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

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

CALFED CONTRACT NO. 4600001703
NAPA COUNTY RESOURCE CONSERVATION DISTRICT

BY

Sarah Pearce
Matthew O'Connor
Lester McKee
Blaine Jones

Sarah Pearce and Lester McKee: San Francisco Estuary Institute
Matthew O'Connor: O'Connor Environmental, Inc.
Blaine Jones: Napa County Resource Conservation District

This report should be cited as:

Pearce, S., O'Connor, M., McKee, L., and Jones, B., 2003. Channel Geomorphology Assessment: A component of the watershed management plan for the Carneros Creek watershed, Napa County, California. A Technical Report of the Regional Watershed Program, SFEI Contribution 67. San Francisco Estuary Institute, Oakland, CA.

Table of Contents

EXECUTIVE SUMMARY

In 2001 a group of concerned stakeholders formed the Carneros Creek Stewardship. The stewardship's mission is to preserve and maintain the natural, economic and human resources in watershed, provide education, initiate watershed assessment and restoration, and create a sustainable stewardship group. The group constructed a set of management questions, and helped to instigate this multi-disciplinary science project to help answer these questions. This report is one of seven technical reports written to inform the development of a watershed management plan through a participatory process that includes the community, agencies and scientists. It was made possible through funding from a project entitled "Stewardship Support and Watershed Assessment in the Napa River Watershed". The Napa RCD led CALFED project also provides the same kind of support for the Stewardship of Sulphur Creek in the head of the Valley and confluent to Napa River in the town of St. Helena.

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

Carneros Creek is a western tributary to the Napa River, entering the river approximately 8 km (5 mi) south of the town of Napa. The lower and middle watershed consists primarily of vineyards and suburban residential areas. The upper watershed is primarily grazing, with some open space, vineyards, and residential areas. Carneros Creek historically and currently supports salmonid spawning and rearing, while also providing habitat for other aquatic species. Data collected in this channel geomorphic assessment include surface and subsurface grain size measurements, channel cross-section geometry, channel slope, bank and riparian vegetation characteristics, bank condition, large woody debris (LWD) in the bankfull channel, debris jams, number, type and volume of bars and sediment deposits, number, type and residual depth of pools, indicators and volume of bank erosion, and type and condition of bank revetment.

Surveyed cross-sections illustrate the wide variety of channel morphologies observed throughout the watershed, including the lower entrenched reaches, the middle bedrock-dominated reaches, and the upper shallow and boulder-dominated reaches. Surface and subsurface sediment size analyses suggest that the lower reaches of Carneros Creek are storing moderate amounts of fine sediment (< 2 mm), while the middle and upper reaches are storing low amounts. The majority of Carneros Creek has a nearly continuous riparian corridor. LWD is important in pool formation, with almost 50% of all pools measured either formed by or associated with a LWD piece. In addition, Carneros Creek contains a wide range of residual pool depths, ranging from 0.2 m (0.7 ft) to 1.5 m (4.9 ft). Sediment deposits and bars were measured in all reaches of the creek, with deposit type and volume generally correlated to bankfull channel cross-

sectional area. Approximately 90% of the total volume of measured sediment deposits are stored in 50% of the total number of deposits. Most (92%) sediment deposits have been active within the past five years, illustrating the mobility of sediment stored in Carneros Creek. Despite the surface storage of moderate amounts of fine sediment in the lower reaches, the subsurface sediment samples in these same reaches reveal that sediment size distributions are within documented ranges for successful steelhead spawning. It appears that suitable gravel patches and hydraulic locations for spawning are reasonably abundant, especially in the middle reaches. Channel bank erosion is the largest contributor of sediment to the channel, especially in the middle reaches. However, reaches with large amounts of measured bank erosion also have large volumes of sediment storage. The lowest reaches, especially adjacent to residences have the largest length of bank revetments and modifications to the channel morphology.

The habitat in Carneros Creek is currently able to maintain a steelhead population. Salmonid success is primarily limited by the lack of perennial flow in all reaches. The middle reaches contain perennial discharge, fed by a groundwater spring. However, the channel is completely dry upstream of this spring, and is partially dry in the lower reaches where only isolated pools persist. The best salmonid spawning and rearing habitat is provided in the middle reaches because these reaches provide the best combinations of perennial discharge, spawning gravels, pool spacing, pool depth and cover, riparian shading and channel complexity.

The riparian corridor in the lower reaches is typically only a single mature tree in width. Because the channel is entrenched and these trees are being undercut, the riparian canopy is in jeopardy of being significantly modified in the future. The loss of the riparian vegetation would increase the number of scour elements in the channel, but would also decrease bank stability and increase the amount of sunlight to the water. Throughout Carneros Creek, LWD is important in the channel form and function. LWD pieces provide pool-forming agents, provide cover, and help to regulate the transport of sediment and nutrients. Although the middle reaches have the highest amount of measured bank erosion, these reaches also have high amounts of local sediment storage. Besides providing steelhead spawning and rearing habitat, Carneros Creek also supplies other resources to watershed residents including flood conveyance, habitat for wildlife and other aquatic species, and an aesthetically pleasing setting to live, work and play.

ACKNOWLEDGEMENTS

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

We also acknowledge the hard work and participation of the Carneros Creek Stewardship group. The enthusiasm of the landowners and of the stewardship was quite contagious. Access to the creek and the shared local knowledge of the watershed provided by landowners were vital to this project's success. The efforts of David Graves and Ellie Insley, as well as their participation in the technical team meetings are greatly appreciated.

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

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

INTRODUCTION

The watershed of Carneros Creek occupies a relatively small fault-bounded valley in the southwest portion of the greater Napa Valley. An active tectonic geology, seasonal rainfall, mild winters, and warm dry summers influence vegetation and topography which in-turn provide an aesthetically beautiful backdrop to a number of world-class vineyards in a peaceful rural setting. The residents of the watershed value the lifestyle provided by this setting but also recognize the inherent pressure on the watershed (and therefore the future of their lifestyle) associated with human population, introduced fauna and flora and intensive land management. In 2001, the Carneros Creek Stewardship, an apolitical, non-advocacy group, was formed to promote and help coordinate a variety of activities including groundwater monitoring, tours, education, watershed assessment and restoration. Their goals are to:

1. Assess the physical features of the watershed on an on-going basis,
2. Provide education about the watershed,
3. Protect and restore natural resources, including native fish and wildlife species,
4. Protect and enhance the economic and human resources,
5. Create a sustainable, enduring watershed stewardship.

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

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

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

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

Objectives (Channel Geomorphology Component)

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

WATERSHED CHARACTERISTICS

Setting

Carneros Creek is a tributary to the Napa River, which flows from the west side of the Napa Valley into the Napa River near Cuttings Wharf and Bull Island, 8 km (5 mi) south of the town center of Napa (Figure 1). Carneros Creek has a drainage basin area of 23.0 km^2 (8.9 mi^2). The highest elevation in the watershed is 506 m (1,660 ft) above mean sea level, while the confluence with the Napa River is at mean sea level and is tidally influenced. The lowest 500 m (1,640 ft) of the creek is confined within levees designed to control flooding of the Napa River. The drainage basin is nearly rectangular, and is approximately 15.5 km (9 mi) in length and 1.6 km (1 mi) in width. Carneros Creek is a third order stream (Strahler, 1957), with a total channel length of approximately 17.9 km (11.1 mi). From an analysis of measured peak discharge for channels in the Napa Valley (from USGS Gauging Station Peak Discharge data, Table 1), a drainage basin the size of Carneros Creek can expect a peak discharge of 15 m^3/s (530 ft^3/s) corresponding to a recurrence interval of 1.5 years (Pearce et al., 2002).

Table 1. Napa Valley USGS gage stations selected for regional recurrence interval analysis. Bay Area Regional 1.5 year discharge is based upon published curves for 30 inches of annual precipitation (Leopold, 1994).

USGS Gauge	Period of record	Flow modification (i.e. regulated or diverted)	Drainage basin area (km^2)	1.5 year discharge (Q1.5) (m^3/s)	Bay Area Regional Q1.5 (m^3/s)
Napa R nr St. Helena	1929-1996	No	210.88	128.05	99
Sulphur C nr St. Helena	1958-1973	No	11.66	13.17	5.7
Conn C nr Oakville	1929-1975	Yes, post 1945	143.52	11.36	59
Dry C nr Napa	1951-1966	No	45.08	33.14	23
Redwood C nr Napa	1959-1973	No	25.36	30.88	13
Napa C at Napa	1970-1983	No	38.60	33.99	18
Tulucay C at Napa	1972-1983	No	32.64	10.06	16
Lk Hennessey trib nr Rutherford	1959-1973	No	2.69	1.22	1.6
Milliken C nr Napa	1970-1983	Yes	44.82	41.36	23
Napa R at Calistoga	1976-1983	No	56.74	35.13	26

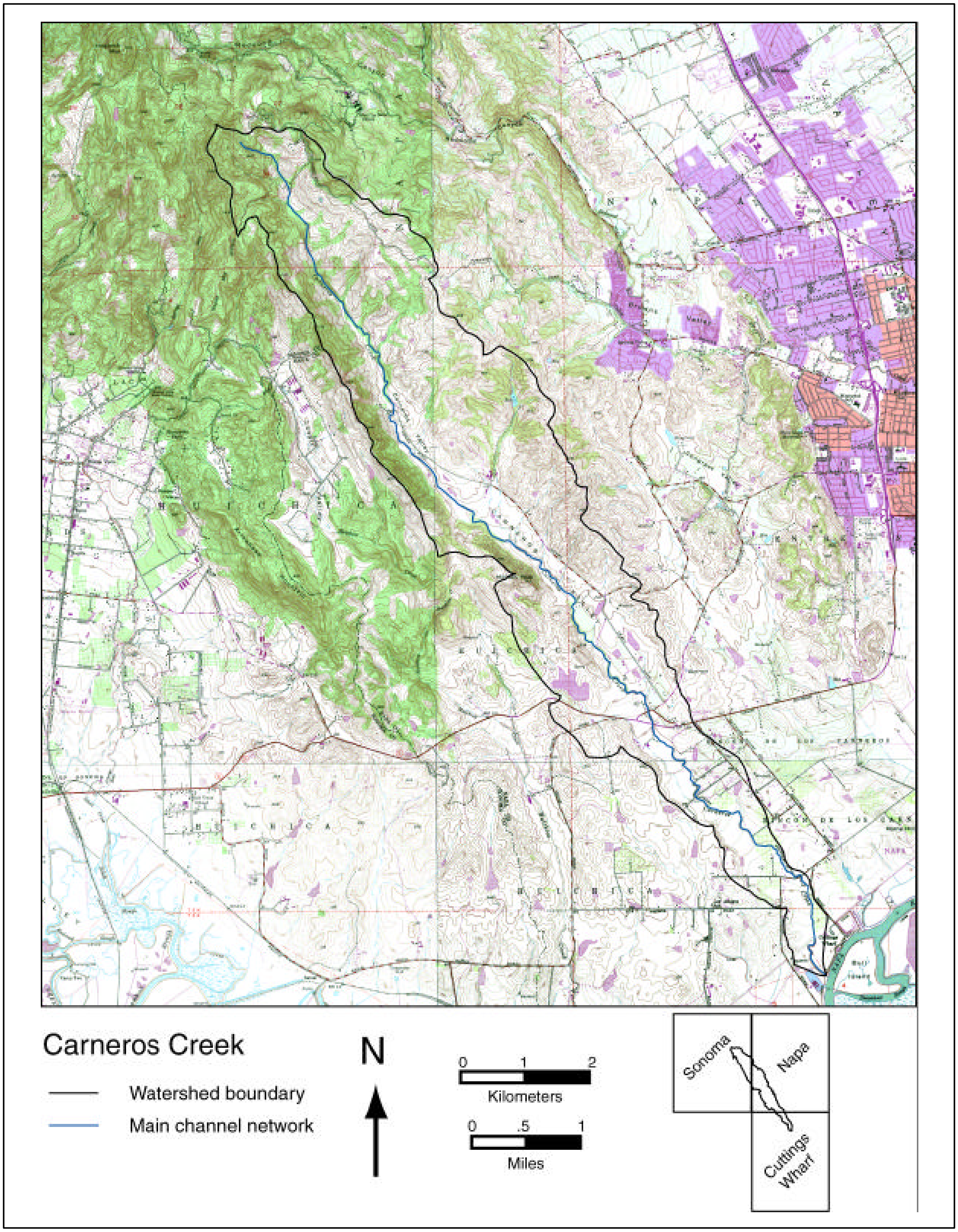

Figure 1. Map of the Carneros Creek watershed.

Geology

The location and orientation of Carneros Creek is controlled by the Carneros Fault (Fox et al., 1973), a normal fault offsetting Miocene marine sedimentary rocks to the southwest from Cretaceous sedimentary rocks to the northeast. Fox et al., 1973 mapped the geology of the Napa and Sonoma Counties, including Carneros Creek. The Carneros Fault is exposed from Henry Road, north to the watershed boundary. The uppermost portion of Carneros Creek is underlain by Tertiary Sonoma volcanics, mainly andesitic and rhyolitic lava flows. Along the middle portions of the watershed, northeast of the Carneros Fault, Late Cretaceous to Early Jurassic Great Valley sequence mudstones and siltstones are exposed. Southwest of the Carneros Fault, Miocene marine Neroly Sandstone and Miocene medium to fine grained white sandstone, siltstone, and sandy shales are exposed. Overlying these sandstones are smaller outcrops of Tertiary Sonoma andesitic lava flows and pumicitic ash-flow tuffs. The lowest portions of the watershed are underlain by Quaternary alluvium deposits of the Napa River, and Pleistocene Huichica and Pliocene Glen Ellen Formations, which consist of fluvial gravel, sand, silt and clay. The steepest hillslopes, and topographically highest portions of the watershed are found along the west and north sides of the watershed, as these are less erosive areas associated with volcanics and sandstones. The more gentle topography along the eastern side of the basin reflects the less resistant mudstones and siltstones.

The underlying geology in the Carneros Creek watershed is the ultimate source sediment to the stream. The Great Valley sequence mudstones and siltstones are less resistant to erosion than other rock types, and likely contribute fine sediment to the channel via headward erosion of channels and mass movement events.

Soils

The soils in the Carneros watershed closely reflect the underlying geology (Lambert and Kashiwagi, 1978). In the lower watershed, the dominant soil type is Cole silt loam, a soil that forms on low-sloped old alluvial fans and floodplains from weathered sandstones and shales. This soil is most often used for vineyards. The soils in the lower west side of the watershed are underlain by sandstones, and are well-drained, have slow to medium permeability and are also used for vineyards. Along the west side of the watershed is a section of Henneke gravelly loam, a soil formed in steep uplands from weathered serpentine that has very low fertility. Vegetation on these soils includes oak, digger pine, scrub oak and manzanita. The soils of the east side of the watershed are mainly clay and gravelly loams formed from weathered sandstones and shales. Most of these soils have medium to rapid runoff with moderate to high erosion hazards, and one soil type is particularly susceptible to landslips. These hillslopes also are used for vineyards, but support some grazing. The upper portions of the watershed include clay loams, gravelly loams, rock outcrops and mixed soil complexes from weathered rhyolite and other igneous rocks. Soils form on slopes that range from 5 to 75%, with medium to very rapid runoff and a high erosion hazard. These hillslopes are only used for wildlife and natural watershed functions.

Climate

The Carneros watershed is located at the southern end of the Napa Valley, and generally has similar climatic patterns as the greater Napa Valley. Overall, the Napa Valley enjoys a mild Mediterranean climate with hot dry summers and mild wet winters. Temperatures range from an average maximum of 27.8° C (82° F) in the summer months, to an average minimum of 2.8° C (37° F) in the winter months (Napa State Hospital) (Figure 2). Because the Carneros watershed is proximal to San Pablo Bay and its marshlands, it maintains the marine layer longer during the summer, keeping temperatures cooler than further upvalley. Rainfall occurs primarily from November to April, with the maximum occurring in January. Rainfall in the Carneros Valley is best estimated by rainfall at the Napa Fire Department gauge (Figure 3). Based upon rainfall records from water years 1906 to the present, this gauge receives an average of 614 mm (24.2 in) of precipitation every water year (California Department of Water Resources, www.cdec.water.ca.gov).

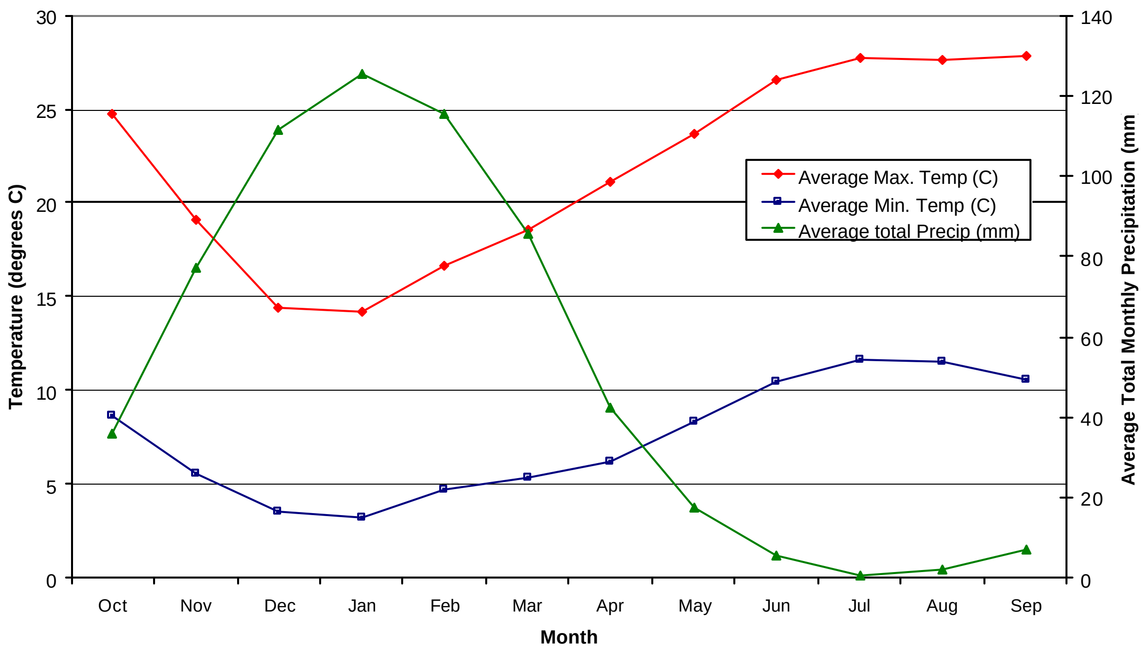

Figure 2. Average maximum and minimum temperatures and average total monthly precipitation recorded at Napa State Hospital, 1917 to 2000. (Data obtained from the Western Regional Climate Center, www.wrcc.dri.edu (1 April 2002).

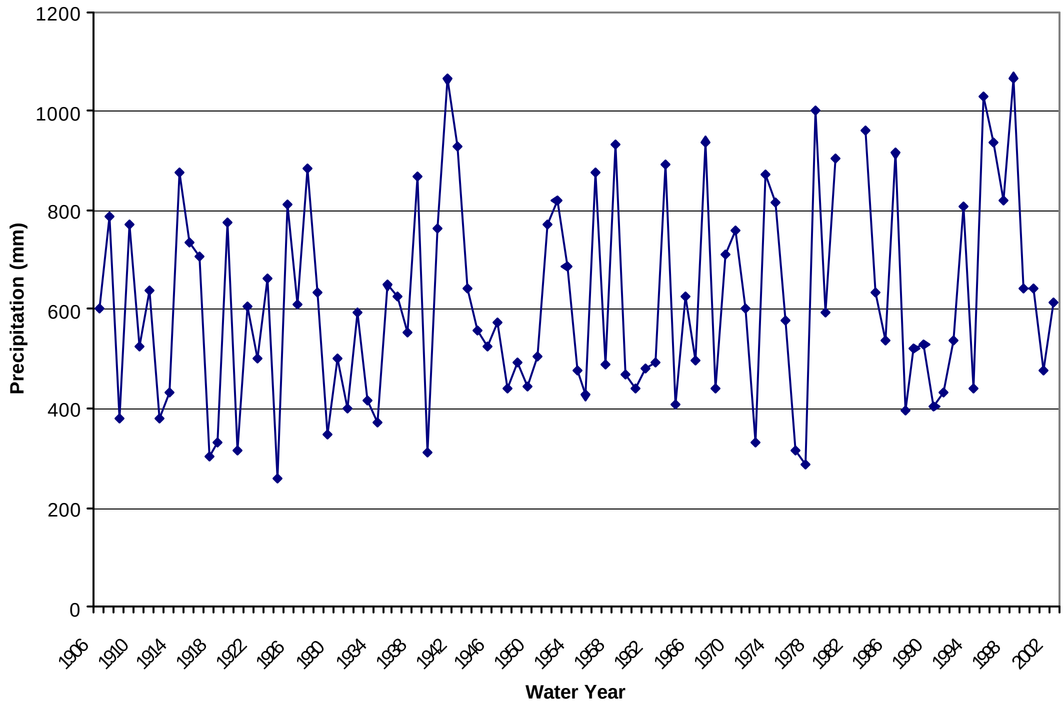

Figure 3. Annual precipitation totals as measured at the Napa Fire Department gauge, water years 1906-2002. (Data obtained from the California Department of Water Resources, www.cdec.water.ca.gov (1 Feb 2003).

