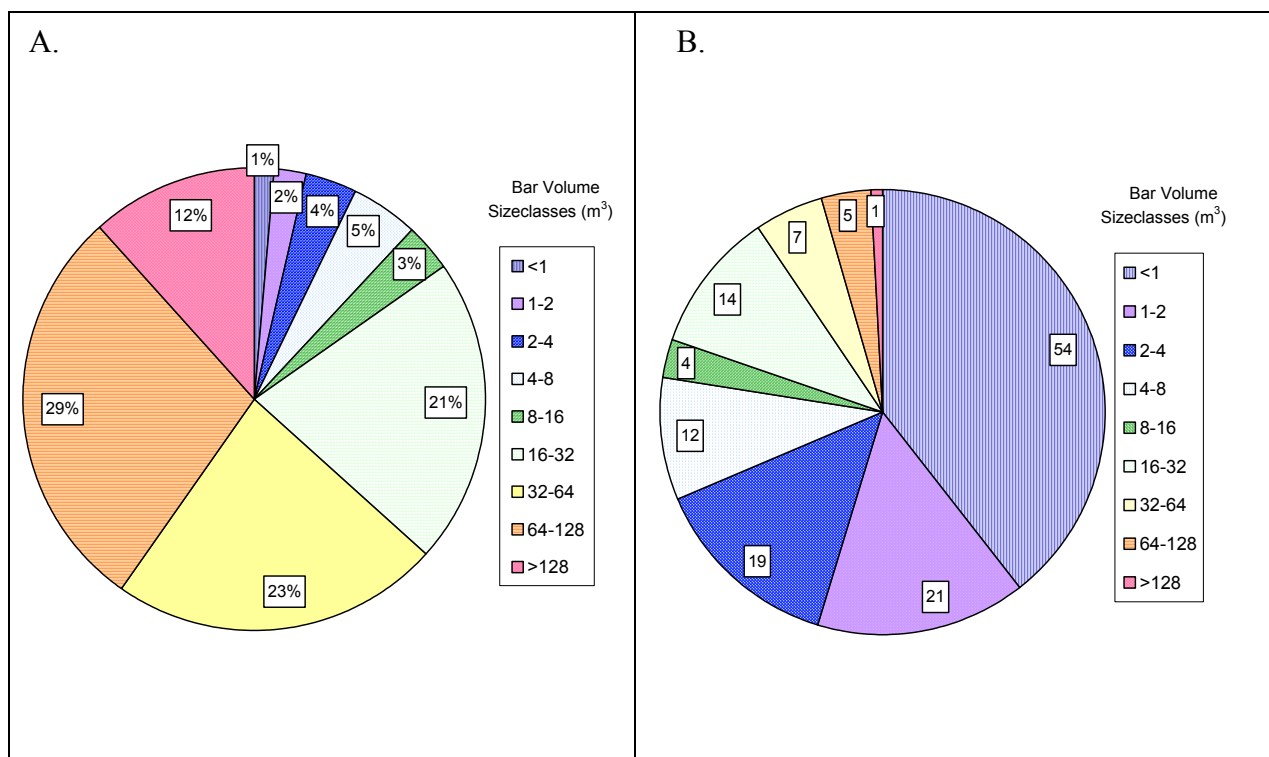


Figure 30. A) Percent of total volume of stored sediment measured in each size class.
B) Number of bars and other sediment deposits measured in each volume size class.

that size class holds only 1% of the total bar material measured. In contrast, six bars were measured in the 64-128 and >128 m³ size classes, comprising 41% of the total bar material measured. Overall roughly 70% of sediment was stored in about 20% of the number of deposits measured. This relationship is also expressed in the plot of cumulative percent of sediment deposit material in each size class (Figure 31).

The volume size class of an individual bar also related to the position of the bar in the watershed. Generally larger bars are found lower in the watershed, and smaller bars higher in the watershed. The single bar measured in the >128 m³ size class was located in reach 2B, and was a forced bar. This bar appears to be a channel expansion deposit because the valley width increases slightly in this location after it leaves a bedrock constriction immediately upstream. Also, this bar is in an area of the sample reach that has a lower slope (1.4%) compared to immediately upstream (3.1%) and downstream (3.7%), respectively. A positive relationship exists between reach-total bar volume and bankfull cross-sectional area; generally as cross-sectional area increases, reach-total bar volume increases (Figure 32).

Although reaches 1A and 1B only had 16 total measured bars, the volume of material in these bars was 43% of all bar material measured (Figure 33). Other reaches with a large volume of bar material included reach 2B with 21% of the total, and reach 3B with 15% of the total. Calculated bar volume per unit channel length does not always correlate with the number of bars measured, or the total percent of bar material (Figure 34). Reach 1A has the highest bar volume per unit channel length, 25% of the total bar volume, and only 6 measured bars. Reach 3B has the highest number of bars measured (42), 15% of the total bar volume, and a fairly low value of 0.46 bar volume per unit channel length. Reach 5B has 16 measured bars, 1% of the total bar material, and the lowest value (0.15) of bar volume per unit channel length.

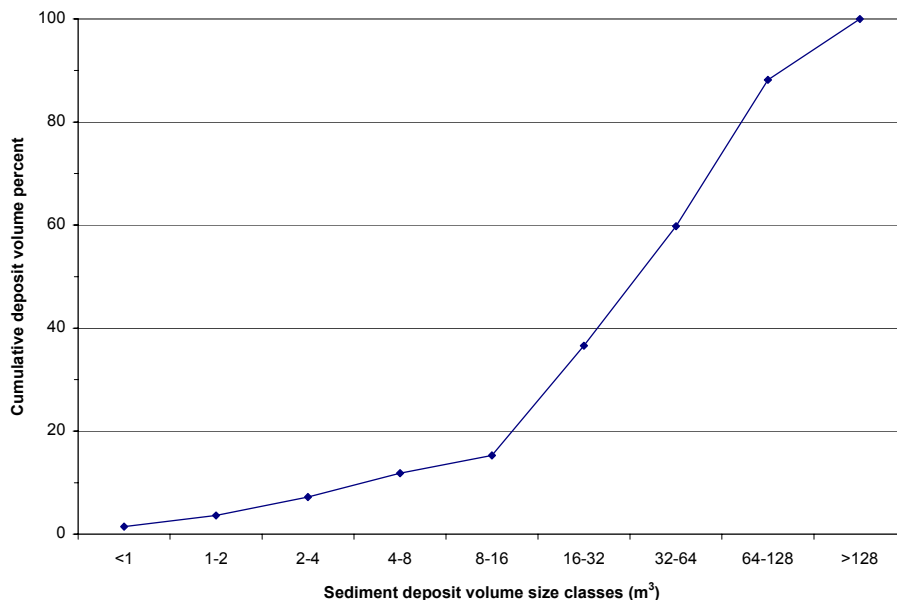


Figure 31. Cumulative percent of sediment deposit volume for all size classes.

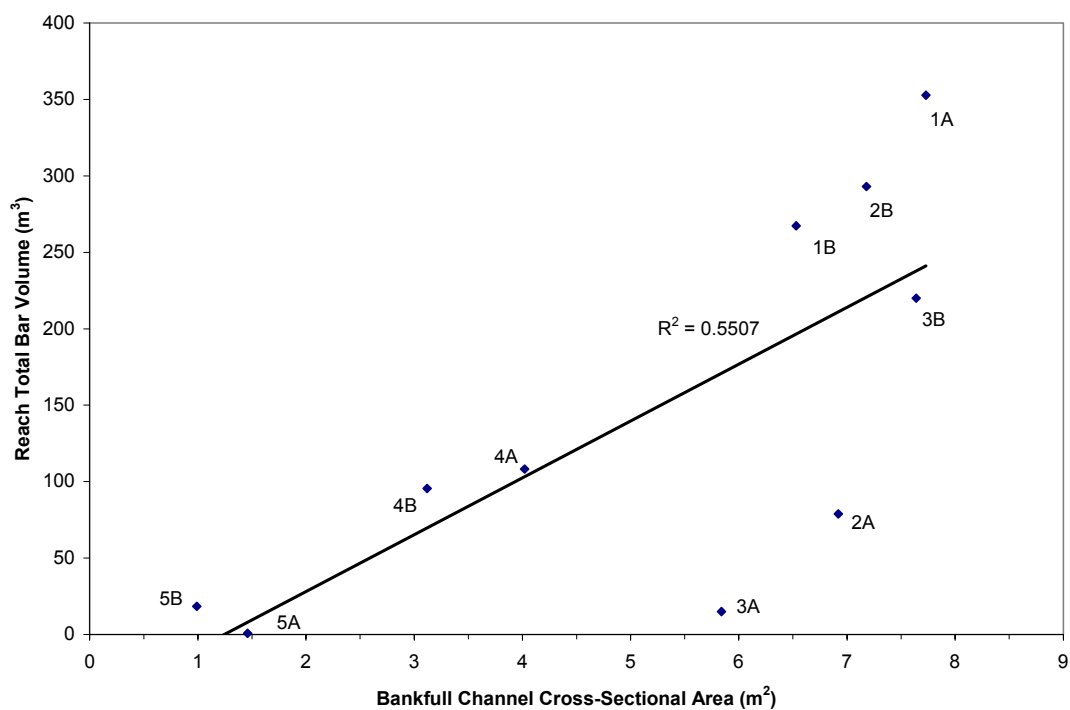


Figure 32. Bankfull channel cross-sectional area versus reach total bar volume.

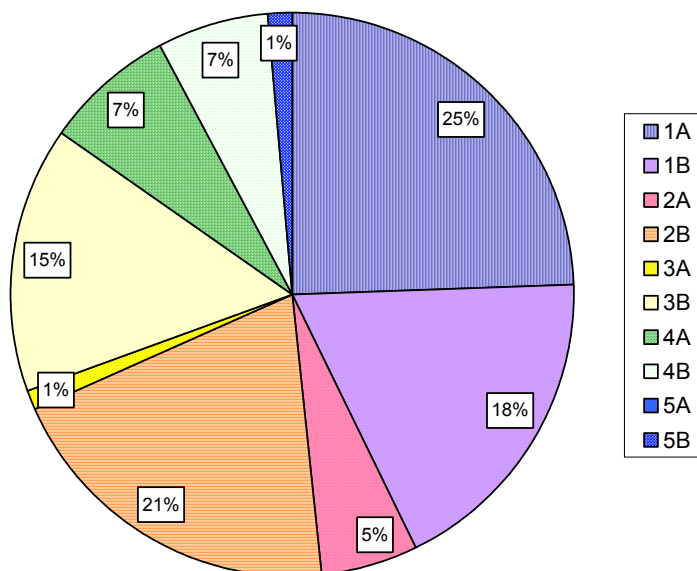


Figure 33. Total volume of bar material measured in each sample reach.

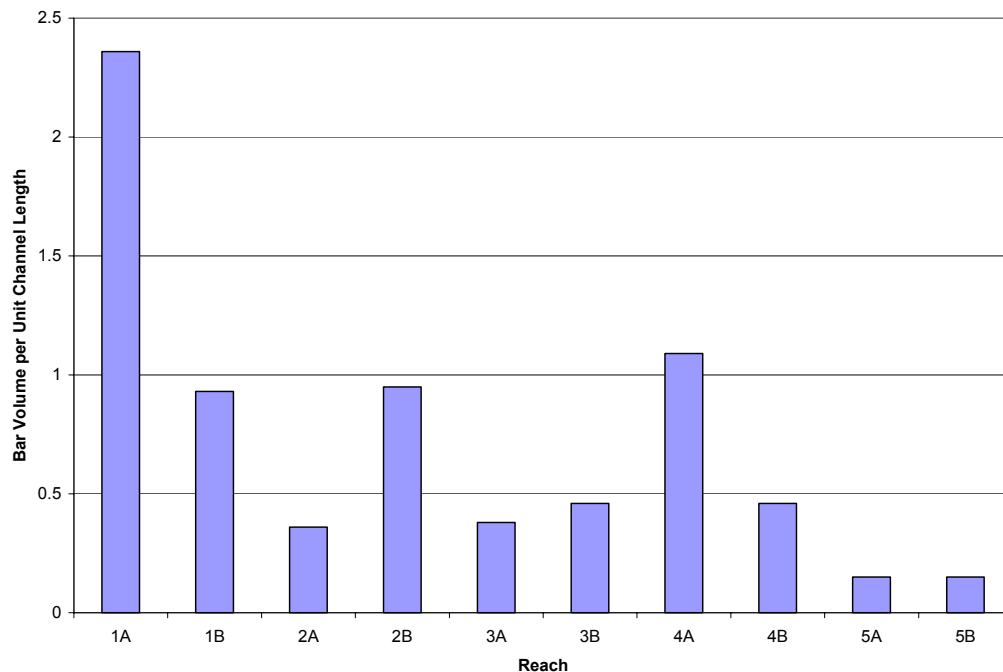


Figure 34. Calculated bar volume per unit channel length in each sample reach.

The reaches downstream of Soda Canyon Falls have bars representing all size classes, and all bar types, except secondary channel bars (Figure 35 A). This is in contrast to the bars above the waterfall, where no bars are greater than 64 m^3 , and lateral, medial and point bars are not represented (Figure 35 B). Grain size of the bars downstream of the waterfall was derived from the pebble counts, and included all bar types except pool deposits and active channel sediment deposits. The bars were broken into “large” bars (size classes $>16 \text{ m}^3$), and “small” bars (size classes $<16 \text{ m}^3$) to provide an index of surface sediment sizes available for spawning habitat (Table 10). These data are generally consistent with the size distributions for surface sediment throughout Soda Creek, however, there is some indication that larger bars have somewhat finer size distributions. Nonetheless, these surface textures are within the range of sizes (5 to 102 mm, 0.2 to 4.0 in) suitable for steelhead spawning (Goals Project, 2000).

In Soda Creek, the bars and sediment deposits are scaled to the size of the bankfull channel. The large volumetric bars tend to have higher elevations above the bed, with the majority of the sediment out of the wetted channel. On the other hand, the smaller volume sediment deposits tend to have lower elevations above the bed, and are located in the lower positions in the bankfull channel, usually in the form of active channel deposits, and are more accessible for spawning habitat. Consequently, smaller bars (volume $<16 \text{ m}^3$) are more representative of the abundance of potential spawning sites and the surface sediment sizes at spawning sites. In particular, active channel bars and forced bars are most likely to represent patches of potential spawning gravel.

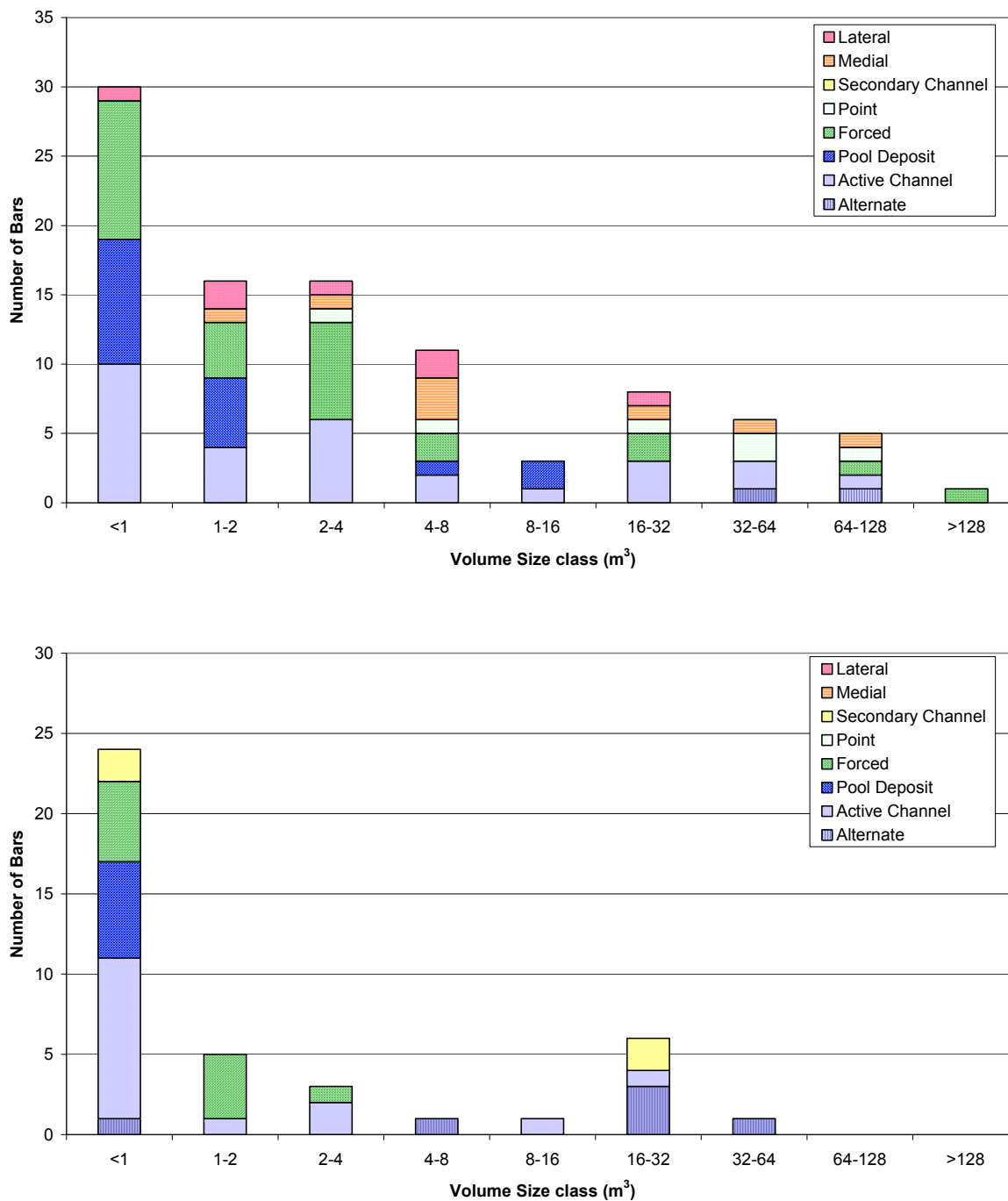


Figure 35. A) Bar type and size class for sample reaches downstream of Soda Canyon Falls. B) Bar type and size class for sample reaches upstream of Soda Canyon Falls. Bars 16 m³ or smaller are representative of gravel patches that could be suitable for spawning, providing an indication of the relative abundance of potential spawning sites.

