GEOMORPHIC CHANGES IN THE LOWER REACHES OF CARRIGER CREEK, SONOMA COUNTY

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By Laurel Collins, Donna Morton, and Paul Amato

WATERSHED SCIENCES, 2002

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EXECUTIVE SUMMARY

Carriger Creek is a tributary of Sonoma Creek, in Sonoma County, California. Its 5.6 mi^2 watershed includes a steep, forested canyon with sparse residential development that drains to a broad alluvial fan that supports mostly viticulture and cattle ranching. Sections of the creek along the alluvial fan lack riparian trees and perennial flow during late fall. The high rate of bank erosion, loss of riparian vegetation and perennial flow, flooding, and loss of fish habitat in the lower creek have raised concern among local residents about the "health" of their watershed. As a result, a detailed quantitative field study of creek conditions and processes was conducted from June through September 2000 in the lower 3.9 miles of Carriger Creek. This lower creek segment is called the Study Site, which includes the lower Sonoma Valley, the Carriger Creek alluvial fan, and a small portion of Carriger Canyon.

The principal objective of this study was to survey current channel conditions, identify relevant geomorphic processes, identify changes in conditions and processes since the time of non-native settlement, and provide the information to land managers in an effort to improve restoration strategies and design, reduce erosion and sedimentation, and improve water quality and habitat in Sonoma County.

This report addresses many problems faced by nearly all communities, counties, and states. Throughout the country, citizens have witnessed the deterioration of natural stream functions that maintain clean water and healthy ecosystems. Many of the local streams that drain to the San Francisco Estuary are so severely impaired that they are no longer self-maintaining. They require dredging of sediment, revetment of channel banks, restoration of riparian vegetation, releases of impounded water for fish, and treatment of water quality. Changes in rates of water and sediment supply caused by agricultural and urban development have caused channels to adjust their natural equilibrium profile, pattern, and dimensions. Landowners and land managers alike have been alarmed by aquatic and riparian habitat loss, increased fine sediment loading, reduced availability of drought season stream flow, and declines in number and diversity of endangered and threatened species.

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The San Francisco Estuary Institute initially performed collection of field data for the Sonoma Watershed Conservancy. Their funding was from EPA through CALFED. Funds for developing a web report were from Watershed Sciences, Kier Associates, and San Francisco Estuary Institute.

The methodology used in this report is an attempt to collect and use factual data obtained on the ground to describe channel conditions that reflect past and ongoing fluvial and geomorphic processes. The method provides measurement data obtained in a limited time, at small cost, that can be used to hypothesize history and trends in various facets of the channel system.

The usual techniques of stream gaging, sediment sampling, and repetitive surveys provide important data at a given point but they require years, not weeks, of data collection. The observational data that we collected provide the basis for hypotheses that can guide further data collection and deeper interpretation. The present method does not replace the usual long-term programs but adds to them. The present study took 5 months with a team of three people.

Although the Carriger Creek study is not a full watershed analysis we have analyzed some aspects of the lower mainstem channel and developed hypotheses concerning the relative impacts of land use activities. This report does not attempt to be a sediment budget or an explanation of short-term supply rates as influenced by just modern activities. Our hypotheses concerning the watershed upstream of the Study Site are preliminary and remain to be verified through quantitative watershed analysis. We generally rely upon a detailed historical investigation to provide context for current conditions. We have discovered historical differences that explain change but details of historical land use were not in the scope of this project.

Our approach of assessing sediment sources and channel conditions differs from other methodologies that quantify bedload transport. It cannot perform the same function of assessing mobility, only supply.

An important finding in our Study Site is that the lower portion of the creek along the alluvial fan has become very unstable due to relatively modern land use practices that have occurred since the time of non-native settlement. We suggest that the channel has been adjusting to modern land practices for about the last 165 years. Portions of the lower mainstem channel have been severely altered from destruction of distributary channels. The remaining mainstem channel along some of its reaches has suffered a reduction of ecological values from loss of perennial flow and riparian vegetation. Based upon a reconnaissance of the mainstem channel in the upper watershed we have observed some channel incision but have not identified specific causes, since this was not part of the Study Site. The incision was not of the same magnitude as observed downstream. Given the high quality of riparian habitat and abundance of steelhead trout observed in the upper watershed, its protection should be a priority. Restoration efforts in the lower watershed should focus on channel stabilization, re-establishment of native riparian vegetation, and aquatic habitat enhancement. Restoring distributary channels might function to increase the amount of fish habitat, as well as potentially decrease flood peaks in Sonoma Creek.

During the 165-year period of modern land use, there has also been severe bank erosion along 81% of the length of both banks in the Study Site. This erosion has supplied a long-term average of 635 yd^3/yr of sediment to the channel. Bed incision, which has occurred over 100% of the Study Site during the last 165 years, has supplied a long-term average of 540 yd^3/yr. The combined sediment supply rate has averaged about 1,175 yd^3/yr. If we estimate that bulk density is about 1.63 tons/cu yd, then 75 loads per year of sediment for a 25.5-ton dump truck would be required over 165 years. Note that this is just for supply from the bed and banks and does not include the amount that would have been fluvially transported from supplies upstream of the Study Site. The amount of bank retreat (lateral erosion) has ranged up to 56 ft, which represents more than two bankfull widths of erosion. The volume of sediment supplied from bed incision exceeds that from bank erosion in the downstream and upstream reaches of the Study Site. Bank erosion dominates the middle reaches. The maximum amount of incision has been about 8 ft, which represents nearly three bankfull depths of incision. Average incision is about 5 ft. At a minimum, we suggest that 60% of the modern sediment supply could be related to non-native land use practices.

The channel instability in the Study Site, especially in its middle reaches, has been promoted by: 1) destruction of distributary channels that used to convey the watershed runoff through at least three distributaries, rather than one main channel; 2) construction of Arnold Bridge that historically had a much smaller flood flow capacity; 3) channel straightening that occurred upstream of Arnold Bridge; and 4) removal and/or modification of riparian buffers along agricultural fields.

We expect that changes in channel geometry of Carriger Creek have contributed to the loss of perennial flow in the lower reaches during the summer and fall. Subsequent losses of aquatic and riparian resources have ensued. Other factors such as agricultural diversions, groundwater extraction through local wells, and downcutting of Sonoma Creek have all probably contributed to the lowering of the local water table through the lower Study Site.

For the Study Site as a whole, the dominant D50 size class is small cobble, which represents 24% of the total for all sediment size classes. Carriger Creek has an unusually coarse bed for its gradient through its middle reaches. The large quantity of cobble and boulder-sized sediment functions as armor, causing the banks to erode more than the bed when the gradient is low. Sand represents only 10% of the sediment on the channel bed. Such a low percentage of fines seems unusual for Bay Area streams.

The number of pools throughout the length of the study site was much lower than that which would be predicted for 5 to 7 bankfull widths, and low numbers of pools would likely indicate that aquatic resources have decreased. Only 117 elements of Large Woody Debris (LWD) that were greater than 8 inches in diameter were found in the Study Site. This is a low amount of wood for such a long reach of channel. Low quantities of LWD significantly reduce habitat complexity and the number of pools in a given stream. In Carriger Creek 20% of the LWD was oak, which reflects erosion of terrace banks, where most of the oaks grow. The loss of mature oaks along Carriger Creek is of great concern to the SCWC.

Only 13 debris jams were found in Carriger Creek and only one of them spanned the entire width of the channel. The lack of debris jams is probably due to a number of reasons including: 1) LWD being artificially removed or modified; 2) the channel being much wider than it used to be, such that LWD cannot get caught by other riparian vegetation; 3) there being less riparian vegetation to provide LWD; and 4) there being less channel length due to the loss of distributaries. Only 3 of the debris jams contributed to pools that were greater than 1 ft deep during the summer season.

Based upon the Rosgen Stream Classification system, an estimated 52% of the channel in the Study Site has cross section geometry that is characterized as presently unstable. Carriger Creek will likely continue to adjust its shape by eroding its bed and/or banks. Banks are expected to be the dominant sediment source until a suitable geometry is attained for the current land use practices, and the associated hydrologic, groundwater, and climatic conditions.

How do these findings relate to restoration? By recognizing how the creek system responds to in-stream engineering and local land use, managers can prioritize restoration sites and improve project designs. In this regard, managers might consider the following recommendations.

1. Protect the upper watershed. The creek in the canyon has abundant ecological value that should be conserved. To this extent perform a full watershed analysis and sediment budget.
2. Consider restoration of the system of distributary channels across the alluvial fan. Natural distributaries formerly prevented the concentration of flow that now erodes the single remaining channel. This restoration will reduce the risk of floods in downstream Sonoma Creek and increase in-stream ecological values.
3. Where feasible, reshape the channel to create a stable cross section; use biotechnical methods of bank stabilization or use boulder veins to direct flow away from eroding banks. A narrower width-to-depth relationship may

restore perennial flow in some portions of the creek and minimize late summer migrational barriers to fish that become trapped in isolated pools.

4. Restore the riparian forest on the alluvial fan to reduce future bank erosion, to create a renewable sources of LWD for in-stream habitat enhancement, and to minimize increases in water temperature that can be fatal to fish. This will require fencing cattle out of the riparian zone.
5. Consider modifying or removing the concrete ford that is located along Steelhead Reach at distance station 19016 ft. It creates a barrier to upstream fish migration.
6. The longitudinal profile of the mainstem channel should be surveyed to establish future monitoring stations within stable reference reaches (Rosgen B-type channels) and unstable reaches (Rosgen F- and G-type channels) that will show differences between stable and unstable channel geometry as well as future changes in dimension and profile[4]. Such a survey will allow correct delineation of local reach gradients. Where appropriate, this information could be used to develop design standards for restoration. Realistic projections for the extent of backwater floods associated with past and present bridges could also be determined.
7. The historical ecology of the watershed should be investigated and described, including native land use practices, patterns of historical land use change, and the chronology of local development, including diversions, impoundments, and engineered stream crossings. Such a perspective would improve everyone's ability to direct management initiatives and to understand the relationships between land use and watershed conditions.

Following these recommendations could also improve water quality by decreasing water temperature and turbidity, and increasing dissolved oxygen and pH. Improving these water quality parameters is beneficial to human and ecological health. Questions regarding this study or the Watershed Science Approach should be addressed to the lead author by emailing her at collins@lmi.net.

[4] Based upon recommendations 5 and 6, the SSCRCD funded Watershed Sciences during fall 2001 to survey a longitudinal profile and cross sections upstream of Arnold Bridge to assist with design plans needed for removal of the concrete fish barrier. Detailed survey results are included in the Appendixof this report.

INTRODUCTION AND OBJECTIVES

A study of physical channel conditions and sediment sources along Carriger Creek, Sonoma County, California was conducted by the San Francisco Estuary Institute (SFEI) during summer and fall of 2000. The study was performed for the Sonoma Creek Watershed Conservancy (SCWC) with funds provided by US Environmental Protection Agency through CALFED. The SCWC includes the Southern Sonoma County Resource Conservation District (SSCRCD) and the Sonoma Ecology Center (SEC). Funds for report writing were later provided by Watershed Sciences, Kier Associates, and SFEI.

Carriger Creek, a tributary of Sonoma Creek, has a 5.6-mi^2 watershed. This study focused on a 3.9-mi long Study Site during the months of June through September 2000. The Study Site was selected to investigate local concerns over excessive of bank erosion, increased flooding, and apparent degradation of aquatic and riparian habitats.

Initial deliverables included: 1) a photographic base map of the study area along the mainstem channel; 2) a graphical representation of existing bed and bank conditions; 3) tables and graphs for displaying field conditions; and 4) a short 4-page discussion of objectives, general methods, accomplishments, key findings, and recommendations for future studies. This report is designed for the Internet as a way to increase its availability. The text is presented mostly as a series of captions for the maps, graphs, and diagrams that illustrate the characteristics of the creek and the processes that influence it.

One objective of the study was to describe historical changes in sediment supply and creek conditions since European contact or non-native settlement in the region. We propose that the channel may have started to respond to non-native land use impacts about 165 years ago. By this time cattle, horses, and sheep were well established and the Mission's population had surpassed 1000 by 1831 (verbal communication Arthur Dawson, Historian, Sonoma Ecology Center). Causes of bank erosion and channel instability were to be identified and recommendations given to reduce sediment supply.