Land use

Based upon the Calveg primary vegetation types, the Carneros Creek watershed is primarily annual grasses and forbs and mixed hardwoods, with smaller areas of California Bay and Pacific Douglas Fir (NCCDP, 2002).

The lower watershed is primarily suburban residential and vineyard. Middle portions of the watershed are experiencing a transition to vineyards. The upper watershed is currently open space with some grazing and a low number of homes. In the past, the watershed supported a cattle operation (in operation from the 1930's to 1972) (Historical Ecology), and the upper watershed supported a large goat dairy farm that was removed in 2001 (Mary Pettis, pers. comm.).

California Department of Fish and Game Stream Surveys

Two past stream surveys have been conducted on Carneros Creek in 1958 and 1976. These surveys provide a means of comparison between the historic and current condition of Carneros Creek. The first stream survey was conducted by the CDFG on November 11, 1958 by R.F. Elwell. Carneros Creek was described as having an average width of 6 to 8 ft (1.8 to 2.4 m) in the upper section, and 15 to 20 ft (4.5 to 6.1 m) in the lower section, and the entire stream was dry on the day of the survey. The middle and upper sections have a rubble and gravel bed, whereas the lower section has sand, silt and scattered gravel pockets. Channel flow was estimated to be 0 ft^3/s in the summer and early fall, and up to 75 ft^3/s (2.12 m^3/s) during peak winter flows. The entire length of the stream was reported as having good dense oak and willow riparian shading. Upstream of Highway 12/121 the watershed was primarily used for cattle grazing, whereas downstream of the highway, the watershed was primarily agricultural. Many domestic and agricultural diversions were noted downstream of the highway. Dense overhanging vegetation, and undercut banks and roots provided in-channel shelter. Pools are described as fairly large but infrequent, and only the concrete slab under the Old Sonoma Bridge was noted as a possible migration barrier. Spawning areas are poor downstream of the highway, and fair to poor upstream of the highway. No fish were observed during this survey, but small steelhead runs are reported, as well as a small resident rainbow trout fishery in the headwaters. Elwell concluded that Carneros Creek was of a minor importance for steelhead spawning or as a nursery area, as the channel was generally dry throughout its length by June.

A smaller survey on December 6, 1976 looked at the reach downstream of Highway 12/121. The average width was 6 ft (1.8 m) ranging from 4 to 15 ft (1.2 to 4.5 m). The channel bed was reported as 40% sand and silt, and 60% gravel and rubble, with large amounts of domestic garbage in the channel. Observed high water marks suggest that flows rise approximately 4 to 6 ft (1.2 to 1.8 m) above the channel bed. This reach was characterized as only a migration route for steelhead, because spawning substrate was poor, and intermittent flows limit available nursery habitat. A study on February 2, 1978 measured discharge at 2.3 ft^3/s (0.065 m^3/s) immediately upstream of the highway. A fish rescue survey was performed on June 29 and July 1, 1981, however no fish were observed in the lowest 4 mi (6.4 km) of channel. The channel was noted as having intermittent flow, good riparian cover, rubble and gravel bed except in areas with cattle present, and three small dams (6 to 10 ft (1.8 to 3.0 m)) upstream of the highway, each a complete fish migration barrier.

METHODS

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

Startup and review of available data

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

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

Five segments, or strata, each identified by a characteristic slope were revealed by a visual inspection of the longitudinal profile. Because channel slope is a good predictor of channel morphology (e.g. Montgomery and Buffington, 1997), these five strata were used to organize the sampling strategy in Carneros Creek. The sample strata were numbered I through V, with Stratum I being the furthest downstream near the confluence with the Napa River, and Stratum V being the furthest upstream in the headwaters of Carneros Creek. Two sample reaches per stratum were characterized in the field (e.g. Sample reach 1A, sample reach 1B, sample reach 2A, sample reach 2B, and so on) for a total of 10 sample reaches (Figure 4).

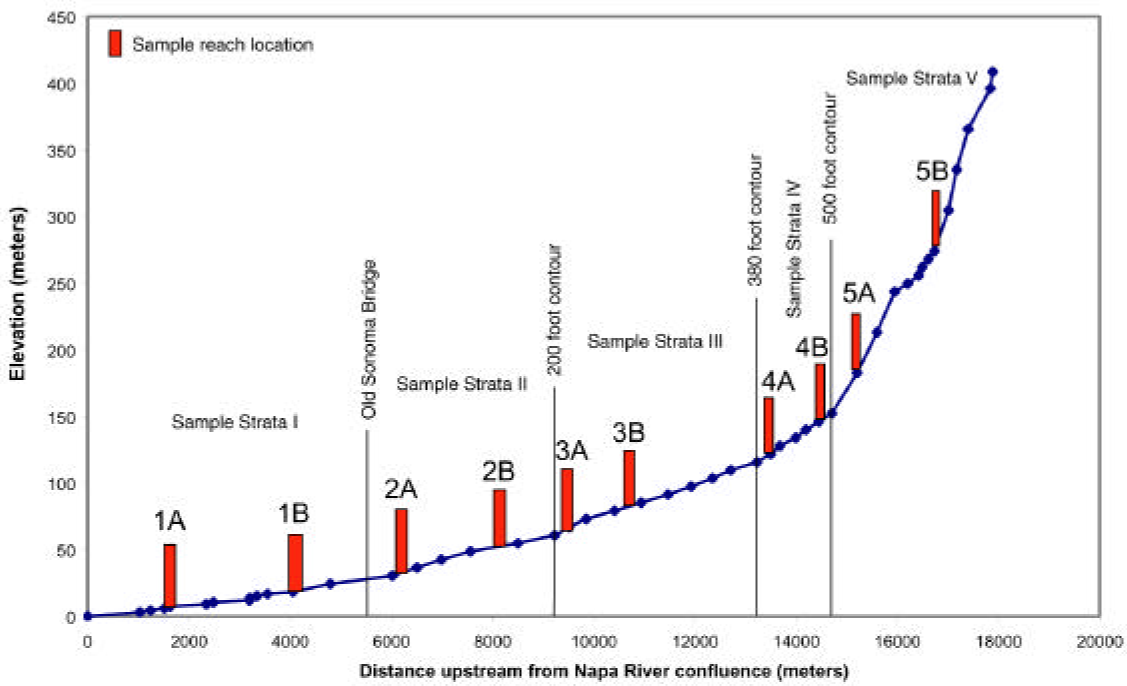

Figure 4. Longitudinal profile of Carneros Creek.

Table 2. Carneros Creek Reach Geomorphic Characteristics.

Sample Strata	Sample Strata % Slope (USGS map)	Cumulative Drainage Basin Area (km^2)	Sample Reach	Drainage Basin Area above Sample Reach (km^2)	Sample Reach Length (m)
I	0.51	22.96	1A	22.11	175
			1B	19.91	149
II	0.88	17.53	2A	16.64	287
			2B	14.86	175
III	1.37	13.19	3A	10.55	175
			3B	9.86	170
IV	2.47	6.56	4A	6.47	112.5
			4B	4.12	100
V	8.06	3.45	5A	3.09	112.5
			5B	1.65	62.5

The length of each sample reach was 25 times the measured bankfull width. A sample reach of this length is necessary to capture in-channel features such a 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 (Figure 5).

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

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

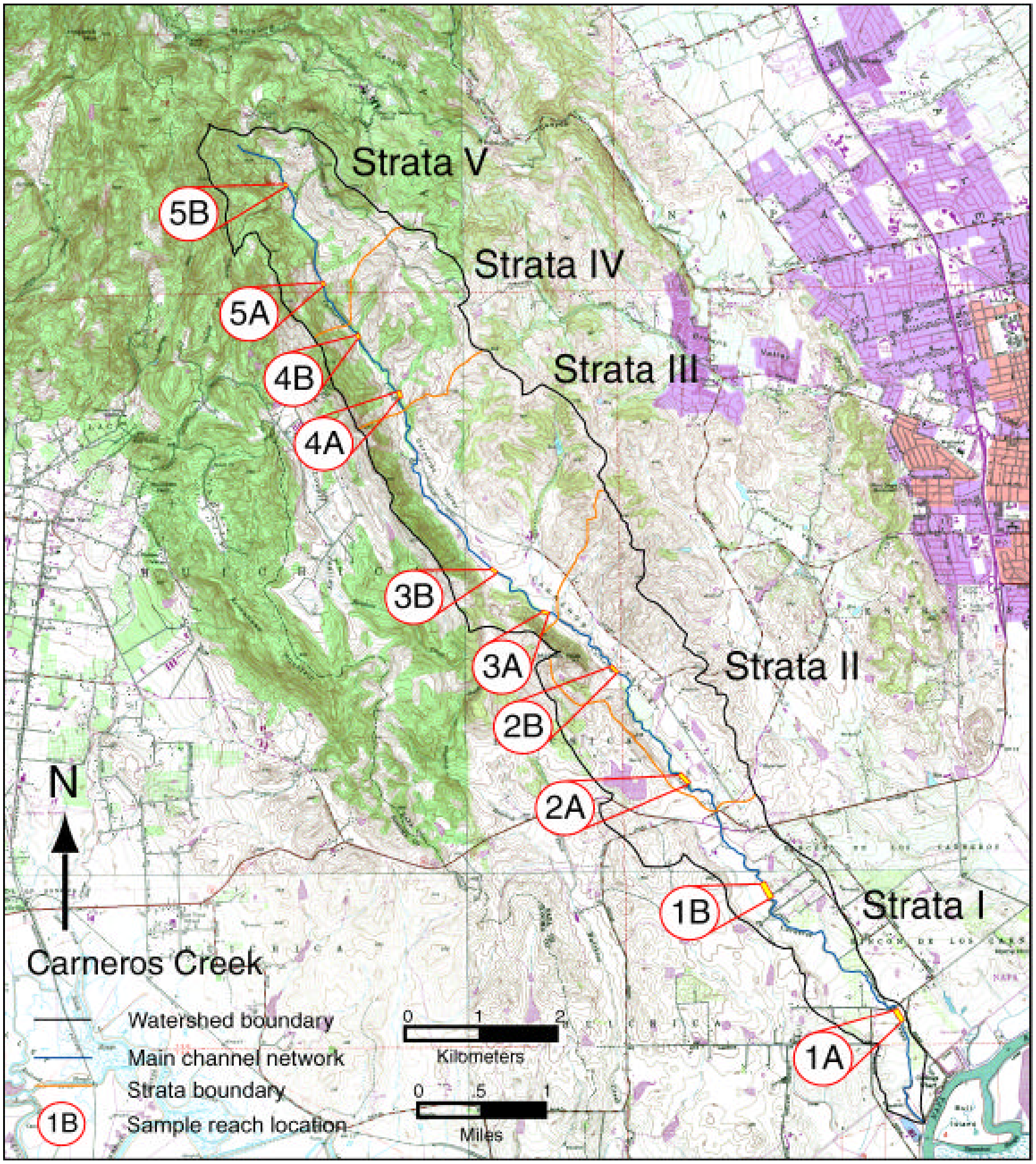

Figure 5. Map of the Carneros Creek watershed, sample Strata and sample reach locations.

Table 3. Field measurements in each sample reach.

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

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

Data collected in channel cross sections

Channel geometry

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

Surface sediment size analysis

In each sample reach, pebble counts at five cross section locations were performed following methods proposed by Bunte and Abt (2001). A systematic random sampling approach was chosen wherein 80 clasts were measured in a grid pattern scaled to the local bankfull width and maximum particle size and centered on the five cross section locations in each sample reach. In most cases, 0.25 to 0.5 m spacing between measures was adequate to avoid double counting a single clast. However, if a single clast was large enough to be counted twice, one measurement and one "no count" was recorded. Clasts were selected by a finger touch guided to a location in the grid, but with eyes averted to retain random selection. Clasts were measured with a ruler and reported as the ½ phi sieve mesh on which the particle would be caught (i.e., 2, 4, 5.6, 8, 11, 16, 22 mm etc.). Clasts finer than 2 mm were reported as < 2 mm. Although it is difficult to select and manipulate the smallest diameter sizes, care was taken to minimize observer bias and measurement error for the finer grain sizes. A total of 400 clasts per sample reach were measured to produce a statistically robust estimate of surface sediment size distribution for the sample reach (Bunte and Abt, 2001).

Bank characterization

Data were collected on the bank and terrace condition and erosion, the extent of riparian forest, and field observations of plant and wildlife species at three out of the five cross-sections in each sample reach. The three "spot measurements" within a sample reach allow comparisons of the bank composition and vegetation to be made between sample reaches, highlighting areas that are potentially more susceptible to erosion, and allowing an analysis of the interaction of the riparian vegetation with the channel. A description of the riparian zone vegetation and management on the terrace or hillslope adjacent to the stream was also included.

Canopy cover

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

Continuous channel metrics

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

Gravel bars and mobile sediment deposits

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

The average depth, width, and length of individual bars and sediment deposits were measured to the nearest 0.1 m. Width and length of deposits are relatively easily identified, however, depth frequently requires consideration of field evidence of likely depth of the deposit, including likely depth of scour. Depth of larger bars is typically determined as a function of the average bar height relative to the thalweg elevation measured adjacent to the bar and/or in pools upstream and downstream. A shape factor (adjustment of deposit depth) is typically included where the bar cross-section geometry is regarded as triangular, with the maximum bar height and the thalweg depth defining the hypotenuse of a right triangle; for a smoothly sloping bar, the shape factor is 0.5, and the average depth of the deposit is estimated as one-half of the maximum bar height above the thalweg. In other words, in order to accurately portray the true thickness of a deposit, an adjustment of the deposit depth is made for deposits that are not rectangular in shape. The shape factor is adjusted on a case-by-case basis to best represent more complex bar geometry for purposes of estimating sediment volume. For some other general types of sediment deposits, depth of the active layer of sediment was estimated according to the following methods.

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

In coarse textured channel segments with relatively shallow and uniform depth, the typical depth of scour determines the depth of the active layer during peak flows. The scour depth is thought to be controlled by the size of the larger sediment clasts on the bed. DeVries et al., (2001) suggested that D84 (the diameter for which 84% of sediment is finer) is an approximate predictor of the depth of scour in ordinary peak flow events in reaches dominated by cobble size clasts. In practice, particularly in coarse bedded channels such as the upper reaches of Carneros 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 the upper reaches of Carneros 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.

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

Bank conditions and erosion

The presence and location of man-made structures including revetments, grade control, bridges, and culverts were recorded. Two measurements were taken in regard to indicators of bank erosion: an average distance of retreat and an average height over which erosion was evident. These measures, when combined with the length of bank that was eroding, gave an average volume of erosion. Indicators of erosion include exposed roots of trees, overhanging vegetation, bank undercut, and undercut bank revetments or bridge pilings. When possible, an estimate of the age of the vegetation or structure was noted, to allow estimation of the rate of erosion. However, caution must be exercised when estimating rates of erosion; the indicator age represents the longest time during which the erosion has occurred, and dating techniques are crude. Along with the location of revetment, the type, condition, and estimate of age was recorded.

Large woody debris

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

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

LWD Survey Abbreviation Key

Minimum LWD Dimensions = > 20 cm diameter and 1.8 m length

Mid-point diameter	Length	Distance fell from

Position	Type	Species
1 = in low-flow channel (LF)	1 = log	4 = Alder
2 = portions in both LF & BF	2 = snag	6 = Willow
3 = in bankfull channel (BF)	4 = live log up	7 = Oak
4 = portions in both BF & above BF	5 = Rootwad	8 = Bay Laurel
5 = above the BF channel	6 = live log down	9 = Unknown Hardwood
6 = portions in LF, BF & above BF	7 = log with rootwad	10 = Ash

Decay Class	Pools (2 letter code)
1 = bark intact, limbs, twigs, and needles present	First letter
2 = bark intact, limbs and twigs present	a = LWD associated
3 = bark intact, limbs absent	f = formed by LWD
4 = bark loose or absent	nn = no pool
5 = bark absent, surface slightly rotted	
6 = sruface extensively rotted	Second letter
7 = sruface completely rotted, center solid	s = shallow, depth < 1 m
8 = surface and center completely rotted	d = deep, depth > 1 m

Entry Process	Key Piece
if logging debris (sawmark) add 0.5	independently stable and in bankfull width or
1 = bank erosion	is retaining other pieces of organic debris
2 = windthrow	**Debris Jam**
3 = mortality	(must satisfy 3 criteria below)
4 = landslide	1 = contains at least one key piece
5 = enhancement structure	2 = spans at least half the bankfull channel
6 = unknown	3 = contains 10 or more LWD pieces

<u>Additional spot measurements</u>

Bulk sediment size analysis

Spot sampling sediment size distribution at likely spawning sites was conducted with a 35 cm diameter McNeil streambed sampler at locations distributed across sample reaches that were accessible to anadromous fish. Potential spawning sites were located by reconnoitering study reaches and locating the first well-defined pool tail-out or the upstream edge of a riffle located between upstream and downstream pools. Sample sites were often dry at the time of sample collection. The McNeil sampler was inserted into the bed to a depth of >15 cm by simultaneously twisting and applying downward pressure on the sample barrel. Bed material enclosed within the sample barrel was then excavated. The coarser layer on the surface of the streambed was included in the sample; however, the majority of the sample was subsurface material. The three largest clasts were measured and weighed in order to determine the proportion of the sample represented by the largest clast; this provides perspective on how representative the sample is with respect to the full size distribution of the streambed. All clasts coarser than 50 mm were removed from the sample during excavation, sorted according to 50 mm, 64 mm and 90 mm median diameter, and weighed in the field to the nearest 0.1 lb (45 g) using an electronic fish scale. Material finer than 50 mm was collected in buckets and transported to a contract geotechnical lab for size analysis according to ASTM C-136.

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

Field measurements of slope

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

Bed shear stress

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

Reach average shear stress was computed as the product of the hydraulic radius (channel cross-section area divided by channel wetted perimeter) at each of three cross-sections measured in each reach, reach average channel slope (assumed to be the best estimator for water surface slope at bankfull flow), and constants for gravitational acceleration and the density of water. The steeper or deeper a channel is, the more bankfull shear stress it will have, allowing it to transport larger grain sizes.

Bed load transport capacity

An assessment of relative bed load sediment transport capacity is provided for each reach by comparing bankfull bed load shear stress estimates with a theoretical bed load transport threshold shear stress. This is accomplished by computing the shear stress necessary to mobilize the stream bed using D50 of the bed surface from surface sediment size distribution data obtained in the field for each reach. Threshold shear stress is computed as the product of critical dimension Shield's stress (0.052), the immersed density of sediment (density of sediment minus density of water, with sediment density assumed to be 2.65 g/cm^3), gravitational acceleration (a constant), and reach D50. This quantity should be interpreted as the shear stress required to mobilize the majority of the stream bed; initial motion of the stream bed, or minor, local bed load transport would potentially occur at lower bed shear stress.

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

RESULTS

Channel Geomorphology

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

Surface grain size variation by reach

Surface grain sizes in Carneros Creek generally fine downstream, but with a substantial amount of variation between sample reaches. Median grain size (D50) ranges between 2 mm in reach 2B and 63 mm in reach 4B (Figures 6 and 7, Table 6). D50 for reaches 1A and 2B are both less than 3 mm, due to the very low gradient of reach 1A, and the unique channel morphology in 2B.

The percentage of fines (grain sizes finer than 2 mm) measured in the surface sediment ranges from 49% in reach 2B down to 5% in reach 5B, again with considerable scatter between sample reaches. Moderate amounts of fine sediment are being stored in the lower reaches, while the middle and upper reaches are storing relatively low amounts. Reach 1A is highly entrenched and has a very low gradient; during low flow events, and on the receding limb of higher flow events, the low gradient, and resultant low stream power, causes the deposition of fine sediment in this reach. Reach 2B is dissimilar to other reaches; it has a large percentage of bedrock outcrop, making it essentially a long bedrock trench, with very low amounts of sediment storage. Sediment is stored as primarily fine-grained, small bars derived from both fluvial transport processes as well as sediment contributed directly from the hillslope immediately adjacent to the channel. The stream discharge flowing through this reach has a higher velocity and is able to transport the majority of sediment supplied because of the low roughness of the exposed bedrock, leaving only small sediment deposits.

Carneros Creek also has reaches dominated by cobble-sized alluvium (reaches 3A through 5B), where the surface D84 ranges between 70 and 285 mm. Although the D84 grainsize is cobble size in all reaches, the upper reaches (4B, 5A and 5B) have large in-channel boulders. These boulders are only potentially mobile during the highest of discharges, and contribute to the channel morphology by creating a velocity shelter for fish habitat and gravel storage, as well as creating many step pools in these reaches.

In-channel bedrock outcrop is only present in reaches 2B through 3B, ranging from 5 to 50%. These bedrock dominated reaches often have different channel morphologies compared to other reaches, with reach 2B being a bedrock trench throughout the majority of the sample reach, and reaches 3A and 3B containing some deep bedrock scour pools. The presence of large amounts of bedrock, as in reach 2B, decreases the bed and bank roughness, increasing water velocities, and generally increasing the amount of sediment transport. Also, incision into bedrock occurs much more slowly than incision into alluvium, forcing work by the channel onto the banks in reaches underlain by bedrock. While reaches 3A and 3B do have a percentage of bedrock exposed in-channel, these reaches are still primarily alluvial, and do contain sediment deposits.