Clearly, there is a wide variety and relative abundance of bar types and sizes in lower Soda Creek below Soda Canyon Falls. The size of the bars and deposits is an important factor in the amount of sediment stored in the channel, as well as for anadromous fish spawning. Small bars tend to have coarser material (Table 10), suggesting potential limitations on spawning suitability if clasts are too large to be moved by spawning fish (Kondolf 2000). However, sediment size distributions for potential spawning sites revealed median grain sizes between about 25 and 40 mm, which is in the upper half of the documented range of sizes utilized by steelhead (Kondolf 1993). Hence, sediment size in Soda Creek may be somewhat larger than ideal for steelhead, and spawning sites may be limited locally by excessively coarse sediment, but suitable spawning gravels appear to be reasonably abundant. The stability (age) of the bars also is a factor in the availability of the sediment for spawning, and the potential source of sediment for the channel to re-work during floods (Figure 36).

Table 10. Grain sizes for “large” and “small” bars downstream from Soda Canyon Falls.

	< 2 mm	D16	D50	D84
“Large” bars	12%	3.2 mm	55 mm	155 mm
“Small” bars	6%	5.6 mm	75 mm	250 mm

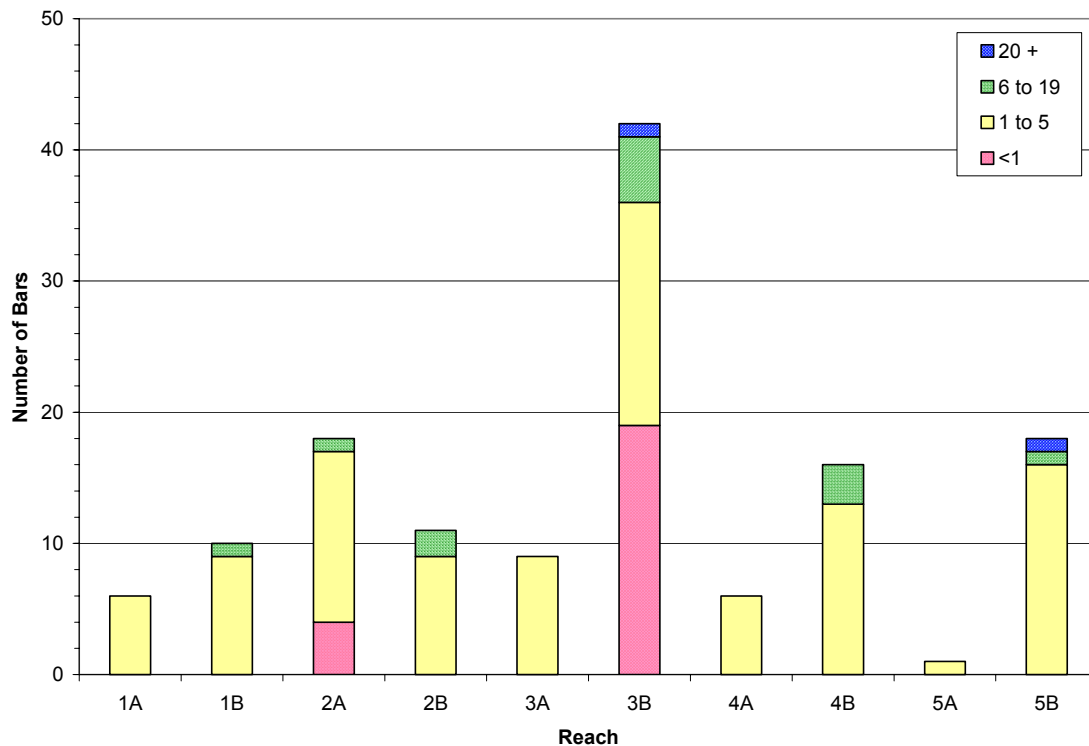


Figure 36. Distribution of estimated age (years) of bars measured in each sample reach.

The age class of sediment deposits was estimated in the field based on position of sediment deposits in the bankfull channel, size distribution of the deposit, and the approximate age of vegetation on the deposit, if any. Age classes <1 year represent relatively fine-grained deposits in pools and in the active channel that would be entrained in high frequency peak flow events. The 1-5 year age class comprises most sediment stored in Soda Creek. These bars and deposits generally had gravel surface textures, frequently have herbaceous vegetation and young shrubs and seedlings of woody plants, and often had upper surfaces relatively high above the active channel (but within the bankfull channel). Owing to recent high magnitude, low frequency floods in 1995 and 1997, it is not surprising that the majority of stored mobile sediment is included in this age-class. Older age classes, 6-19 yrs and >20 years, are relatively uncommon, and consist of vegetated bars at elevations above bankfull but lower than adjacent floodplain or terrace surfaces.

Bank Erosion

Information on bank erosion was collected continuously in each sample reach, and included both total volume and average erosion per unit channel length. A total of about 730 m³ of bank erosion was measured in the 10 sample reaches (Figure 37). The average bank erosion per unit channel length of channel was also calculated from this data (Figure 38). Whenever observed, an estimated age of each erosion measurement was recorded, based upon exposed roots, undercut bridge pilings, revetments, or other indicators. 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 39). However, field evidence allowing age estimates were not always available. Reaches 1B and 2A have the most evidence of recent erosion in the form of fresh bank faces, exposed roots of young vegetation, and partially eroded bank revetments composed of fresh non-vegetated soft sediment. Caution must be used in associating ages with amounts of erosion; these estimates represent the longest amount of time over which the erosion could have occurred, and dating techniques are crude. The visible erosion could have occurred slowly over the past stated number of years, or quickly, all in the past 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 the reach.

Modifications made to the banks of the channels, including erosion control measures mainly occur in the lower reaches of the watershed (Figure 40). These modifications range in intensity from the installation of rock gabions to more passive placement of rocks along the channel banks probably associated with clearing rocks from fields for agricultural purposes. The amount of erosion control reported in each reach in Figure 40 is representative of the entire reach, with the exception of reach 1A. This reach has the most erosion controlling devices of any reach because bank erosion rates are high, and the property owners are responding by installing more erosion control along their creek frontage. The extent of erosion control measures in sample Strata I is consistent

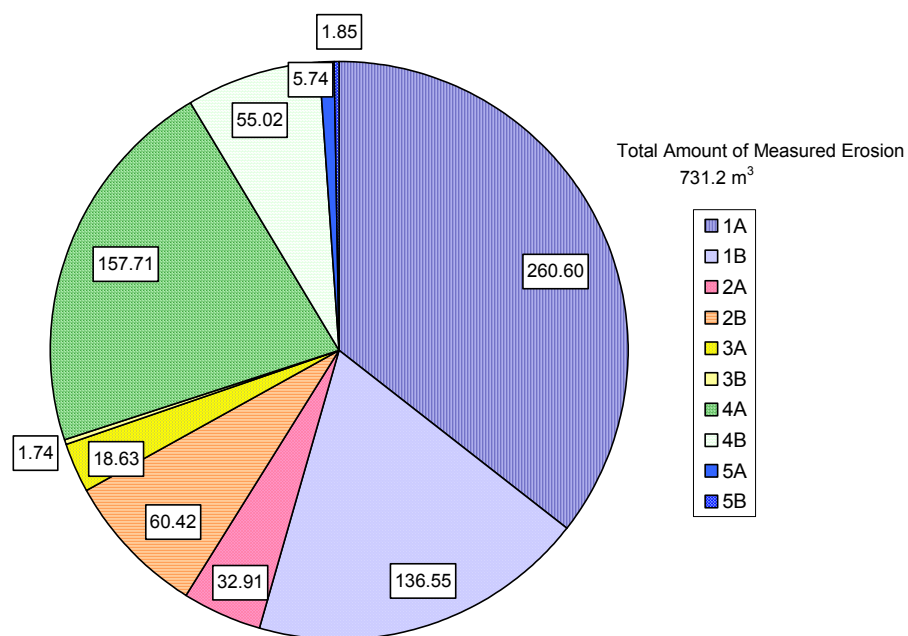


Figure 37. Total volume of measured bank erosion in each sample reach (in cubic meters).

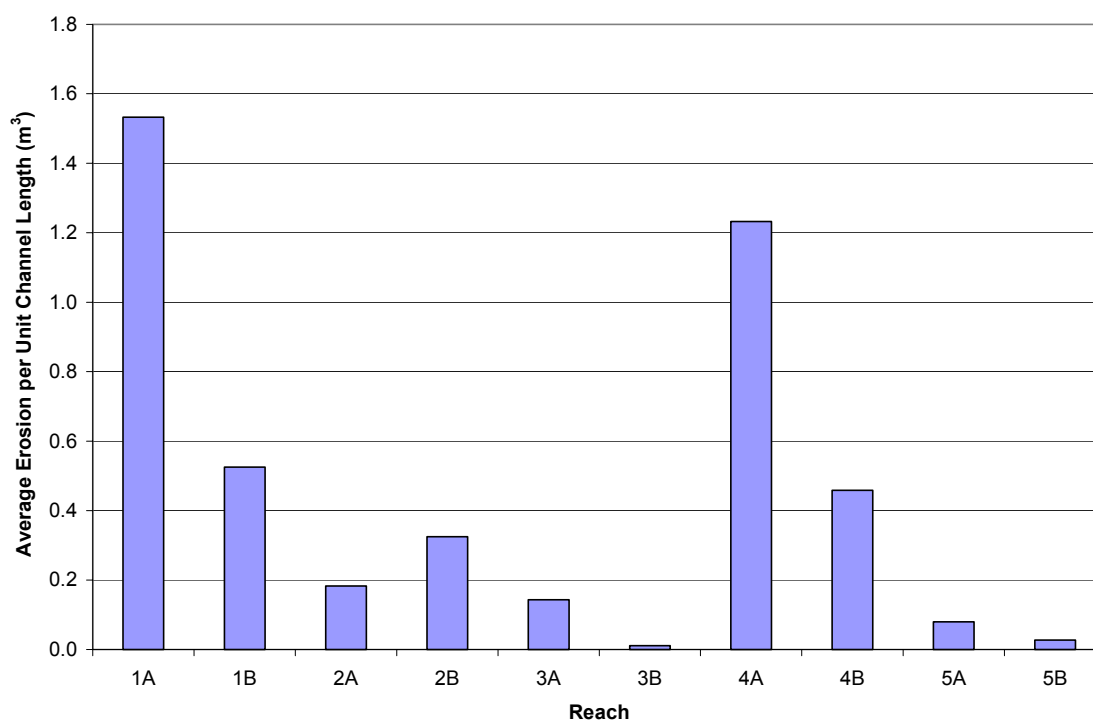


Figure 38. Average bank erosion per unit channel length in each sample reach.

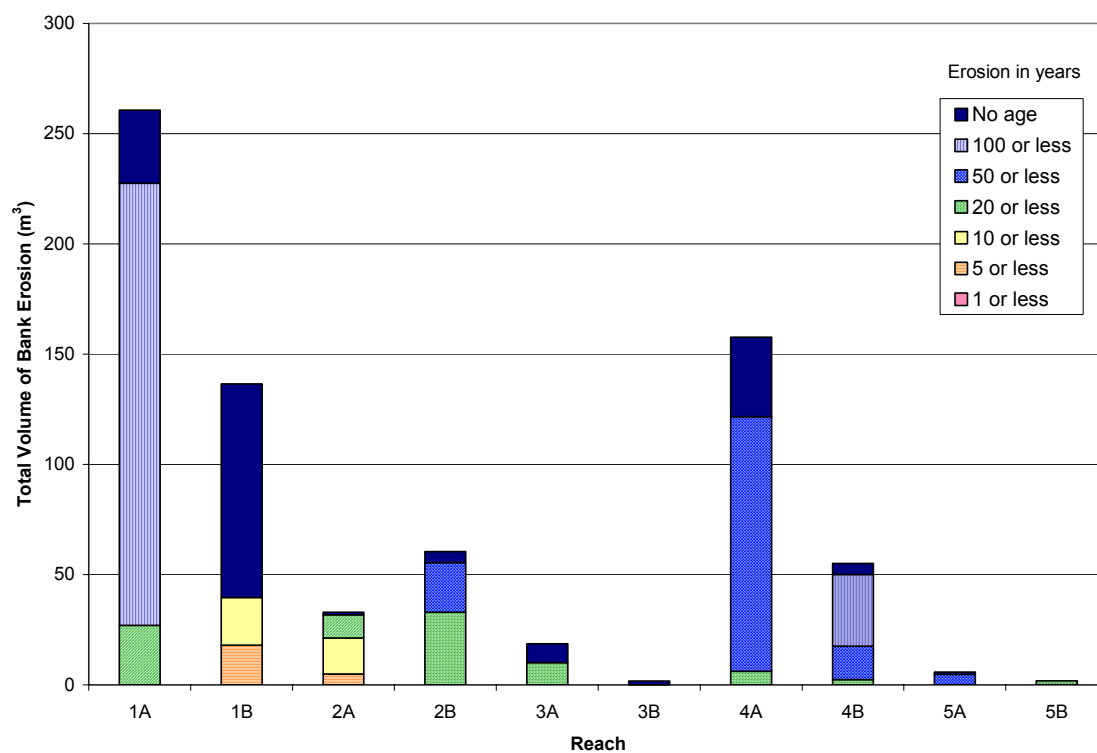


Figure 39. Age estimates associated with measured erosion in each sample reach.

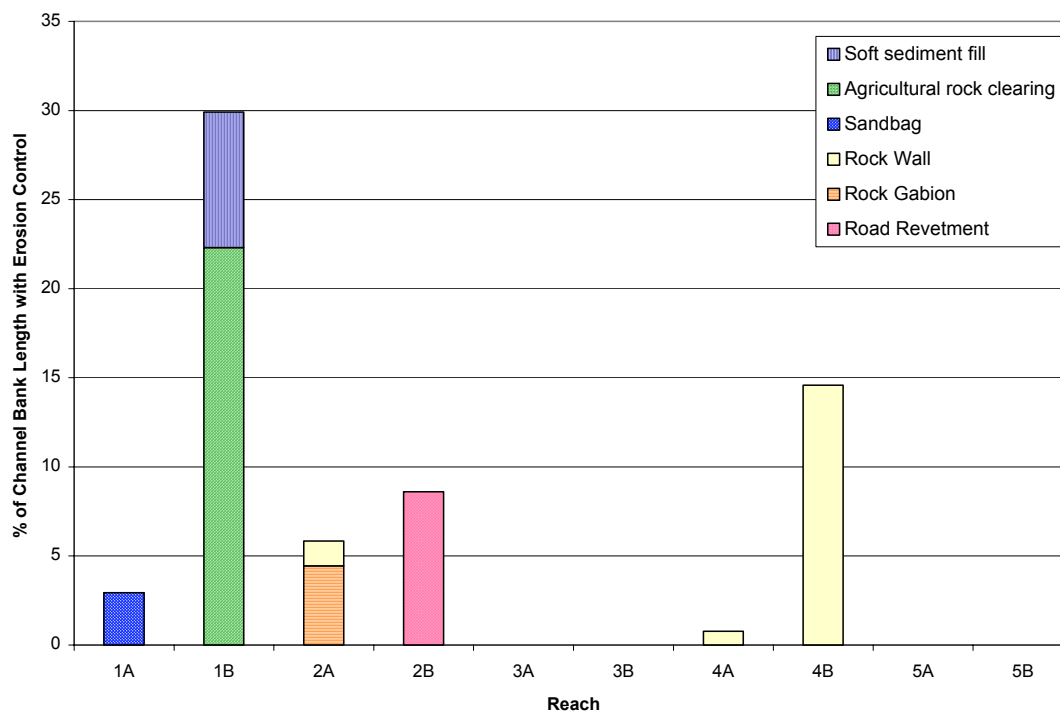


Figure 40. Type and percent of measured channel banks with erosion control.

with the observed bank erosion; where erosion rates are high, more erosion control devices are observed. During data collection, rock gabions, wooden flow deflection panels, sandbags, plastic sheeting, gravel emplacement, boulder piles, and willow plantings were observed along the banks of this reach. The disparity between the large amount of erosion control efforts on the right bank (residential side) versus the smaller effort on the left bank (vineyard side) was striking, possibly reflecting the property owner's attitudes about controlling the bank erosion. Also, the erosion control devices limited the amount of erosion that could be measured because these devices stopped erosion in that location, making the total erosion measurements a minimum value for sample reaches containing erosion control devices.