The approach we used to quantify channel conditions includes field measurements of different key parameters that together determine the sources, causes, and amounts of creek erosion and its effect on creek form in cross section, plan view, and longitudinal profile. If a full watershed-scale analysis is conducted, these data can be used to estimate the amounts of natural and unnatural erosion, such that land managers will have some sense of what portion of the sediment supply can be controlled by adjusting land use practices. The key parameters measured to quantitatively document existing condition and establish geomorphic processes and inter-relationships are listed below. The field measurements and their objectives are briefly summarized and followed by some details in methodology.

- To determine bank condition and volume of sediment, we measured length, depth of retreat, location, and type of sediment sources associated with features along the banks and terraces.
- To assess amount and kind of bank revetment we measured its length, location, and assessed its condition and type.
- To assess influence of tributaries and effects of human alterations we recorded locations, size, and types of culverts and other engineered structures crossing the creek.
- To determine bankfull and geometric relationships we measured cross sections to establish bankfull width, and terrace heights.
- To assess the percent length of different D50 size classes on the bed surface we continuously recorded their distribution.
- To determine the volume of sediment generated by bed incision we measured height of incision that we determined to occur within the 165-year time frame.
- To determine whether incision occurred within some expected time frame, we cored trees and continually assessed the age of vegetation, evaluated the age of terraces based upon tree ages, studied historical aerial photos, and tried to reconstruct what the historical channel elevation and planform were while we were in the field.
- To assess the condition of the bed, and determine pool spacing as well as to assess availability, abundance, and volume of pool habitats, we measured width, depth, max depth, pool tail-out depths, location, number, and causes of pools greater than 1ft deep; and
- To determine abundance of woody debris and mechanisms of its recruitment, we measured number, spacing, species, and recruitment processes of woody debris.

To determine where channel reaches were stable or unstable and to develop future restoration strategies we determined Rosgen Stream Classes by frequently assessing changes in width/depth and entrenchment ratios.

A glossary of some technical terms is provided at the end of the report.

OUTLINE OF BASIC METHODOLOGY

A Quality Assurance Program with protocols of the methods is on File at SFEI and EPA. The time to accomplish this study was half a year with a modest amount of funding. The approach is aimed at learning things about a basin in a very short time to produce information that cannot be obtained from any long-term measurement of repeated cross-sections or from installed point gages. This technique does not replace the standard techniques but adds to them in a short period of time. It is not a hydrologic analysis but is a geomorphic one. Standard hydrologic data help explain some of the conditions and history, but do not fulfill the same objectives we sought here.

1. A photographic base map was created using aerial photos at scale 1:7,200.

2. A centerline tape was pulled continuously along the channel. All data were referenced to distance stations along the tape. Flagging, annotated with distance stations, was tied every 100 ft. These distance stations, when combined with the Photo Map, could be used to revisit the same stations during future monitoring. The distances between engineered structures such as bridges and culverts were noted.

3. Telescoping survey rods were used to measure bankfull width, height of terraces, and heights and depths of bank and terrace erosion. Bank measurements were separated into sections below and above bankfull height, as determined from field indicators and regional correlations between bankfull cross-sectional area and drainage area. Level-line surveys were used to measure cross-sections relative to bankfull height, which in concept, is equivalent to the height of the active floodplain. Bank erosion was measured wherever the lateral bank retreat was at least 1/4 ft retreat for the entire bank, above and below bankful height.

4. Standard sieve size classes were used to determine the distribution of creek bed sediments and to determine the percent of the bed surface represented by different "D50" size classes. After performing numerous pebble counts the D50 size classes along the entire length of the study site could be visually estimated. The length of different patch sizes was recorded relative to the centerline tape distances. If the bed had different size classes across the channel or had a bimodal distribution, then two D50 size classes were reported. By definition, 50% of the sediment particles are no larger than the D50 size class.

5. The locations and volumes of pools at least 1 ft deep were documented at the time of initial field data collection from June to September. Because the lower reaches dried out by September, these reaches had the depth re-measured during minimum base flow during mid-September.

6. Photographs of the channel were taken at places of obvious changes in channel conditions. Photographs were referenced to distance stations, placed in a notebook, and arranged in order from downstream to upstream. These photos are on file at Watershed Sciences.

7. Data were entered in field books specifically designed for the WSA, and later entered into data templates linked to analytical and graphical programs to calculate or display the desired stream parameters. The raw data is on file at Watershed Sciences.

WATERSHED CHARACTERISTICS

The 5.6-mi^2 watershed for Carriger Creek is located west of the town of Sonoma in Sonoma County, California. The canyon in the upper portion of the watershed is Miocene-aged basaltic lava, with some ash flow tuff and rhyolite (Fox, 1983). The lower portion of Carriger Creek flows across its Quaternary-aged alluvial fan toward Sonoma Creek where it intercepts alluvial terrace sediments deposited primarily by Sonoma Creek.

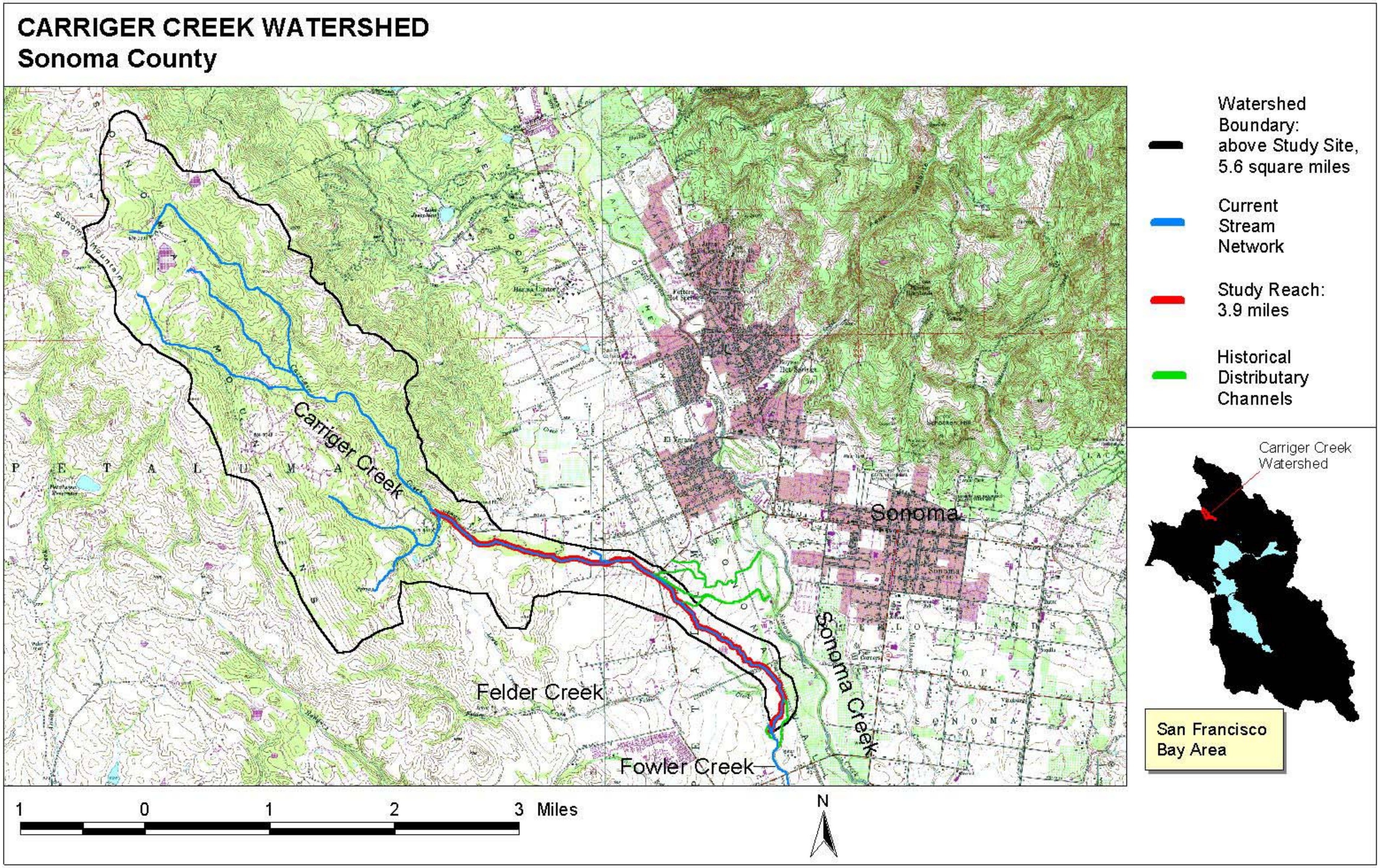
The mean annual precipitation for the area is about 40 in/yr. About 90% of the rainfall occurs during a six-month period from November to April. Wet winters and dry summers are characteristic of the coastal Mediterranean climate. Dominant vegetation types in the watershed include oak/bay woodland, oak savanna, grassland, and vineyards. There is a discontinuous riparian community typically comprised of white alder, willow, bay, and big leaf maple.

The watershed is characterized by sparse residential development interspersed with viticulture and cattle ranching on the lower fan. The predominance of these different land use practices has shifted over time. Cattle ranching used to occur over a greater proportion of land than today. It extended well throughout the western side of the canyon. We have estimated that impacts to the watershed from non-native land use practices started by 1835, or 165 years ago. Grazing is less intensive now and limited to upper and lower extremes of the watershed, while large segments of the lower alluvial fan are rapidly being converted from ranching to vineyards. Other agricultural croplands may have been more extensive during the 1800's.

Figure 1. Watershed Map and Study Site Setting

Carriger Creek has a single thread, low sinuosity channel that flows southeastward toward Sonoma Creek. Below its confluence with Felder Creek, the channel is called Fowler Creek, which flows another 2.6 miles before entering Sonoma Creek just upstream of Highway 121 crossing. The channel ranges from moderately to highly entrenched through the 3.9 mi Study Site, the downstream boundary of which is Felder Creek. The drainage area above this confluence is 5.6 mi^2. As indicated on the USGS map, most of the canyon area is forested (oak bay woodland). The watershed ranges in elevation from 30 ft to 2,295 ft above sea level (NGVD 1929).

Historically, Carriger Creek divided into at least three distributaries on its alluvial fan near Arnold Bridge. These are shown in green on the Watershed Map.



San Francisco Estuary Institute, 2000

Base Map Source: USGS 7.5' Quadrangles, Sonoma, CA, 1951, photo revised 1980 and Glen Ellen, CA, 1954, photo revised 1968

Remnants of some of these channels are still present in the field, and they are apparent in historical 1946 photographs on file at the SSCRCD. We expect that portions of the northern and middle distributaries were plowed-over for agricultural purposes before the mid 1800's.

The present distribution of riparian vegetation along Carriger Creek can be seen in the Photo Maps, Figures 2a-e. The northern and middle distributaries flowed an estimated 1.0 mi and 0.9 mi to historical Sonoma Creek. Note that Sonoma Creek was an anastamosing stream and may have had its own system of distributaries. The distance between the confluences of Sonoma Creek and the northern and middle distributaries was about 3.8 mi. Such a long distance separating the confluences of these distributaries along Sonoma Creek means that their channel beds would have been graded to very different base elevations. The southern distributary is the present course of Carriger Creek. After the northern and middle distributaries were destroyed, all the flow from Carriger Creek watershed was funneled into the southern distributary (now Carriger and Fowler Creeks).

The hydraulic geometry of the one remaining distributary adjusted to increased amount of water by both eroding its banks and incising its bed. The channel became straighter and more entrenched. Because more flood flow is contained between the banks when a channel becomes highly entrenched than when it is only slightly entrenched and able spread over a valley floor, higher shear stresses will perpetuate bank erosion and bed incision. In Carriger Creek Study Site the channel is incising into Quaternary alluvium that consists of silt and clay in this vicinity. During large floods very large cobble to boulder-sized sediment is transported as bedload to the lower gradient reaches farther downstream, effectively armoring the bed. Discharges of smaller magnitude cannot move the cobbles and boulders but do erode the banks, thereby exposing the Quaternary silt and clay. As the channel laterally migrates in this fashion, it incises below the level of the armored bed. Subsequently, during the next large flood a veneer of coarse bedload moves onto the fine-grained bed. A new cycle of lateral erosion and incision is thus initiated. Incision and armoring alternates through an "armored aggradation and erosion sequence", at increasingly lower elevations of the bed. This explains the stair-stepped morphology across the mainstem channel that is observed in some reaches, especially where there has been extensive bank retreat. It also explains segments of channel that look like "bald" patches of Quaternary clays that have not yet been covered by a coarse veneer. Some bald patches are nearly 100-ft long. They probably represent bank erosion and channel incision that occurred during low magnitude floods or bankfull discharges that did not have sufficient capacity to mobilize the coarse armor.