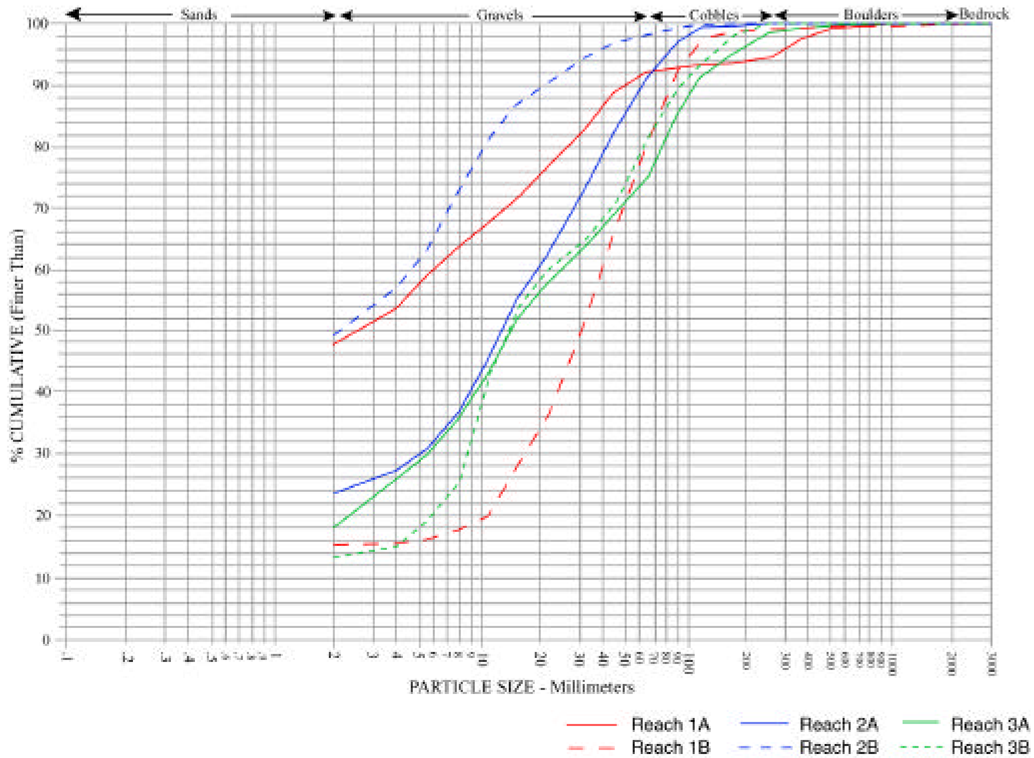

Figure 6. Particle size distribution curves showing the grain size distribution for sample reaches 1A through 3B.

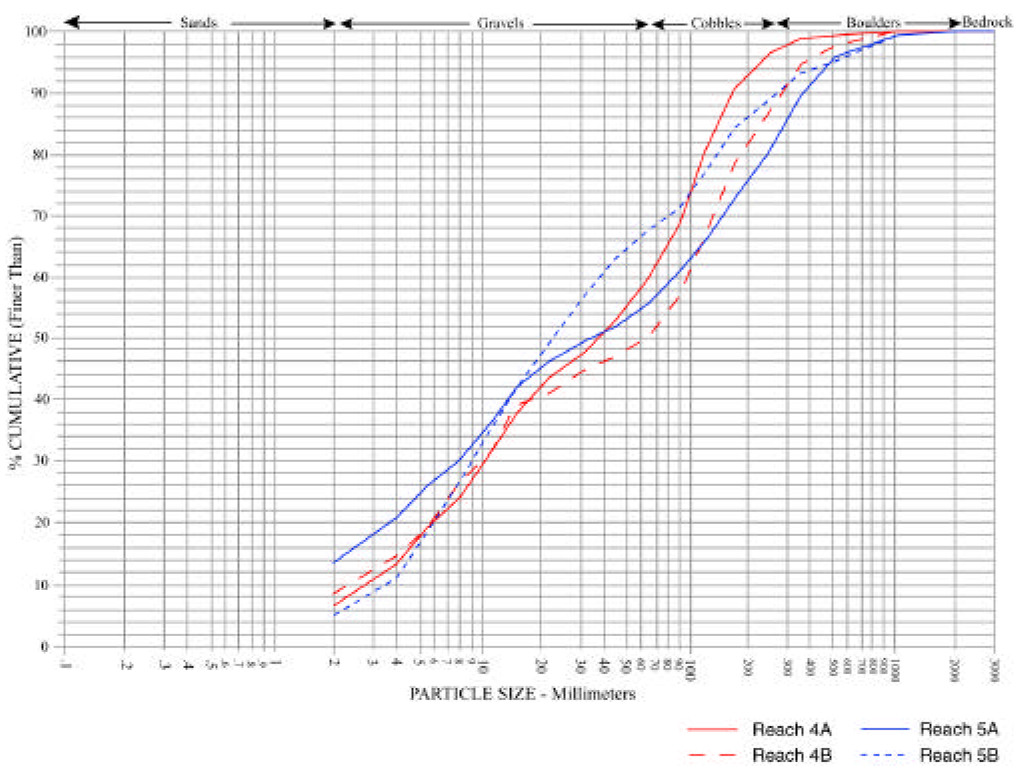

Figure 7. Particle size distribution curves showing the grain size distribution for sample reaches 4A through 5B.

Table 6. Surface grain size data for each sample reach.

Reach	% <2 mm	D16 (mm)	D50 (mm)	D84 (mm)	% Bedrock
1A	48	<2	3	34	0
1B	16	5	30	71	0
2A	24	<2	14	47	0
2B	49	<2	2	14	50
3A	18	<2	15	86	5
3B	13	4	15	70	36
4A	7	5	38	140	0
4B	8	4	63	220	0
5A	14	3	34	285	0
5B	5	5	23	180	0

Subsurface grain size variation

Samples taken for analysis of subsurface grainsize ranged in volume from 10.8 l to 14.9 l (2.8 to 3.9 gallons); bulk density of samples average about 2.2 t/m3 (140 lb/ft3). The weight of the largest sediment clast in each sample was approximately 3% of the total sample mass. Ideally, samples would be sufficiently large to reduce the weight of the largest grain to not more than 1 % of the sample mass. If the three samples are bulked together and treated as one sample, the largest clast will be less than about 1.2 % of the sample mass. Hence, interpretation of the data with respect to spawning suitability should consider the mean for the selected parameters as well as the individual samples for a more robust evaluation (Table 7).

Table 7. Summary of subsurface sediment size distributions.

Reach	Sample Mass (kg)	% < 1 mm	% < 6.35 mm	D50 (mm)	D84 (mm)
1A	24.2	9	30	13	36
1B	32.6	11	31	22	63
2A	33.5	16	26	33	79
Composite	90.2	13	30	23	63

Kondolf (2000) suggests that the subsurface D50 and D84 (the framework material) of potential spawning gravel be compared to documented spawning gravel size distributions. Kondolf and Wolman (1993) compiled such data for salmonids, including steelhead trout. The range of D50's from these data for steelhead is about 18 mm to 34 mm; D84's are about 100 mm. The data for Carneros Creek indicate framework bed sediment is generally within the range documented for steelhead trout. The bed surface sediment in Carneros Creek is primarily medium to coarse gravel and cobble, while the subsurface sediment is primarily medium gravels.

Kondolf (2000) suggests based on a review of prior studies that spawning gravels with less than 12 to 14% sediment finer than 1 mm (fines) is correlated with 50% survival to emergence on average. The 50% emergence is an arbitrary cutoff, yet is widely accepted by biologists as a benchmark for comparison. Kondolf also suggests that a downward adjustment should be applied to bed samples to account for removal of fine sediment during redd construction. An empirical relationship estimates the final percentage of fines as 0.67 times the initial percentage. Hence, samples with up to 21% fines would be predicted to have levels of about 14% after spawning. However, fines deposited in the redd during the egg incubation period could fill the gravel interstices and ultimately bring fine sediment levels back up to pre-redd construction levels. Carneros Creek has levels of sediment finer than 1 mm in the subsurface sediment that is within the range that does not excessively impact steelhead egg incubation.

With respect to fine gravel impeding steelhead fry emergence, Kondolf (2000) suggests that previous studies are somewhat variable. However, for steelhead in particular and salmonids in general, the 50% emergence criterion indicates that sediment finer than 6.35 mm should not be greater than about 30%. Again, a correction for removal of fines during redd construction is recommended. An empirical relationship estimates the final percentage of sediment finer than 6.35 mm as 0.58 times the initial percentage. Hence, samples with up to 52% sediment finer than 6.35 mm would be predicted to have levels of about 30% after spawning. This empirical relationship has a relatively wide scatter, however, and the specific correction should be used with caution. In Carneros Creek, samples ranged between 26 and 31% sediment finer than 6.35 mm, suggesting that with a moderate removal of fines during redd construction, these gravels would not have an adverse effect on emergence. However, additional sediment samples in other reaches, especially the middle reaches, would give a more comprehensive picture of sediment quality. Overall, spawning conditions in terms of subsurface sediment size distributions in Carneros Creek appear to be acceptable for steelhead.

Stream slope by reach

Channel slope is generally regarded as an important control on channel morphology (Montgomery and Buffington, 1997). The reported stream slopes represent reach average slopes; the slopes in each reach vary locally. Reach average slopes range between 0.5% in reach 1A and 9.5% in reach 5B (Table 8). Slopes generally decrease from the headwaters to the mouth, with a few exceptions including reach 2B, which is a narrow bedrock trench reach. Reaches with lower slopes tend to be areas of aggradation, because of reduced stream power. Increased sediment deposition can affect morphology, resulting in widening and shallowing of the channel, as well as filling of pools. For example, reach 2A has low slope, a wide channel cross-sectional, and has more sediment storage than surrounding reaches.

In addition to the upstream increase in slope, the standard error reported also increases upstream in response to greater influence of boulder step-pools shaping the morphology of the 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 8) shows a scatter of points with D50 generally increasing with increased slope, and two outliers, reach 5A and 5B. These reaches are both narrow steep channels, where the fluvial processes are masked by hillslope influences and inputs of fine sediment.

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

Reach	Reach average % slope	Standard error	Coefficient of variation
1A	0.5	0.6	1.4
1B	0.7	0.3	0.4
2A	0.5	0.2	0.5
2B	1.2	0.6	0.5
3A	0.9	0.3	0.3
3B	0.7	0.1	0.1
4A	1.9	1.5	0.8
4B	2.2	0.1	0.04
5A	6.3	2.7	0.4
5B	9.5	4.2	0.4

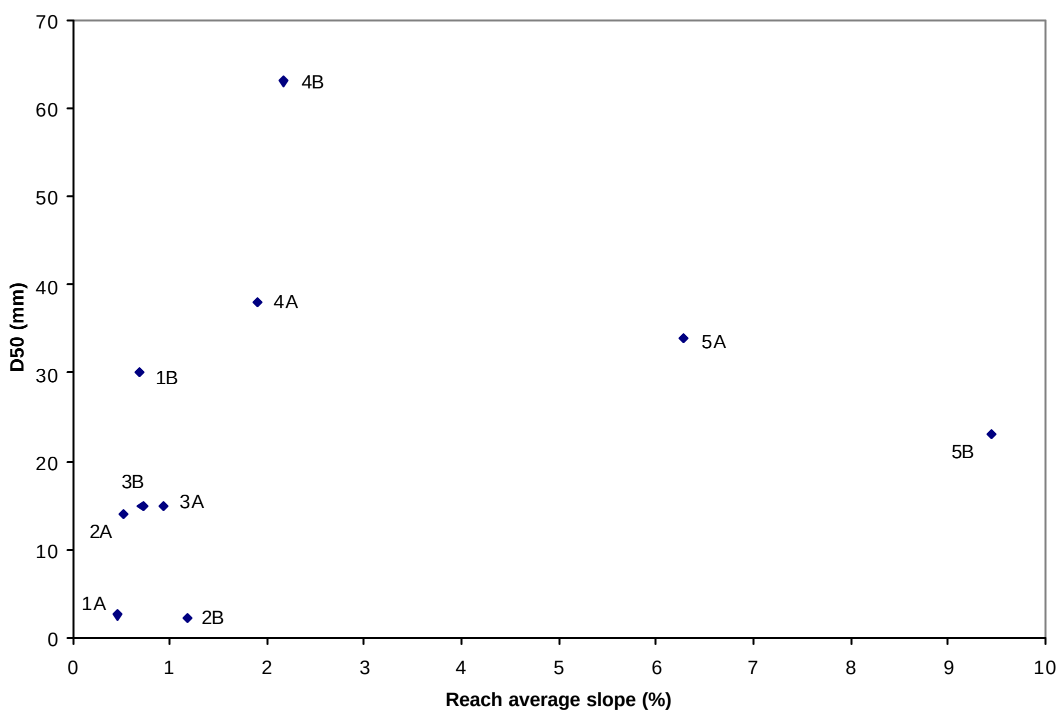

Figure 8. Reach average slope versus mean grain size (D50) for each sample reach.

Cross-sections

Scale drawings of cross-sections generated from field measurements demonstrate the variability of morphologies present in Carneros Creek (Figures 9 through 13). The cross-sections illustrate the channel's width, depth, entrenchment, bank slope, and floodplains. Where water was present, the water level on the date that the cross-section was surveyed is shown. The field interpretation of "bankfull" flow depth is also shown; this is considered to be the flow depth of the 1.5 to 2 year recurrence interval flood, as opposed to the depth that would fill the channel to the top of its banks. Cross-sections from Stratum I show that the channel is highly entrenched, with low channel complexity. The cross-sections from Stratum II are more variable; reach 2A is generally wider, with some areas of undercut banks, while reach 2B is a narrow and deep bedrock trench with few sediment deposits. The channel in Stratum III is slightly wider, with bars and terraces shaping the morphology of the cross-sections. Stratum IV is much less entrenched, with the cross-sections reflecting the shallower channel, and the greater influence of individual boulders. The channel in Stratum V, near the headwaters of Carneros Creek, is much more narrow and influenced by large boulders and pieces of large woody debris. Overall, Carneros is an incised channel, especially in its middle and lower reaches. There is no data to suggest that this incised morphology represents a recent change in channel pattern; Carneros has likely been incised long before European contact.

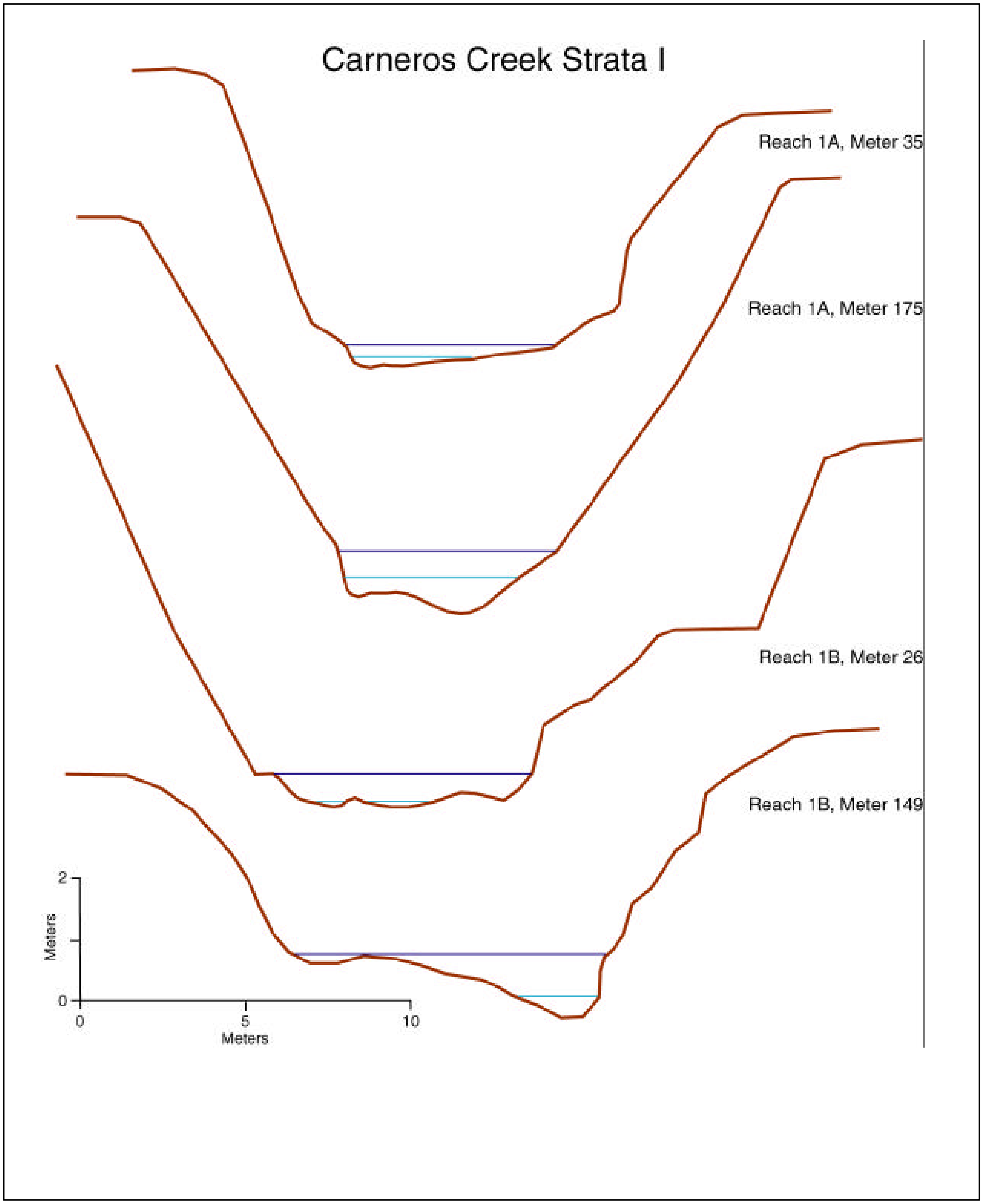

Figure 9. Carneros Creek cross-sections for sample Stratum I. The thick line represents the ground surface, the lower line represents the water depth on the date the cross-section was surveyed, and the upper line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

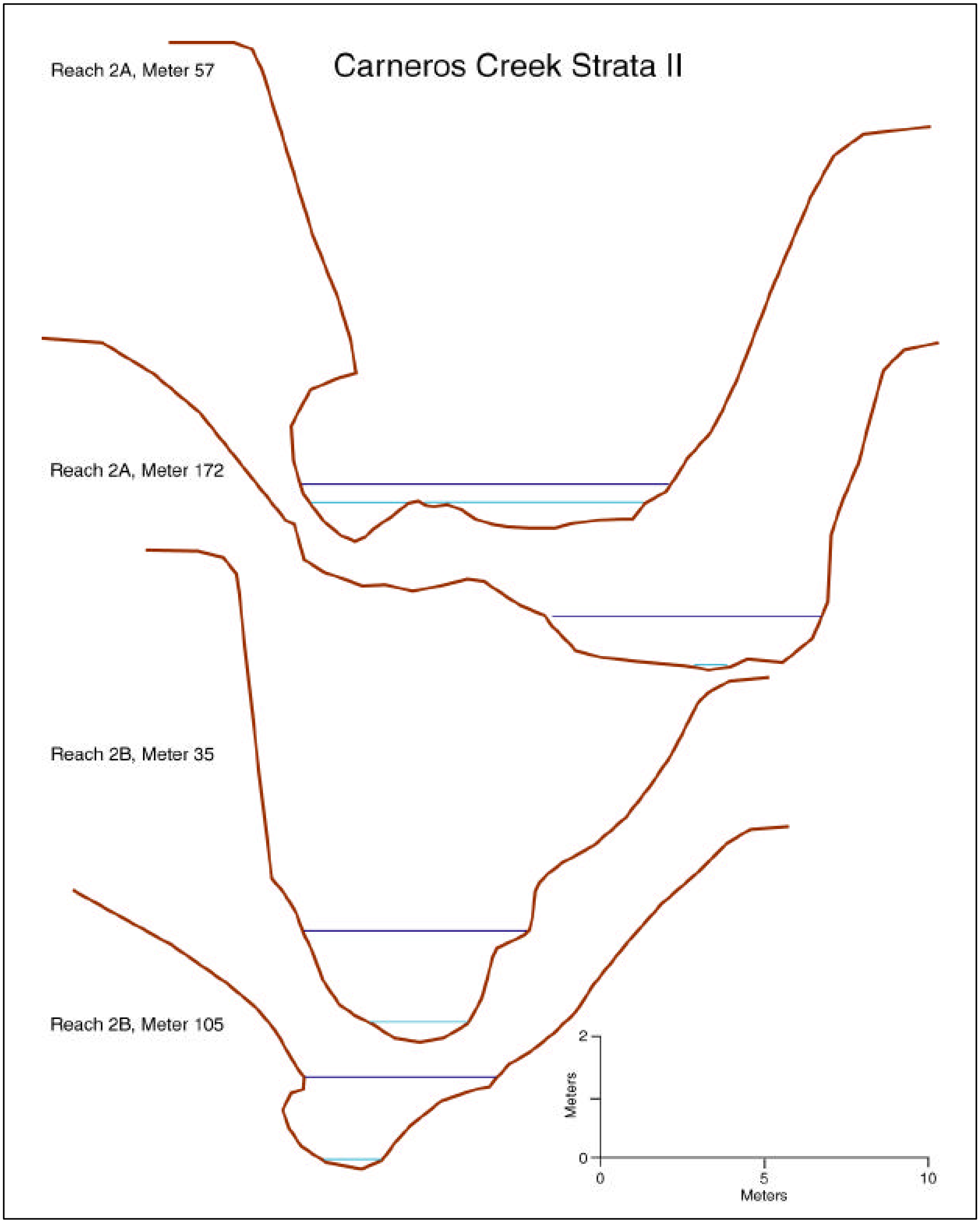

Figure 10. Carneros Creek cross-sections for sample Stratum II. The thick line represents the ground surface, the lower line represents the water depth on the date the cross-section was surveyed, and the upper line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream,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