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, are reported (Table 11). 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 the vegetation increases the shear strength of the bank when it is well rooted. In addition, the terrace vegetation and land use was also characterized (Table 12). 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 roll in stream health, providing shade for the stream necessary for stable and cool waters temperature, carbon and plant nutrients for fueling the instream food web, bank stabilization, as well as providing a source for the recruitment of LWD.

The characterization of materials comprising the bank for each sample reach correlates reasonably well with total measured bank erosion. Reaches 1A, 1B and 4A have banks containing a high proportion of alluvium and soil with relatively small quantities of cobble, boulder and bedrock. These reaches also have relatively uniform bank heights, suggesting that bank materials are comprised primarily of fluvial sediment deposits. Most other sites have highly variable bank heights, including some very high banks representing erosion resistant bedrock outcrops in most cases. This conclusion is further supported by the relatively low channel gradient in these reaches where sediment deposition might be expected; reach 4A is located near the bottom of what could be described as the upper watershed, and has a substantially lower channel gradient than upstream and downstream reaches. In addition, the relatively high proportion of bedrock in reach 4A (23%) suggests that flow peaks cannot be accommodated by increased channel scour, and that lateral channel expansion might be expected in response to flood events.

Table 11. Average bank characterization of each sample reach. Numbers in parentheses are average values.

Reach	Bank composition	Bank slope	Bank vegetation type	Bank vegetation age (years)	Bank vegetation condition	Bank height (m)
1A	Alluvium, silt and sand	20°-45° (33°)	Blackberry, wild grape, poison oak, annual grasses	5	Dense growth, overhanging	2.2
1B	Soil profile with cobbles	25°-47° (34°)	Blackberry, grasses, young oaks	10	Dense blackberry, moderate grasses	2.0
2A	Boulders, cobbles and soil, rock gabion	4°-90° (55°)	Shrubs, grasses, oak, young willow, ferns	<20	Sparse	0.6-7.0 (2.5)
2B	Alluvium with cobbles and soil, bedrock with thin soil	10°-64° (30°)	Grasses, buckeye, shrubs	<20	Sparse	1.5
3A	Boulders and cobbles with soil, bedrock	25°-80° (55°)	Woody vines, shrubs, bay, oak, buckeye	<50	Dense vines, moderate trees	1.0-5.0 (1.5)
3B	Boulders, cobbles with soil, debris jam	28°-80° (55°)	Bay, willow, poison oak, blackberry, ferns	20	Dense	0.5-7.0 (1.2)
4A	Coarse alluvium, soil	15°-80° (35°)	Blackberry, shrubs, poison oak, alder roots	<20	Dense, overhanging	0.9
4B	Boulders, cobbles, soil, rock wall	16°-90° (33°)	Birch, bay, oak, willow, alder, vines	50	Moderate, stable	0.5-1.7 (0.8)
5A	Boulders, cobbles, soil, bedrock	15°-70° (40°)	Shrubs, grasses, vines, willow, poison oak, young willow	<20	Moderate	0.3-1.8 (1.0)
5B	Boulders, bedrock, soil	53°-85° (67°)	Vines, poison oak, ferns, willow, bay, ceanothus	<20	Dense	0.8

Table 12. Average riparian characterization for each sample reach.

Reach	Riparian vegetation type	Riparian vegetation age (years)	Riparian width (m)	Terrace land use	% canopy cover
1A	Bay, oak, willow, grasses, blackberry, vinka, planted redwoods	<100	10	Suburban backyard, vineyard	50
1B	Cultivated grasses, sparse oaks	<100	5 m canopy, 30m terrace	Cultivated grasses, recreation	25
2A	Oak, buckeye, bay, poison oak, grasses	<100	3-20 (10)	Suburban backyard, natural hillslope	50
2B	Buckeye, oak, bay, shrubs	<50	8	Rural residential, paved road, natural hillslope	0
3A	Bay, oaks, shrubs	<100	10	Natural	50
3B	Oak, bay, willow, chestnut, poison oak	<100	20	Natural	75
4A	Mixed hardwoods	>50	10	Natural, paved road	100
4B	Oak, bay, willow, blackberry, vines	<100	15	Natural	100
5A	Oak, bay, willow	<50	5	Natural, cleared for recreation	100
5B	Bay, oak, chaparral, shrubs, poison oak	<50	10, grading into hillslope vegetation	Natural	100

Channel Hydraulic Geometry

The bankfull width and depth measurements taken along the entire length of the channel in each study reach help constrain the lower end of a regional relationship between drainage basin area (discharge) and the bankfull channel cross-sectional area of the channel. In general, there appears to be a fairly linear relationship between watershed areas above a sample reach and channel cross-sectional area (Figure 41). Channel cross-sectional area is important to the calculation of channel bankfull shear stress, which is the product of bankfull depth, channel slope, gravity, 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. Thus, reaches with higher shear stress values should be characterized by coarser channel bed grain sizes (Figure 42).

The channel in reach 3B has a bigger cross-sectional area than might be predicted based upon the trend of the other Soda Creek data. Reach 3B is immediately downstream from a reach that has just exited a bedrock-confined canyon section in which all sediment supplied was carried due to the high bankfull shear stress. Reach 3B does not have bedrock control, allowing the channel to expand laterally, greatly increasing the bankfull width, causing the loss of streampower relative to the canyon upstream, and inducing sediment deposition. In Soda Creek the pool residual depth is not strongly related to the amount of sediment storage volume per unit channel length (Figure 43). Other than sample reach 1A, the pool depths are likely controlled by factors such as bedrock or boulder scour rather than the size and depth of sediment deposits. Reach 1A is controlled by strong pool-riffle forces, and is a highly sinuous reach with relatively fine grain sizes, allowing sediment deposit size to have a greater control on pool residual depth compared to other reaches. Additionally, the number of bars per unit channel length does not appear to have a strong relationship with the number of pools per unit channel length (Figure 44). This also suggests that boulder and bedrock pool scour have a greater control on pool formation rather than bar size and location.

Field observations of bankfull flow stage were used to estimate stream discharge associated with those flows using WinXSPRO software. Given the need for approximation of the water surface slope as the bed slope, and given uncertainty regarding field indicators of bankfull flow (1.5 yr return interval), results have been averaged for interpretation (Table 13). Data are not reported for strata V because channel geometry and slope are not appropriate for the flow resistance relationship used to estimate Manning's n . The average predicted discharge for reaches in strata I and II is 5.2 cms (184 cfs), which is somewhat lower than the trend line in Figure 6, but within the range of scatter. Somewhat lower flows should be expected from tributaries on the east side of Napa valley, as suggested by lower annual precipitation values observed in eastern and southern portions of the region relative to more western and northern areas.

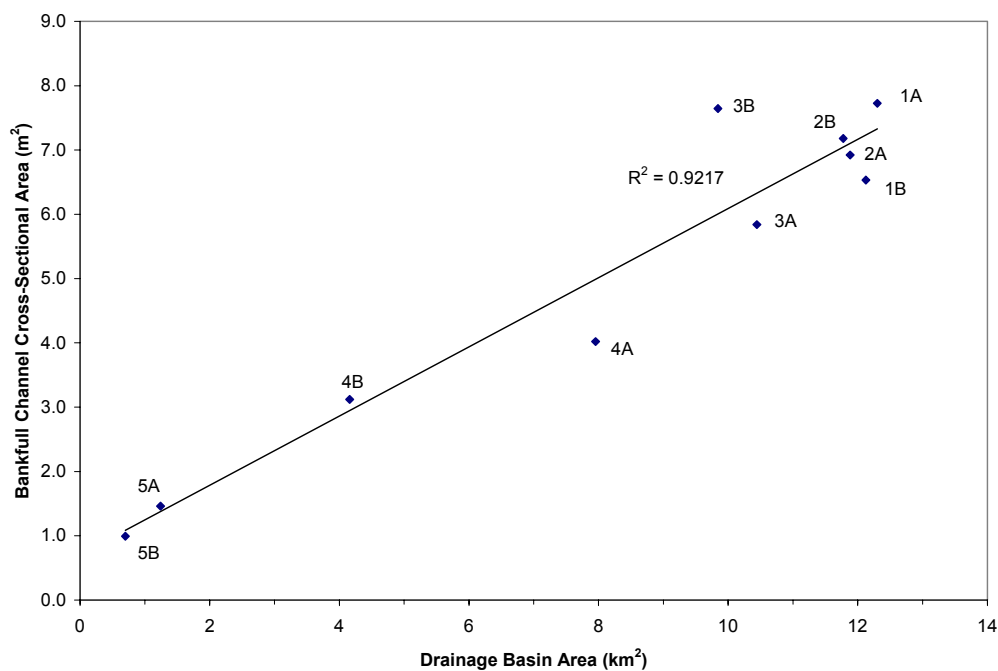


Figure 41. Drainage basin area versus bankfull channel cross-sectional area.

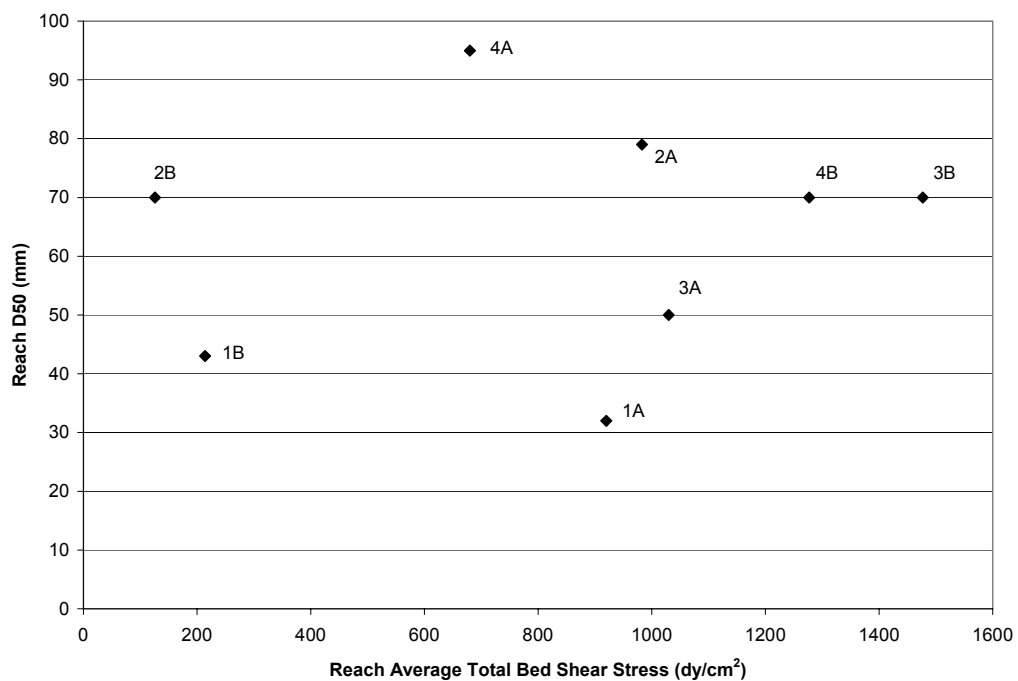


Figure 42. Reach average total bed shear stress (dy/cm²) versus median grain size (D50 in mm) for each sample reach; data for Strata V are omitted because shear stress estimates are likely to be skewed by the geometry of shallow, steep channels.

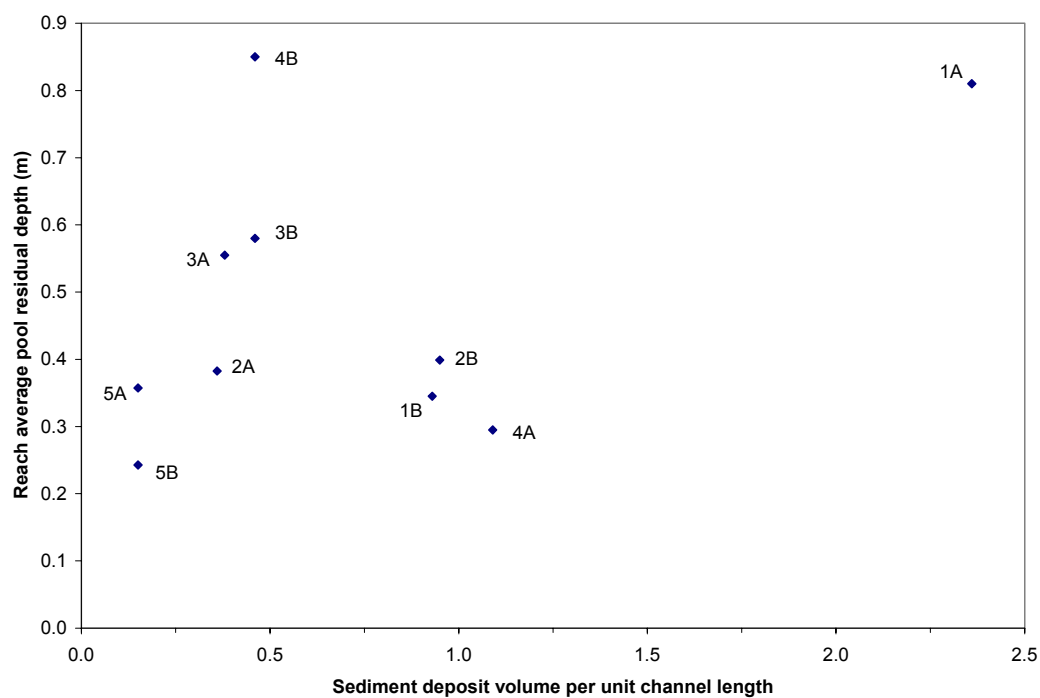


Figure 43. Sediment deposit volume per unit channel length versus reach average pool residual depth.

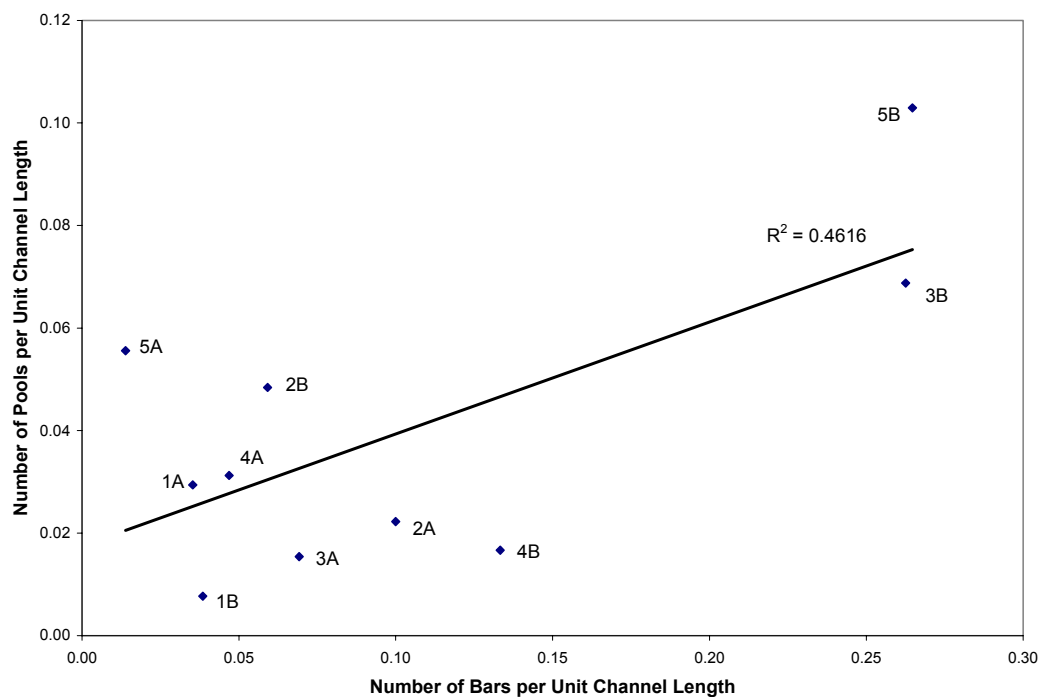


Figure 44. Number of bars per unit channel length versus number of pools per unit channel length.