Hence, entrenchment of the channel, which disconnects a channel from it floodplain, has increased overall flood capacity and increased the shear stress that efficiently erodes the bed and banks, and transports coarse bedload that armors the bed. A self-perpetuating cycle of armored aggradation and erosion may likely continue until a wide inner floodplain develops that will accommodate large floods and develop the appropriate sinuosity and gradient that would maintain stable channel geometry, providing that watershed conditions and climate do not change.

The reach of channel upstream of Arnold Bridge has also undergone obvious physical changes. We have been told that several thousands of feet of the channel were probably straightened in the past for flood management by the Sonoma Water Agency (personal communication David Luther, SSRCD).

As we quantified sediment supply from bank retreat from fluvial processes we also looked for evidence of gullying from surface runoff over the banks. Gullies were rare and the land is fairly flat. We did not observe much field evidence of increased surface runoff from the vineyards yet we did observe occasional evidence of side casting soil into the channel along some lands that were undergoing conversion to vineyard. Between Leveroni and Arnold Bridges we observed numerous cattle trails leading into the creek. During intense storms when soils are saturated these trails function as ephemeral channels, transporting fine sediment and nutrients from the pastures directly to the channel.

The bankfull discharge for the watershed might be about 260 cfs according to published regional curves for the San Francisco Bay Area (Leopold, 1994. A View of the River, Harvard University Press). Within the Study Site during late fall 2000, the lower 73% of the channel could be characterized as intermittent, while the remaining 27% of the upstream reaches were perennial. We encountered only one small dam along the Study Site in Steelhead Reach near distance station 20,170 ft. The amount of water diverted from the creek is unknown. As vineyard development increases, water withdrawals during periods of freeze and/or summer drought may increase potentially creating adverse affects upon fish habitat.

Some factual information is compiled in the following Table 1 for quick reference.

Table 1. Carriger Creek Facts

CARRIGER CREEK FACT SHEET	
Present & historical dominant land uses within watershed	Sparse suburban development, vineyard, range land
Dominant vegetation types	Oak bay woodland, oak savanna, grassland, vineyards
Dominant geology	Sonoma Volcanics, Pleistocene alluvium
Mean annual precipitation (in)	40 in
Drainage area	5.6 sq mi
Bankfull Discharge estimated from Regional Curve*	260 cfs
Flow regime of Study Reach	72.3% intermittent, 27.7% perennial
Range of slope of Study Reach on USGS 7.5' quad	0.2% - 7.7%
Highest point in watershed	2295 ft
Maximum relief in watershed	2265 ft

Length of entire mainstem channel	8.05 mi
Length of mainstem Study Site	3.9 mi
Study Site as percent of total mainstem length	48%
USGS gage station #	No gage
Record flood year	1982?
# Small dams in Study Reach	1
# Small dams in unquantified reach along Mainstem	Undetermined
# Large reservoirs along Mainstem	0
# Permitted water diversions	0
# Unpermitted water diversions	1
Year grazing began in watershed	1835

***Leopold, 1994. View of a River, Harvard University Press.**

Figure 2a-c. Photo Map with Reach Breaks and Distance Stations

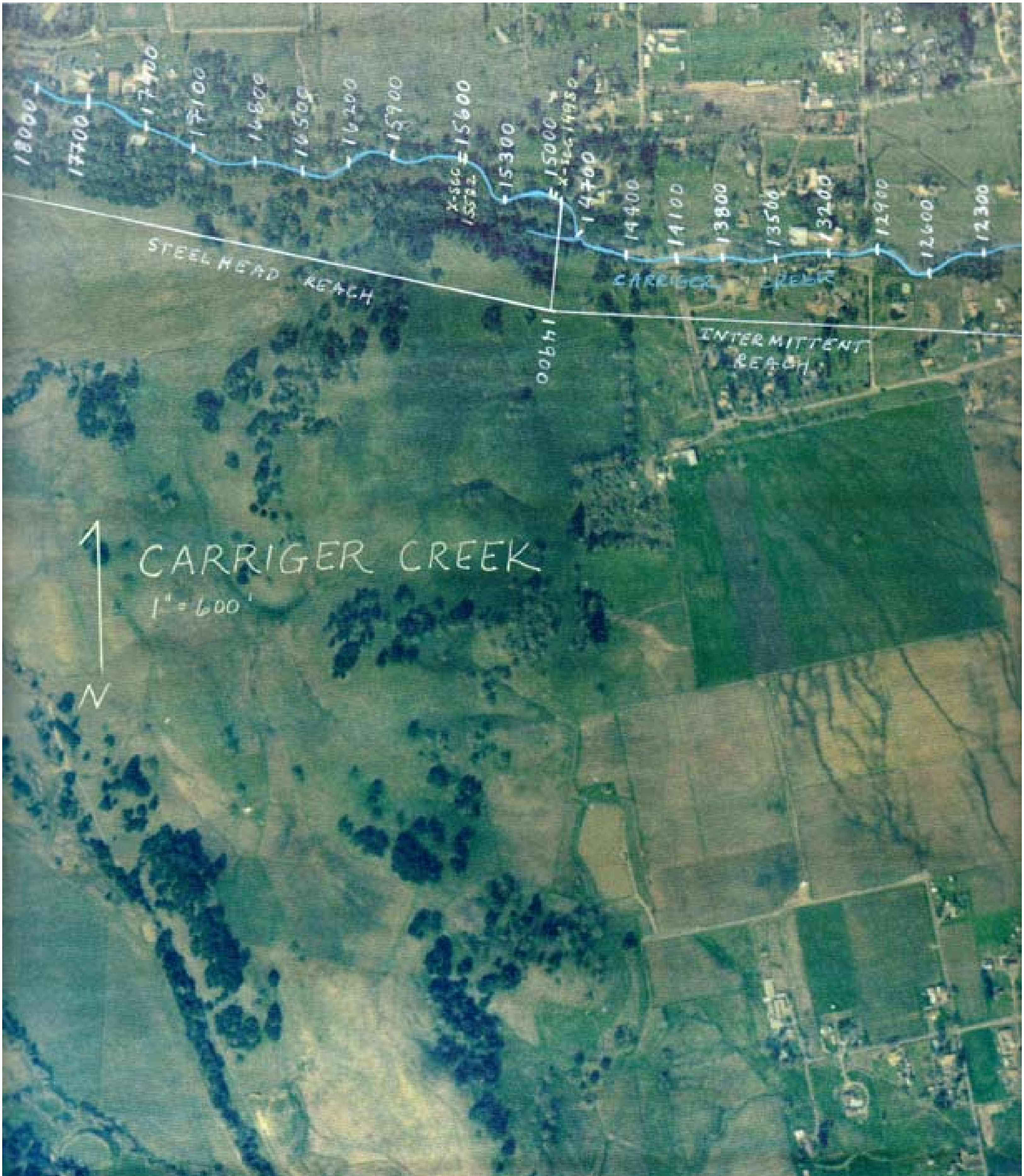
Station distances, in feet, and reach breaks are shown on three pages of Photo Maps based on 1999 photos. The scale of the photography is 1:7,200 (1 in equals 600 ft). The zero station is shown at the confluence of Carriger Creek (shown in blue) and Felder Creek. Stream flow is from left to right, while the orientation of north changes from page to page. The maps show the former location of distributaries which re mapped from earlier 1946 photos. Yellow presentation circles indicate riparian vegetation along these distributaries.

The Study Site was subdivided into 13 Reaches, which are also shown on the Photo Maps. The linear extent of each reach was based on geomorphic differences observed in the field and locations of Arnold and Leveroni Bridges. While viewing the Photo Map pages it is worthwhile to note the lack of riparian vegetation in the middle reaches of the Study Site. On the alluvial fan, near “Intermittent” and “Few Willows” reaches, a number of very old abandoned channels can be seen to fan out toward the west. None of the old channels appear to have ever been entrenched and are fairly shallow surface features that may have formed when the fan was aggrading. Table 2 below provides descriptive characteristics for each reach within the Study Site, in order of downstream to upstream.

Table 2. Reach Characteristics

Reach Name	Reach Distance (ft)	Characteristics
Confluence	700	Downstream end starts at confluence of Felder Creek which is Distance Station 0’. Is entrenched with inset banks that are well vegetated with young riparian vegetation. The adjacent land use is vineyard. The channel is in an avulsion or old diversion. Bed dominated by coarse gravel.
Distributary	650	Downstream end starts at 700’ and has more riparian vegetation at avulsion or diversion. Bed is dominated by very coarse gravel.
Riparian	1991	Downstream end starts at 1,350’ near the confluence of the avulsion or diversion to which the lower reaches flow. Has a mix of riparian vegetation along its terrace and bankfull banks. It is less entrenched than downstream reaches. Very coarse gravel and sand dominate

		bed.
Quercus	1387	Downstream end starts at 3,341' at downstream end of Leveroni Bridge. It is characterized by a narrow corridor of large oaks on adjacent terrace banks and agricultural fields of grasses dominating the high terrace. Riparian vegetation is not very abundant at bankfull elevation and channel starts to become wider. Bed is dominated by small cobble.
Few Oaks	2298	Downstream end starts at 4,728' and has a few sparse oaks growing along the high terrace, which is a mix of agricultural cropland, and grazing land. Very young shoots of riparian vegetation are found along wet areas of the bed. The channel is much less entrenched and terrace banks start to widen significantly from the bankfull banks. Channel Bed is dominated by small cobble.
Denuded	1915	Downstream end starts at 7,026' where minimal vegetation is present on any of the banks, otherwise is similar to Few Oaks Reach. Cattle have direct access to the channel. Midway through the reach the channel used to have a distributary that flowed eastward. Bed is dominated by small cobble.
Shamrock	544	Downstream end starts at 8,941' and is adjacent to a cement factory and stables. Vegetation is still minimal and it is directly below Arnold Bridge. The bed is dominated by small cobble.
Arnold	1030	Downstream end starts at 9,485' at downstream edge of Arnold Bridge. The channel once broke into 2 distributaries above upstream of the bridge. The reach was probably influenced by previous backwater floods and has had channel-straightening activities. Older vegetation is absent on terrace on banks but there are a few young willows on channel bed and inset banks. Bankfull width and distance between terrace banks is very wide. The bed is dominated by small cobble.
Few Willows	1465	Downstream end starts at 10,515' and has more young willows than Arnold Reach. It was also subjected to channel straightening activities and may have been influenced by backwater flooding. It has adjacent residential development. Both small cobble and large cobble dominate bed.
Intermittent	2920	Downstream end starts at 11,980' and has occasional areas of flow during fall. It is otherwise fairly similar to Few Willows Reach except large cobble and small boulder dominate the bed.
Steelhead	4216	Downstream end starts at 14,900' and has perennial flow in channel that is slightly more entrenched. More mature riparian vegetation is present on terrace and channel was not subjected to straightening activities. The bed is dominated by large cobble.
Diversion	1054	Downstream end starts at 19,116' where channel starts to become more confined by canyon and entrenched. Vegetation is similar to Steelhead Reach. Residential development is minimal but there is an old concrete cattle crossing that spans the bed of the channel in the downstream part of the reach and a diversion dam at upstream extent of reach. The bed is dominated by large cobble.
Grove	430	Downstream end starts at 20,170' at the upstream edge of a diversion dam and is similar to Diversion reach regarding confinement, vegetation and entrenchment. The reach ends at the upstream edge of the Grove St. box culvert wingwalls at 20,600'. Large cobble and small boulder dominate the bed.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12900
12600
12300
STEELHEAD REACH
14900
CARRIGER CREEK
INTERMITTENT REACH
CARRIGER CREEK
1" = 600'
N

SONOMA CREEK
FOWLER CREEK
FELDER CREEK
CARRIGER
RIPARIAN REACH
CONFLUENCE REACH
QUERCUS REACH
FORMER OUTLET OF FELDER CR.