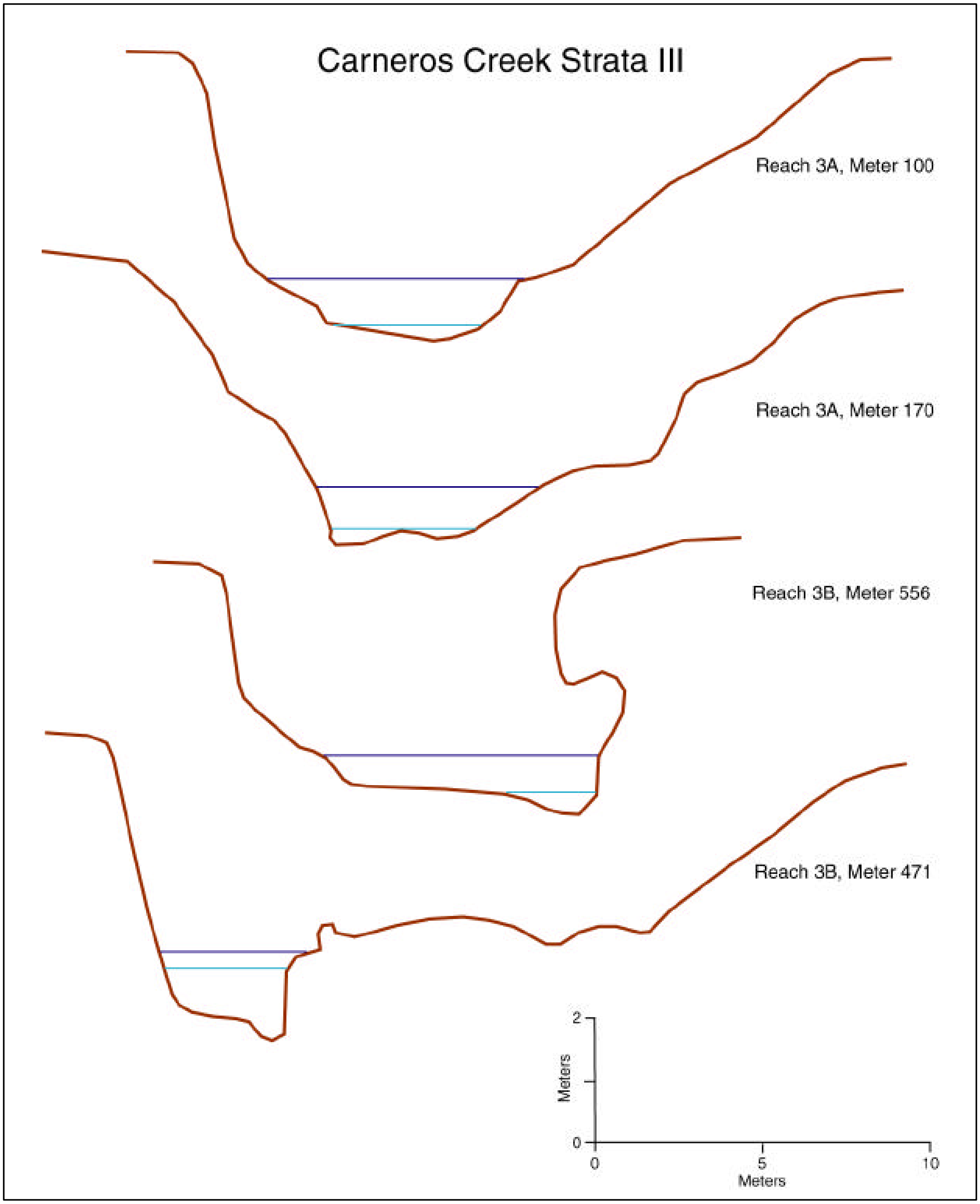

Figure 11. Carneros Creek cross-sections for sample Stratum III. The thick line represents the ground surface, the lower line represents the water depth on the date the cross-section was surveyed, and the upper line represents the field interpretation of bankfull. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

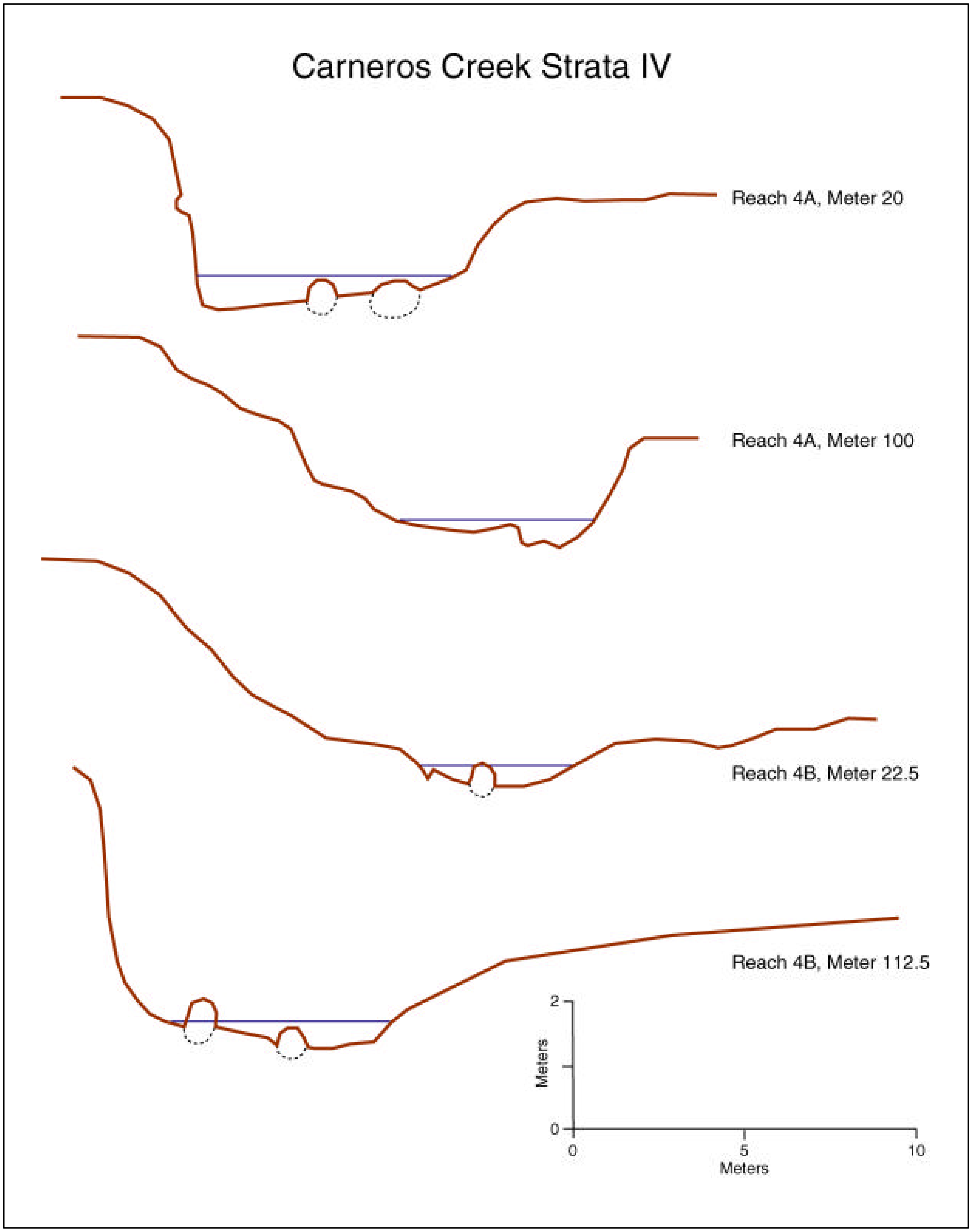

Figure 12. Carneros Creek cross-sections for sample Stratum IV. The thick line represents the ground surface, and the thin line represents the field interpretation of bankfull. Dashed lines indicate the inferred extent of boulders in the cross-section. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

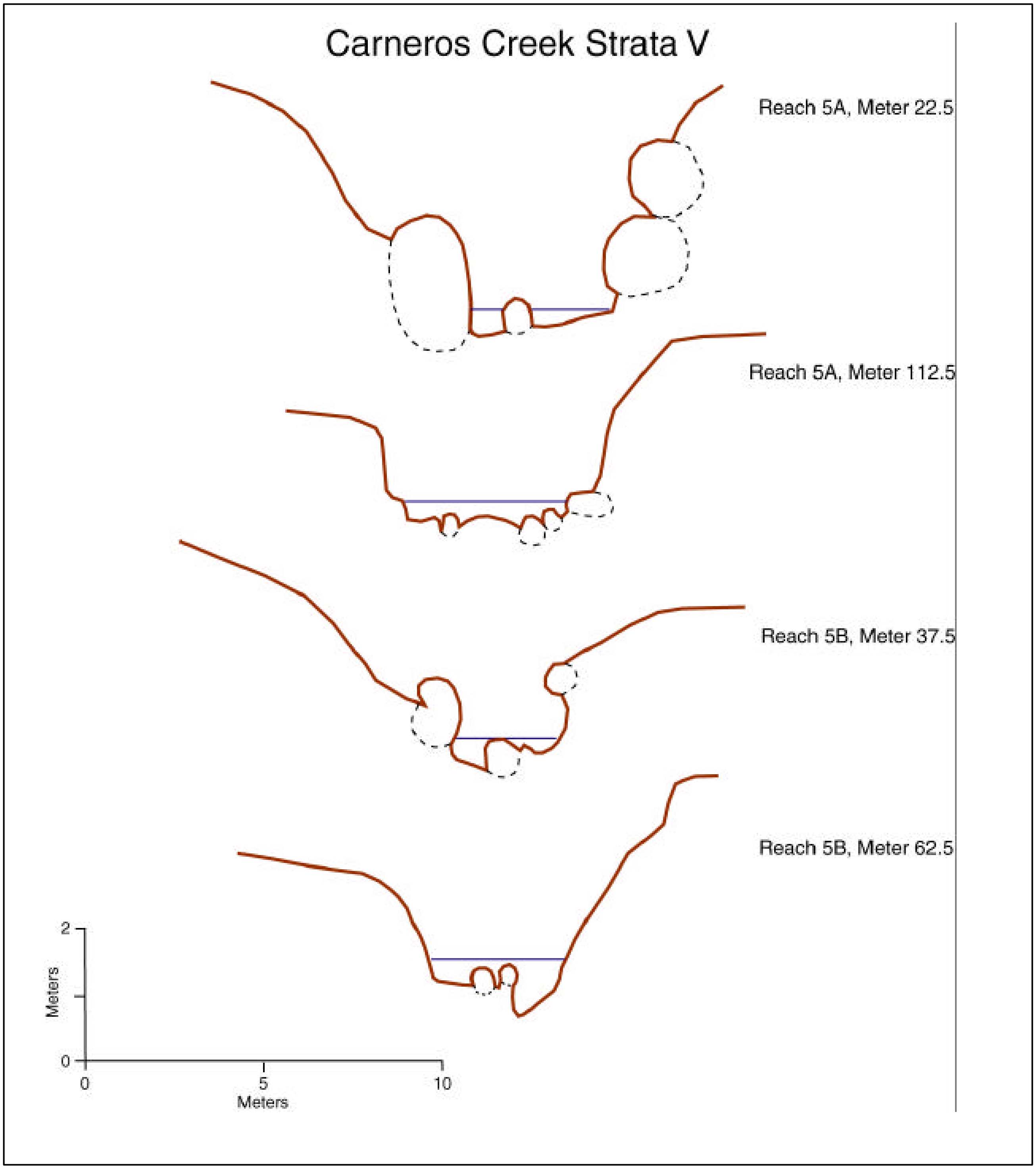

Figure 13. Carneros Creek cross-sections for sample Stratum V. The thick line represents the ground surface, and the thin line represents the field interpretation of bankfull. Dashed lines show inferred extent of large boulders and logs in cross-section. Cross-sections are oriented looking downstream, with the left bank on the left-hand side.

Large woody debris (LWD)

A wide variety of species of live trees and LWD were recorded along the length of Carneros Creek (Figure 14). The Carneros watershed has a well-developed riparian corridor along most of the channel length, causing the density of live trees and LWD pieces to be high. This is important especially considering that this watershed has a very low percentage of conifers and redwood trees compared to other small coastal streams in the Pacific Northwest that support anadromous salmonids. Bay laurel (bay) dominates the riparian corridor in the watershed, with lesser numbers of eucalyptus, willow, oak, maple and alder present. Reaches 3A and 3B are the only reaches with alder present, largely due to the perennial discharge, and a less entrenched channel with large, more stable bars for the alder to colonize. Moreover, reaches downstream of 3B are the only reaches with willow present, again, largely due to the perennial discharge. Reach 1B has the highest number of LWD pieces, with the majority in the continuous riparian corridor and a single large LWD jam. With the exception of individual LWD pieces, and a few smaller partial LWD jams, the majority of pieces in the sample reaches were live upright trees (Figure 15). Although the riparian corridor in the lower reaches was generally continuous, it is important to note that the corridor usually consisted of a single row of mature trees. Because of the size of these mature trees, when they are recruited into the channel, they will become important LWD pieces, yet will leave a large gap in the riparian canopy. The middle and upper reaches have the greatest proportion of live trees, while reach 2B only has a single piece of LWD down in the channel. Excluding the live upright trees, every reach except reach 1B, has less than 12 pieces of LWD.

LWD pieces provide shade and cover for aquatic species, habitat complexity, leaf litter for aquatic bioenergetics, and flow roughness during peak flow periods. Live upright trees help stabilize the banks and bars while also shaping the morphology of the channel. Based upon our observations and measurements of LWD pieces, the amount of LWD present in Carneros Creek appears to be suitable for these functions. Additionally, the large LWD jam in reach 1B, and smaller jams in the upper reaches can help trap small volumes of sediment for spawning while providing a velocity shelter during high flows. In-channel LWD is also important in pool formation because the pieces provide objects for the channel to scour around and create new pools.

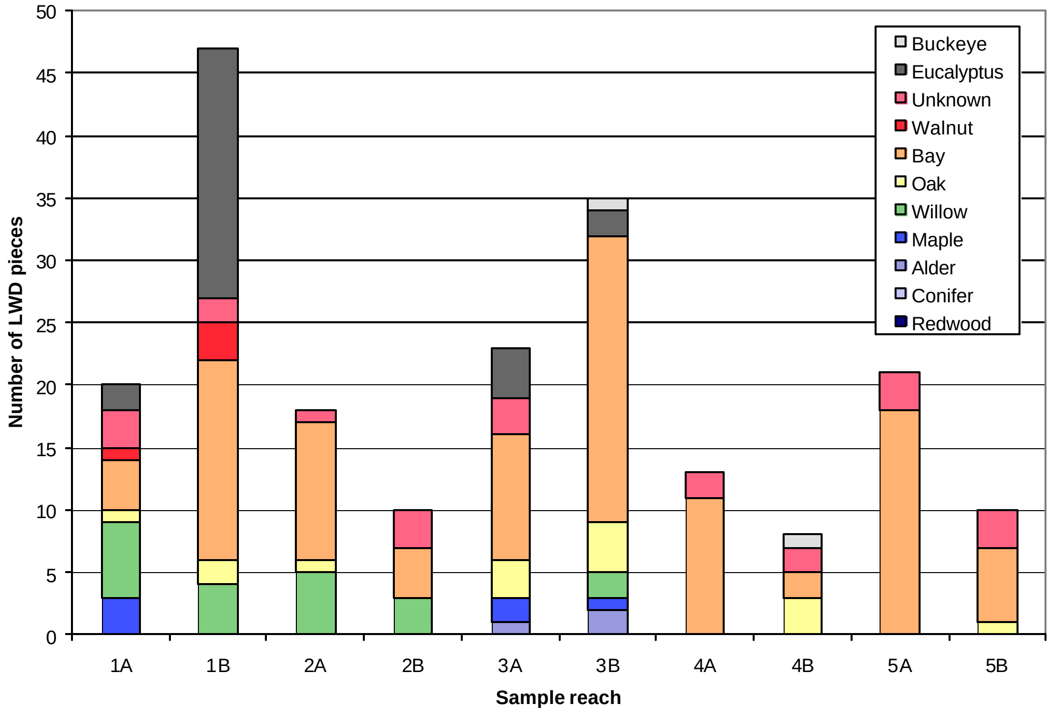

Figure 14. Number and species of woody material (LWD and live trees) per sample reach.

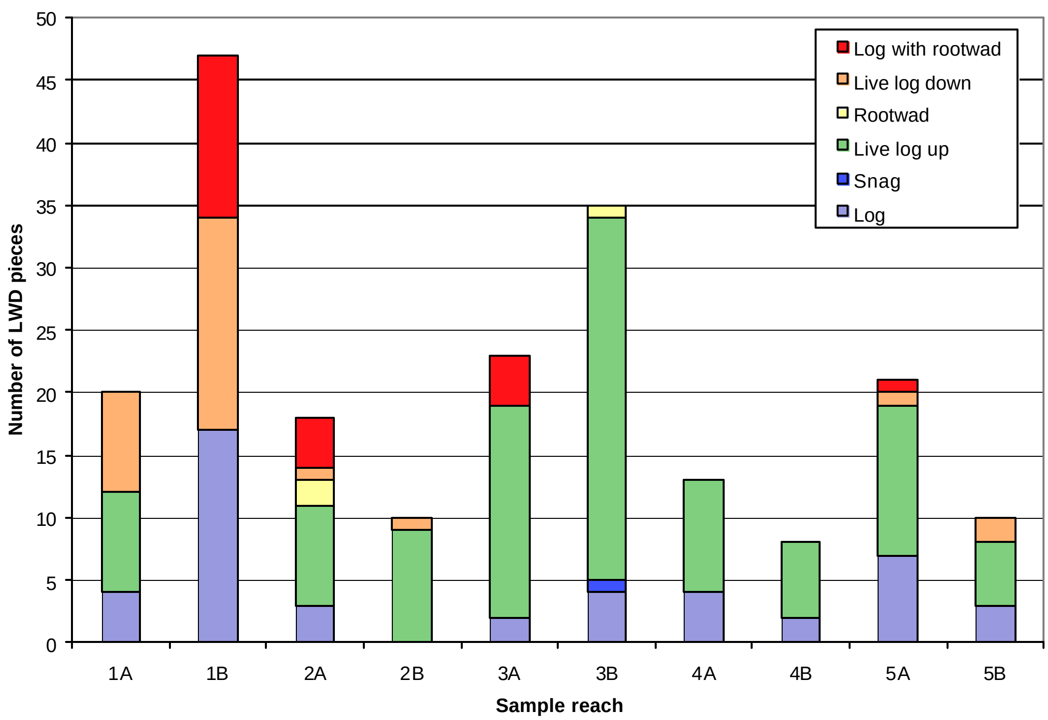

Figure 15. Number, position, and form of large woody debris (LWD) per reach.

Pools

A total of 74 pools were measured in the 10 sample reaches of Carneros Creek. The causes of pool formation were categorized into five classes (after the California Department of Fish and Game Salmonid Stream Habitat Restoration manual, Flosi et al., 1998): step-pools, plunge pools, dammed pools, main channel/ bedrock trench pools, and lateral scour pools. Lateral scour pools comprise 70% of all pools measured, followed by main channel/bedrock trench pools, step pools, and dammed pools (Figure 16).

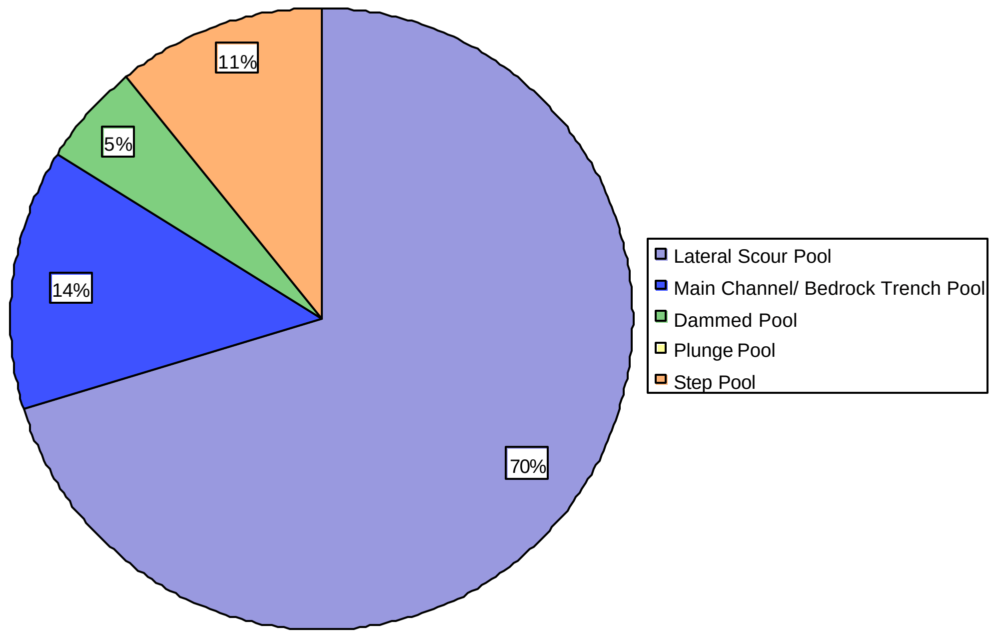

Figure 16. Percentage of each pool class measured in the 10 sample reaches combined.