Table 13. Summary hydraulic conditions predicted from field indicators of bankfull flow assumed to be approximately equivalent to a 1.5 yr return interval discharge.

Reach	Bed Slope	Manning's n	Mean Velocity (m/s)	Discharge (cms)	Maximum Flow Depth (m)
1A	0.017	0.075	1.2	5.3	1.0
1B	0.006	0.054	0.8	2.7	0.6
2A	0.019	0.079	1.2	6.7	0.9
2B	0.030	0.097	1.1	6.3	0.9
3A	0.029	0.098	0.9	2.4	0.7
3B	0.039	0.107	1.2	3.6	0.7
4A	0.020	0.087	0.8	1.8	0.7
4B	0.038	0.110	0.9	2.3	0.6

Although roughness values (Manning's n) are relatively high, mean velocities are reasonable and predicted discharges are variable but of the appropriate order of magnitude (Figure 6). It is possible that roughness values are set somewhat too high, which would increase predicted flow. This would be offset if water surface slopes were used instead of bed slope, hence these average values are probably reasonably accurate estimates. These estimates could be easily confirmed or adjusted based on a set of discharge measurements taken during periods of peak flow.

The WinXSPRO analysis also generated estimates of total bed shear stress, providing a basis for assessing relative bedload transport capacity among sample reaches. The availability of surface grain size data provide a basis for estimating the threshold shear stress required to mobilize the bed and initiate bed scour in a given reach. The critical Shield's stress used to estimate threshold shear stress of the surface D50 was 0.052. The ratio of the total bed shear stress to the critical bed shear stress (Table 14) provides a relative measure of potential mobilization of the streambed and potential of bed scour. The shear stress values and ratios formed here should not be considered an absolute indication of bed mobility because the total shear stress has not been adjusted for losses of momentum in rough channels; the values and ratios are intended only as a means to compare among reaches.

Higher bed shear stress values indicate relatively high bedload transport capacity. Lower values indicate lower bedload transport capacity. Hence, relative to reach 4B upstream, 4A has a substantially lower bedload transport capacity, and may therefore have a tendency for deposition of sediment transported from upstream. Similarly, reach 1B has substantially lower bed shear stress and is likely to accumulate material transported from upstream. Reaches 1B, 2A, and 4A have ratios of total to threshold shear stress that are relatively low compared to the other reaches. Surface sediment in these reaches would be expected to have a lower likelihood of being mobilized and/ or

scoured during peak flow of this magnitude (1.5 yr return interval). Because the bed shear stress is a maximum estimate of shear stress that could be applied to sediment on the bed, it is likely that when the threshold stress is greater than the total bed shear stress (ratio less than 1), entrainment of the surface material is unlikely for these flow conditions.

Table 14. Summary of bed shear stress estimates and relative bedload transport capacity among sample reaches.

Reach	Estimated Total Bed Shear Stress (dy/cm ²)	Estimated Threshold Shear Stress (dy/cm ²)	Ratio of Total to Threshold Shear Stress
1A	920	260	3.5
1B	210	350	0.6
2A	980	640	1.5
2B	1300	570	2.3
3A	1000	410	2.4
3B	1500	570	2.6
4A	680	780	0.9
4B	1300	570	2.3

DISCUSSION

Channel morphology reflects interactions between discharge, sediment supply, climate, tectonics, geology, vegetation, human influence, and time. The hydraulic geometry of a channel may change in response to changes in sediment and runoff inputs from the hillslopes. Measurements of channel geometry (width, depth, slope) help to indicate how the channel is responding to historic and current conditions in the watershed. 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 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. The data collected during this study provide the basis for assessments presented below regarding the current conditions of Soda Creek, and help in making recommendations for future management.

A set of preliminary working hypotheses previously stated are reviewed below. General conclusions regarding these hypotheses are provided. In addition, based on field data and greater knowledge of conditions in Soda Creek, three additional hypotheses are developed and evaluated. These focus on current management issues in Soda Creek:

historic changes in fish habitat, flooding and sedimentation, and riparian vegetation. Although these issues are discussed as they pertain to Soda Creek, they are likely to be relevant in other Napa River tributary systems on the eastern side of Napa Valley with similar watershed geologic and hydrologic conditions.

Working hypotheses

- a) Because Soda Creek currently has minimal areas of intensive land use within its watershed, the current condition and functioning of the channel is not substantially affected by intensive anthropogenic land use, and represents a condition that has not significantly changed from its natural form.

This hypothesis appears to be largely supported by the available data. Land use changes have been modest. With the exception of channel and bank modifications associated with grade control and bank revetments in Strata I and likely removal of LWD in accessible reaches, there is little compelling evidence of watershed-wide effects of modern land use and land management on channel conditions.

- b) Soda Creek provides quality spawning and rearing habitat for steelhead trout (*Oncorhynchus mykiss*) because the ideal grain sizes for spawning are present, the channel does not contain large amounts of fine sediment, the majority of the channel is shaded by riparian vegetation, and the channel contains pool and riffle morphology necessary for habitat complexity that is favorable for salmonid fishes.

This hypothesis appears to be reasonably well supported by the available data. Channel morphology and sediment characteristics indicate reasonably good habitat quality, however, deep pools are not common, and LWD is not present in significant quantities. While these conditions might be expected to seriously affect habitat for Chinook or coho salmon, steelhead are thought to be adapted to shallower, swifter streams such as Soda Creek.

- c) Habitat for anadromous steelhead trout in Soda Creek is limited to the lower portions of the watershed by the Soda Canyon Falls migration barrier, and the lack of perennial flow in the lower half of the watershed decreases the quality of habitat while significantly reducing the probability of downstream migration.

This hypothesis appears to be well supported by available data, including nearby stream gauging records, observations of long-time residents on Soda Creek, and field observations over Water Year 2002.

- d) Previous land uses and channel modifications in Soda Creek do have some effect on the current form and function of the channel. Understanding the land use

history will help in assessing the current condition of Soda Creek, and will help us make predictions of how the watershed will react to future changes in land use.

This hypothesis is generally supported in Strata I where bed and banks have been subject to management (grade control at Silverado Trail and bank revetments primarily downstream of Silverado Trail). In other portions of the channel network, effects of land use and/ or channel modification are not evident, or are uncertain. Removal of LWD may be inferred to have had some effect on channel form and function.

Study Design

This study was designed to characterize the current condition of the stream and the processes occurring presently and previously in the watershed. Watershed conditions such as the quality of current anadromous fish habitat, the flood response of the watershed, and the sediment production and storage characteristics of the stream, and condition and function of riparian vegetation communities are of particular importance for Soda Creek and other tributaries of the Napa River in the context of management initiatives being implemented by CDFG, the County of Napa, and others to preserve or enhance numbers of steelhead trout, initiatives for the control of sediment source and transport being encouraged by the RWQCB through the sediment TMDL processes and by the County through the hillslope ordinance, and the reduction of the risk of flooding through the partners of the Napa flood control project.

To make assessments of habitat for fishes, flood response, sediment production and storage, and riparian vegetation, detailed measurements in 10 representative reaches of the entire stream length of Soda Creek were made. The sample reaches were carefully selected so that all slope classes (channel morphologies) were included, yet were randomly located to avoid bias towards particular features or reaches. The sampling strategy allowed a very good working knowledge of the spatial variability of the stream process without making measurements along the entire length (this was not possible because of access limitations). Because this sampling strategy only includes data from 10 representative reaches, the possibility exists that this characterization of Soda Creek and its habitat are unrepresentative. However, we walked or were able to observe from Soda Canyon Road a majority of the channel (approximately 80 %), confirming that the sample reaches were representative of the entire channel length.

Although most of the channel morphological data for Soda Creek were collected during the fall of 2001, historical stream surveys, interviews with watershed residents, “as-built” diagrams for structures crossing the stream, and other historical documents were included in this study to enhance our understanding of changes that may have occurred in the watershed. In this way, the data collected in this study were compared to historic stream form and function to provide an understanding of how and at what rate the stream is changing over time. Because each sample reach was tied to a stable location, it would be possible to compare the data presented in this report with any future study of

the same reaches. In this way, the data collected in these 10 sample reaches can become baseline data for a future analysis of any changes within the watershed.

Anadromous Fish Habitat

The primary beneficial use of Soda Creek is the habitat it provides for anadromous fish, especially steelhead trout. Soda Creek has been home to an historical steelhead run, as evidenced by the historic California Department of Fish and Game (CDFG) stream surveys. A 1958 survey states that Soda Creek is second only to Dry and Redwood Creeks for annual steelhead runs, and appears to be one of the better steelhead spawning streams in the lower end of the Napa River drainage (Yountville CDFG). Spawning and nursery areas are reported as fairly good in this survey, and all management recommendations include continuing to manage Soda Creek primarily as a steelhead spawning and nursery area. In a second CDFG survey (1980), Ellison and Carnine emphasize that Soda Creek sustains a major steelhead spawning run, and the limited spawning habitat appears to be more than sufficient to saturate what nursery habitat is available during the summer.

In 2002, some 44 years after the earliest stream survey (that we are aware of), does Soda Creek still provide successful steelhead habitat? Rural residential housing and new vineyards have put new pressures on the stream, but many aspects of the watershed are similar to the historic conditions. Soda Creek is still a fairly undisturbed stream flowing through chaparral uplands, oak and other hardwood forests and savanna, but now flows through a rural residential neighborhood in its lowest reaches. Fish passage structures under the Silverado Trail Bridge and on the aprons of two other bridges have been installed in an effort to provide access to habitat for anadromous fish. In general, the channel dimensions, slope, and grain size appear to be in equilibrium with the current climate and land use.

The majority of the channel has coarse-bedded pool-riffle and plane bed morphology with substantial bedrock influence, while the morphology of the headwaters are primarily boulder-formed step-pool. The middle and upper portions (sample Strata IV, and parts of sample Strata III and V) are fed by groundwater seepage, providing the channel with year-round flow, but the lower portions (sample Strata I, II and parts of Strata III) are ephemeral. The majority of the channel, with exceptions in reaches 1B and 2B, has continuous riparian canopy cover, however Soda Creek does not have a large number of LWD pieces in-channel. Stream flow is not heavily regulated; there are few diversions from the creek. In the past few years, both Chinook salmon and steelhead have been reported in Soda Creek (John Emig, CDFG, pers. comm.), but does the channel currently provide habitat of the same quality and quantity as historical conditions? Using our knowledge of the historical character of Soda Creek, and the current data collected, we can evaluate a hypothesis regarding anadromous fish habitat in Soda Creek.

Hypothesis 1: The quality and quantity of spawning and rearing habitat for steelhead trout has not changed over the past 50 years, and is sufficient to maintain a viable anadromous population.

Barriers to migration

Barriers to migration include the lack of adequate discharge for upstream migration of adults, downstream migration of spawned out adults and juveniles, as well as physical barriers such as jumps, dams and culverts. A natural bedrock constriction (resistant Sonoma Volcanics) exists between the boundary of Strata III and Strata IV that forms a series of vertical waterfalls, including the 4.5 m fall known as Soda Canyon Falls. Although this waterfall makes upstream passage by fish much more difficult, during periods of higher flow the depth of the plunge pool below each waterfall may allow some percentage of fish to pass and spawn upstream. Steelhead/ rainbow trout ranging from zero to two years were observed in the pools immediately upstream of Soda Canyon Falls (data collected by the Friends of the Napa River, 2002). For fish unable to ascend the falls, the potential fish-spawning habitat is limited to the lowest 4.1 km (13,450 feet or 2.5 miles) of channel.

Other potential barriers to migration exist, including the culvert under the Silverado Trail bridge, the hydraulic jump beneath the old stone masonry bridge, a culvert associated with a footbridge in Strata I, and a culvert associated with a bridge upstream of reach 2B. However, these locations have been identified by the CDFG, and modified to allow continued fish passage. For example, a fish ladder and low-flow weir were installed under the Silverado Trail bridge in 1973, and are cleared of sediment every summer by the Napa County Public Works, and a low-flow weir was constructed in 1982 on the apron of the footbridge to aid steelhead passage (CDFG memo). The fish ladder and hydraulic jump associated with the Silverado Trail bridge and the masonry bridge are not a barrier to steelhead, as two adults were observed during data collection in reach 2A, upstream of these locations (December 7th and 18th, 2001). But these structures are thought to be impassable by Chinook salmon (Bob Snyder, CDFG, pers. comm.), limiting potential salmon habitat to the reaches downstream of Silverado Trail. Because the CDFG has installed fish passage structures in Soda Creek, the amount of potential habitat is similar to the amount available before any structures were built across the channel. New structures across the Creek should include fish passage features, to maximize the amount and accessibility of habitat available in Soda Creek. Soda Canyon Falls historically was, and always will be a difficult location for fish to pass.

The lack of perennial flow in the lower reaches is by all indications the limiting factor for adequate steelhead habitat in Soda Creek. Documents on file at the CDFG, retrieval and review of other historical documents, our observations during 2001 and 2002, and interviews with watershed residents all confirm that the reaches of Soda Creek below Loma Vista Drive are annually dry beginning in May or June, and do not have flow until after the first two or three rains of the wet season, usually in November (Table

15). The seasonality of water flow appears to restrict the period within each year in which juvenile steelhead may emigrate downstream.

Although the discharge of Soda Creek is not gauged, the discharge records from other Napa Valley east-side tributaries illustrate the temporal flow characteristics of the region. Three Napa Valley eastern tributaries have USGS gages that have recorded daily discharge in the past: Conn Creek near Oakville (gage no. 11456500), Milliken Creek near Napa (gage no. 11458100), and Tulucay Creek at Napa (gage no. 11458350) (Figure 45). Discharge records show that for the years on record, each of these three streams tend to have flow from approximately January to May, and very little or zero flow from June to December. A single year (water year 1980) of discharge is graphed for Tulucay Creek using an arithmetic scale plot (Figure 45, C) and a log scale plot (Figure 45, D). The arithmetic scale plots shows the seasonal discharge patterns very clearly, and the log scale plot shows that during the summer and fall when discharge appears to be zero, the channel is still carrying water, although discharges are much lower than 1 cfs ($0.028 \text{ m}^3 \text{ s}^{-1}$). These discharge records suggest that it is not unusual for these eastern tributaries to have very little flow from June to December.

Table 15. Flow conditions in reaches of sample Strata I, II, III and IV of Soda Creek.

Reach	Date	Flow condition	Source
1A	Between March and June	Dries up	Residents, SFEI observation
1B	April 23, 1986	Completely dry	CDFG survey
1B	May	Dries up	Residents, SFEI observation
2A and 2B	May to June	Dries up	Residents, SFEI observation
Sample Strata I and II	November 16, 1958	Dry	CDFG survey
Sample Strata I and II	February 24, 1964	Completely dry	CDFG memo
Sample Strata I	May 21, 1980	Dry	CDFG survey
Sample Strata I and II	June 18, 1981	Dry, with a few shallow pools	CDFG survey and memo
3A	June	Dries up	Residents, SFEI observation
3B	February 24, 1964	Isolated pools	CDFG memo
4A	July 25, 2002	Dry segment	SFEI observation

The precipitation patterns of the past 50 years have not changed significantly within the Bay Area. Nevertheless, average rainfall has increased slightly in the last 30 years (1971-2000) in comparison to 1941-1970. For example, annual rainfall in San Francisco has increased by 51 mm (2 inches) and annual rainfall at Napa State hospital has increased by 56 mm (2.2 inches) (Figure 46). The seasonal precipitation patterns most likely have controlled the ephemeral nature of lower Soda Creek for the past 50 to 100 years, and possibly during the time of Spanish settlement. The earliest maps of the area label Soda Creek as “Arroyo Seco” or Dry Creek (see Figure 9A). However, it is possible that periods of higher precipitation in the past, including the flood-dominated climate between 1850 and 1890 (McKee et al., 2002), resulted in year round flow in Soda

Creek and other Napa River tributaries. It is also possible that vegetation changes in the watershed in the past century could have reduced stream flow. A significant decline in grazing pressure and the suppression of wildfires presumably resulted in an increase in brush and trees and a corresponding decrease in grasslands. Evapotranspiration rates in winter and spring would be lower in grasslands, potentially allowing more rainfall to percolate to the water table and increasing streamflow.