12300
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11700
11400
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10800
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10200
9900
FEW WILLOWS REACH
ARNOLD REACH
9600
ARNOLD DR BRIDGE
9300
SHAMROCK REACH
9000
8700
8400
X-SEC 8303
8100
FORMER DISTRIBUTARY
FORMER DISTRIBUTARY
7800
7500
7200
X-SEC 7102
6900
DENUDED REACH
6600
6300
6000
X-SEC 5787
5700
5400
CARRIGER CREEK
FEW OAKS REACH
2

Figure 3. Topographic Map Longitudinal Profile

The energy slope of a stream is approximated by its gradient. Local stream gradient largely depends upon discharge, bed-material size and load. The slope of Carriger Creek, derived from a USGS 7.5" quadrangle is shown for the entire mainstem channel. Individual reaches within the Study Site are shown in color at the downstream end of the profile. The reach breaks were based upon differences in morphology and/or the presence of instream structures such as dams or bridges as described in Table 2. The reported percent slopes are based upon the end point elevations within each reach. Channel distances measured on the topographic map do not match the distances measured in the field because the topographic map does not depict much of the channel curvature. For accurate distances refer to Table 2. The length of the Study Site represents slightly less than 50% of the length of Mainstem Carriger Creek. Grove Reach is the steepest reach in the Study Site. Riparian Reach is the least steep.

Figure 4. Details of Longitudinal Profile with Morphologic Zones and Stream Reaches

Reaches within the Study Site fall within certain morphologic zones that we have defined by a range of stream slopes. These zones include the Sonoma Valley Alluvial Terraces (slopes < 0.5%), Carriger Creek Alluvial Fan (slope between 1% and 6%), a Transition Zone between the latter two zones (slopes between 0.5% and 1%), and Carriger Canyon (slopes > 6%). About 55% of the Study Site channel flows across the Alluvial Fan.

Please note that a more recent and accurate representation of actual surveyed slopes for the different reaches is shown in the Appendix, Figure 4. It shows a comparison of the topographic map slopes versus the surveyed field conditions for the length of channel between Arnold Bridge and the Grove St. box culvert.

CONDITION OF BANKS

The banks of a channel can be divided into two categories, either above or below bankfull flow. The banks above bankfull flow in Carriger Study Site are terraces. The bankfull channel is maintained by flows that occur on average every 1.3 to 1.7 years and are often referred to as the channel forming flows. At bankfull elevation, a floodplain may exist, so the flow that would be defined as bankfull would be that which would be at the incipient stage of flowing onto a floodplain if one exists. Since terraces are by definition abandoned floodplains, whether they are floodprone depends upon their elevation above bankfull. Banks below bankfull are subjected to flow more frequently, but their overall height and therefore contribution of sediment by erosional processes may not be as great as the contribution from terrace banks that can be tens of feet high. Effective discharge is a term used for the flow that is most effective at moving the most sediment over time. Within incised channels, the effective discharge may be greater than the bankfull discharge.

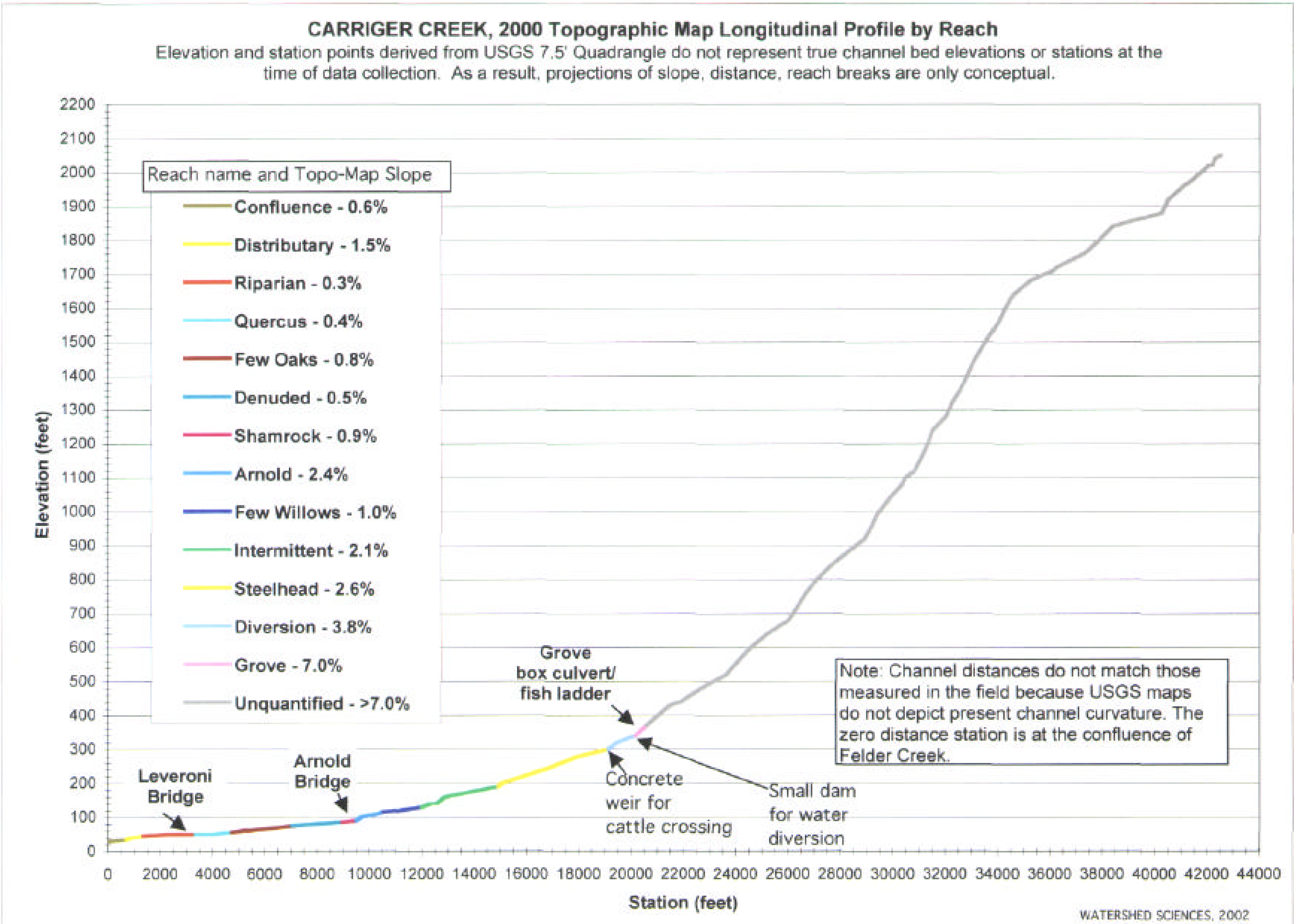
CARRIGER CREEK, 2000 Topographic Map Longitudinal Profile by Reach
Elevation and station points derived from USGS 7.5' Quadrangle do not represent true channel bed elevations or stations at the time of data collection. As a result, projections of slope, distance, reach breaks are only conceptual.
Reach name and Topo-Map Slope
Confluence - 0.6%
Distributary - 1.5%
Riparian - 0.3%
Quercus - 0.4%
Few Oaks - 0.8%
Denuded - 0.5%
Shamrock - 0.9%
Arnold - 2.4%
Few Willows - 1.0%
Intermittent - 2.1%
Steelhead - 2.6%
Diversion - 3.8%
Grove - 7.0%
Unquantified - >7.0%
Grove box culvert/ fish ladder
Leveroni Bridge
Arnold Bridge
Concrete weir for cattle crossing
Small dam for water diversion
Note: Channel distances do not match those measured in the field because USGS maps do not depict present channel curvature. The zero distance station is at the confluence of Felder Creek.
Elevation (feet)
Station (feet)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000 24000 26000 28000 30000 32000 34000 36000 38000 40000 42000 44000
WATERSHED SCIENCES, 2002

Figure 3

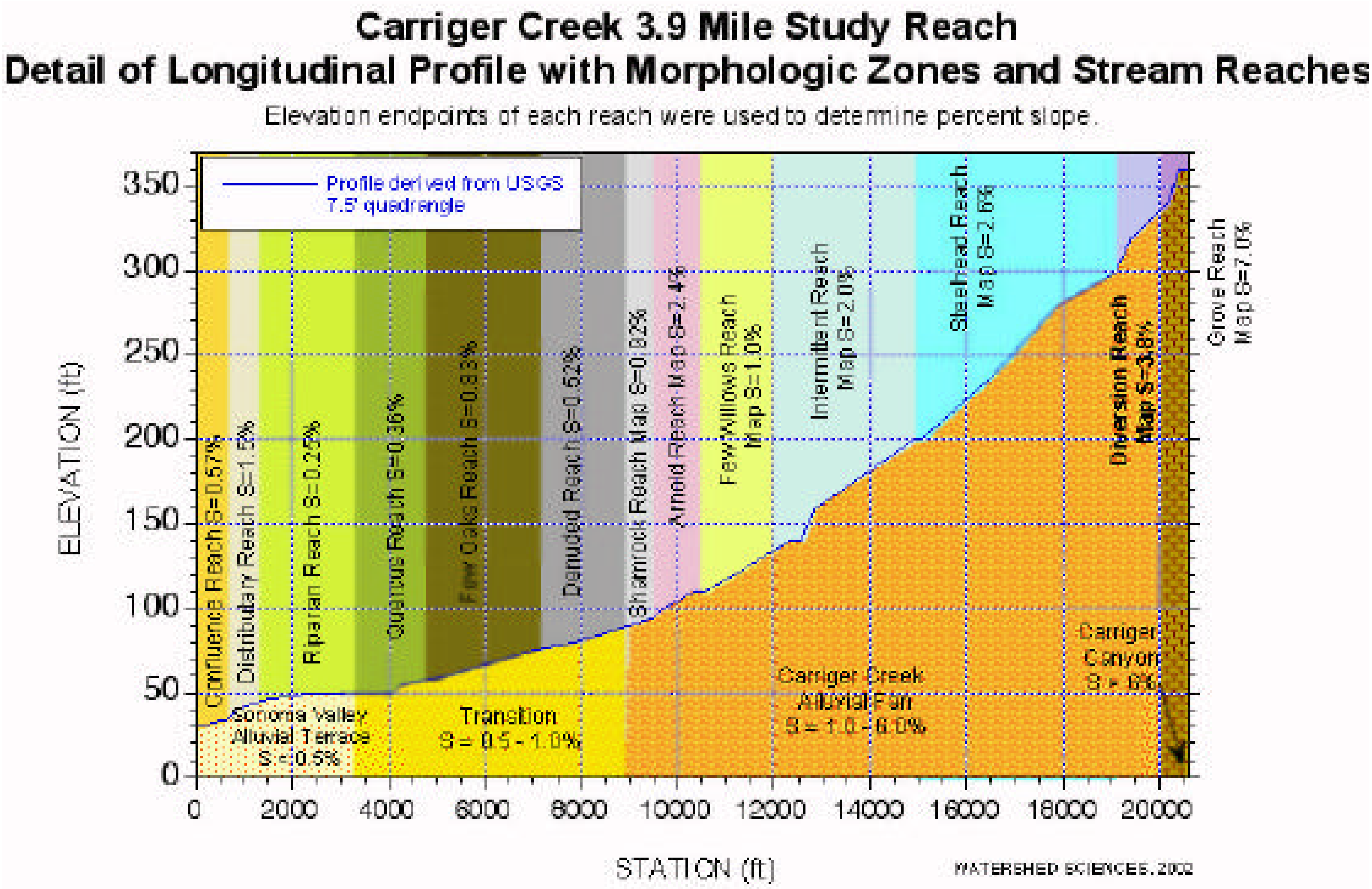
Carriger Creek 3.9 Mile Study Reach
Detail of Longitudinal Profile with Morphologic Zones and Stream Reaches
Elevation endpoints of each reach were used to determine percent slope.
Profile derived from USGS 7.5' quadrangle
ELEVATION (ft)
STATION (ft)
Confluence Reach S=0.57%
Distributary Reach S=1.5%
Riparian Reach S=0.25%
Quercus Reach S=0.36%
Five Oaks Reach S=0.83%
Denuded Reach S=0.52%
Shamrock Reach Map S=0.82%
Arnold Reach Map S=2.4%
Few Willows Reach Map S=1.0%
Intermittent Reach Map S=2.0%
Steelhead Reach Map S=2.6%
Diversion Reach Map S=3.8%
Grove Reach Map S=7.0%
Sonoma Valley Alluvial Terrace S < 0.5%
Transition S = 0.5 - 1.0%
Carriger Creek Alluvial Fan S = 1.0 - 6.0%
Carriger Canyon S > 6%
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Figure 4

Along the entire length of the Study Site, we assessed the physical condition of banks above (terraces) and below bankfull (active channel), and quantified their relative contribution of sediment.