The type of pool formed generally follows a spatial pattern related to channel geometry (Figure 17). For example, step-pools only form in the upper watershed, in reaches 5A and 5B, and dammed pools only form in the middle and lower reaches, 1B and 2B. Lateral scour pools are the most prevalent because many objects are in-channel and available for scour, including boulders, bedrock, and LWD pieces. With the exception of 4B and 5B, all reaches have an average pool spacing of less than five bankfull widths between each pool, with pools in most reaches spaced less than three bankfull widths apart (Table 9). Although management efforts could focus on increasing the total number of pools in these upper reaches by increasing the number of in-channel LWD pieces, and fully fencing animals out from the stream, these efforts may not be the highest priority. Reach 5B is upstream of a reservoir, and reach 4B is dry during the summer and fall, with both factors limiting the habitat value of an increased number of pools.

Table 9. Carneros Creek average pool spacing.

Reach	Reach length (m)	Number of pools	Average pool spacing (in bankfull widths)
1A	175	6	4.2
1B	149	5	5.0
2A	287	9	2.8
2B	175	8	3.1
3A	175	10	2.5
3B	170	11	2.3
4A	112.5	9	2.8
4B	100	4	6.3
5A	112.5	9	2.8
5B	62.5	3	8.3

Nearly half of all pools measured are either formed by or are associated with LWD in Carneros Creek (Figure 18). A pool that is associated with LWD is defined by the LWD piece being present, however, the piece is not one of the primary factors contributing to the pool formation. 25% of all pools measured are directly formed by LWD, and an additional 20% are associated. Clearly, in-channel LWD presence plays an important role in the watershed, both contributing to pool formation, as well as providing cover and complexity for existing pools.

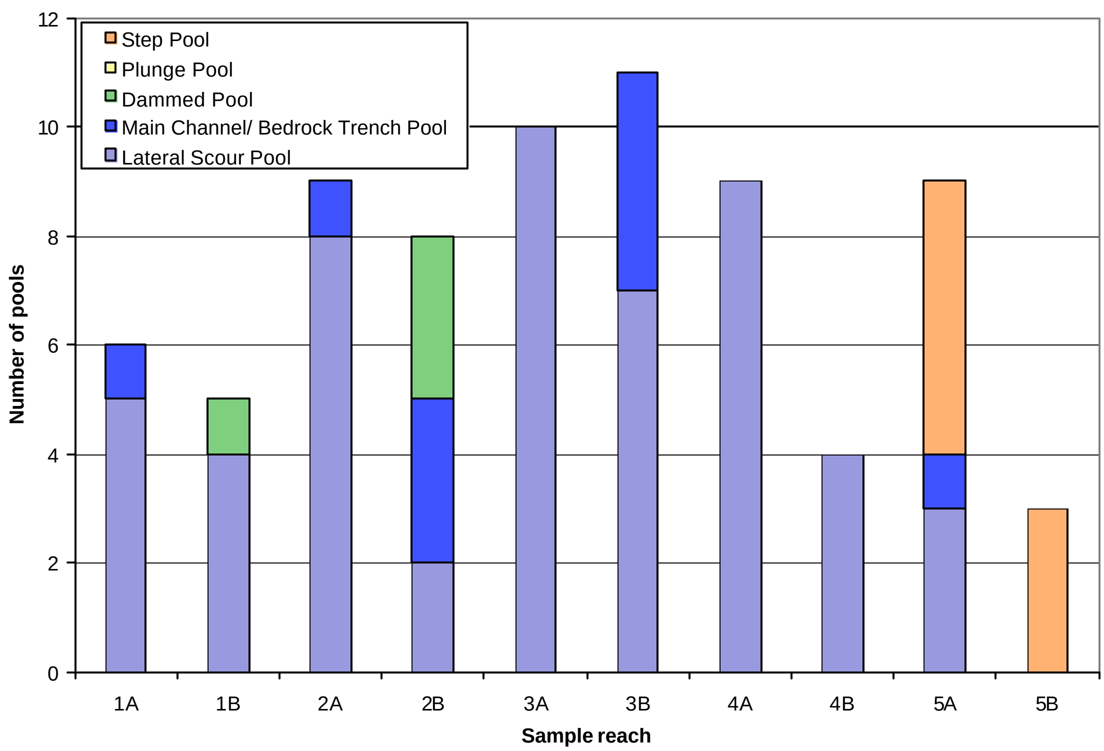

Figure 17. Number and class of pools in each sample reach.

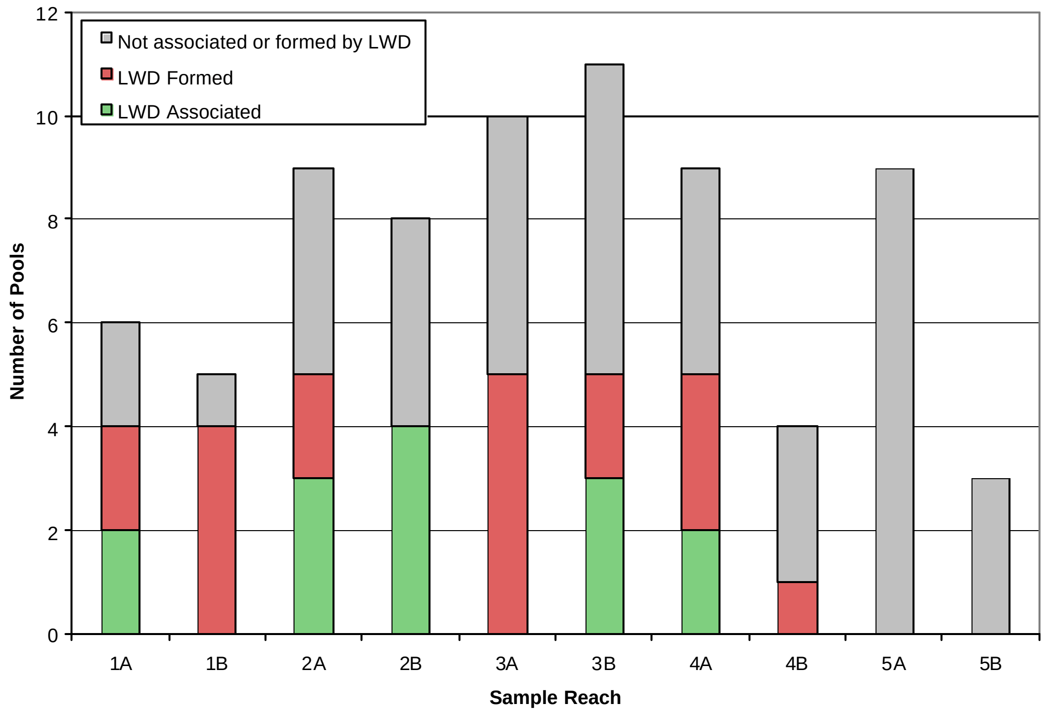

Figure 18. Number of pools formed or associated with LWD in each sample reach.

Pools measured in Carneros Creek were segregated into residual depth size classes, ranging from 0.2 – 0.4 m up to >1 m in depth (Figure 19). Pools in every size class are measured in Carneros Creek, with generally the larger and deeper pools located in the lower reaches of the creek. The deepest pools tend to be either lateral scour or main channel/ bedrock trench pools, while the shallowest tend to be step-pools, reflecting the influence of bankfull cross-sectional area and pool-formative agent upon pool residual depth. Residual depths occasionally exceed 1 m, primarily in scoured bedrock pools, but residual depths are usually < 0.8 m. Pool residual depth is inversely related to reach slope; as slope increases, residual depth decreases (Figure 20). This reflects the greater stream power and ability to scour deeper pools in the lower reaches of the channel. Pools with the greatest residual depths are found in reaches with slopes ranging between 0.5 and 1.5%.

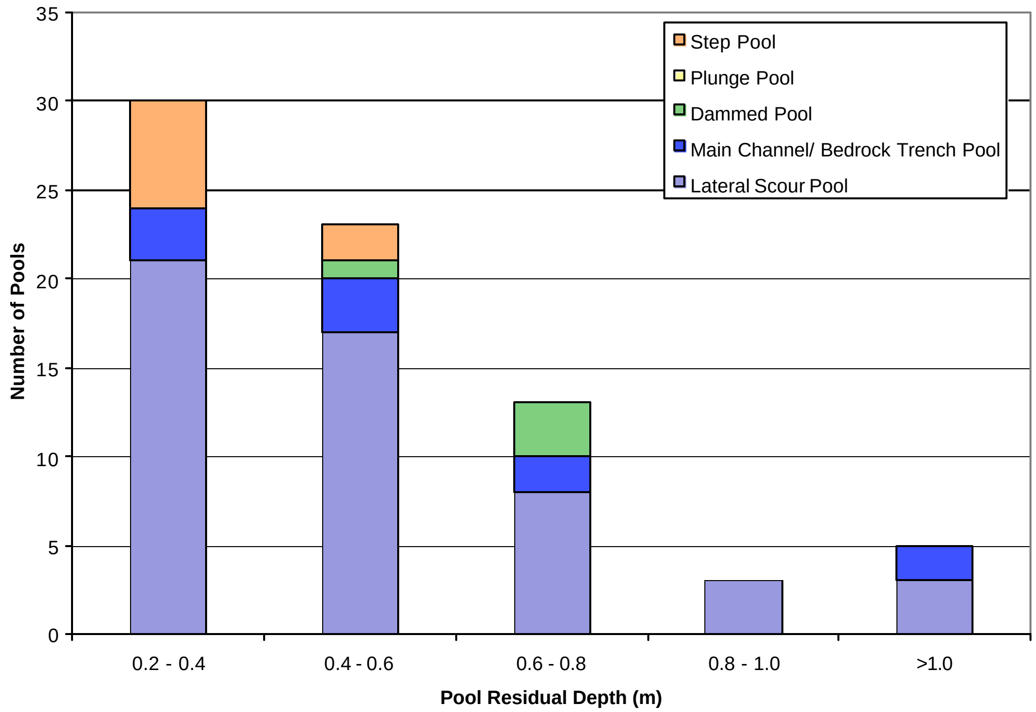

Figure 19. Number of pools per residual depth class and their associated cause for all sampled reaches.

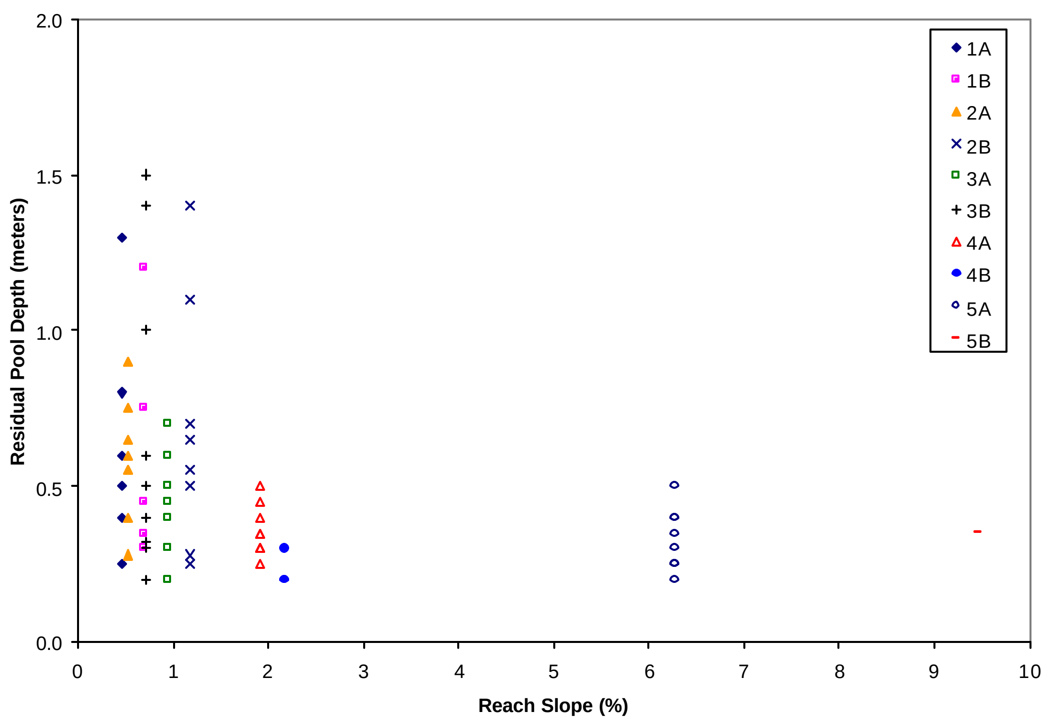

Figure 20. Residual pool depth versus reach average slope.

Sediment deposits and bars

The number, type, and volume of sediment deposits and bars were measured in each of the 10 sample reaches of Carneros Creek. The total volume of each deposit type is calculated, with point bars comprising the largest volumetric proportion (Figure 21). The total number of deposits measured varies from 7 in 2B to 31 in 2A, with most reaches ranging between 10 and 20 deposits measured. Pool deposits comprise the highest number of deposits measured, followed by active channel deposits and forced bars, with the three types combined making up nearly 75% of all deposits measured. While pool deposits and forced bars are found in all reaches, active channel deposits and other various bar types vary spatially relating to bankfull channel cross-sectional area and dominant fluvial processes at that location in the watershed (Figure 22). For example, alternate and point bars only form in the lower reaches, where cross-sectional area and discharge are large enough for these bar types to form.

The volume of material currently stored in each reach is calculated based upon the amount of sediment measured during field data collection. The percentage of sediment stored in each reach varies from reach to reach (Figure 23). Reach 2A is storing the largest percentage of sediment (30% of the total), followed by 3A, 3B and 1A. Strata IV and V are only storing 17% of the total amount of sediment measured, reflecting the smaller cross-sectional area, and the position in the watershed. Reach 2A is storing such a large volume of sediment because the reach is slightly wider than other reaches, and has a lower gradient than either up or downstream. With the decrease in slope and increase in accommodation space, stream power decreases, encouraging the deposition of bars and pool deposits.

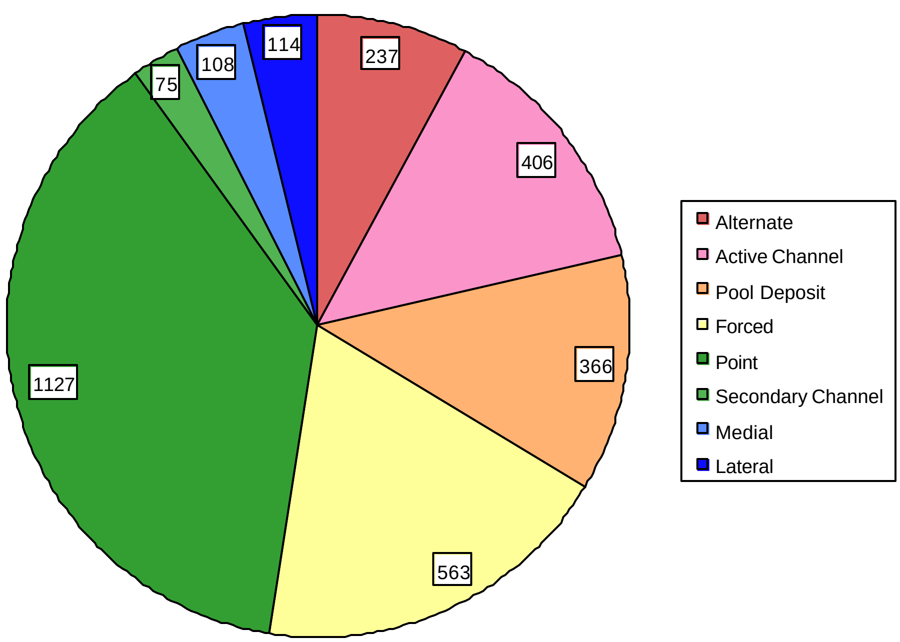

Figure 21. Volume (m^3) and type of sediment deposits measured in all 10 sample reaches.

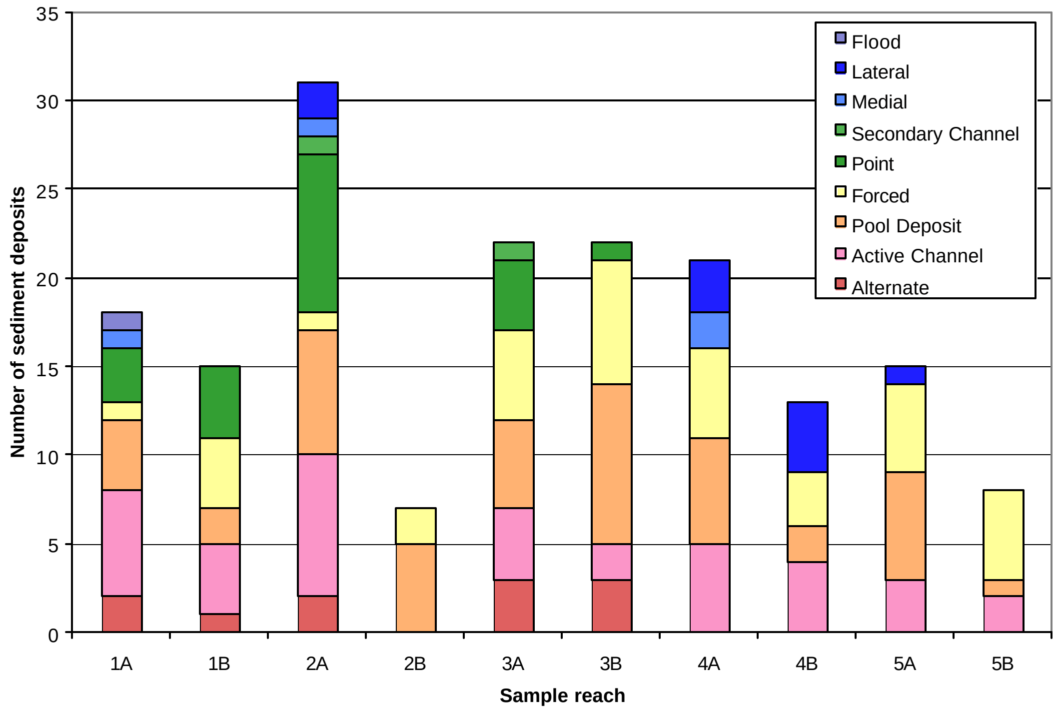

Figure 22. Number and type of sediment deposits in each sample reach.

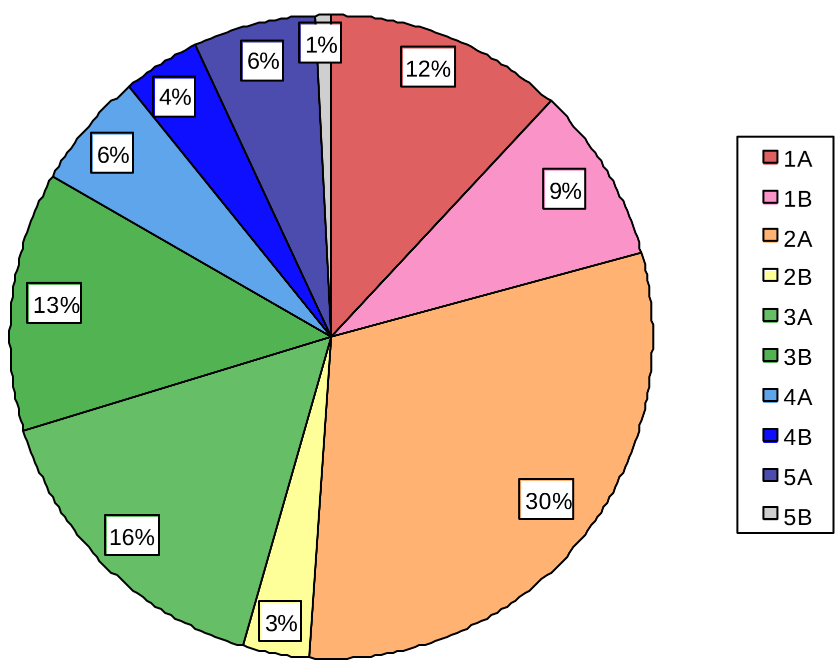

Figure 23. Volumetric contribution of each sample reach to the total volume of measured sediment deposits in all sample reaches.