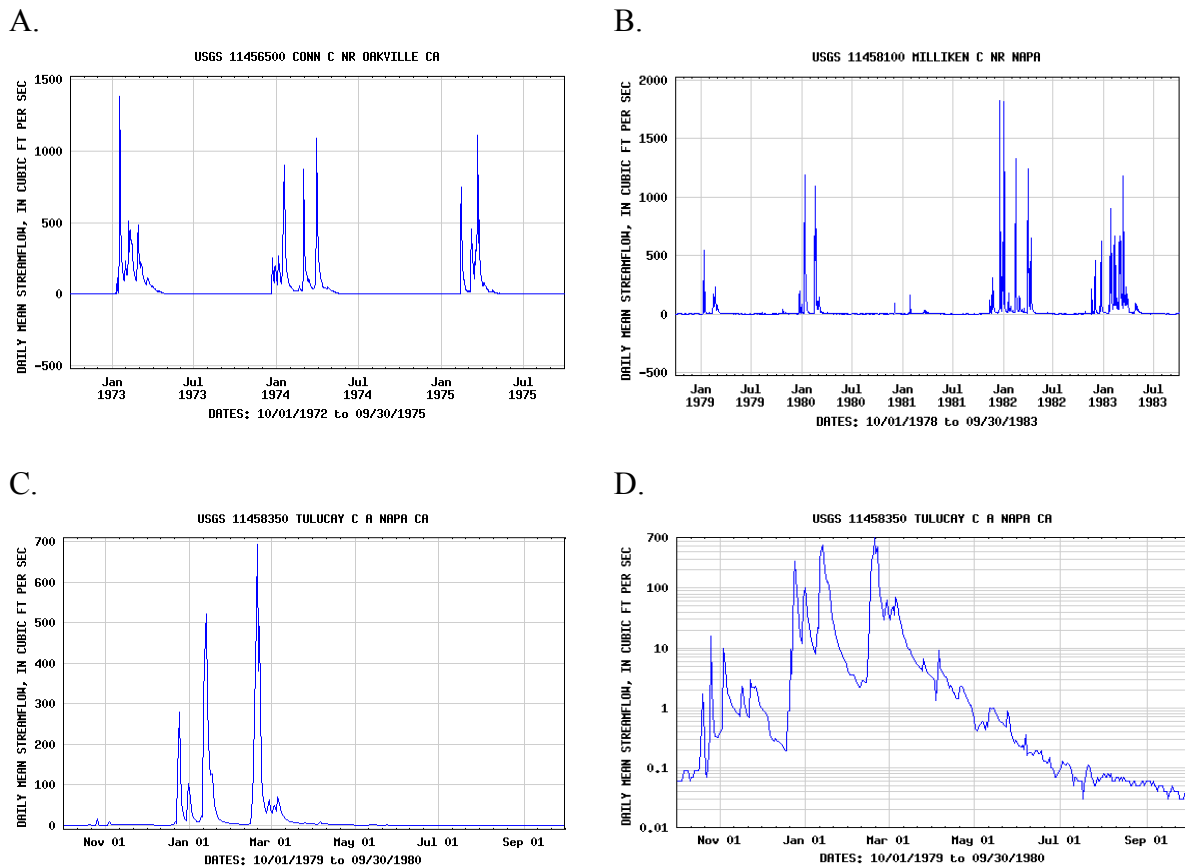


Figure 45. A) Discharge for Conn Creek (gage no. 11456500), water years 1973-1975. B) Discharge for Milliken Creek (gage no. 11458100), water years 1979-1983. C) Discharge for Tulucay Creek (gage no. 11458350), water year 1980, arithmetic scale. D) Discharge for Tulucay Creek (gage no. 11458350), water year 1980, log scale. All data obtained from the USGS.

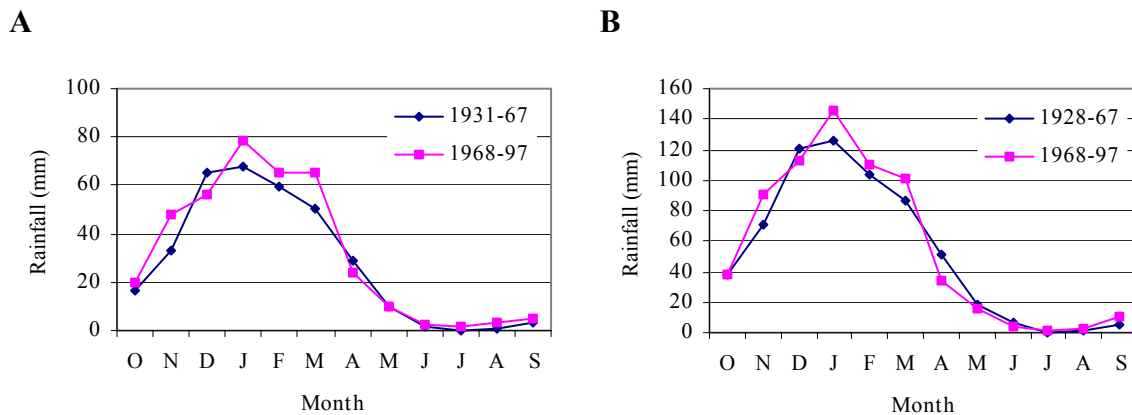


Figure 46. Changes in monthly rainfall distribution for two locations in the Bay Area A) San Jose and B) Napa State Hospital (McKee et al., 2002).

The primary impediment to migration in Soda Creek appears to be the lack of perennial flow in the lower reaches of the channel. The grade control structure for the old stone masonry bridge at Silverado Trail, as well as channel modifications in this reach, has caused substantial sediment deposition upstream over a distance of hundreds of meters, and may cause discontinuity in surface flows to occur somewhat earlier in the spring and later in the fall. Usually between the months of June and November, most of sample Strata III, and all of sample Strata I and II are dry. Because these reaches are fed by groundwater, the channel will dry up once the water table aquifer has been exhausted, and falls below the elevation of the channel bed, usually by the end of spring. Climatic records suggest that the low to zero discharges during the summer and fall months probably have not changed within the past 50 years, causing this to be a constant factor in the quality and quantity of steelhead habitat over this time period. However, any future anthropogenic changes in the watershed that would disrupt the timing or amount of flow, especially during times of steelhead migration, could have significant deleterious effects upon the habitat available in Soda Creek.

Spawning Habitat

The in-channel habitat requirements for successful anadromous fish-spawning have been studied in many northern California streams (Lisle, 1989; Lisle and Lewis, 1992; Kondolf, 2000). Successful steelhead spawning initially requires adequate streamflow, temperature, and lack of migration barriers for the adult steelhead to reach the spawning location. The female will choose the location to build the redd, usually just upstream of a riffle crest in gravel ideally ranging between 0.2 and 4.0 inches (5 to 102 mm), but steelhead will utilize various mixtures of sand-gravel and gravel-cobble (Goals Project, 2000). Other size ranges of spawning gravels have been reported, for example 0.5 to 6 inches (13 to 152 mm) in diameter, dominated by 2 to 3 inch (51 to 76 mm)

gravel (Flosi, 1998). Kondolf (1993) compiled sediment size distributions observed in redds constructed by steelhead trout. The range of D50's from these data is about 18 mm to 34 mm; D84's are about 100 mm.

The female lays the eggs in an excavated pit, and buries them under a gravel layer averaging 0.2 m in thickness (Lisle and Lewis, 1992), removing excess fine particles from the gravel during the process (Kondolf, 2000). Once the redd is built, embryo survival is extremely dependant upon discharge and sediment transport during the incubation period (Lisle and Lewis, 1992). The redd is vulnerable to scour and fill processes, which can remove or bury the eggs, as well as infiltration of fine particles into the gravel, which limits permeability of oxygenated water through the gravel.

Lisle (1989) conducted a study in three California streams showing that scour and fill was frequently equivalent to the depths at which eggs are laid, and deposition of fine bed load (grain sizes between 0.25 and 0.5 mm) creates a seal in the gravel substrate that endangers egg survival rates. Generally, it is not the lack of gravel substrate that limits steelhead production, however it is the deposition of fine sediments in spawning gravels that impairs spawning success (Flosi et al., 1998). A Kondolf (2000) review of prior studies suggests that spawning gravels with less than 12 to 14% sediment finer than 1 mm can be expected to produce about 50% emergence of fry from redds. Grain sizes smaller than 2 mm in excess of 30% of the subsurface are considered detrimental for fish habitat (Collins, 2001). Besides these substrate requirements, other spawning requirements include water depths of six to 24 inches (15 to 61 cm), water velocities of approximately two ft/sec (0.6 m/sec), and water temperatures between 39° and 52° F (3.9° to 11.1° C) (Goals Project, 2000).

Field data collected on the morphology and grain size distributions of subsurface sediment at likely spawning sites in Soda Creek provides a basis for evaluating the quantity and quality of physical habitat available for spawning. Quality of habitat is evaluated on the basis of surface and subsurface grain size data. Quantity of habitat is evaluated based on inferences drawn from survey data pertaining to size of sediment bars and pool frequency.

Characterization of surface grain size distributions for each sample reach reveals the D50 for reaches 1A through 3B ranges from 32 mm to 79 mm, consistent with the size ranges reported suitable for spawning by Flosi (1998) and Kondolf (1993, 2000). This interpretation assumes that the surface D50 is representative of the coarser fraction of the framework gravels as described by Kondolf (2000). The subsurface grain size data for Soda Creek (Table 7) indicate framework bed sediment that is in the upper end of the range documented for steelhead trout. The bed sediment in Soda Creek is quite coarse, and it appears that appropriate spawning sites for steelhead might be limited to some degree by excessively coarse sediment that cannot be moved by fish attempting to construct redds. Soda Creek clearly has very low levels of sediment finer than 1 mm (about 5%) in the subsurface sediment, suggesting that there would be relatively high survival to emergence of steelhead fry from redds. The percentage of subsurface sediment sizes finer than 6.35 mm (about 20%) in Soda Creek does not appear to be an

impediment to emergence of fry from redds. Overall, spawning conditions in terms of subsurface sediment size distributions in Soda Creek appear to be good with respect to fine sediment, with potential limitations related to excessively coarse framework gravels that could limit the ability of spawners to build redds.

Survey reaches accessible to anadromous fish (strata I, II and III) of Soda Creek contain a large number of bars and bar types among bars smaller than 16 m^3 , suggesting that there are spatially well-distributed and diverse patches of substrate for redd construction (Figure 35A). Although the measurement of bars focused on estimating the volume of mobile bed sediment, the primary visual cue used to discern these bars proved to be the appearance of patches of finer sediment among the relatively immobile cobble, boulder and bedrock-dominated substrate. The bar types most likely to represent potential spawning sites are forced and active channel; there are 46 of these bar types smaller than 16 m^3 in 1,086 m of surveyed sample reaches in strata I, II and III. Extrapolating to the 4 km reach of Soda Creek accessible to anadromous fish, this suggests there might be about 170 spawning sites in relatively small-scale patches. These patch-scale spawning sites appear to be concentrated in reach 3B (Figure 28). In addition, there are 6 active channel bars larger than 16 m^3 in the anadromous reach. These areas represent larger, contiguous stretches of bed sediment of appropriate size for spawning. Such potential spawning beds were particularly significant in reaches 1B and 2A.

Mean pool spacing in free-formed pool-riffle reaches averages 5-7 channel widths (Leopold et al., 1964; Dunne and Leopold, 1978), but pool spacing decreases to 1-4 channel widths in steeper step-pool reaches (Grant et al., 1990). In reaches 1A through 4A of Soda Creek, most pools had spacing of 1-4 bankfull widths, with the exception of reach 3A that has a mean pool spacing of 6.5 bankfull widths, and reach 2A that had a portion of the sample reach 10 bankfull widths in length devoid of a pool (Table 9). A total of 36 pools were measured in reaches 1A through 4A, with the majority being lateral scour, main channel/ bedrock trench, and step-pools, reflecting the scale of the bankfull channel, and the prevalence of lateral scour against stream banks, bedrock outcrops and boulder steps. The paucity of LWD contributes to the general absence of dammed pools and plunge pools.

Spawning is most often observed in gravels in the tails of pools, just upstream of the riffle crest, where a positive hydraulic head drives oxygenated streamwater into the bed, to emerge downstream within the riffle (Keller et al., 1990). The number of pools measured suggests that locations optimal for spawning exist in Soda Creek. There were 33 pools in surveyed reaches accessible to anadromous fish, suggesting overall pool frequency of about 3 per 100 m of stream. In 4 km of Soda Creek accessible to anadromous fish, there might be roughly 120 pools and an equal number of pool tails. This estimate of suitable spawning locations is reasonably consistent with the estimate derived from field data on bars discussed above.

The low number of LWD pieces measured in these reaches (Figure 22) may reduce the depth of pools, the number of pools, and possibly the abundance of sorted spawning gravels associated with the variations in velocity induced by LWD. In the

absence of LWD, the role of the large boulders and bedrock outcrops in Soda Creek is elevated in importance as the mechanism for creating pools and local velocity changes that sort bed sediment, potentially affecting the abundance of suitable spawning sites. Large boulders and bedrock controls effect channel processes by providing hydraulic roughness and morphologic influence and provide fish habitat through velocity shelter, agents for pool scour, and provide forces for sorting gravels as indicated by deposits of finer gravel often found downstream of boulders. In the absence of LWD, these mechanisms will also be important in other tributaries of the Napa River watershed.

Adequate streamflow is also necessary for successful steelhead spawning. The literature shows that adult steelhead enter the tributary streams to spawn from November to May (Flosi et al., 1998). However, a channel without discharge during this time of migration will obviously prevent spawning adults from entering the tributary. The lowest reaches of Soda Creek are ephemeral, and do not support surface flows from approximately June to November, until after the first few precipitation events of the rainy season. This pattern is observed in many other tributaries in the region, suggesting that the steelhead have most likely adapted their lifecycles to fit the annual discharge patterns.

Evidence exists that the annual precipitation regime has shifted slightly, pushing the start of the rainy season later in the year. Rainfall records from San Jose and Napa State Hospital reflect a trend in the seasonal timing of rainfall that is seen across the Bay Area (Figure 46). Monthly rainfall totals for the period 1968-1997 have shifted slightly compared to the period 1928-1967, so that the majority of the rainfall is occurring slightly later in the year (McKee et al., 2002). These data suggest that slight shifts in the timing and amount of rainfall may contribute to the limited success of steelhead spawning in some tributaries of the Napa River watershed. However, this slight shift in the precipitation regime could help steelhead migration in Soda Creek by maintaining discharge in the stream from January to March.

The majority of deposits and bars suitable for spawning are estimated to have been stable from one to five years (Figure 36). Many of these bars were likely deposited during the 1995 flood event (recurrence interval of approximately 21 years), and were scoured and modified during the 1997 flood event (recurrence interval of approximately six years). Thus our field observations suggested that the reworking of bars regularly occurs during flood events with recurrence intervals larger than five years. The flood with the five year recurrence interval may represent a critical threshold for redd scour and hydrologic change within the Soda Creek watershed.

Although definitive evidence for the stream condition 50 years ago does not exist, based upon the comparison between the previous CDFG stream surveys and the current condition of Soda Creek, it appears that the channel morphology, functioning and salmonid habitat have not significantly changed over the past 50 years. Current salmonid-spawning habitat conditions are acceptable for maintaining a steelhead population. The abundance of spawning sites may be limited by excessively coarse sediment textures.

Rearing Habitat

Rearing habitat is comprised of a combination of appropriate habitat features and the in-channel interactions of water depths, velocities, temperatures and quality, LWD, pool and riffle spacing and volume, riparian zone effects, food supply, and migration barriers. An extensive list of habitat criteria for steelhead spawning and rearing is compiled in the Napa River Basin Limiting Factors Analysis report (Stillwater Sciences Inc., 2002). Substantial changes in any of these watershed components may have deleterious effects upon steelhead rearing success. Studies illustrating the importance of pools (Keller et al., 1990; Nakamoto, 1994; Nielsen et al., 1994) and LWD (Lisle, 1986; Keller and MacDonald, 1995;) on steelhead habitat can be used to evaluate the function of these features in Soda Creek.