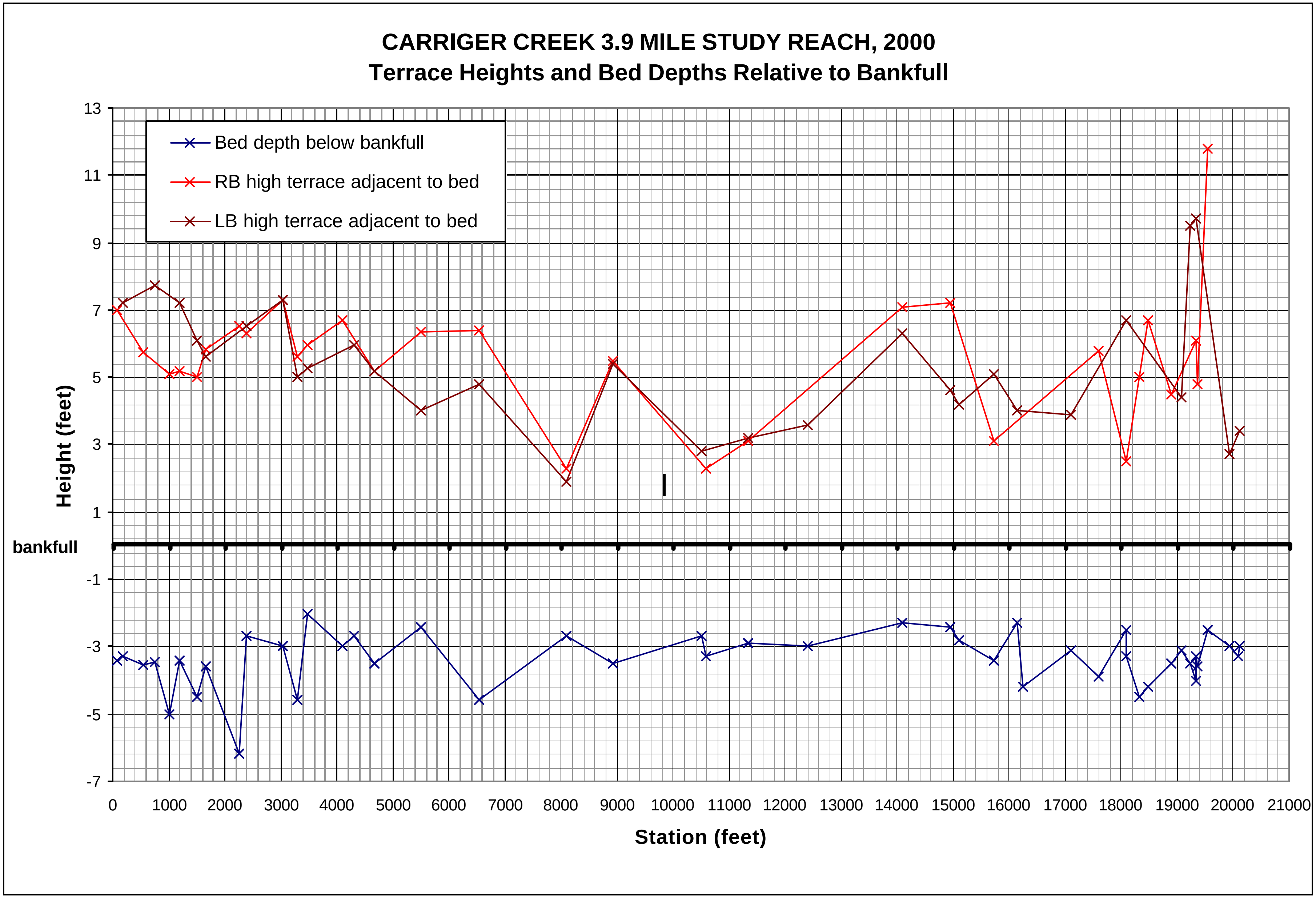
Bank condition was characterized as eroding, revetted or stable. Bank erosion was independently measured for banks above and below bankfull and noted if at least 0.25 ft of retreat could be averaged over the height and length of a specific bank segment. Additionally, a line of evidence had to be present to indicate that the erosion occurred within the last 165 years. The age of the erosion was evaluated by assessing the freshness of the feature, by dating trees that had exposed roots (often by increment borers if their was question regarding tree age), and reviewing historical photos and maps. Length and height of eroding banks were measured to determine the volume of sediment supplied to the channel. If a bank had some type of structural revetment, its length, type and condition was noted. If neither erosion nor revetment defined the bank condition, it was considered stable.

The location for each of the three conditions was documented by recording its beginning and ending distance station. The specific documentation can be viewed by looking at the Streamline Graphs Appendix. The specific volume of sediment associated with each erosional feature is also shown on the Streamline Graphs.

Figure 5. Terrace Heights and Bed Depth Relative to Bankfull

If the bankfull elevation is used as the zero datum, terrace heights and depth of the bed can be measured relative to bankfull and plotted along a longitudinal continuum without having to survey actual elevations. Changes in height of the highest terrace and the thalweg (maximum bed depth) relative to bankfull are plotted to show maximum relief along the length of the Study Site. We find that although bankfull height may be difficult to distinguish over certain reaches, when we survey very long reaches even in incised channels, we can usually find a few bankfull field indicators. These can include nick points, inner benches, top of a point bar, transitions between coarse to fine sediment, riparian vegetation such as alders, and wash lines relative to a known discharge. This plot in Figure 5 gives a visual perception of the degree of incision within the terrace banks and helps us visualize where the supply from terrace bank erosion might be large because of increased terrace height. For Carriger Creek, the slightly concave shape of the profile that depicts the height of the right and left terrace banks, combined with the convex profile of the bed, indicates that the channel is less incised through its middle reaches. The average relief between the bed and high terrace through the middle reaches appears to be about 6 ft. In the downstream and upstream reaches, it appears to be about 10 ft.

Although Carriger Creek shows higher relief between terrace and bed at the upstream and downstream ends of the Study Site, sediment supply from bank


CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Terrace Heights and Bed Depths Relative to Bankfull
Bed depth below bankfull
RB high terrace adjacent to bed
LB high terrace adjacent to bed
Height (feet)
bankfull
Station (feet)
13
11
9
7
5
3
1
-1
-3
-5
-7
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000

erosion is actually greatest in the middle reaches where the relief is relatively low. The high supply is from extensive bank retreat. In our other stream sites throughout the Bay Area, we find that the middle reaches tend to have similar high sediment supply from bank erosion, but the high supply is not from extensive bank retreat. Instead, it is usually from moderate retreat of very high banks in deeply incised channels.

Armoring of the channel bed from large cobbles and boulders that force extensive bank retreat has prevented much incision in the middle reaches of Carriger Creek. Bed incision rather than bank erosion is greater at the end reaches of the Study Site where the supply of sediment from the bed exceeds the supply from the banks. The incision that is taking place upstream may be partially driven by channel straightening activities that may have occurred in the past. The incision in the downstream reaches may relate to base level changes of Sonoma Creek. We hypothesize that incision throughout most of the Study Site relates to the loss of the distributary channels shown in Figure 2b. If there has been increases in runoff upstream of the Study Site from development and land use practices, these could also account for some incision, but this has not been quantitatively assessed since it is beyond the scope of the study. From our initial impressions we hypothesize that large increases in runoff have not occurred in the watershed upstream of the Study Site. This is based upon the very porous nature of the coarse soils that are filled with cobble and boulder-sized clasts that increase infiltration rates and increase surface roughness, effectively reducing the likelihood of surface erosion. We did not observe gullies or rills at the edge of impervious surfaces such as roads or driveways during our reconnaissance. Some local incision may be due to the effects of culverts.

Figure 6. Percent Length of Bank Condition

These graphs show the combined condition of banks above and below bankfull that have been subjected to fluvial processes since the time of non-native settlement 165 years ago. There are two graphs. The graph on the left shows bank condition by reach. The graph on the right shows the summation of bank condition for the entire Study Site. The green color represents stable banks, the red-stippled pattern indicates eroding banks, and the gray diagonal pattern indicates banks with revetment.

The graph on the right shows that 76% of the total length of both banks has eroded and supplied sediment to the channel. Only 19% of the banks are stable and 5% of them have structural revetment. Although a stable channel will clearly have some proportion of its banks eroding over time, we consider that only 19% stable banks is extremely low and represents accelerated erosion rates from past and present land use activities.

The graph on the left shows that the highest percentage of unstable eroding banks exists through the middle of the Study Site, particularly at Shamrock and Intermittent Reaches. Upstream of Arnold Bridge, a very high percentage of bank

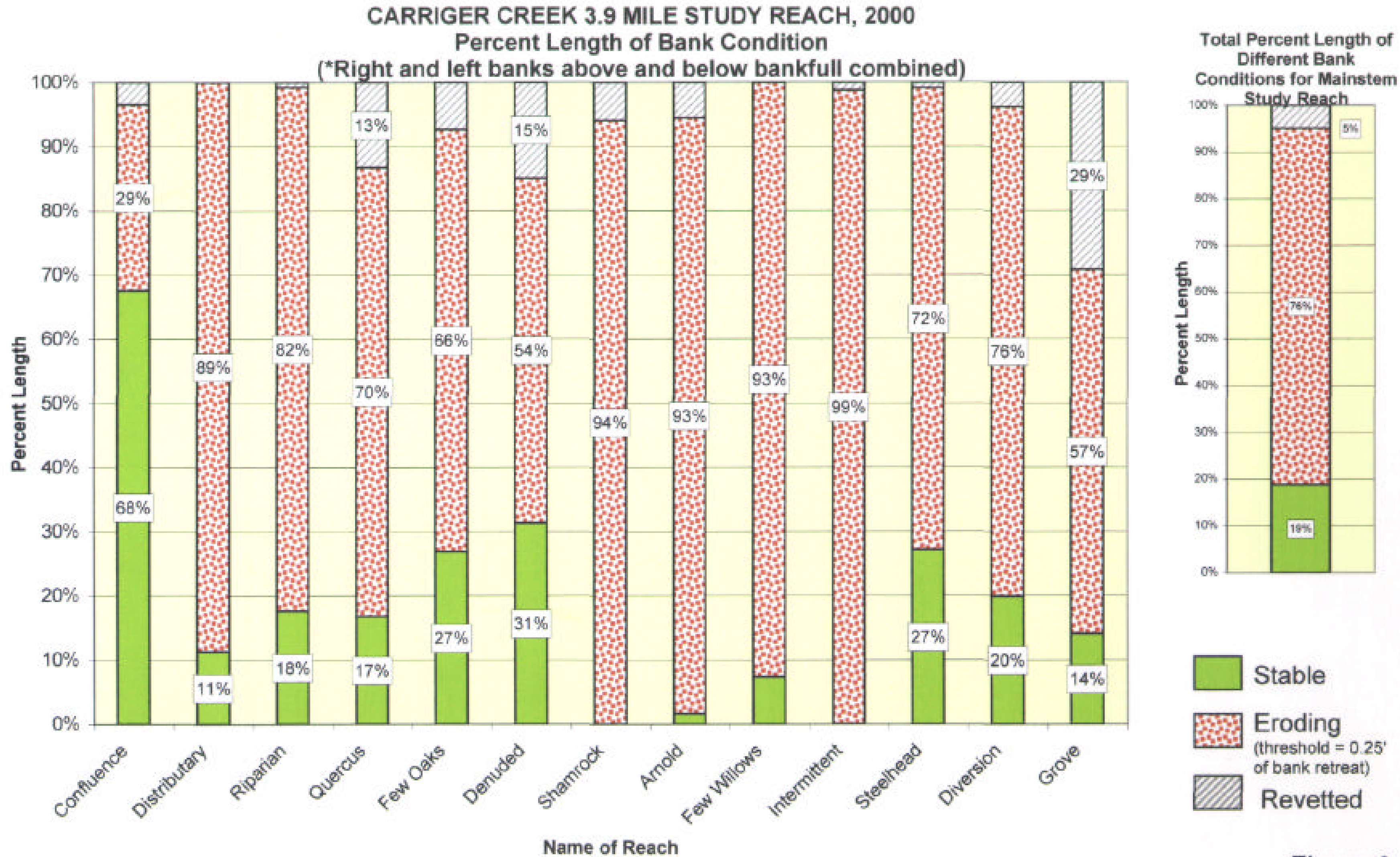


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Figure 6

length has eroded along Arnold, Few Willows, and Intermittent Reaches. These reaches represent 29 % of the entire length of the Study Site. We expect that the pre-existing Arnold Bridge, which still has a remnant of its former concrete structure exposed in the channel, largely contributed to the retreat of these upstream banks. The capacity of the former Arnold Bridge was probably too small to convey large floods. Its remnant structure indicates that it was much smaller than the present-day bridge. The bank erosion was probably caused during backwater floods. Downstream bank erosion may have also ensued when the backwater floods spread around the bridge structure and back over the banks into the channel. The historic channel straightening activities that were reported by David Luther, SSCRCD may have been a management effort by the Sonoma Water Agency to minimize future property loss. We hypothesize that the gradient through Few Willows Reach is probably steeper now than historical times due to its loss of sinuosity.