The total volume of material stored in each sample reach is dependant upon the length of the sample reach. To account for the various sample reach lengths, total sediment storage was normalized, giving sediment volume per unit channel length (in m^3/m) (Figure 24). Reach 2A has the greatest storage per unit channel length, but reaches 3A and 3B also have high sediment storage relative to other reaches. Reach 5B has a low sediment storage per unit channel length due to the narrow channel width and steep gradient. Reach 2B also has low sediment storage but in this case due to a bedrock trench decreasing bank roughness and increasing sediment transport capacity. A positive relationship exists between reach-total bar volume and bankfull cross-sectional area; generally as cross-sectional area increases, reach-total bar volume will also increase (Figure 25). The outlier to this relationship is reach 2B, again, relating to its unique bedrock morphology.

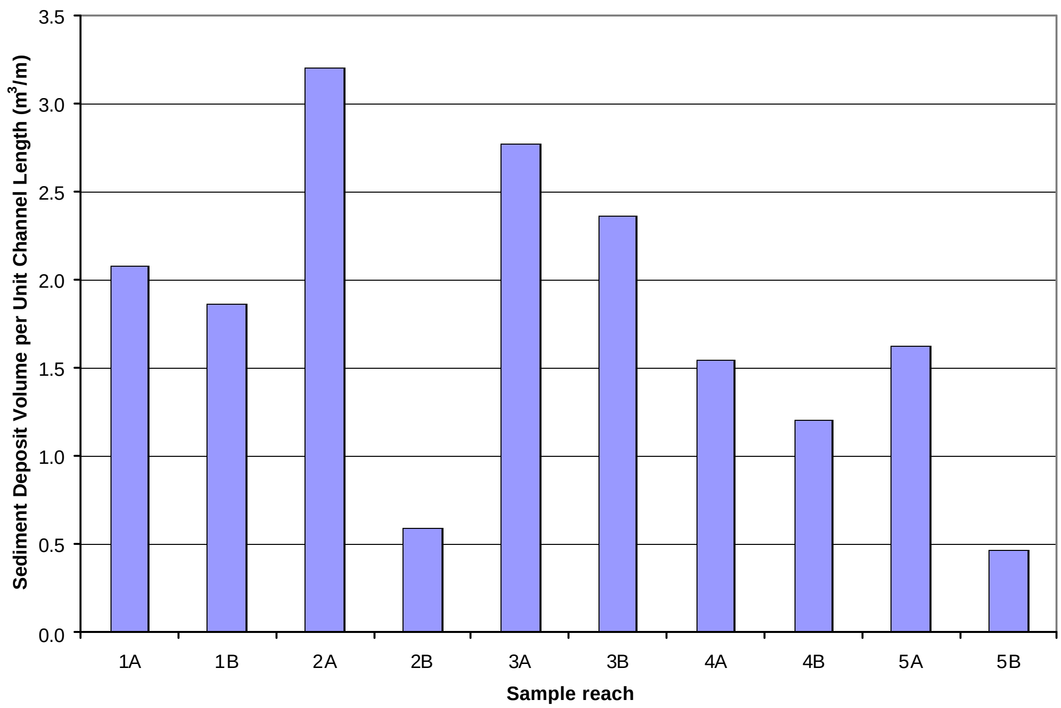

Figure 24. Calculated sediment deposit volume per unit channel length in each sample reach.

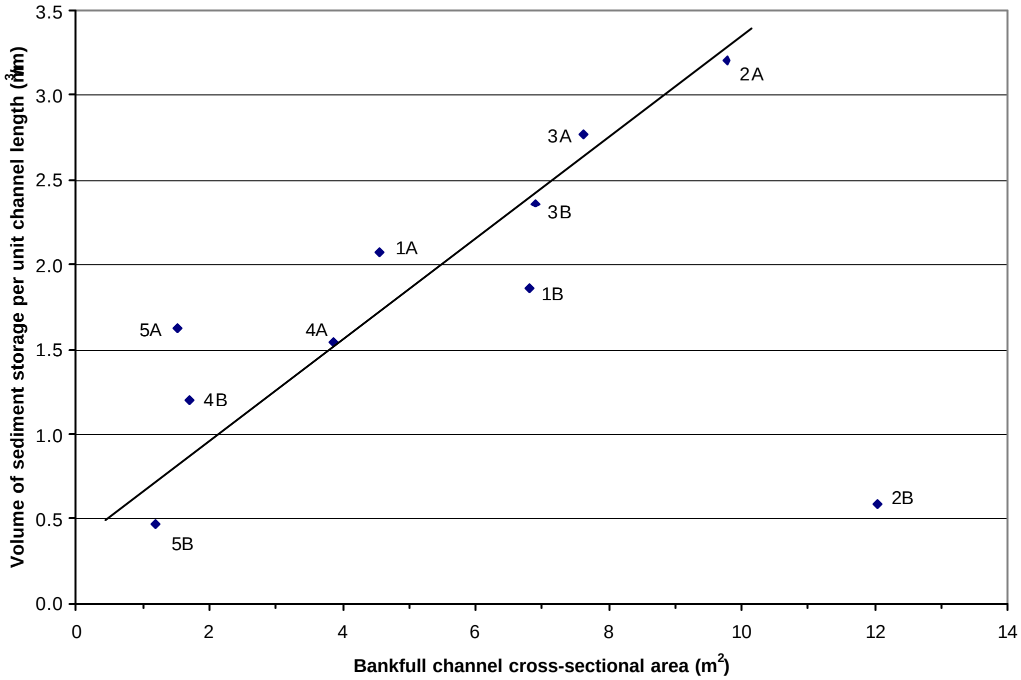

Figure 25. Bankfull channel cross-sectional area versus sediment deposit volume per unit channel length. A generalized trend line is shown for the data points, excluding reach 2B.

The volume of material stored in each deposit is calculated based on field data, and used to segregate individual bars into volume size classes. In Carneros Creek, an inverse relationship exists between the number of bars measured in a particular size class, and the proportion of total bar material in that size class. For example, deposits with a volume greater than 8 m^3 comprise only 50% of the total number of bars measured, but comprise 90% of the total volume of material measured. The volume size class of an individual bar typically relates to the position of the bar in the watershed; generally larger bars are located lower in the watershed, and smaller bars located higher in the watershed. The large volumetric bars tend to have higher elevations above the bed, with the majority of the sediment out of the wetted channel. Alternatively, the smaller volumetric bars tend to have lower elevations above the bed, are usually located in the wetted channel, and are more accessible for spawning habitat. In particular, stable active channel deposits and small forced bars that remain wetted until steelhead fry emergence (approximately 30-60 days) represents patches of potential spawning gravel.

In alluvial channels typically as drainage basin area increases, reach-total sediment deposit volume will also increase. This relationship is weakly defined in Carneros Creek (Figure 26). In reaches 5B through 3A, as drainage basin area increases, reach total sediment storage volume also increases. However, the lower reaches do not follow the trend. Reach 2A is storing more sediment than expected due to its wide cross-sectional area and low slope, while reach 2B has very low sediment storage due to its unique morphology. Reaches 1A and 1B are the most entrenched reaches, with the highest stream power, making it difficult for volumetrically large and wide bars of sediment to deposit and remain stable.

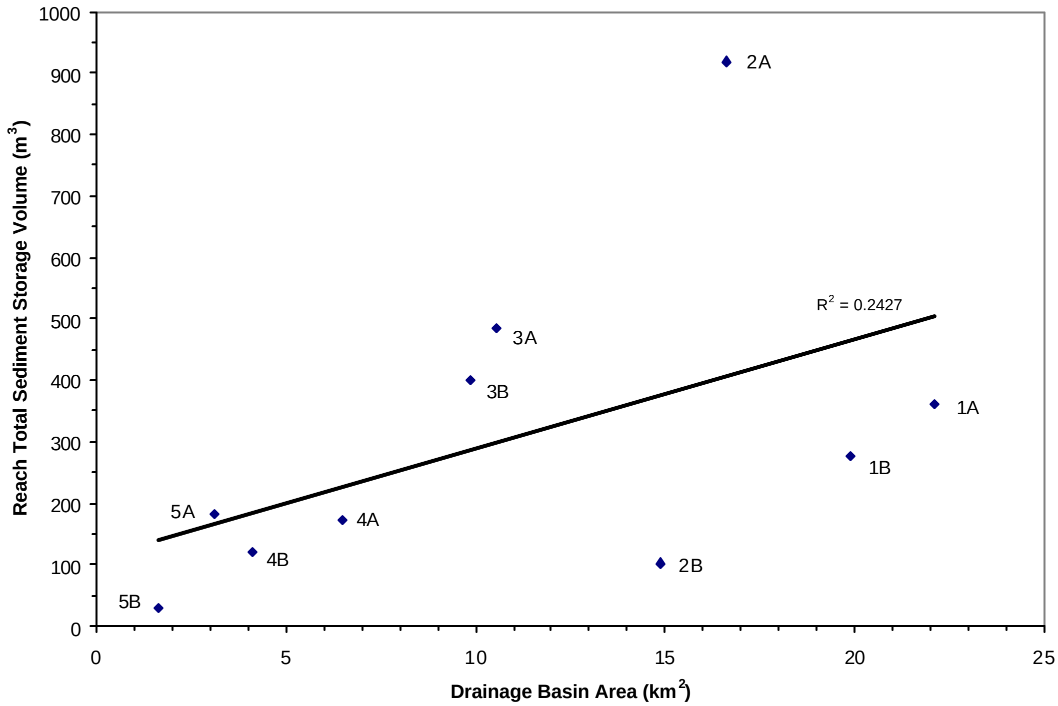

Figure 26. Drainage basin area (km^2) versus reach total sediment storage volume (m^3).

The stability (age) of bars and sediment deposits affects the availability of sediment for spawning, and for the potential source of sediment for the channel to re-work during floods. The age class of sediment deposits was estimated in the field based on the position of the deposit in the bankfull channel, the size distribution of the deposit, and the approximate age of vegetation on the deposit, if any (Figure 27). The <1 year age class represents fine-grained deposits in pools and in the active channel that would be entrained in high frequency flow events. The 1-5 year class represents deposits with coarser surface textures, young shrubs, and seedlings and herbaceous vegetation, often with upper surfaces above the active channel, but within the bankfull channel. The 6-19 year class and the >20 year class represent deposits at elevations above the bankfull channel, but lower than adjacent terraces, that often have older vegetation and trees colonizing the surface. In Carneros Creek, 44% of all deposits are in the <1 year age class, 48% are in the 1-5 year class, and 8% are in the 6-19 year class. The recent high magnitude, low frequency floods in 1995 and 1997 are probably responsible for a majority of the 1-5 year deposits. Overall, Carneros Creek has a large amount of stored sediment available for transport in a fairly low magnitude flood event.

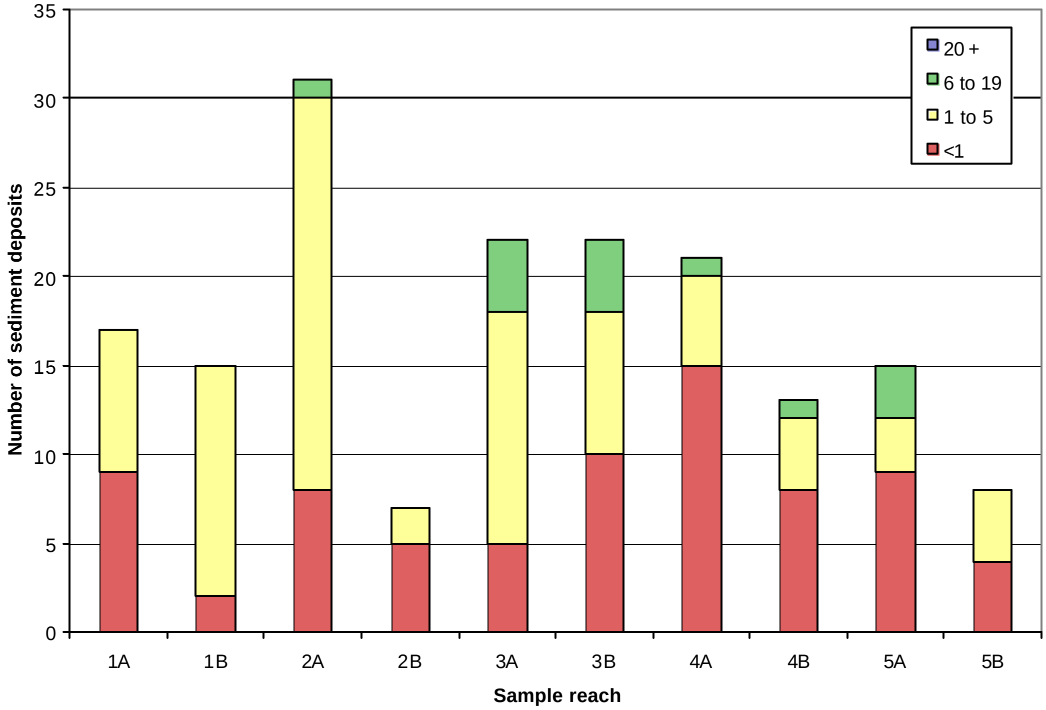

Figure 26. Distribution of estimated age (years) of sediment deposits measured in each sample reach.

When the total volume of sediment in each reach is normalized to the reach surface area (sediment volume in m^3 per unit channel surface area in m^2) a simple measure of sediment storage, depth in meters, allows comparison from reach to reach (Figure 28). Sediment deposits are grouped into three general categories: pool deposits, active channel deposits, and bars. A reach average depth of sediment storage is shown for each category. The majority of sediment in Carneros Creek is stored in the form of bars, however in some reaches, pool deposits and active channel deposits comprise half of the total sediment storage. For example, pool deposits comprise 60% of all sediment stored in reach 2B, and active channel deposits comprise 56% of all sediment in reach 4B. However, because of the unique bedrock trench morphology of reach 2B, bedrock scour pools provide nearly the only place for sediment deposition, thus a large percentage of pool deposits should not be surprising. This metric has implications for salmonid spawning and rearing; pool deposits can decrease the total volume of pools for rearing, while active channel deposits supply a majority of the gravels for spawning. For example, in reach 3B, 83% of all sediment is stored in bars, 15% in pool deposits, and 2% in active channel deposits, potentially a limiting factor in the use by salmonids for spawning.

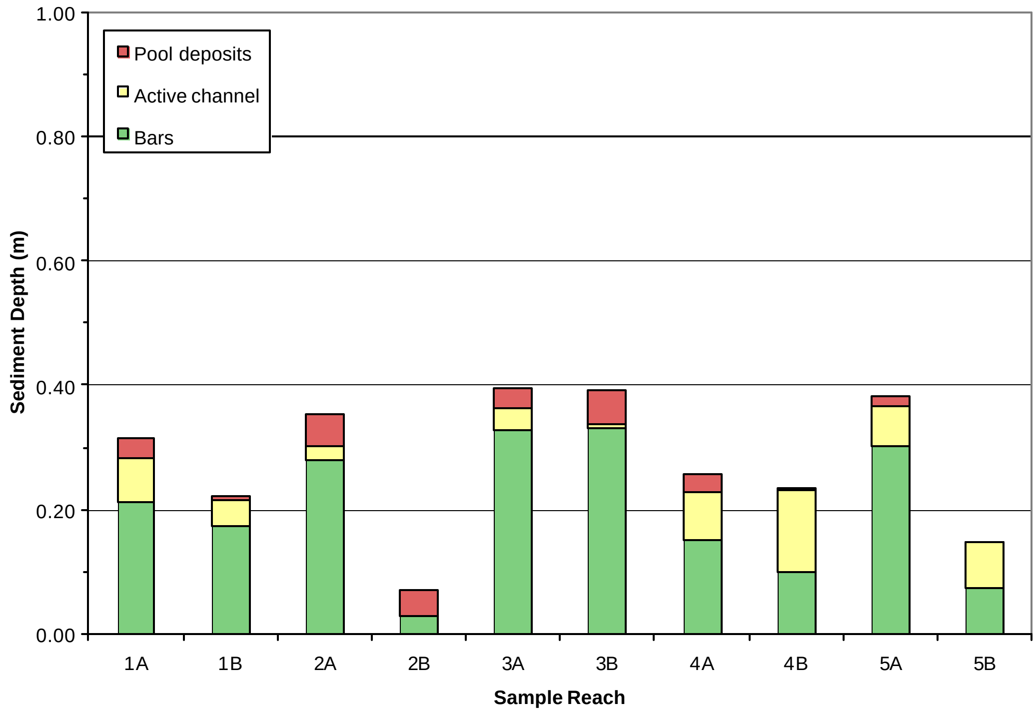

Figure 28. Volumetric percentage of pool deposits, active channel deposits, and all types of bars measured in each sample reach.

Bank erosion and revetments

A total of 2,300 m^3 of bank erosion was measured in the 10 sample reaches of Carneros Creek (Figure 29). Reach 3A has the largest total amount of erosion measured (647 m^3), followed by reaches 3B, 2A and 4A, with these four reaches containing 70% of all erosion measured. The average bank erosion per unit channel length is also calculated from this data (Figure 30). Again, reach 3A has the highest erosion per unit channel length, but using this measure, reaches 4A, 3B and 5A have the next largest volumes of erosion, respectively. An estimate of the age of erosion that was measured allows the erosion rate to be calculated (Figure 31). 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. The visible erosion could have occurred slowly over several years, or quickly in just a few years. However, these observations do provide a quantitative comparison of the relative age and magnitude of bank erosion, as well as an estimate of approximate minimum erosion rates within each sample reach. A majority of erosion measured in Carneros Creek is based on indicators that are at least 50 years old, suggesting that most erosion has occurred over a long period of time. However, some reaches such as 3A and 5A have significant proportions of erosion that has occurred in the past 20 or fewer years. These reaches are areas where management efforts could potentially reduce the total amount of sediment supply to the channel from bank erosion.

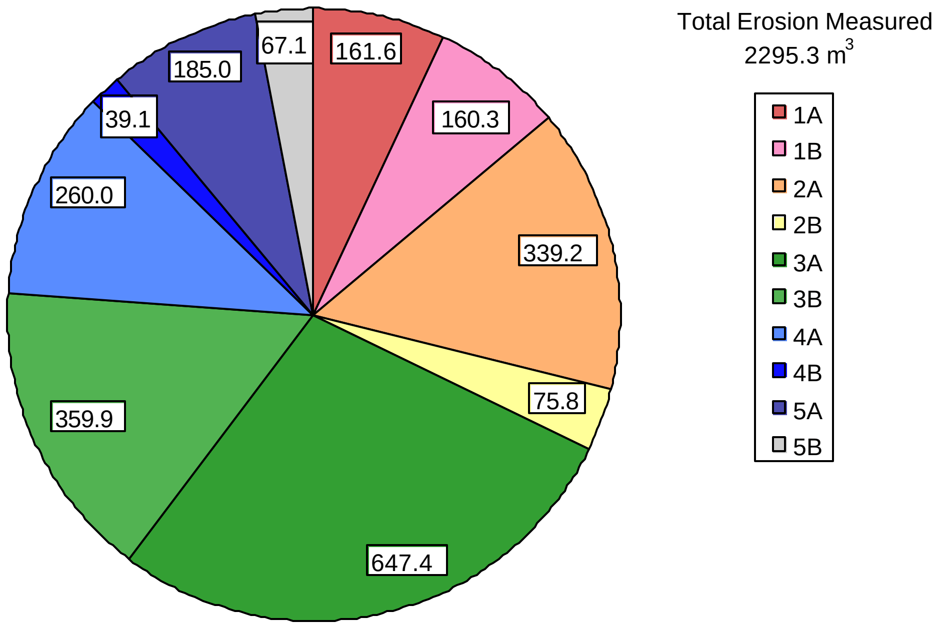

Figure 29. Total volume of measured bank erosion in each sample reach (m^3).

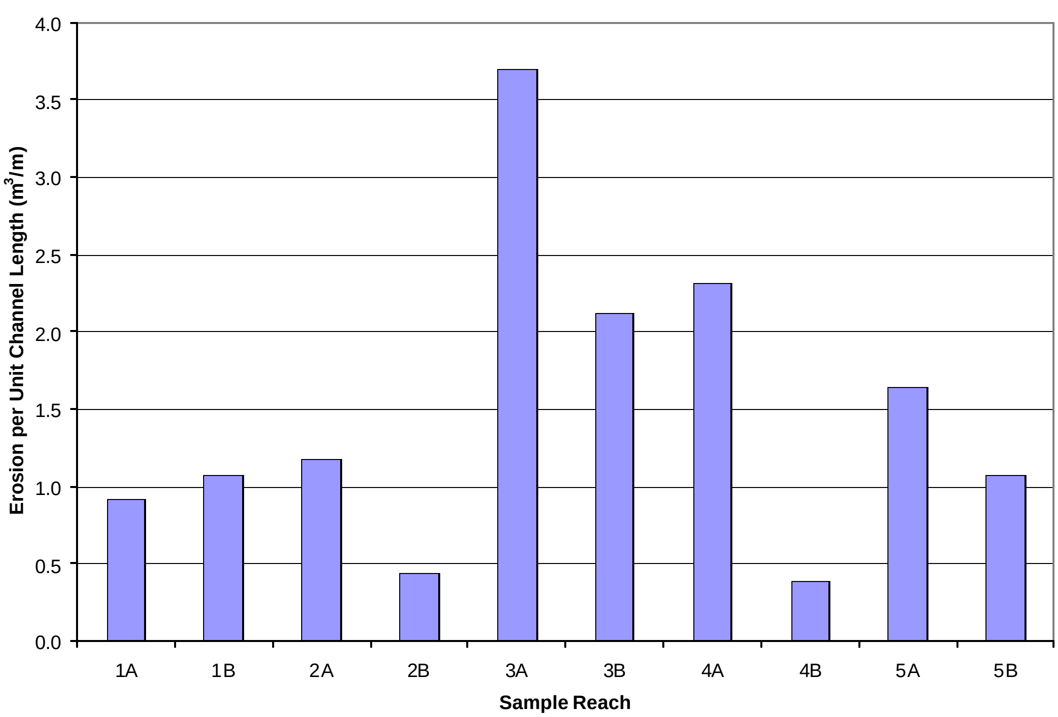

Figure 30. Average bank erosion volume per unit channel length in each sample reach.