Based upon the frequency and depth of pools, the rearing habitat in Soda Creek is currently of fair quality. When summer flow levels are considered, however, overall rearing habitat is severely limited. Pools comprise the most important rearing habitat feature because juvenile steelhead require pools with water temperatures and cover sufficient to survive the summer months. Juvenile steelhead may use groundwater fed pools as thermal refuge during periods of low streamflow and marginal habitat (Nielsen et al., 1994). In Redwood Creek, Humboldt County, California, Keller et al., (1990) cite recent aggradation that has fully or partially filled pools, thus reducing the available habitat for juvenile rearing and increasing the water temperature as a cause for the reduction of available habitat for rearing. Increased erosion in some reaches of a stream can provide a source of sediment that can cause other reaches to aggrade and pools to fill.

Given the number and depth of pools measured in the lower reaches of Soda Creek, it is suggested that cool temperatures might be maintained if the pools persist through the dry season and are not isolated from surface or groundwater flow. Aggradation of the channel bed locally or at the reach scale could contribute to lower water levels in surface channels and tend to isolate pools from surface and/or subsurface flow by elevating the bed relative to the water table. Such aggradation may have occurred in Soda Creek in sample reach 1B, just upstream from Silverado Trail, where sediment is deposited upstream of the old stone masonry bridge that now acts as grade control. The aggradation in reach 1B is likely the result of the grade control structure rather than significant changes in coarse sediment load in Soda Creek. Bank erosion in the lower reaches of Soda Creek (Figure 37) and the movement of sediment stored in bars and channel deposits (Figure 36) is sufficient, over time, to have generated the localized zone of aggradation associated with the grade control structure.

The relatively shallow depth of pools in Soda Creek (median residual depth is 35 cm), suggests that pool filling by fine sediment could have a negative effect on rearing habitat. The sediment available in the fluvial system from channel deposits, bank erosion, and from terrestrial erosion sources, could potentially reduce the depth of these already relatively shallow pools. Studies of pool filling in the Napa River Basin Limiting Factors Analysis (Stillwater Sciences, 2002) included a three-pool sample located in sample Stratum II of Soda Creek. Stillwater found almost zero pool filling at these sites.

Furthermore, they found little evidence for widespread significant pool filling by fine sediment, with median values of 2% of pool volume filled by sediment in a sample of 18 Napa River tributaries. Our survey of pools and sediment storage in pools indicate somewhat higher levels of sediment storage in pools in Soda Creek. For example, out of 50 total pools measured, 23 had measurable sediment deposits, with all measured pool deposits smaller in volume than 16 m³. Because true pool volume was not measured, values of pool filling by fine sediment are not available. However, Soda Creek has relatively low volumes of sediment supplied from the watershed (compared to other Napa River tributaries), and a lack of landslides or slumps that impinge upon the channel, suggesting that pool in-filling is currently not significantly affecting salmonid habitat in Soda Creek. Future changes in land use that increase the amount of sand and fine gravel that typically is deposited in pools could have detrimental effects upon the number and depth of pools in the lower reaches of Soda Creek.

In the 1958 CDFG survey of Soda Creek, the pools in the middle third (sample Strata III) were characterized as fair, typically less than 15 ft (4.6 m) long, 4-6 ft (1.2-1.8 m) wide, and 1.5 ft (0.45 m) deep. The data collected in 2001 show that the pools in this same reach are typically 13 ft (4 m) long, with some up to 69 ft (21 m), 9.8 ft (3 m) wide, and 1.6 ft (0.5 m) deep, illustrating that the pool morphologies have not changed much in the past 44 years. The primary changes are the increased length and width, but this is most likely a result of slight differences in measurement protocols and is probably not significant. During the collection of pool measurements in our 2001 surveys, we did not measure wetted channel dimensions and enlarged our measurements to reflect pool dimensions at higher stream stage more typical of winter base flow. In other words, pool dimensions were measured based upon the depth of flow during typical winter discharge, rather than the depth of flow on the date of measure. Depth measurements are the most comparable, and there is no indication of significant change in average pool depth. Sample Strata I, II and III contain the deepest and largest volume pools (Figure 24), with low percentages of fines (Figure 13). The limiting factors in pool use by steelhead are the low number of cover elements and the low to zero stream discharge during the summer.

The quality of steelhead rearing habitat is also dependent upon the quality of cover, which in watersheds with abundant coniferous forest is largely a function of the quantity of LWD pieces. Relatively large pieces of woody debris in streams influence the physical form of the channel, movement of sediment, retention of gravel, and composition of the biological community (Flosi et al., 1998). The presence of LWD in a channel has been shown to control the location and development of pools, add complexity to the aquatic habitat, and provide cover for fish populations. Quality habitat is supplied in pools created by LWD that provide undercut stream banks and shelter beneath LWD, particularly complex arrangements of LWD, and root mats of living trees (Keller and Macdonald, 1995). Rearing habitat in Soda Creek may be limited due to the low number of LWD pieces present in the channel. With the exception of reaches 1B and 2B, the riparian corridor is fairly continuous, providing a source for recruitment of LWD, yet a total of only 61 LWD pieces were measured in reaches 1A through 4A. The live upright LWD along Soda Creek has an affect upon flow velocities, but is not creating large amounts of undercut bank cover areas for salmonids. However, in reaches with

perennial pools, large boulders and bedrock outcrops are providing cover elements in the pools.

Many landowners along Soda Creek have removed LWD pieces to prevent flooding on their property. The removal of debris from channels is a common practice in the region, as it prevents scour of the bed and banks around the debris pieces. For example, landowners described the removal of a 100+-year-old oak tree that fell into the channel in reach 1A in 1995, and other landowners in sample Strata II and III reported removing LWD to prevent damage to their bridges. The removal of LWD from the channel has most likely increased over the past 50 years in an effort to prevent scour and flooding problems, because a greater number of people now live in the residential area along Soda Creek. Alternatively, the low number of LWD in these reaches could be caused by naturally low recruitment rates from hardwood riparian forest stands, past land uses, and/ or the lack of landslides in Soda Creek watershed. In general, no evidence for historical landslides that reached the channel was observed. In some locations in the watershed, the hillslopes adjacent to the channel are bedrock with thin soil, thus limiting the number of LWD pieces directly recruited into the channel because landslides and other failures that directly input wood into channels tend to occur on hillslopes with a thicker soil profile. Also, given the relative abundance of live, mature hardwoods in the riparian zone of Soda Creek, the relative absence of LWD could also reflect historic land use. It may be that the riparian forests were either less dense, immature, absent or removed in the previous century, and that only in the past few decades has the riparian growth achieved a level that might be expected to deliver LWD to the channel. However, a comparison between the 1940 and 1999 aerial photographs does not show a wholesale change in riparian density in the Soda Creek watershed. In any event, LWD currently has a low impact upon the morphology of Soda Creek (Figure 22).

Pool locations were generally not controlled by LWD; in all measured reaches, only six pools were associated with LWD, and two were clearly caused by the LWD. Montgomery et al., (1995) show that mean pool spacing can be related to the amount of LWD loading in pool-riffle, plane-bed, and forced pool-riffle channels. More importantly, they found that less than 40% of LWD pieces force the formation of a pool. In this context, it is not surprising that the pools of Soda Creek are not heavily controlled by the location of LWD in the channel. Nevertheless, pool spacing in many sample reaches of Soda Creek is between two and four bankfull widths, similar to that reported by Montgomery et al. (1995), indicating that boulders, bedrock and other hydraulic conditions are sufficient to create relatively abundant pools. It is likely that an increase in well-placed LWD (increasing the total LWD load) could reduce the mean spacing of pools in Soda Creek, increasing the habitat heterogeneity necessary for steelhead, however, the public might be cautious given the potential risk to bridges and other creek structures that they manage. Although LWD is not the main cause of pool formation in Soda Creek, the channel does have many pools that provide rearing habitat for steelhead. Reach 2A lacks the benefits of pool formation and cover by LWD (the reach only has one piece of LWD), yet during data collection two adult steelhead trout were observed resting in pools in this reach. The observation of these two steelhead helps to confirm that Soda

Creek is still able to function as anadromous fish habitat, in spite of the low number of LWD pieces it contains.

Steelhead rearing also requires water depths of 10 to 20 inches (25 to 50 cm), water temperatures for incubation and emergence between 48° and 52° F (8.8° to 11.1° C), water temperatures for fry and juvenile rearing between 45° and 60° F (7.2° to 15.5° C), habitat heterogeneity, sufficient flows, and well developed cover (Goals Project, 2000). The rearing juvenile steelhead are primarily drift feeders utilizing a variety of terrestrial and aquatic insects (Goals Project, 2000). All sample reaches, with the exception of 1B and 2B, had at least 50% canopy cover from the riparian vegetation. The shading effect reduces direct sunlight that would increase stream temperatures during the summer months. Riparian vegetation also provides organic carbon to the channel, and habitat for insects, both necessary to support the aquatic food chain. The current condition of the habitat elements and riparian vegetation only provides limited rearing habitat, because the temperature and flow requirements are not met during the summer months when the lowest reaches of Soda Creek are dry.

The lack of flow in Soda Creek during summer months leaves steelhead vulnerable to predation, isolation, or mortality from the increased water temperatures, or dissipation of surface flow. Because of these factors, we suggest rearing habitat in Soda Creek is classified as marginal or non-existent during these months. However, because groundwater conditions maintain year-round flow in sample Strata IV and portions of sample Strata III, discharge is maintained year round in these locations. This allows the existing habitat features in these reaches to be used by juvenile steelhead as rearing habitat when the lower reaches are dry. Alternatively, juvenile steelhead may be able to migrate downstream to the mainstem of the Napa River for summer rearing. This pattern of ephemeral flow in the lower reaches most likely has not changed over the past 50 years, making limited rearing habitat in Soda Creek the norm. But the increasing demand for groundwater by the small vineyards and residential areas in the watershed has the potential to decrease the already small amount of discharge in the channel, potentially causing the limited rearing habitat to become non-existent at some future time.

A study of Redwood Creek, Humboldt County, California by the North Coast Watershed Assessment Program found that the steelhead population has declined, but not as dramatically as other salmonid species because they can inhabit many of the tributaries to Redwood Creek. "These tributaries have steep gradients, migration barriers, lack of channel complexity, and exhibit higher water temperatures that limit production of other salmonid species. Steelhead have displayed more adaptability to these conditions" (North Coast Watershed Assessment Program, 2002). This suggests that although Soda Creek may not have ideal spawning and rearing habitat, steelhead are adaptable enough to be successful. Despite the lack of perennial flow, steelhead continue to use Soda Creek as spawning and rearing habitat, and thus, the stream should continue to be managed as steelhead habitat.

Based upon our comparisons between the previous CDFG stream surveys, and the current condition of Soda Creek, we do not see any evidence of major changes in stream

function or quality of steelhead habitat over the past 50 years. Although Soda Creek has experienced slight channel modifications in the urban reaches, channel aggradation behind the grade control at Silverado Trail, and contains relatively low numbers of LWD and lack of perennial surface flows in some reaches, the watershed still supports steelhead spawning and rearing. Soda Creek currently provides migration access for steelhead during the wet season, shade and some LWD input from the riparian vegetation, gravels appropriate for spawning, and pools appropriate for rearing.

Flooding and Sedimentation

Channel morphology is a consequence of a number of factors including the interaction of streamflow, sediment supply, and watershed geology that controls channel location and elevation. In this complex system, changes in water or sediment inputs can cause a complex response as the channel adjusts. Watersheds that are being developed or modified for more intensive land use are subject to increased discharge, faster routing of water from the hillslopes to the channel network, and increased sediment load. However, watersheds may experience similar changes because of slight changes in climate. Predictive hypotheses of the response of a channel to increases in sediment or discharge have been made (most recently by Montgomery and MacDonald, 2002), but actual response is governed by both local channel conditions and overall watershed conditions. Thus, a general understanding of the flood frequency and sediment output of a particular watershed must be placed in the context of the local forcing mechanisms driving the processes.

Bed and bank erosion and flooding are currently an issue in Soda Creek, because they pose a threat to property and transport infrastructure, and possibly the quality of aquatic habitat in Soda Creek and the Napa River. These effects are most evident in the reach downstream of Silverado Trail, and at the confluence of Soda Creek and the Napa River. This reach has the most potential for response to changes in watershed conditions because it must route the cumulative amount of sediment and discharge from the entire Soda Creek watershed, as well as respond to elevation changes of the Napa River mainstem. Because the majority of the Soda Creek watershed has not been heavily developed, we can test a hypothesis regarding the cause of change in this reach.

Hypothesis 2: Changes in watershed land use have increased peak flows and channel sedimentation, have accelerated bank erosion rates and have increased flood frequency in Soda Creek.

Many in-channel features interact to create the driving and resisting forces of erosion. Bank erosion is controlled by flow, sediment transport, material weight and texture, shear and tensile strengths, groundwater level, permeability, stratigraphy, geometry, and vegetation (Abernethy and Rutherford, 1998). Numerous studies support the role of vegetation in reducing bank erosion (Hupp and Osterkamp, 1996; Abernethy and Rutherford, 1998; Jacobson and Pugh, 1998; Simon and Collison, 2001). Woody vegetation contributes to flow resistance and energy dissipation, decreasing total shear

stresses transmitted to the streambed and banks, while contributing to the strength, resisting erosion, and creating greater channel stability (Jacobson and Pugh, 1998). The benefits of riparian vegetation are greatest on banks that are subjected to high velocity flows, are fine grained or have an unstable geometry. Although woody vegetation can reduce the soil moisture content by canopy interception and evapotranspiration, some destabilizing effects such as higher moisture contents due to increased infiltration capacity along macropores have been observed (Simon and Collison, 2001).

The resisting forces of riparian vegetation are important in Soda Creek because a majority of the channel remains in a largely natural state, with relatively undisturbed riparian vegetation. Nevertheless, the major source of erosion documented by this study was bank erosion. Landslides were not observed to be a contributor to in-channel sediment because the soils developed on the underlying Sonoma Volcanics are relatively thin and rocky. Analysis of hillslope processes contributing to sediment supply to the channel was limited to observations from the 1942 and 1999 aerial photographs (COF, 1942, and WAC Corp, 1999). Evidence of landslides and debris flows within the watershed was not observed on the aerial photographs, and no evidence was found during in-channel data collection.

A significant source of sediment in this watershed is probably located at the interface between small ephemeral and intermittent channels and hillslopes in the upper reaches of the Soda Creek watershed. Presumably episodes of overland flow on hillslopes and channel and bank erosion near channel heads also occur, contributing substantial quantities of sediment to the channel network. Small channels in the headwaters of Soda Creek and its tributaries are likely able to produce, store and transmit substantial quantities of sediment due to the proximity of these channels to the source of sediment, soils on the hillslopes. Evidence for this includes, the grain size distribution for reach 5B (Figure 14), illustrating that the uppermost channel reaches have a proportionally larger component of fine sediment. Reach 5B is adjacent to a two lane paved county road, and collects some runoff from the road, increasing the sediment input to the channel from the runoff-associated ditch erosion. Despite the steep channel gradient, reach 5B has a notable quantity of fine-grained sediment. In reach 5B this is a bi-modal grain size distribution with modal values of 7 mm and 180 mm. The proximity of similar intermittent and ephemeral headwater channels to hillslope sediment source ensures that these reaches will periodically or continuously deliver fine-grained sediment to the channel network. Overall, Soda Creek is a relatively coarse bedded stream with high-transport capacity and comparatively low sediment supply, indicated by the lack of landslides and the abundance of bedrock exposures in-channel. Field observations, reflected in the grain size distributions, also indicate substantial quantities of coarse sand, reflecting the underlying volcanic geology in this watershed that is providing sediment to the system.

Bank erosion was measured in all reaches of Soda Creek, but the most severe erosion issues are found in the lower reaches, especially the reach downstream of Silverado Trail, including sample reach 1A. Reach 1A and 1B had the first and third highest values of measured erosion of all sample reaches, with 260 m³ and 137 m³,

respectively (Figure 37). The large total measures of erosion are corroborated by high values of erosion per unit stream length, with the lower reaches (1A through 2B) again having the highest values. These high values of erosion are likely due to the position of these reaches in the watershed, and the cumulative amount of sediment and discharge routed through these locations. Along with most channels in the region, the reach downstream of Silverado Trail is highly entrenched, again contributing to the bank erosion potential in this reach. However, the erosion measured in this reach may also be affected by the recent (about 50 years) urban development, as well as from a historic re-routing of the lower channel (Figures 9 through 11).