Confluence Reach is 68% stable. It has the greatest percent length of stable banks of all reaches. Although this reach is entrenched, substantial amounts of riparian vegetation grows upon inset benches. These vegetated inner terraces function to protect the terrace banks from further retreat and the kind of pervasive erosion that is found in the scantly vegetated upstream reaches. The data also show that minor amounts of structural bank revetment exist in this reach. The greatest amount is located in Grove Reach where a box culvert exists at the upstream end. A minor amount of suburban development occurs along the channel banks upstream of Few Willows Reach where some efforts have been made to stabilize banks to protect structures or private improvements.

Several reaches downstream and upstream of Arnold Bridge have few, if any riparian trees. We have observed that along many of the vineyards and pasturelands, the remaining riparian corridor is often only as wide as one tree when historically, it used to be at least several trees wide. In recent historical times, the riparian zone has often been cleared or diminished in width to increase the amount of acreage for pasture and cropland. By reducing the width of the riparian corridor, the buffer to bank erosion that is created by the added root strength of trees is lost. The subsequent widening of the channel from bank erosion has caused a loss of sinuosity, and increased stream gradient and water velocity.

Figure 7. Mainstem Bankfull Widths and Structures Crossing Channel

Variations in bankfull width are shown along the length of the Study Site. Bankfull measurements were taken no less than every 300 ft. Additional measurements were taken where the channel width significantly widened or narrowed.

Width ranges from a minimum of 15 ft at Grove Reach to 74 ft in both Few Oaks and Intermittent Reaches. Based upon field evidence we consider that the average pristine width used to be 27 ft. This was determined by measuring the

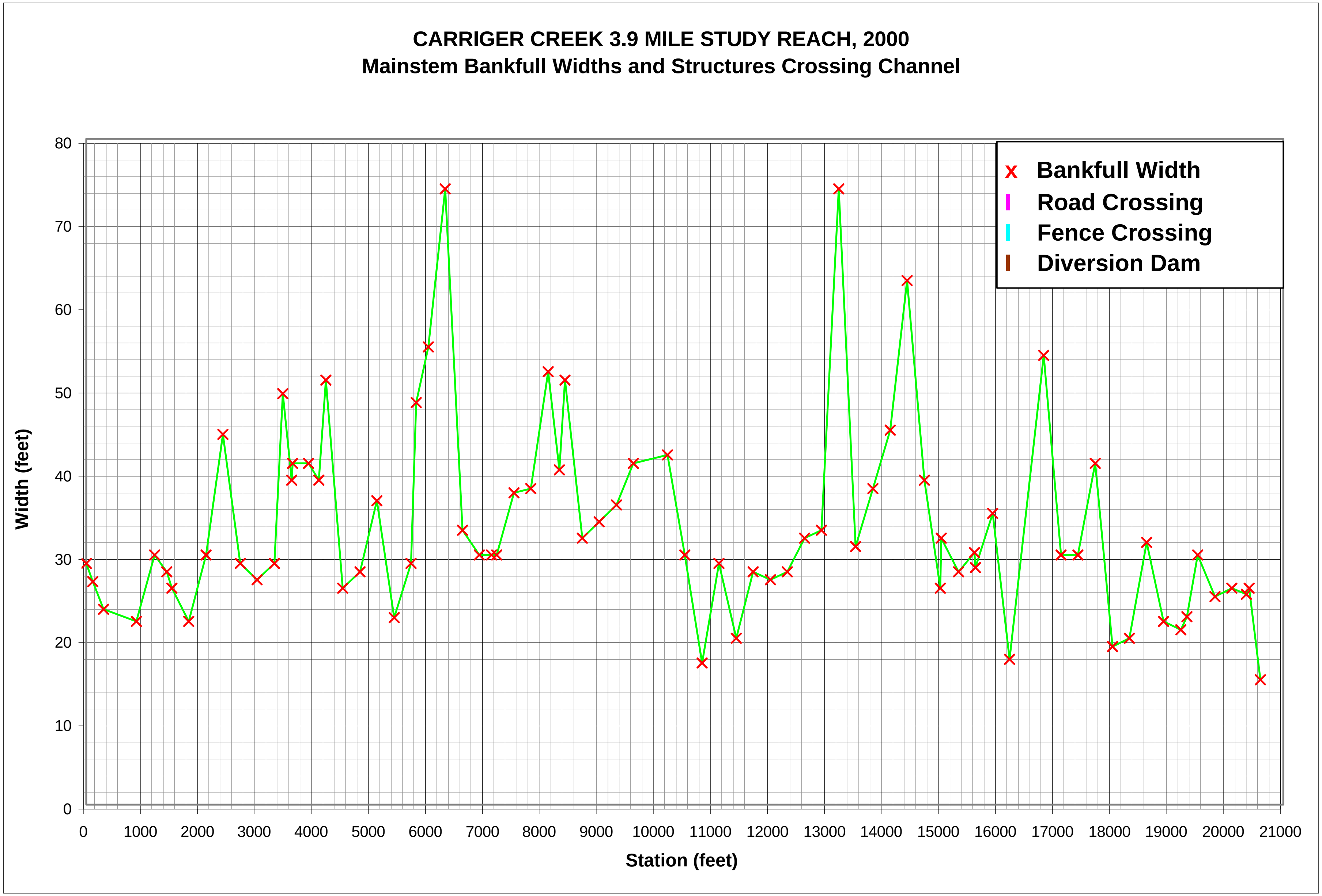

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Mainstem Bankfull Widths and Structures Crossing Channel
Width (feet)
Station (feet)
Bankfull Width
Road Crossing
Fence Crossing
Diversion Dam
0
10
20
30
40
50
60
70
80
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000

Figure 7

width between trees older than 100+ years that were on opposing banks that still had their exposed roots defining the former bank. We also measured this width in some of the remnant distributaries and abandoned channels. The average width for the entire Study Site now is about 32 ft. There is one minor tributary streams along the Study Site, so the general reduction in bankfull width in the upstream reaches is likely due to decreased discharge, more riparian vegetation along the banks, and increased gradient. The 5 ft increase in average bankfull width relates to the increased discharge in the single channel downstream of where the distributaries were destroyed by plowing, the instability of the banks from loss of riparian vegetation, adjustments in cross sectional area as the gradient adjusts to changes in quantity and size of bedload, and the channel straightening activities upstream of Arnold Bridge.

The locations of particular structures such as road and fence crossings, and a diversion dam are shown along the longitudinal profile. Most of the road and fence crossings are associated with an increased width upstream of the structure. This is not so apparent at Arnold because after the channel increased its width, it cut down and reduced its bankfull width within the over-widened terrace banks. It is important to note that although some sections of channel presently have bankfull widths close to average, many of these sections have already undergone a cycle or two of bank erosion (widening). Subsequent downcutting has caused a reduction in the present bankfull width.

Figure 8. Average Bank Retreat per Linear Foot

The average amount of bank retreat for both banks combined is shown for each reach. The least amount of bank erosion is occurring where Carriger Creek flows through the alluvial terraces of Sonoma Valley. Bank erosion is greatest where the creek flows across Carriger Creek's alluvial fan from Shamrock through Intermittent Reaches. If we use 27 ft as the average, pristine bankfull width, then the amount of erosion on the alluvial fan has equaled at least one bankfull width, except for Arnold Reach where it exceeds two. This is the section of channel that has been most influenced by the armored aggradation and erosion sequence that requires the occurrence boulder to cobble-sized bedload in a relatively low gradient channel of <2% slope (as later surveyed through Arnold reach, see Figures 4 Appendix, 5a, and 5b Appendix).

Figure 9. Percent Length Right and Left Bank Conditions

When the amount of bank erosion and stable bank are compared for each side of the stream, a trend in overall direction of lateral migration can occasionally be detected. In Carriger, there is only a 3% difference in the length of stable banks, indicating no significant trend in migrational direction. If we assume that the length of revetted banks represents former eroding banks, then the length of eroding banks is only different by 3%. The northeast (left) bank has 8% of its bank length revetted; the southeast bank has 2%.

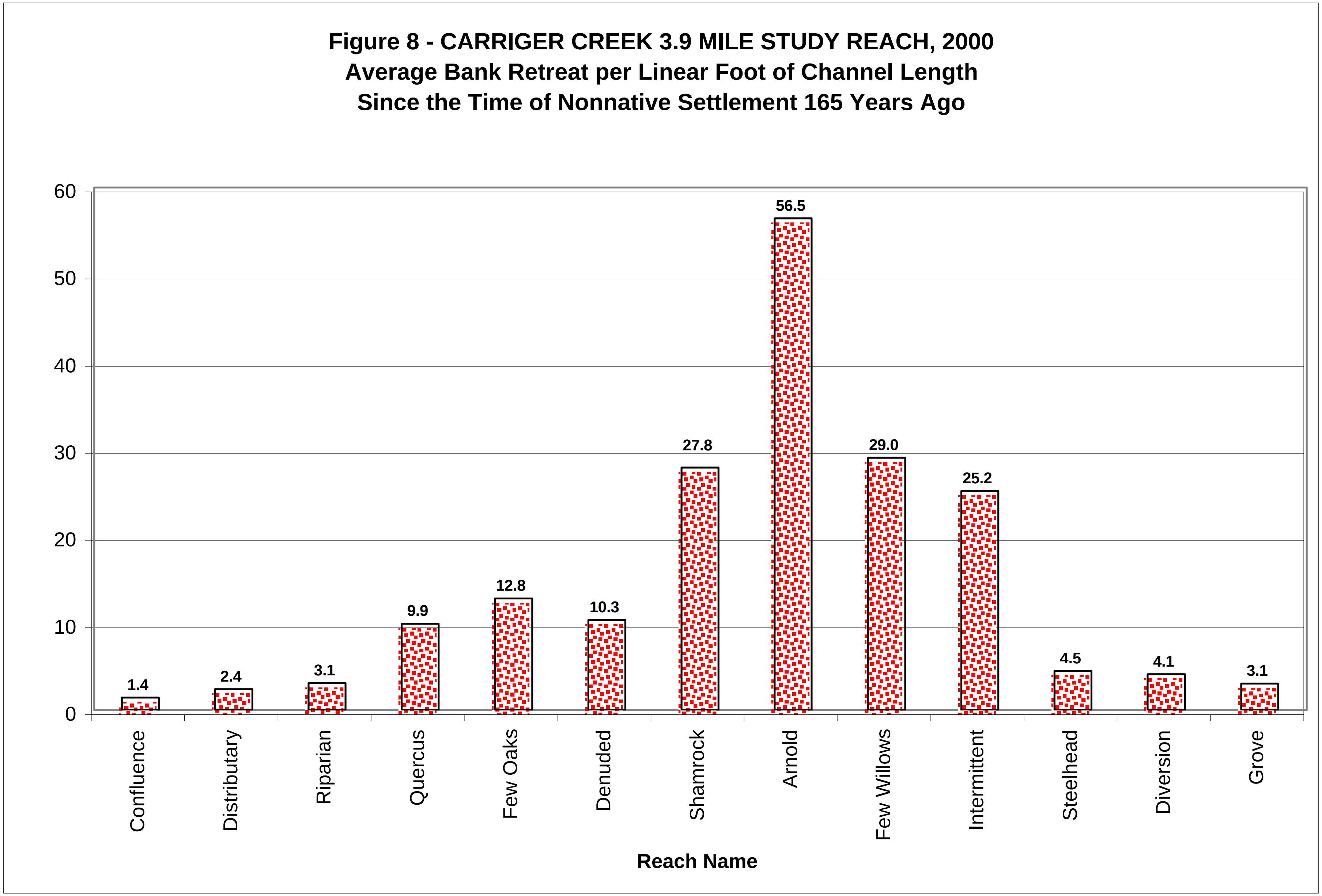


Figure 8 - CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Average Bank Retreat per Linear Foot of Channel Length
Since the Time of Nonnative Settlement 165 Years Ago
60
50
40
30
20
10
0
1.4
2.4
3.1
9.9
12.8
10.3
27.8
56.5
29.0
25.2
4.5
4.1
3.1
Confluence
Distributary
Riparian
Quercus
Few Oaks
Denuded
Shamrock
Arnold
Few Willows
Intermittent
Steelhead
Diversion
Grove
Reach Name