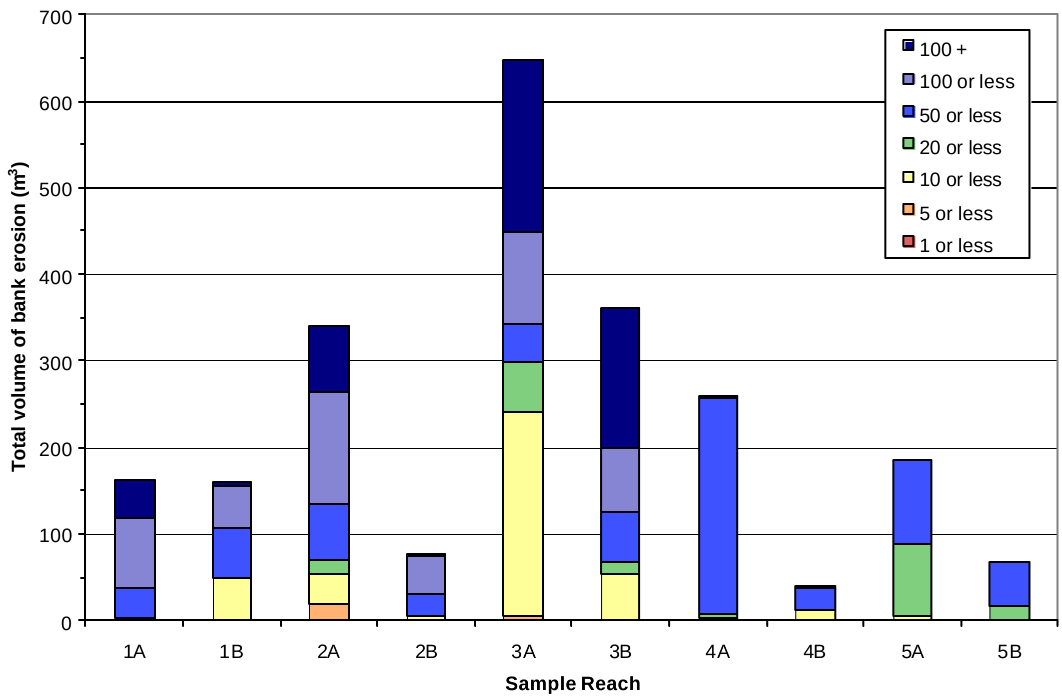

Figure 31. Age estimates associated with measured erosion in each sample reach.

Using the amount of lateral bank erosion measured, and associated age class estimates made in the field, an average rate of lateral erosion for each erosion age class in each sample reach can be calculated (Figure 32). These rates of retreat are for portions of the sample reach that are actively retreating, and thus, represent the highest rates of erosion in each sample reach. In seven out of 10 sample reaches, erosion that has occurred in the past 10 years has the highest rate. Of the remaining three reaches, two have the highest rates occurring in the 20-year age class, and one reach has the highest rates in the 5-year age class. In all reaches, the 50-year and 100-year age classes have the lowest rates of erosion. Some reaches, particularly reach 3A and 4B, have higher rates of erosion. The high rate of erosion measured in the 10-year age class in reach 3A represents two locations where the bank has collapsed and slumped into the channel, likely due to the natural processes of wood recruitment into the channel. The 10-year age class erosion in reach 4B represents a single location where a bank also has failed and slumped into the creek, however, it is unclear at this location if past bank trampling contributed to the collapse. It appears that erosion within the past 10 years has been at a greater rate compared to erosion occurring over longer time periods. This is likely due to the erosion that occurred in the high flow events of 1995 and 1997. The real or perceived higher rates of recent erosion are likely due to the presence of more indicators of erosion that are likely to still exist from erosion that occurred 10 years ago, compared to 100 years ago. For example, exposed tree roots will rot and snap off after a certain length of time, preventing the older erosion from being measured. Any recent erosion could remove the older indicators, essentially “resetting the clock”. All of these caveats aside, a majority of erosion observed in Carneros Creek has occurred in the past 10 years.

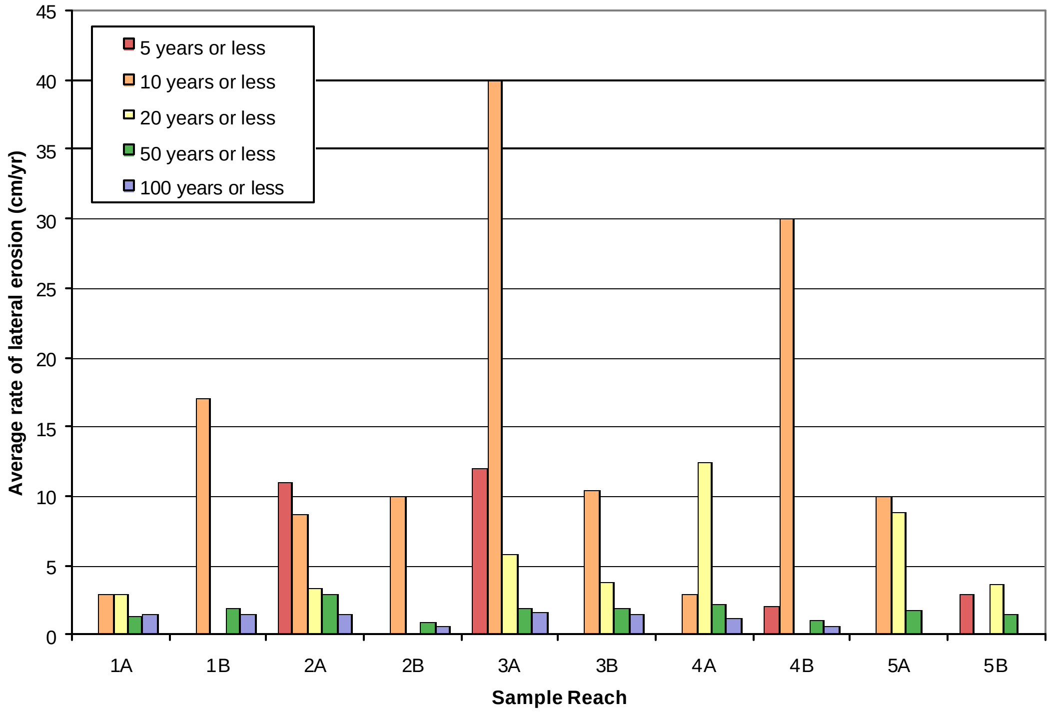

Figure 32. Average rates of lateral bank erosion (cm/yr) in each sample reach.

Modifications made to the banks of the channels, including erosion control measures only occur in the lower reaches of the watershed (Figure 33). These bank revetments include riprap, poured concrete slabs, and stacked concrete or stone walls placed along the banks. Reach 1A clearly has the longest length of bank with revetments; the channel in this reach is fairly narrow and deeply entrenched. Without the riprap, high flow events would likely saturate the bank, reducing its strength, and causing the bank to erode, threatening the property and structures along the banks. The revetments in reaches 1B and 2A are not nearly as continuous or recently emplaced. It is important to remember that measurements of erosion in reaches with erosion control devices are minimum measures, because the devices limit the amount of erosion occurring.

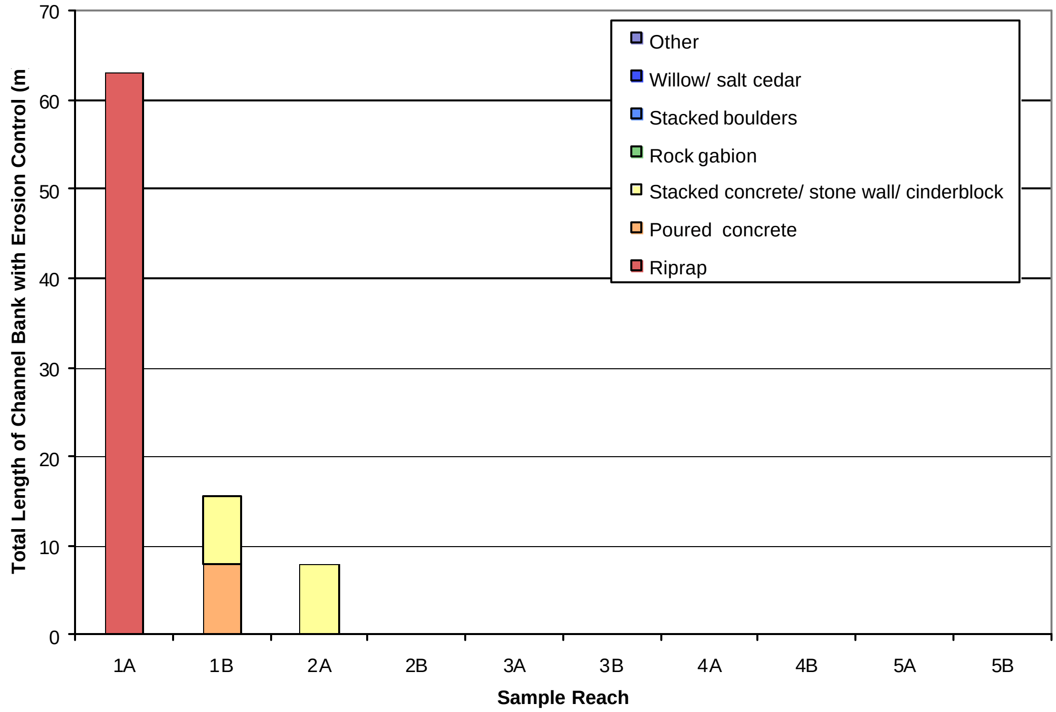

Figure 33. Type and percent of measured channel banks with erosion control revetments.

Bank characterization

Characteristics of the banks observed at three locations in each sample reach are reported (Table 10). The composition of the bank, as well as the types and age of vegetation on the banks have a direct correlation to the susceptibility to erosion of the bank because the vegetation increases the shear strength of the bank when it is well rooted and established. In addition, the terrace vegetation and land use was also characterized (Table 11). In all reaches, canopy cover was found to be in excess of 50% and mostly in excess of 75%. Canopy cover is important for providing stream shading that reduces evaporation and maintains cool water temperatures, and also providing cover for salmonids to reduce predation. Riparian vegetative canopy cover does not appear to be a limiting factor for the aquatic habitat in Carneros Creek. Riparian zone vegetation plays a large role in stream health, providing shade for the stream necessary for stable and cool water temperatures, carbon and plant nutrients for fueling the in-stream food web, bank stabilization, as well as providing a source for the recruitment of LWD.

The characterization of materials comprising the bank for each sample reach correlates reasonably well with general channel morphology and total measured bank erosion. Reaches 1A, 1B and 2A all have a bank composition of consolidated silty alluvium, relatively tall banks, and sparse bay and other tree species roots as the primary bank vegetation. These reaches are highly entrenched, with large proportions of bank revetment and moderate amounts of bank erosion. Reaches 3A, 3B and 4A generally have a bank composition of coarser alluvium, soil profiles, and some bedrock outcrop.

The coarser alluvium contains less clay than the silty alluvium, reducing its resistance to erosion. The bank composition of reaches in the upper watershed generally includes cobbles and boulders, increasing the bank strength and resistance to erosion. Because bank vegetation is generally similar throughout the majority of the watershed, bank composition and hydrologic factors appear to be more important in determining bank strength and erosion potential.

Table 10. Average bank characteristics for each sample reach.

Reach	Bank composition	Bank slope	Bank vegetation type	Bank vegetation age (years)	Bank vegetation condition	Bank height (m)
1A	Consolidated silty alluvium, riprap	35°-75° (50°)	Roots of bay, walnut, maple, grasses, blackberry, thistle	100	Sparse	5.5
1B	Consolidated silty alluvium with some cobbles	25°-60° (45°)	Roots of bay, blackberry, grasses, woody shrubs	<50	Sparse roots, dense blackberry	4.0
2A	Consolidated silty alluvium grading up to gravels	25°-80° (55°)	Roots of bay, maple, oak, grasses, blackberry, woody shrubs	100	Sparse roots, moderate blackberry	5.0
2B	Bedrock with soil profile, fine alluvium	34°-70° (48°)	Roots of bay, oak, grasses, woody shrubs, sedge, snowberry, blackberry, weeds	100	Moderate	4.0
3A	Cobble supported alluvium, overlain by fine alluvium and colluvium	17°-66° (47°)	Roots of bay, oak, grasses, weeds	100	Sparse roots, moderate grasses	4.5
3B	Sandy alluvium with some gravel and cobbles, bedrock	15°-90° (75°)	Roots of bay, oak, grasses, nettle	100	Sparse roots, dense grasses	4.0
4A	Bedrock, sandy cobble soil profile	20°-80° (50°)	Roots of bay, grasses	<50	Sparse	2.5
4B	Sandy soil, with some cobbles	10°-60° (30°)	Oak, grasses, weeds, Bay, thistle, snowberry	<50	Sparse	1.5
5A	Boulders, Cobble supported soil profile	35°-80° (65°)	Poison oak, roots of bay, ferns, vines, grasses, sedge, nettle	<50	Moderate	3.5
5B	Silty soil, some boulders	20°-45° (30°)	Roots of bay, oak	<50	Sparse to none	1.0

Table 11. Average riparian characteristics for each sample reach.

Reach	Riparian vegetation type	Riparian vegetation age (years)	Riparian width (m)	Terrace land use	% canopy cover
1A	Bay, Oak, Eucalyptus, Maple, Walnut	100	5	Residential, driveway	75
1B	Bay, Oak, Maple, Eucalyptus	100	15	Natural, vineyard road	100
2A	Bay, Maple, Oak, Buckeye, blackberry	100	15	Golf course, vineyard	75
2B	Oak, Bay, Walnut, Willow, Buckeye	100	8	Vineyard	75
3A	Oak, Bay, Walnut, Maple	100	15	Natural, grazing, vineyard	75
3B	Oak, Bay, grasses	100	20	Natural, grazing	75
4A	Bay, Oak, Maple, Buckeye	<50	10	Grazing	75
4B	Oak, Bay, Ash	<50	15	Grazing	50
5A	Bay, Buckeye, Oak, Maple	<50	15	Natural, grazing, dirt road	50
5B	Bay, Oak, Conifer	<50	15	Goat grazing	100

Channel hydraulic geometry

The bankfull width and depth measurements taken in each sample reach of Carneros Creek help constrain the lower end of a regional relationship between drainage basin area (discharge) and the bankfull channel cross-sectional area. A general linear relationship exists between watershed area and channel cross-sectional area (Figure 34). Reaches 1A and 1B appear to have a slightly smaller than expected bankfull cross-sectional area, while reach 2B appears to have a slightly larger than expected area. These results could be due to the obscuring of field bankfull indicators in entrenched reaches. However, reach 1A has the highest amount of bank revetment (riprap), limiting the amount of cross-section modification the channel can make, and possibly contributing to the lower than expected bankfull cross-sectional area.

A positive relationship exists between reach total measured bank erosion and reach total volume of sediment stored (Figure 35). Often, sediment that is eroded from the banks is locally stored, causing this positive relationship. Two reaches are outliers; reach 2A, and reach 3A, with higher volumes of storage, and erosion, respectively. Aside from one outlier (Reach 1B), the D84 of the grain size distribution is correlated with bed shear stress as is usually observed in channel networks (Figure 36 and Table 12). The median grain size, D50, is not correlated with shear stress, reflecting the relatively high degree of mobility of D50 sediment sizes in general, and local variation in sediment supply throughout the channel network.

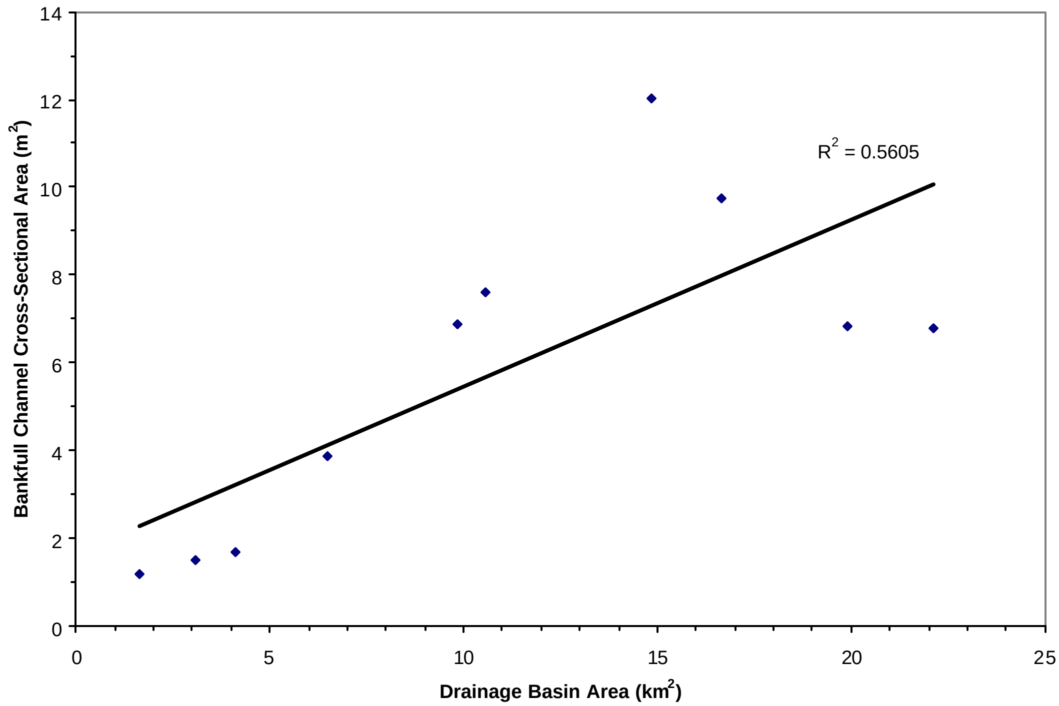

Figure 34. Drainage basin area versus bankfull channel cross-sectional area.

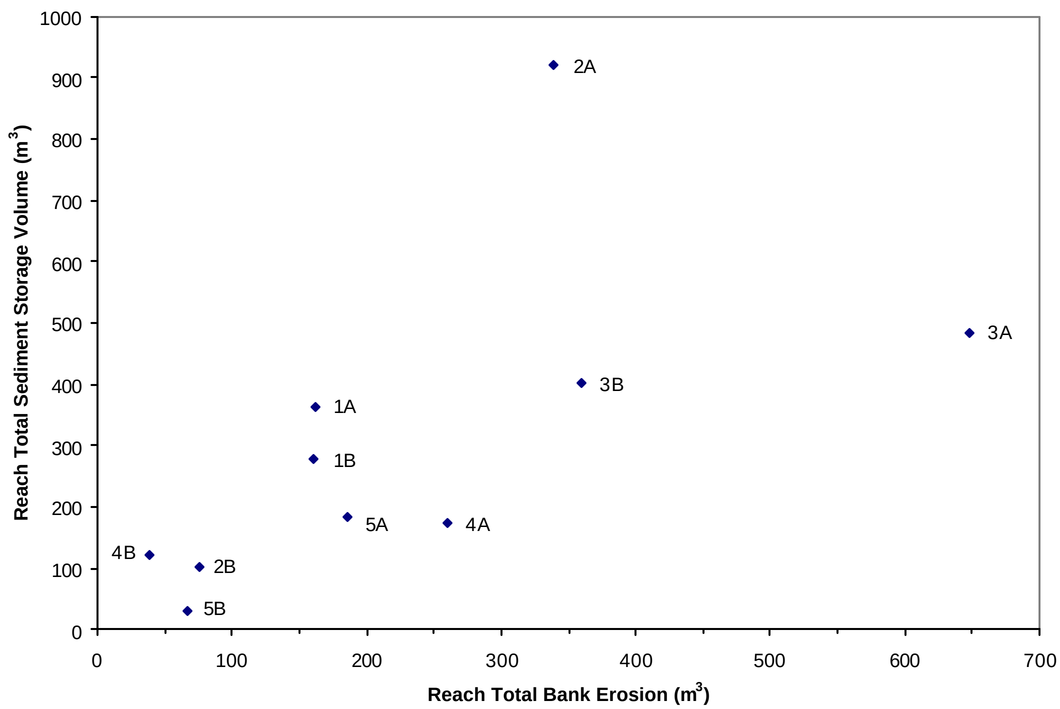

Figure 35. Reach total measured bank erosion (m^3) versus reach total sediment storage volume (m^3).