The practice of removing LWD from the channel may have reduced the amount of bank erosion in some locations, and increased it in others. LWD may either concentrate streamflows against banks, enhancing erosion potential, or divert flow away from banks, reducing erosion potential. The absence of substantial amounts of LWD and debris jams, however, effectively prevents the development of local bank erosion associated with LWD. If more LWD was recruited to the channel and allowed to remain in the channel, higher rates of bank erosion and channel migration associated with LWD would likely be manifested over a period of years to decades. It is not clear that this would increase overall bank erosion. Despite the general absence of LWD, reaches 1A through 2B contain the highest proportion of bank revetments, illustrating both the existence of significant bank erosion in the absence of significant LWD as well as the efforts of landowners and Napa County to control bank erosion. Reach 1A in particular contains a large amount of engineered bank revetments ranging from plastic sheeting and sandbagging to rock gabions. Using these strategies to control erosion may succeed locally, but may cause increased erosion in other locations. For example, the increased bank strength provided by isolated segments of plastic sheeting or rock gabions can cause scour of the banks both immediately upstream and downstream of these measures. Also, the emplacement of gabions that extend into the channel will deflect flow onto the opposite bank, causing erosion in a location that may have never historically experienced problems. Erosion control measures in this reach should be coordinated to reduce the potential that erosion may be worsened by the installation of bank stabilization features.

There is some indication that erosion rates may have increased locally during the past 10 to 20 years. An increase in erosion that correlates with changes in land use within the watershed suggests that it could be these changes that are driving the erosion. Alternatively, the increasing amount of annual precipitation over the past 30 years, and the slight seasonal shift of maximum precipitation could be driving the increased levels of erosion. Most of the erosion measured in reach 1A is based upon the exposed roots of approximately 100-year old Bay trees (Figure 39). Because of this, we are unable to say whether the erosion has occurred at a steady rate over that timespan, or whether this erosion is recent. But most of the erosion measured in reaches 1B and 2A is younger than 10 years, suggesting that some of the erosion in 1A may also be recent. Notable floods in the region have occurred in 1997, 1995 and 1983, and it is difficult to determine whether observed bank erosion is merely a consequence of such floods or whether potential management effects are strong enough to affect bank erosion rates.

The banks downstream of Silverado Trail are composed of alluvium, soil, silt, sand and cobbles, including some alluvial strata in the lower half of the banks that are heavily cemented and resist erosion. The upper banks, and in some cases the lower banks, are more easily eroded compared to the predominantly boulder banks of the upper reaches (Table 11). This reach is entrenched, creating tall (up to 7 m), banks, bounding the most sinuous reach of the channel, which transmits the largest discharges. Some portions of this reach were characterized as having dense blackberry growth, but large portions of the banks were also unvegetated. When these factors are combined, the high rates of bank erosion could be expected.

The hydraulic effects of the Napa River also drive erosion in this reach. When the Napa River is at flood stage, the floodwaters slow the transmission of Soda Creek discharge, creating a backwater effect that extends approximately 500 m upstream from the confluence with the Napa even during relatively frequent floods (1:2 years). When the discharge from Soda Creek meets the Napa River floodwaters, the velocity instantaneously decreases, sometimes almost to zero. Sediment transport capacity is lost, forcing the bedload and some suspended load to be deposited as bars. As the backwater diminishes, the deposited bars may create new flow patterns within the stream, causing new areas of the bank to experience greater flow velocities, encouraging bank erosion. Also, when the backwater in Soda Creek is at its maximum, significantly more of the bank height compared to normal flows becomes saturated. The saturation is not a problem when the backwater is still present, because the weight of the water provides support for the banks. But once the water level falls, the saturated banks have much less external support, and the potential for bank slumps is significant. Field observations of bank slump features were made in sample Strata I. Hence, during the recession of a flood event, drawdown bank failure and seepage erosion of saturated banks can contribute significant amounts of sediment into the channel. However, a bank that supports woody vegetation will be less likely to fail because of the strength provided by the root network. The vegetation along the banks downstream from Silverado Trail should be maintained in order to reduce the potential for bank failure during periods of flood.

Although bank erosion is greatest in the lowest reaches, bank erosion and bar volume are correlated to some degree (Figure 47). The fact that bank erosion volumes and stored sediment volumes are comparable in many survey reaches strongly suggests that bank erosion is a significant source of coarse sediment in the watershed. The absence of other large sources of coarse sediment (landslides) observed in the field further suggests the importance of bank erosion in supplying coarse sediment to the channel. The predominance of coarse bed sediment (cobbles and boulders) and local bedrock outcrops in the channel suggest that sediment supply is limited in Soda Creek.

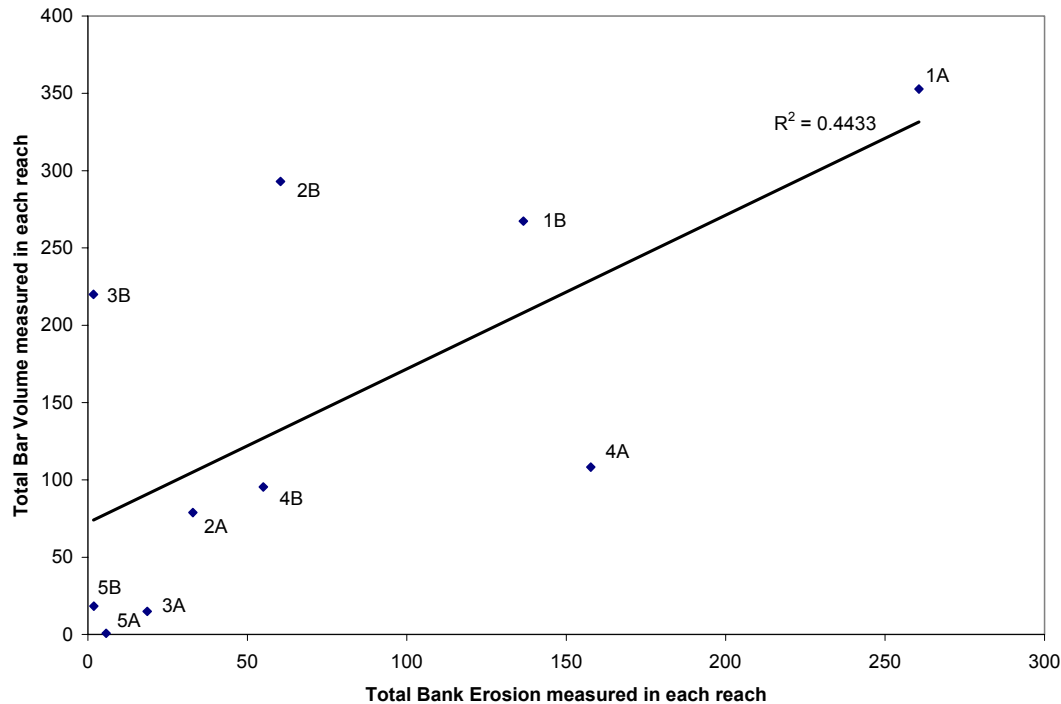


Figure 47. Total measured bank erosion in each reach versus total measured bar volume in each reach.

Bank erosion is most extensive in sample Strata I and IV (Figure 37), where observations of bank materials include a higher proportion of finer-grained alluvium and a lower proportion of cobble and boulder (Table 11). These distributions of bank material likely result from watershed scale sedimentation patterns inferred from the longitudinal channel profile (Figure 7). Sample reaches 4A and 4B are located in reaches of declining slope relative to upstream reaches, suggesting that during extreme floods, substantial deposition of alluvium would be likely. Sample reaches 1A and 1B are located in lower Soda Creek where channel and bank material sizes are substantially smaller than in upstream reaches, reflecting the likely historic alluvial, meandering character of this reach. Problems associated with bank erosion are most severe in the lower reaches of Soda Creek, where public and private roads are immediately adjacent to the channel, and where residential properties are affected. Erosion of the banks of Soda Creek threatens property, and potentially threatens the water quality necessary for anadromous fish, and contributes to the overall sediment load of the Napa River. The extent to which bank erosion conditions in Soda Creek may be affected by watershed management and land use is unknown in quantitative terms, however, bank erosion is a natural stream process that is continuing to occur despite efforts by local residents and the County authorities. There is no evidence of large increases in bedload sediment supply that could drive increases in bar volumes and bank erosion rates, and there is only a suggestion that peak flow rates may have increased somewhat in response to development of homesites and

vineyards in the watershed. Hence, there is at present no compelling evidence that bank erosion rates are related to existing levels of land use.

Flooding is also an issue in Soda Creek, with the most severe problems, and the most potential property damage from flooding occurring from the confluence with the Napa River upstream to Loma Vista Drive, including sample reaches 1A through 2B. Reports of flood stages in these reaches were gathered from interviews with watershed residents, illustrating the dangers during periods of flood. In 1995, after a flash flood created by an agricultural dam failure further upstream in the watershed, the house of Helen and Don Johnson, located just downstream of Loma Vista Drive (between sample reaches 2B and 3A), had flood water approximately 3 feet (0.9 m) deep. This is the only time water has overtopped the banks in this location since they moved into their house in 1971. Penny Mallen reported that in 1995 the floodwater covered a lower bank along her property in reach 2B, approximately 0.3 m higher than the measured bankfull depth. During this same flood, Brian Hunter reported that portions of Soda Canyon Road adjacent to reach 2B were under water, making the road impassable. Melanie Apallas-Johnston reported that the lower terrace in reach 1B (upstream of the old stone masonry bridge) is flooded, but “only during big floods” (Figure 16, left side of reach 1B, meter 132 cross-section). She recalled that the last time the terrace was flooded was during the 1997 flood. Loren Vanderschoot reported that during the 1995 flood the flood height maximum was 1 m higher than the right bank, as measured from the water line on trees along the bank (Figure 16, 60 m downstream from the right side of reach 1A, meter 670 cross-section). Evidence such as overflow channels exist in other reaches of Soda Creek, especially in Sample Strata II, III, and IV, however flood damages in these locations are not as costly because the channel and hillslopes remain undeveloped and in a natural state (Figure 17, cross-section 2A, meter 180 and Figure 18, cross-section 3A, meter 326).

Based on the evidence and multiple reports of flooding, the main concern for damages to property is between the confluence with the Napa River and Silverado Trail. The southern-most houses along Petra Drive, downstream of reach 1A are prone to flooding from the Soda Creek when the Napa River stage is high and creates a backwater effect in Soda Creek, and from Napa River water inundating a topographic low immediately upstream from Petra Drive. One location along the left (southeast) bank of Soda Creek, approximately 200 m upstream from the confluence with the Napa River, has historically overtopped the banks during periods of backwater, causing significant erosion problems. This overflow channel allows Soda Creek to spill through a topographic low in a vineyard and abandoned orchard, eventually returning to the Napa River. This location is the likely previous path of Soda Creek, flowing through the present day agricultural reservoir, and joining with Milliken and Sarco Creeks before joining with the Napa River (Figures 9 – 11). The landowners, Wilma and Robert Keig, reported that Soda Creek has overtopped the bank at this location two or three times in the past 50 years, and they are currently placing large boulders along the bank to prevent further erosion and overtopping. However, aerial photos (Figure 11) show that the Napa has been a highly anastomosing system in the past, and a channel in this location could be attributed to a past meander of the Napa River. But if this channel had in fact been the lower reach of Soda Creek, it is likely that this reach would have provided significant

rearing habitat for steelhead trout. This reach is less likely to have been seasonally dewatered owing to its low topographic position and likely interception of the water table in the Napa River floodplain/ terrace system. Hence, any anthropogenic changes in the course of Soda Creek that occurred prior to 50 years ago may have had significant effects on anadromous fish habitat by removing approximately 600 m (2000 ft) of low gradient habitat.

On January 2, 2002, a field reconnaissance of the flooding in reach 1A and the Napa River was conducted. Based upon the USGS gage on the Napa River at Napa (USGS gage no. 11458000, data from 1929-1932, 1960-2002) the daily mean discharge for January 2 was 6,670 cfs ($189 \text{ m}^3 \text{ s}^{-1}$), corresponding to a recurrence interval of 2 years. The Napa River was approximately 100 m wide at the confluence with Soda Creek, and flowing at a relatively fast velocity. The backwater effect in Soda Creek caused by the Napa River extended approximately 450 m upstream from the confluence. At this point the water velocity of Soda Creek decreased dramatically, almost to zero. The depth of the floodwaters was measured on January 15 using the high water marks. At the confluence of Soda Creek and the Napa River, the high water mark was 5.3 m above the bed of Soda Creek. The elevation of high water in Soda Creek gradually decreased moving upstream from the confluence with the Napa River, to a point approximately 500 m upstream where the high water mark coincided with the bankfull depth. Some indication of channel bed dynamics in Soda Creek during flows of this magnitude is provided by field observations near the upstream margin of the backwater pool. These observations include vertical exposure of 0.5 m of gabion (rock-filled wire baskets installed to control bed or bank erosion) that was formerly buried in the channel bed. In addition, cobbles up to 140 mm in diameter were mobile during this event. Despite these observations of streambed mobility, we did not observe evidence of substantial bank erosion after this two-year recurrence interval flood. This suggests that larger flood events may be responsible for bank erosion in Soda Creek. Table 16 below summarizes the ten highest flow events recorded for the Napa River by the USGS, six of which have occurred since 1982. These data imply that observations of recent bank erosion in Soda Creek could easily be explained by the occurrence of six peak flows with recurrence intervals > 5 yr, including two with recurrence intervals of > 20 yr.

Flood hazards will persist, especially in the lower reaches of Soda Creek due to the local topography and the backwater effects caused by Napa River. Changes in land use that increase the amount of discharge or the timing of water entering the channel network could cause the flooding problems to worsen. However, management of the upper watershed, and of the banks along sample Strata I can reduce the deleterious effects of flooding and the associated erosion. Based upon the data presented, the hypothesis that changes in watershed land use have increased peak flows and channel sedimentation have accelerated bank erosion rates and increased flood frequency in Soda Creek should be rejected.

Table 16. The 10 highest discharges on record from the USGS gage no. 11458000, Napa River near Napa, CA (218 mi²). Data available from 1929 to 1932 and from 1960 to 2002.

Year	Discharge (m ³ s ⁻¹)	Recurrence Interval (years)
1986	1051	42 (reported as 100 yr flood)
1995	924	21
1963	708	14
1967	606	10.5
1982	592	8.4
1998	561	7
1997	527	6
1965	513	5.3
1983	490	4.6
1978	433	4.2

Riparian Vegetation

Before humans occupied the Soda Creek watershed, the morphology of the channel reflected the balance between geology, climate, fluvial processes, hillslope processes, and the hillslope and riparian vegetation. The creek's primary function was to remove water and sediment supplied to it from the basin. It also provided substrate for vegetation and aquatic species. The watershed also provided a home for Native Americans evidenced by finds of obsidian arrowheads, grinding stones and middens adjacent to the creek both in the upper and lower reaches. However, the arrival of the Spanish and Europeans put many more demands upon the watershed, including land and water for grazing, residential sites, vineyards, and recreational uses. In spite of these pressures, the channel of Soda Creek has remained reasonably similar to its previous condition largely because the thin soils present are of limited value for agriculture compared to other areas of the larger Napa River watershed.

However, the natural beauty of this stream continues to draw people, and encourage them to live and play along the banks of Soda Creek. Currently, reaches of the stream are being modified and managed by landowners to increase the recreational and aesthetic value of the stream. These management efforts include removal of riparian vegetation for increased visibility of the stream, removal of hillslope vegetation for recreational areas, removal LWD to keep the channel tidy, preventing additional bank erosion, and limiting flooding by maintaining maximum channel capacity to convey water. In general, removal of riparian vegetation and LWD are detrimental to the aquatic habitat and functioning of the stream (Gurnell and Gregory, 1995; Piegay and Gurnell, 1997; Reid and Hilton, 1998). For example, woody riparian vegetation adds channel stability, substrate, cover, shading, rainfall-energy dissipation, and filtering of nutrients to aquatic ecosystems (Jacobson and Pugh, 1998). Management of the riparian vegetation and stream channel should consider both the positive and negative effects upon the channel.

Hypothesis 3: The removal of riparian vegetation along Soda Creek will not affect channel processes.

Areas along the banks that are cleared of vegetation offer space for recreation, allow greater access to the channel, and may thus increase the aesthetic value of the property for some landowners. However, removing riparian or hillslope vegetation, removing in-channel LWD, or modifying the channel's floodplain will trigger a complex response by the system, potentially having negative repercussions. For example, the clearing of riparian vegetation reduces the bank strength by removing the interlocking roots, making it more prone to erosion, slumping or sliding during periods of high discharge (Jacobson and Pugh, 1998). Without riparian vegetation, sources for the recruitment of LWD, and organic carbon input necessary to support the food chain are substantially reduced. Also, the amount of shading for the stream will be reduced, probably causing water temperatures to rise and adversely affecting steelhead habitat requirements. The removal of hillslope vegetation could cause an increase in production of the total amount of sediment by increasing the likelihood of overland flow, slumping and other mass movement processes. Once sediment is produced from the hillslopes, it can enter the channel directly, rather than being trapped by the root structure, grasses and leaf litter of the buffering riparian zone. The removal of riparian vegetation, especially in the upper reaches of the creek, would likely increase the amount of sediment delivered to the channel from the hillslopes.