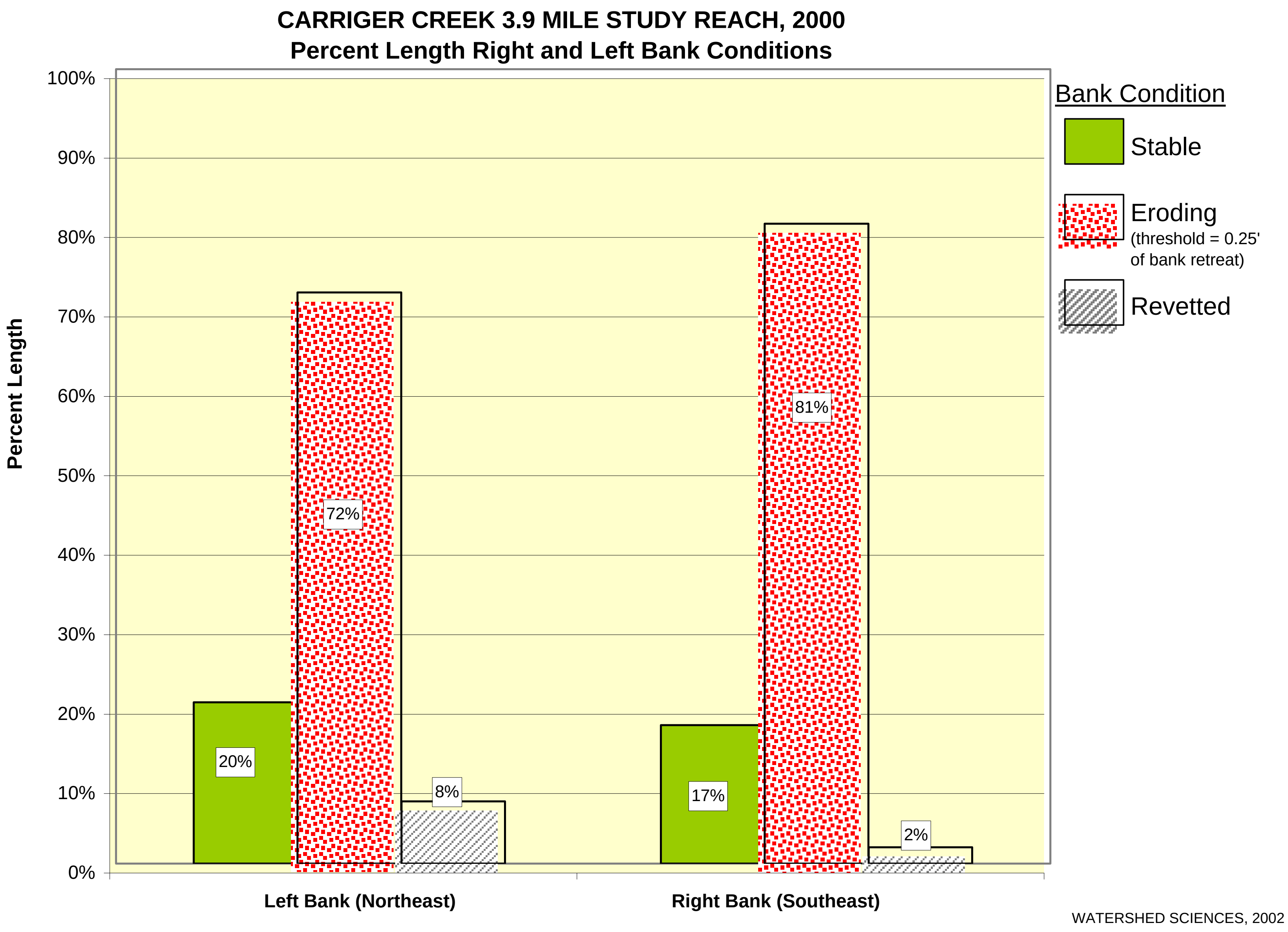

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Percent Length Right and Left Bank Conditions
Percent Length
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
20%
72%
8%
17%
81%
2%
Left Bank (Northeast)
Right Bank (Southeast)
Bank Condition
Stable
Eroding
(threshold = 0.25' of bank retreat)
Revetted
WATERSHED SCIENCES, 2002

Figure 10. Length of Different Revetment Types per Reach

This graph shows the kind of revetment that has been used on Carriger Creek banks. The bar graph on the left shows the total length of different revetment types per reach, while the pie chart on the right shows the total percent length and actual length of revetment types for the entire Study Site. As shown in Figure 6, only 5% of the combined length of both right and left banks have revetment. Of this total, 75% is riprap (shown in pie chart), which has included large boulders and concrete debris. Revetment of both right and left banks represents 1,524 ft of channel length. This indicates considerable cost and effort by landowners to minimize property loss. About 18% of the revetments are composed of concrete. Sackcrete and a few creative types of revetment methods contribute to only 7% of the total.

The bar graph shows that most of the riprap is found in Quercus, Few Oaks, and Denuded Reaches, located between Leveroni and Arnold Bridges.

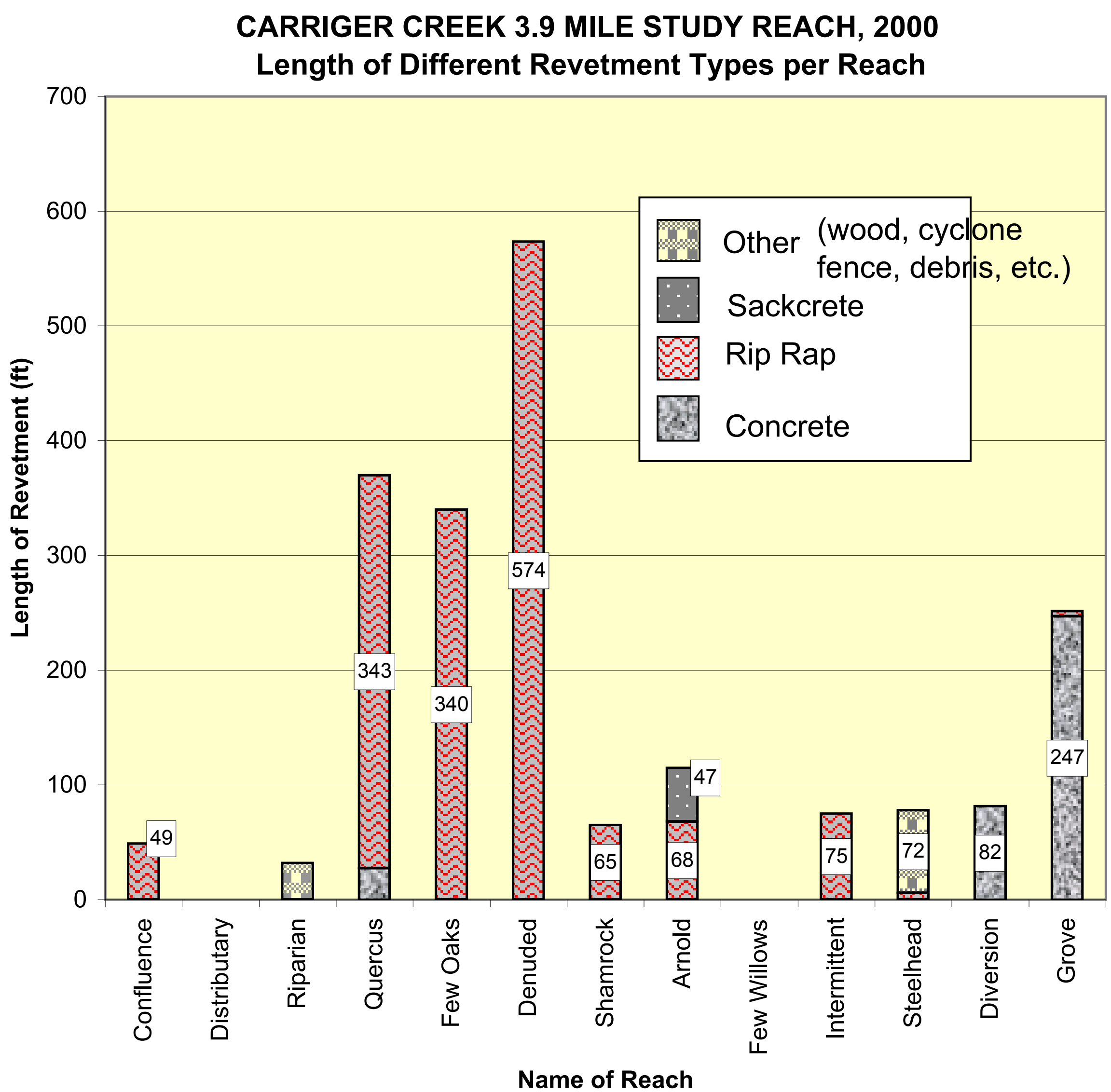
Figure 11. Revetment Conditions per Reach

Condition and performance of individual bank revetments were evaluated at each structure. If at least 85% of a structure was functioning as designed, it was rated as good. If only 50% - 85% was functioning, it was rated as moderate. If less than 50% was functioning, then it was rated as failing. To evaluate the revetments, we had to determine their functions. All were designed to reduce fluvial erosion of the banks. In other circumstances, not present within the Study Site of Carriger Creek, revetments may also be designed to reduce mass wasting by supporting a hillside, for example, that is prone to landslide failure.

Denuded Reach had the greatest length of revetment rated as either failing or good. All of it was riprap. Quercus and Few Oaks Reaches had the greatest length of moderately performing revetments, which were also riprap. Grove Reach had the second greatest amount of revetment rated as good; most of it was concrete from the box culvert located at Grove St. The overall status of existing revetments along the entire Study Site is 10% failing, 30% moderately functioning as designed, and 60% good.

Figure 12. Percent of Adjacent Bank, Terrace, and Canyon Slope Erosion for Entire Study Reach

The length of erosion for banks above and below bankfull elevation can be compared to determine whether erosion is limited to the lower banks or extends up onto the terraces. Erosion on terrace banks within the last 165 years represents erosion that occurs either during present day floods in the recent past before the channel cut down, or from present day low flows that undermine the high terraces. In highly entrenched channels, the erosion is usually from all three causes and the length of erosion will be nearly equal for each. Data for Carriger Creek indicate such a relationship, where the length is nearly 50% for each. About 1% of the eroding bank length does not occur within alluvium deposited by



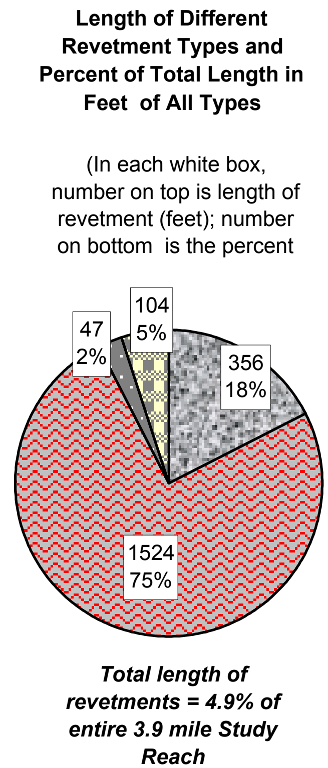


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Figure 10

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Revetment Conditions per Reach