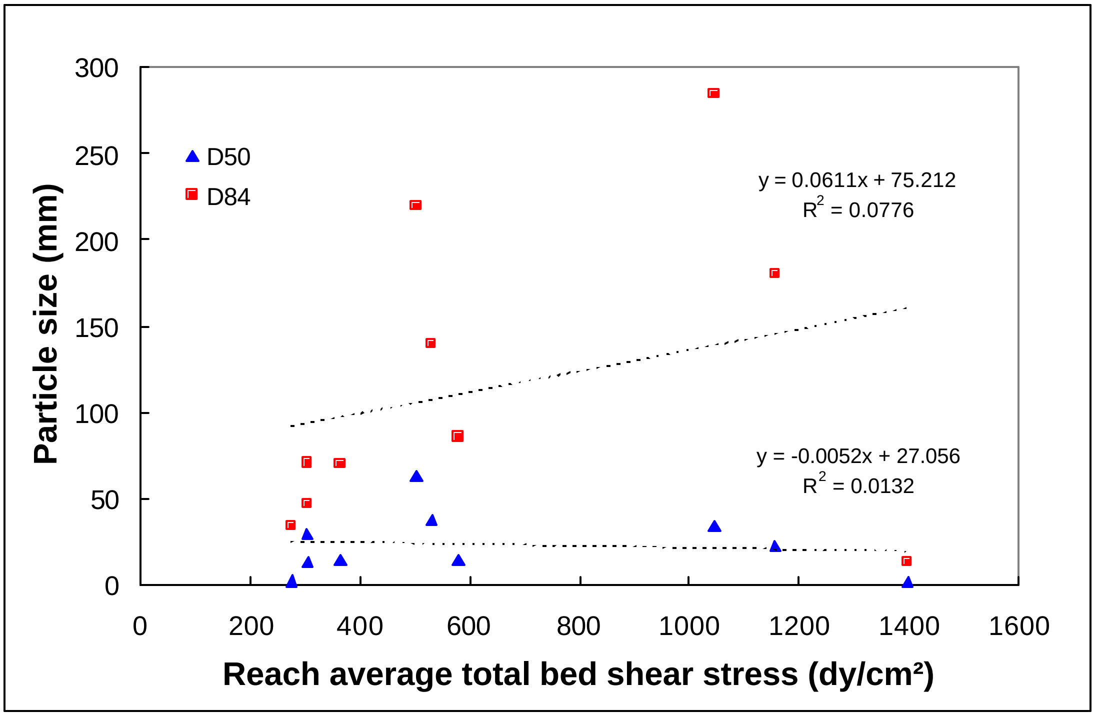

Figure 36. Reach average total bed shear stress versus particle size for each sample reach.

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

Reach	Estimated total bed shear stress (dy/cm^2)	Estimated threshold shear stress (dy/cm^2)	Ratio of total to threshold shear stress
1A	280	22	12.62
1B	300	252	1.20
2A	300	117	2.58
2B	1390	18	75.47
3A	580	126	4.59
3B	360	126	2.88
4A	530	320	1.66
4B	500	530	0.95
5A	1050	286	3.65
5B	1160	193	5.97

Bed shear stress in Carneros Creek generally decreases toward the bottom of the watershed. Reaches in Strata IV and V have consistently high shear stress owing primarily to increasing slope, despite the smaller channel size. There are two deviations from consistent downstream decline in shear stress. Reach 3B shear stress is about 50% lower than reaches above or below, suggesting the presence of a zone of local deposition or relatively low transport capacity. Reach 2B, in contrast, has high shear stress owing to a relatively steep and narrow channel. This reach is characterized by high bedrock exposure, and is a transition reach from the middle alluvial reaches and lower alluvial reaches of Carneros Creek.

Threshold shear stress is extremely low in Reaches 1A and 2B, where the majority of the streambed surveyed lies in long pools where fine sediment has accumulated. Most of the drop in stream elevation in these reaches occurs in relatively short, steep drops. Consequently, most of the bed is mantled by relatively fine material deposited during the recession of peak flows, and these deposits would be expected to be re-entrained relatively easily. In the middle reaches (2A, 2B, 3A, 3B), intermediate threshold shear stress values are found, suggesting that in these reaches, bed material is neither excessively fine nor excessively coarse.

DISCUSSION

Measurements of channel geometry (channel width, depth, slope, etc) help to indicate how the creek 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. From the channel geomorphology data collected, a series of management implications have arisen. The implications relate to: riparian vegetation, channel processes, sediment production and storage, and salmonid habitat in Carneros Creek.

Although the current riparian vegetation is fairly continuous along the lower reaches of Carneros Creek, the corridor and the functions that it provides are in jeopardy. The majority of the lower reaches have a corridor that consists of only a single mature tree in width. For example, reaches 1A and 1B primarily have mature (approximately 100 year old) bay laurel (bay) and oak trees, with lesser numbers of maple, eucalyptus, walnut, and other species (Table 11). These reaches currently have 75 to 100% canopy cover (Table 11), provided largely by a single row of mature trees located on the top edge of the bank. However, because these reaches are highly entrenched, many of these trees are being undercut, and with continued bank erosion, will eventually fall into the channel. The cross-section from sample reach 1A, Meter 175 illustrates a common entrenched morphology of the channel in these lower reaches (Figure 9). The large trees sit on the top of the bank, and often are overhanging, sometimes up to 2 meters. While these reaches currently have moderate amounts of bank erosion (about 1.0 m^2 per unit channel length, Figure 30), a single large storm event could cause significant erosion along the banks, undercutting many of these trees, causing many to fall into the channel. For example, the high rates of bank erosion in the 10-year age class in reach 1B likely represent discrete bank erosion events that occurred during the storm events of 1995 and 1997 (Figure 32). The addition of LWD pieces to the channel will increase pool-forming agents, and will increase habitat complexity and cover. However, if a single storm or wet season does cause the loss of a significant portion of the riparian canopy, the stream will receive less shading, potentially increasing water temperatures in pools. Additionally, with the loss of tree roots, the banks will have less strength, and will be more prone to increased erosion. Although a wider riparian width along the creek would likely provide shade and bank strength even with the loss of current single row of large trees, this may not be an easy solution due to the current proximity of other land uses to the creek. While the single-tree width riparian corridor found along a majority of the lower reaches of Carneros Creek is currently adequately functioning, it is in jeopardy of being significantly modified or lost by a single large storm event.

In-channel LWD appears to play a significant role in the physical functioning of Carneros Creek. A riparian vegetation corridor along the majority of the channel length provides a continuous source area for LWD recruitment. In-channel LWD pieces can be important roughness elements, inducing scour and the formation of pools in alluvial channels. The main pool-forming agents in Carneros Creek are lateral scour around boulders and bedrock, lateral scour around LWD pieces, main channel/bedrock trench pools, dammed pools and step pools (Figure 16). LWD is important in pool formation and quality of cover, with 45% of all pools measured either directly formed, or associated with LWD (Figure 18). With each sample reach having 8-47 pieces of LWD measured (Figure 15), pieces are available to induce pool-forming scour or to form LWD jams and actively do so. Median LWD loads per km of stream for second growth redwood forests in northern California are approximately 220 m^3/km, whereas loads for old growth forests are approximately 1,200 m^3/km (O'Connor Environmental, 2000). LWD loads in Carneros Creek average 87 m^3/km, ranging from 4 m^3/km to 438 m^3/km. Although not every sample reach contained a LWD jam, observations of other areas in the creek confirm that debris jams do occur throughout the watershed. These jams can help with the entrapment of sediment, including spawning gravels, while also encouraging the formation of deep pools. Besides sediment, LWD also regulates organic material movement through the system by providing temporary storage (Gurnell and Gregory, 1995), thus buffering any effects of a large storm, landslide, or large bank slump. Clearly LWD is important in Carneros Creek because it provides elements for pool formation, pool cover, and a mechanism for trapping sediment.

The middle reaches of Carneros Creek have the largest amount of bank erosion, with reaches 3A, 3B, and 4A supplying the largest volumes of sediment (Figure 29). A high rate of sediment supply to the channel, especially fine sediment, can threaten the quality of steelhead habitat in a number of ways, including reduced gravel permeability and reduced volume of pools. In the Carneros watershed, sediment is delivered to the creek from many sources, including direct input from bank erosion (Sediment Source Assessment). These middle reaches are underlain by bedrock, reflected by the highest percentage of bedrock outcrop measured in surface grain size samples (Table 6). The bedrock is slowing the rate of incision of the channel in these reaches, directing any work done by the channel onto the banks. These reaches are also more sinuous than other reaches, providing another possible mechanism for increased rates of bank erosion. The banks could be responding to an episode of past intensive land use which destabilized the banks and its vegetation. Yet another cause could be localized aggradation in these reaches, creating larger bars that deflect more flow onto the channel banks. Reaches that have erosion measured in all age classes, and of similar rates, typically represent more continuous bank erosion throughout the reach, compared to more isolated and punctuated events occurring in other reaches (Figure 32). Although these reaches are providing the largest volumes of sediment from bank erosion, large volumes of sediment are also being stored in these reaches (Figure 21). Reach 3B has nearly equivalent volumes of erosion and sediment storage, but reaches 3A and 4A have slightly more erosion than storage (Figure 35). The high volume of sediment in storage could reflect a slug of sediment that is moving through the watershed, and driving the formation of large bars. These reaches currently have a moderate to low impact from landuse; reaches 3A and 3B are adjacent to vineyard, and reach 4A is in an area grazed by cattle, but a majority of the stream is fenced off and lined by riparian vegetation. This large amount of sediment could be sourced from the localized bank erosion, a period of greater hillside mass-movements, or possibly from high intensity historic land use adjacent to this reach, in the upper watershed, or on the tributaries. Whatever the cause, the middle reaches of Carneros Creek currently have the largest amounts of measured bank erosion.

Based upon geomorphic data, the middle reaches offer the best spawning habitat for steelheads. Steelheads tend to spawn in pockets of gravel and cobble at pool tail-outs, measured primarily as active channel deposits in this study. Although the middle reaches have the highest percentage of bedrock outcrop, these reaches are still alluvial, and observations in reaches 3A, 3B, and 4A suggest that many pockets of sediment within the bankfull channel are available for spawning. While these reaches only store 2-30% of the total measured sediment in active channel deposits (Figure 28), other appropriately sized gravels on the margins of bars can also be utilized. For example, sediment stored on the margins of alternate, lateral and forced bars tends to be closer to the average bed elevation and remains wetted for a longer period of time, compared to taller point bars. The primary danger in using this sediment for spawning is the threat of redd scour or the threat of dewatering during periods of low flow. Relative bed load transport capacity in Carneros Creek, as described by the bankfull shear stress ratio, is generally > 1, suggesting that in most reaches, stream bed sediment can be mobilized during high frequency, low magnitude floods (Table 12). As noted earlier, reaches 1A and 2B have unusually low threshold shear stress, and consequently the shear stress ratio is unusually high. A zone of relatively low shear stress ratio is located in reaches 4A and 4B, which, when combined with relatively high bankfull shear stress, suggests that a relatively coarse sediment size distribution with low mobility is present. This contrasts with upstream reaches (5A and 5B) and downstream reaches (3A and 3B), where the shear stress ratio is about three or greater, and bed sediment is expected to be smaller and relatively mobile. Reaches 2A and 1B represent a zone of somewhat less mobile beds with relatively mobile beds found in upstream (2B and 3A) and downstream reaches (1A).

These middle spawning reaches are also storing large volumes of sediment in bars, with a majority likely sourced from the bank erosion in these same reaches (Figure 35). In addition to storing large volumes of sediment, reaches 3A and 3B have the second and third highest number of LWD pieces present, 23 and 35 pieces, respectively, suggesting favorable juvenile rearing habitat complexity. While neither sample reach included a large LWD jam, each had accumulations of multiple pieces of wood that can provide cover, habitat complexity, and help trap some sediment. Surface and subsurface analysis of sediment grain sizes suggest that these reaches are acceptable for steelhead spawning. Excess fine sediment can clog spawning gravels, limiting infiltration, and lowering salmonid fry emergence rates. The lower reaches of Carneros have levels of fine sediment (<1 mm and 6.35 mm) and framework gravels (D50 and D84) within documented ranges of successful salmonid spawning (Table 7). Although appropriate gravels exist, other habitat features, primarily perennial flow, is lacking in the lower reaches. In most alluvial channels, surface sediment distributions are coarser than subsurface sediment distributions, typically by a ratio of 2:1. A comparison of surface and subsurface sediment distributions in the lower reaches of Carneros Creek reveals an irregular pattern. The surface grain size distribution is coarser than the single subsurface sediment sample distribution by 12 to 27% in reach 1B, but in reaches 1A and 2A the single subsurface sample in each reach is actually coarser than the surface distribution, sometimes by 40%. This is likely due to channel slope; both sample reaches are areas of low gradient, which encourages the deposition of fine sediment. Surface sediment size distributions include the sediment in pools (localized areas of low gradient), whereas the subsurface sample represents the distribution at the top of a riffle (a localized area of higher gradient). Local bank erosion is also likely contributing; channels without a high local fine sediment supply tend to have coarser bed grain size distributions, due to winnowing of the fine sediment. However, if the banks are continually contributing sediment, the surface sediment size distribution will likely remain fine. Reaches 3A and 3B are areas of low slope, and both have very high amounts of measured bank erosion. These reaches contain surface sediment with median (D50) sizes ranging from 15 to 38, and percentage of fines (<2 mm) ranging from 7 to 18% (Table 6). Besides appropriate sediment sizes, successful spawning also requires appropriate hydraulic locations, such as areas of intra-gravel flow often found in pool tail-outs (Kondolf and Wolman, 1993). These middle reaches have high complexity, the highest number of pools measured, ranging from 9 to 11 (Figure 17), and the closest average pool spacing (Table 9), implying that a number of pool tail-out locations exist for potential spawning. With the combination of available spawning gravels, appropriate size distributions of gravels, LWD to provide cover and complexity, and a number of potential spawning locations, the middle reaches of Carneros Creek appear to have the best habitat for steelhead spawning.

Besides being the best reaches for steelhead spawning, the middle reaches also appear to be the best reaches for juvenile rearing. As shown earlier, sample reaches 3A, 3B and 4A have the highest number of pools measured, and relatively high numbers of LWD. On average, pool spacing is less than every three bankfull widths (Table 9). These reaches also have the most bedrock outcrop in-channel, ranging from 5 to 50%. Some very deep (1 m or greater) pools have been scoured in the bedrock, providing good cover (deep water) and consistently cool water temperatures. Overall, pools have relatively deep residual depths (Figure 20), and half are directly formed by or are associated with LWD pieces (Figure 18), suggesting favorable pool quality. Excess fine sediment that is deposited in pools can threaten the amount of pool habitat available by decreasing the volume of water in each pool. The amount of sediment stored as pool deposits ranges from 8 to 15 % in the middle reaches of Carneros Creek. Although these reaches have a high local sediment supply from bank erosion, the amount of fine sediment stored in pools does not appear to be significantly decreasing pool volumes (Figure 19). Stillwater Sciences (2002) measured the amount of fine sediment in pools (using a modified V* methodology) in many tributaries throughout the Napa Valley. The middle and upper measurements taken in Carneros Creek (located in Strata II and III of this study) showed pool in-filling over 40% and 20%, respectively, the two highest values measured in the study. However, the lower measurement (located in Stratum I) only showed approximately 10% pool in-filling. In this study, moderate volumes of pool deposits were measured (Figure 28), especially in the long, low gradient pools of reaches 1A, 1B and 2A. Pool deposits were also measured in reaches 3A and 3B, likely sourced from local bank erosion, but pool depths in these reaches did not appear to be significantly impacted (Figure 20). While pool in-filling is likely not a limiting factor for steelhead success, additional inputs of fine sediment could have negative repercussions; addressing sediment inputs from local bank erosion and upstream land uses will ensure appropriate pool depths in the future.

Salmonids require pool habitat, with cool temperatures and cover elements for successful summer rearing. While the middle reaches are supplying the required habitat, a significant limiting factor in steelhead rearing success in Carneros Creek may be lack of perennial flow. The overall low levels of flow in Carneros Creek are likely the historical norm. Reaches 3A and 3B contain discharge throughout the year, supplied by a point source, the Iron Mine Spring. The reaches upstream of this spring dry up in the summer and fall months, limiting available perennial aquatic habitat. Reaches 1B, 2A and 2B only support isolated pools throughout the summer months. These pools represent marginal habitat at best, because water quality is likely poor (potentially even lethal to sensitive species), variations in water temperature are possible, the pool could dry up, and steelhead are easy targets of predation in these pools. Because of the available habitat, and perennial flow conditions, the middle reaches of Carneros Creek supply the best habitat for steelhead rearing.

Besides providing spawning and rearing habitat for steelhead, Carneros Creek also provides many other resources to residents of the watershed. For example, the creek supplies a source of water for cattle and vineyards (Water Balance Study). The channel functions to convey flood waters and sediment supplied from the watershed. The creek also supplies habitat to other aquatic species other than steelhead, such as macroinvertebrates, stickleback, California roach, and sculpin (Water Quality, Fish Habitat Assessment). The upper watershed is habitat for wildlife and many flora species. And the entire creek length provides an aesthetically pleasing setting in which people have chosen to live, work and play (Historical Ecology).

REFERENCES

Bunte, K., and Abt, S.R., 2001. Sampling frame for improving pebble counts accuracy in coarse gravel-bed streams. The Journal of the American Water Resources Association, v. 37, p. 1001-1014.

Collins, L., and Collins, J., 1998. The watershed science approach (WSA). A methodology developed for the evaluation of geomorphic processes in Bay Area watersheds. San Francisco Estuary Institute, Richmond, CA.

DeVries, P., Burges, S.J., and Daigneau, J., 2001. Measurement of the temporal progression of scour in a pool-riffle sequence in a gravel bed stream using an electronic scour monitor. Water Resources Research, v. 37 (11), p. 2805-2816.

Dunne, T., and Leopold, L.B., 1978. Water in environmental planning. W.H. Freeman, San Francisco. 818 p.

Flosi, G., Downie, S., Hopelain, J., Bird, M., Coey, R., Collins, B., 1998. California salmonid stream habitat restoration manual, 3rd edition. State of California, Department of Fish and Game, Inland Fisheries Division.

Forest, Soil and Water, Inc., O'Connor Environmental, Inc., and East-West Forestry, 1998. Watershed assessment and cooperative instream monitoring plan for the Garcia River, Mendocino County, California. Compiled for Mendocino County Resources Conservation District and the California Department of Forestry and Fire Protection, January, 1998.

Gurnell, A.M., and Gregory, K.J., 1995. Interactions between semi-natural vegetation and hydrogeomorphological processes. Geomorphology, v. 13, p. 49-69.

Harrelson, C., Rawlins, C., and Potyondy, J., 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. RM-245, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Jarrett, R.D., 1984. Hydraulics of high-gradient streams. Journal of Hydraulic Engineering, Am. Soc. Civil Engr. v. 110, no. 11, p.1519-1539.

Kondolf, G.M., 2000. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society, v. 129, p. 262-281.

Kondolf, G.M., and Wolman, M.G., 1993. The sizes of salmonid spawning gravels. Water Resources Research, v. 29, no. 7, p. 2275-2285.

Lambert, G., and Kashiwagi, J., 1978. Soil Survey of Napa County, California. U.S. Department of Agriculture, Soil Conservation Service.

Leopold, L.B., 1994. A View of the River. Harvard University Press, 298 p.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964. Fluvial Processes in Geomorphology. W.H. Freeman, New York. 522 p.

Lisle, T.E., 1999. Channel processes and watershed function. Pages 4-14, *in:* Taylor, Ross N. (ed.). Proceedings of a Workshop, Using Stream Geomorphic Characteristics as a Long-term Monitoring Tool to Assess Watershed Function, 18-19 March 1999, Humboldt State University, Arcata, California.

Lisle, T.E., Ikeda, H., and Iseya, F., 1991. Formation of stationary alternate bars in a steep channel with mixed-size sediment: a flume experiment. Earth Surface Processes and Landforms, v. 16, p. 463-469.

Lisle, T.E., and Hilton, S., 1999. Fine bed material in pools of natural gravel bed channels. Water Resources Research v. 35, p. 1291-1304.

Montgomery, D.R., and Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geologic Society of America Bulletin, v. 109, p. 596-611.

NCCDP, 2002. Napa County Conservation, Development and Planning Department, Land use GIS coverage download from website (1 August 2002). www.co.napa.ca.us

O'Connor Environmental, Inc., 2000. Garcia River large woody debris instream monitoring. Prepared for Mendocino County Resource Conservation District. 20 p.

Pearce, S., O'Connor, M., Grossinger, R., and McKee, L., 2002. Napa River Sediment TMDL Baseline Study: Geomorphic processes and habitat form and function in Soda Creek. San Francisco Estuary Institute.

Stillwater Sciences, and University of California, Berkeley, 2002. Napa River Basin Limiting Factors Analysis. Prepared for San Francisco Bay Water Quality Control Board and California State Coastal Conservancy. 71 p.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. American Geophysical Union Transcripts, v. 38, p. 913-920.

USDA, 1998. United States Department of Agriculture, Forest Service. WinXSPRO: a channel cross-section analyzer. User's manual. Prepared by WEST Consultants, Inc., San Diego, CA, for USFS Rocky Mountain Experiment Station, Ft. Collins, CO.

Washington Forest Practices Board, 1997. Standard Methodology for Conducting Watershed Analysis.

WRCC, 2002. Data obtained from the Western Regional Climate Center website. (1 April 2002). www.wrcc.dri.edu