Removing in-channel LWD decreases the habitat complexity, cover areas, and pool formative agents in the channel, necessary for steelhead trout survival. Also, the channel uses LWD as roughness agents that dissipate energy (Buffington and Montgomery, 1999); without the LWD, the channel will theoretically have more energy to erode its bed and banks, however, experience shows that LWD often directs flow against banks, inducing erosion. LWD regulates sediment and organic material movement through the system (Gurnell and Gregory, 1995), thus buffering any effects of a large storm, landslide, or bank slump.

Retaining the riparian vegetation and LWD in-channel in its natural state could both maintain and improve the quality of anadromous fish habitat. Thus, the hypothesis that removal of riparian vegetation will not affect channel processes in Soda Creek should be rejected.

Comparisons between three Napa River tributaries

Data has been collected on two additional Napa River tributaries, Sulphur Creek and Carneros Creek. Comparing Soda Creek to other Napa River watershed streams helps in putting the habitat conditions in perspective. Sulphur Creek is a 23.2 km² (8.9 mi²) watershed that enters the Napa River in the town of St. Helena. Carneros Creek is also a 23.2 km² (8.9 mi²) watershed, which enters the Napa River approximately 8 km (5 mi) south of the town of Napa. Field datasets are not yet fully complete for portions of

Sulphur and Carneros creeks, however, this preliminary data allows some comparisons to be made. Field data collection methods were the same in these three creeks. Figure 48 shows the relationship between slope and median grainsize (D50) for the three creeks. The data for Sulphur Creek shows a linear relationship, while the data for Soda Creek groups near the top of the graph, and Carneros Creek data groups near the lower left. The number of LWD pieces in each type category for the three creeks is shown in Figure 49. Sulphur and Carneros creeks have overall more LWD pieces than Soda Creek, with logs and downed trees playing a larger role in these two creeks. The effect of LWD on pool formation is shown in Figure 50, with LWD playing a significantly larger role in Carneros Creek than in Soda or Sulphur creeks. The overall sediment storage per unit channel length is shown in Figure 51. Both Carneros and Sulphur creeks generally have larger amounts of in-channel sediment storage than Soda Creek, mainly due to the differing underlying geology in the watersheds. The two large peaks of sediment storage in Sulphur Creek correspond to a sample reach downstream from a large landslide (NW4A), and a braided alluvial fan reach with a <20 year-old terrace included (2A).

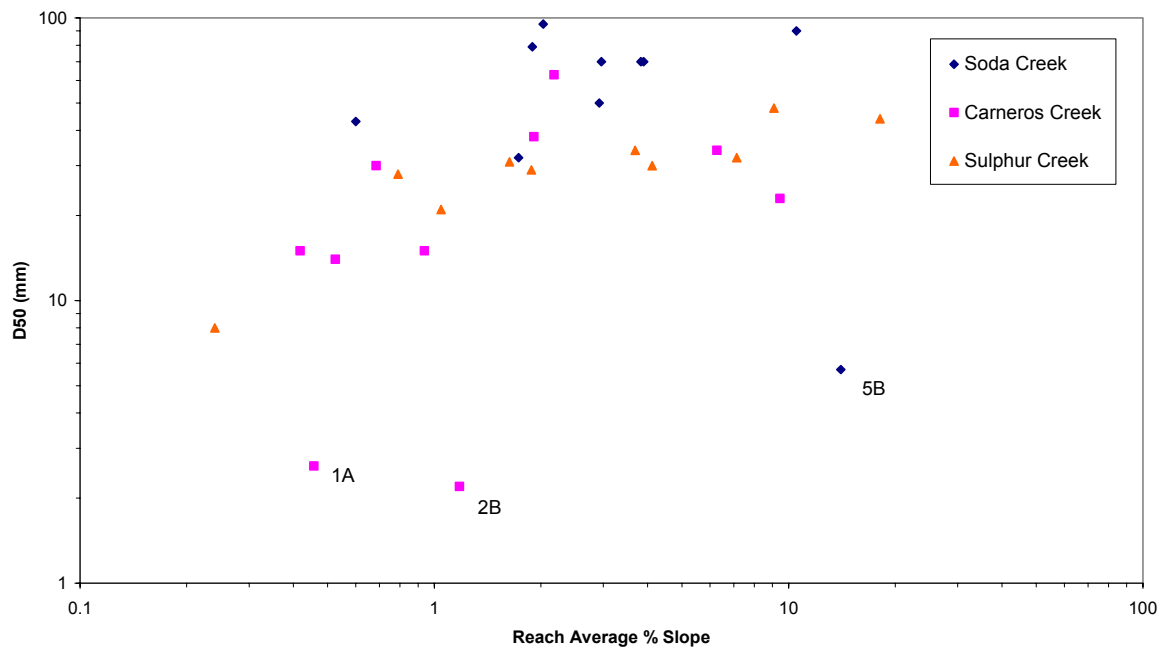


Figure 48. Reach average percent slope versus reach average sediment grain size (D50).

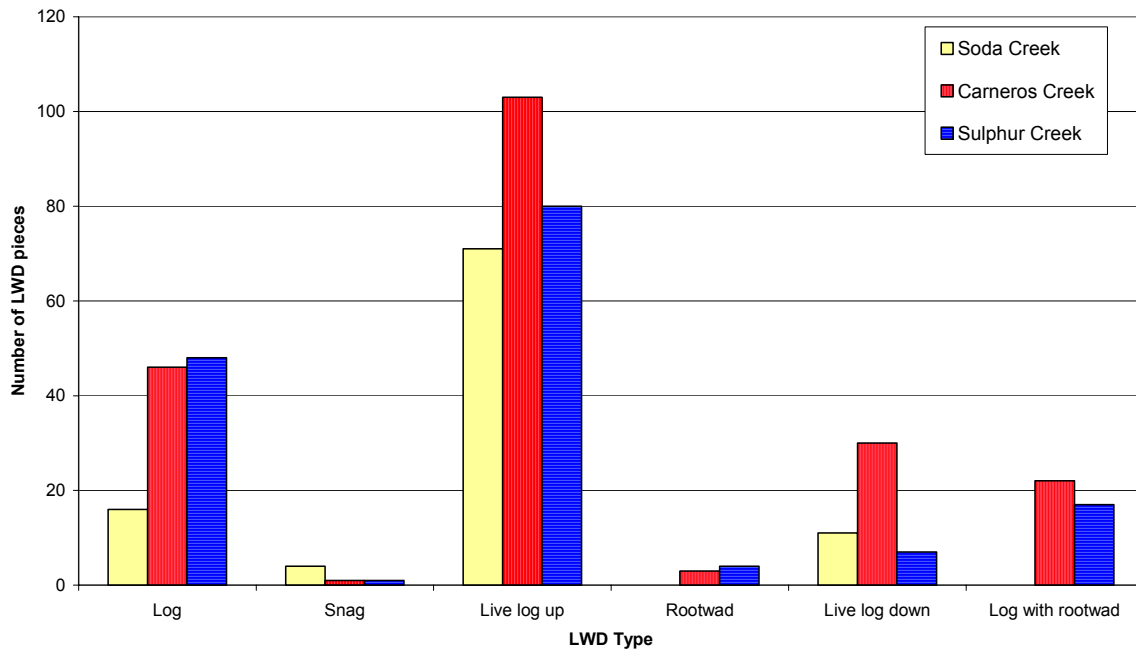


Figure 49. Comparison of the number of LWD pieces in each type category in each creek.

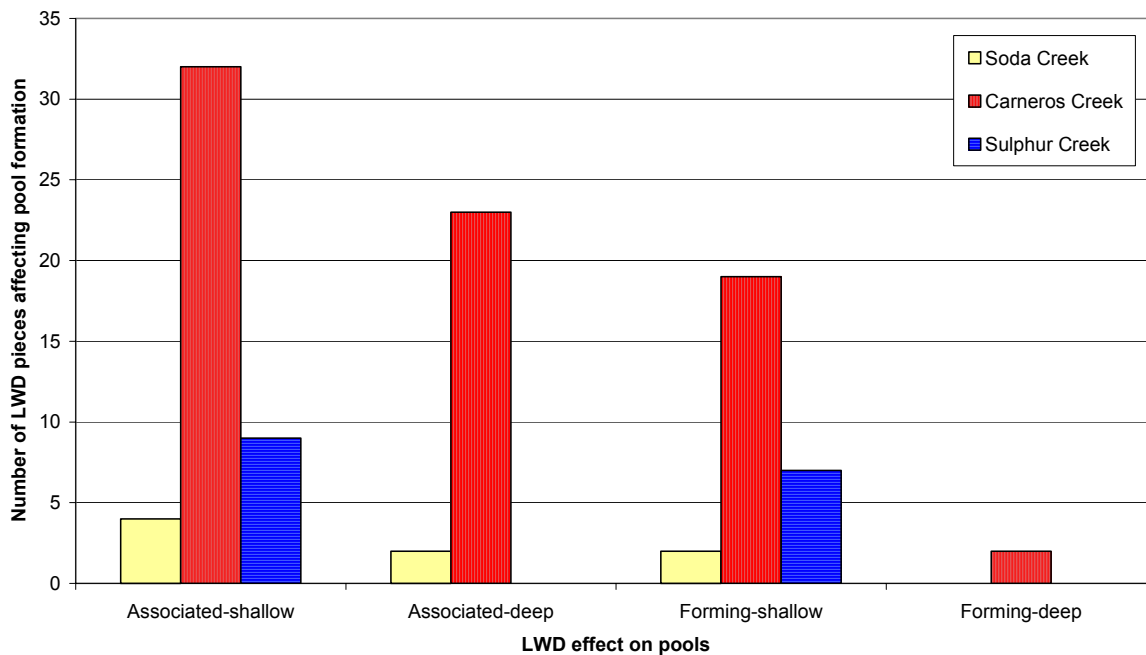


Figure 50. The effect of LWD on pools in each creek.

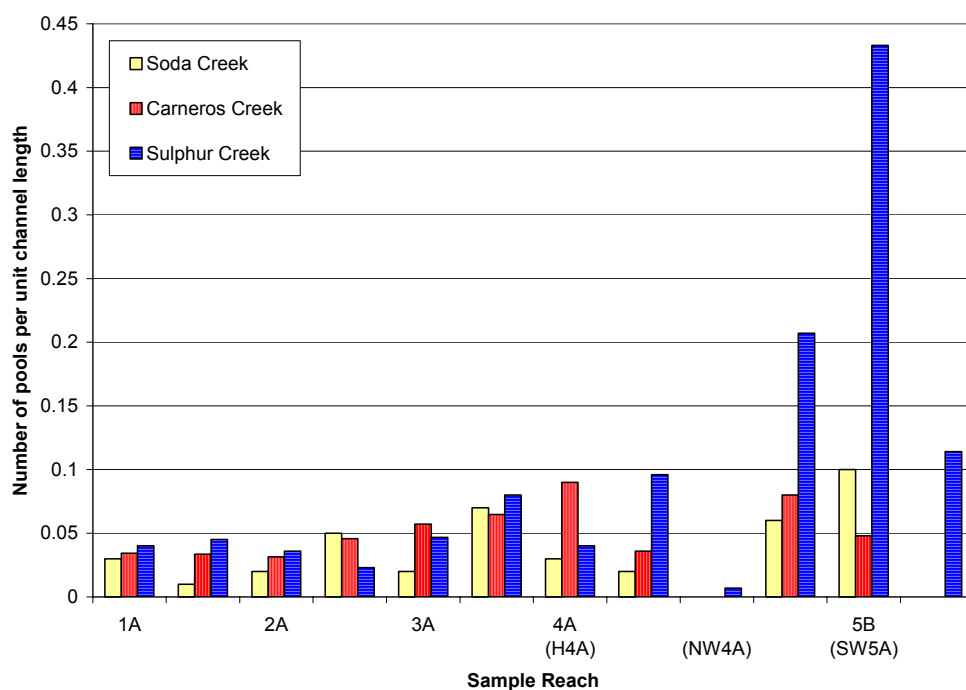


Figure 51. Number of pools per unit channel length in each creek. Sample reach labels in parentheses refer to Sulphur Creek.

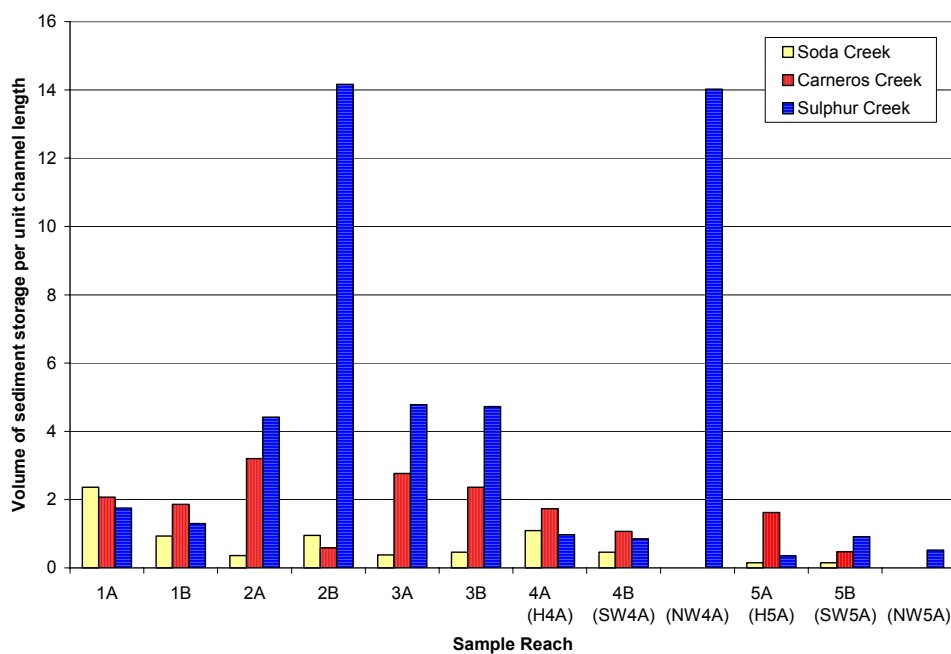


Figure 52. Total sediment storage per unit channel length in each sample reach of each creek. Sample reach labels in parentheses refer to Sulphur Creek.

RECOMMENDATIONS

1. Further conversion of the Soda Creek uplands to vineyard or rural residential should be carefully considered before plans are implemented, particularly with respect to potential effects on stream flow (both peak flow and ground water supply for maintenance of rearing habitat) and sediment supply (either from hillslopes or from bank erosion caused by changes in flow regime).
2. Bank erosion problems affecting landowners should be approached from an ecological and geomorphological perspective. Development of a bank erosion control strategy to facilitate coordinated planning that will increase the potential benefits to habitat and reduce potential harm caused by ill-conceived or poorly planned erosion control measures is strongly recommended. Erosion control should not be handled on a case-by-case basis (site specific), rather it should be developed at a reach scale in the context of the watersheds and stream function both above and below problem areas. The use of biotechnical streambank stability techniques should be encouraged.
3. Provide education and technical support to residents that will limit the practice of removing LWD from the channel. Guidance regarding circumstances under which removal of LWD may not be necessary to reduce potential flood damage and when LWD may provide significant habitat benefits should be provided. Over time, increased LWD loading in Soda Creek can increase the number and quality of pools, providing steelhead rearing habitat, and potentially improve spawning conditions by increasing the sorting of sediment into more suitable sizes.
4. Develop a habitat restoration and enhancement plan focused on improving pool habitat, increasing accumulations of well-sorted spawning gravels (finer than the ambient size distribution) and maximizing continuity of surface flows. This should include suggestions regarding locations where construction of instream structures would be most likely to improve pool habitat (particularly with respect to depth and cover factors) and collect or sort medium and coarse gravel in patches suitable for spawning, as well as a feasibility study regarding options for mitigating the partial migration barrier and aggradation associated with the historic stone masonry bridge at Silverado Trail.
5. Maintain the riparian corridor to the extent possible throughout the watershed to maximize LWD recruitment and shade, to protect banks from excessive erosion, and to encourage setbacks from high-value development that could be threatened by naturally-occurring floods and bank erosion.

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