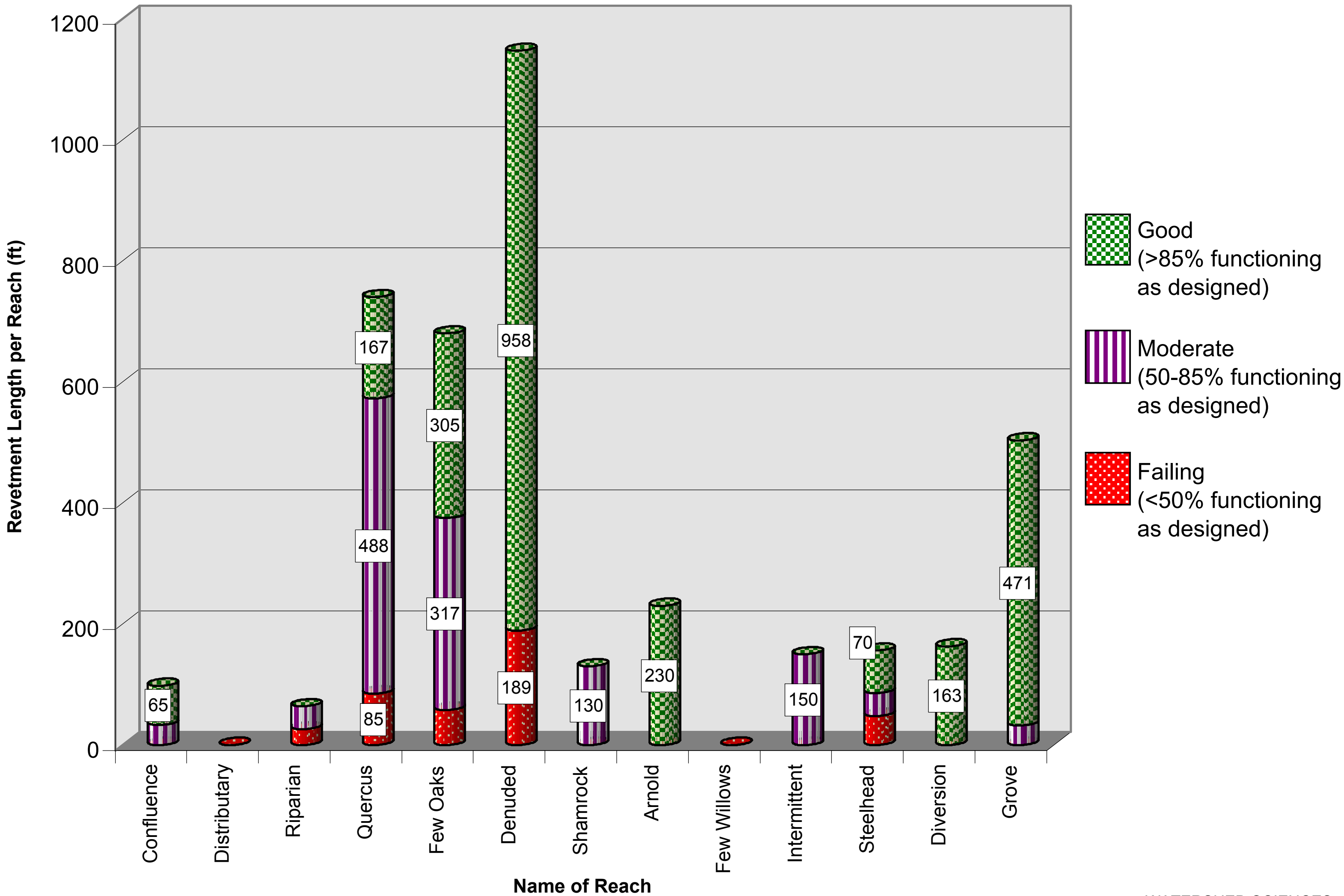

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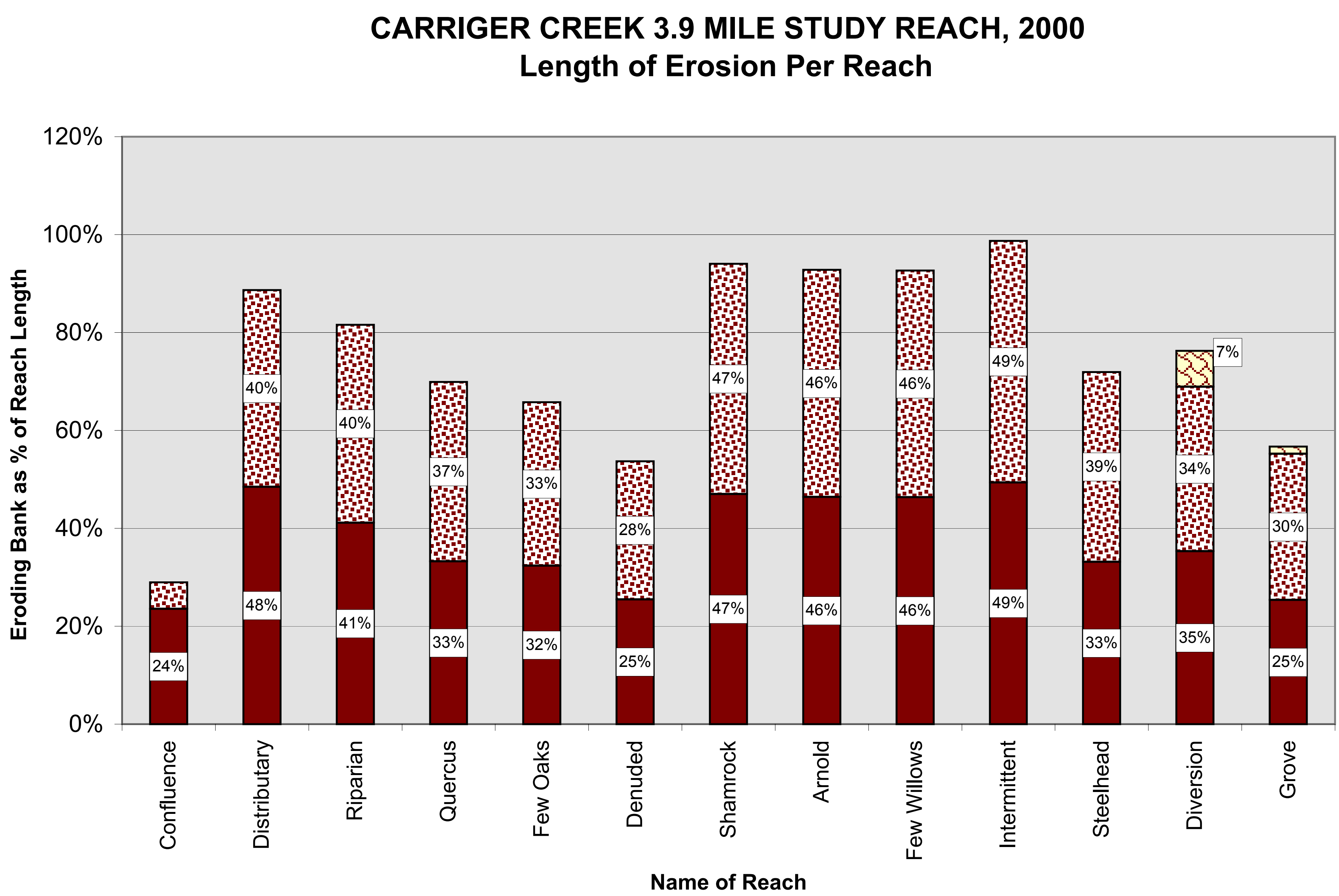
Figure 11


CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Length of Erosion Per Reach
Eroding Bank as % of Reach Length
120%
100%
80%
60%
40%
20%
0%
24%
48%
40%
41%
40%
33%
37%
32%
33%
25%
28%
47%
47%
46%
46%
46%
46%
49%
49%
33%
39%
35%
34%
7%
25%
30%
Confluence
Distributary
Riparian
Quercus
Few Oaks
Denuded
Shamrock
Arnold
Few Willows
Intermittent
Steelhead
Diversion
Grove
Name of Reach

the stream. Instead, fluvial erosion is occurring on the canyon slope that is intersected along Diversion Reach.

MECHANISMS AND AMOUNTS OF SEDIMENT SUPPLIED TO THE CHANNEL

Sediment supplied to a channel can be associated with various processes that can be temporally and spatially distributed among multiple types of sources from different parts of a watershed. Some examples include bed incision, bank erosion; fluvial transport of bedload; landslides; soil creep; and surface erosion from overland flow on hillsides, roads, cattle trails, and inboard ditches. All of these may be happening in different areas at different times. The amount and rate of sediment supply can be influenced by anthropogenic versus natural causes. If the anthropogenic causes are identified and separated from natural causes, reductions in the rate of supply from the man-related sources can be addressed through prioritization, mitigation, and restoration.

The volumes of sediment from bed incision represent the long-term supply from downcutting processes since the settlement of non-indigenous peoples. The volumes reported do not represent the flux from bedload transport. The amount of sediment supplied by bed incision was determined by multiplying bed width by incision height by length of bed between width measurements. Bed width measurements were taken at the same interval as the bankfull width measurements every 300 ft minimum and at obvious changes in width. We estimated the amount of incision by looking for evidence of old channel beds, nick points in the terrace banks, dating of trees along the channel, and estimating depth of aggradation.

This project does not create a complete picture of all these influences because it is not a full watershed study. Yet, we can begin to identify the amounts and sources of sediment associated with the different processes along just the mainstem channel. In such an effort, the volume of sediment contributed from local sources along the length of the Study Site has been categorized as being supplied from bed, banks, gullies, or landslides. Whether these sources can be directly attributed to man-related activities such as culverts, cattle trails, or bridges, for example, is noted only when we can attribute 90% confidence to a direct man-related impact.

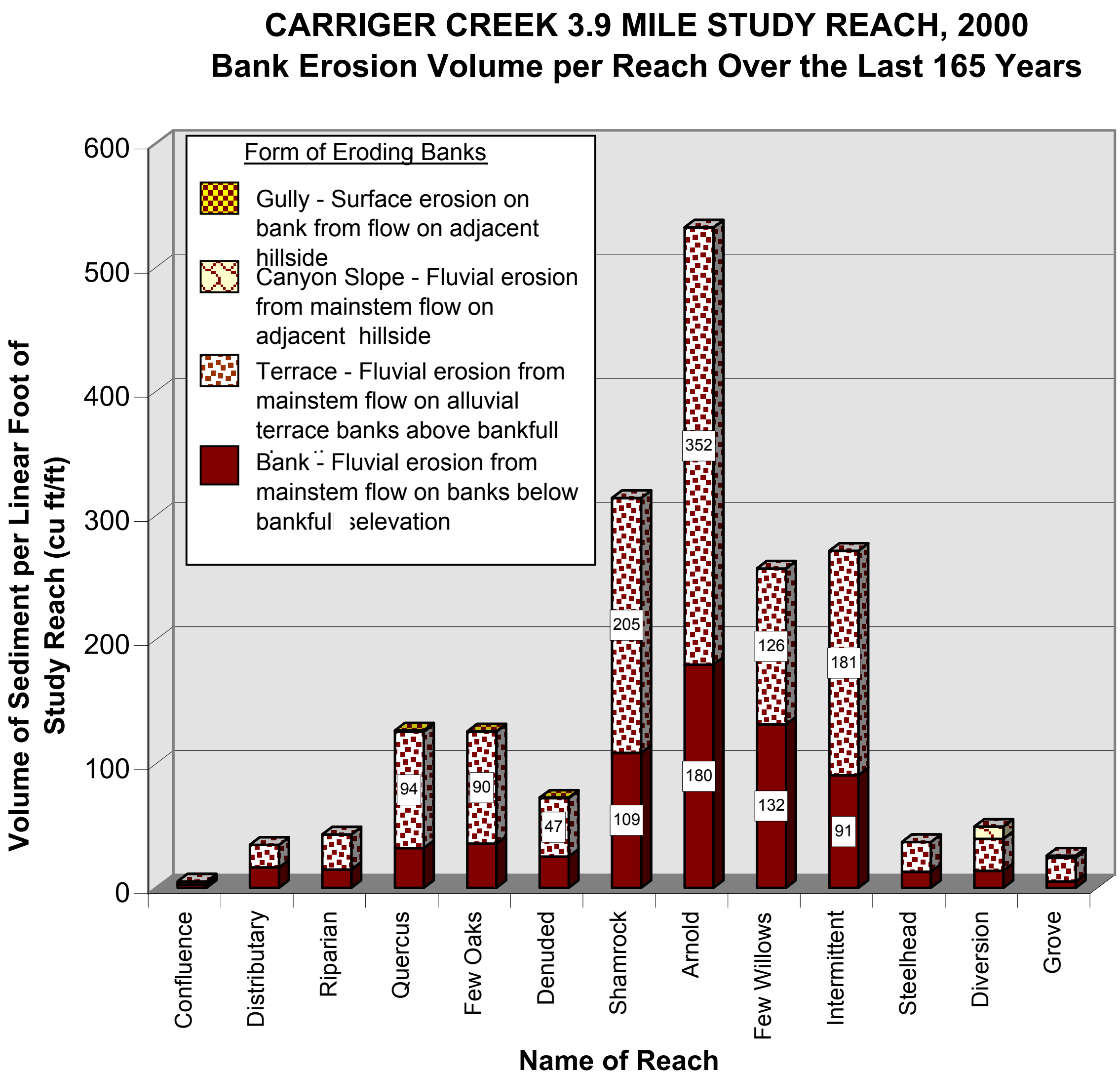
The indirect effects of man's influence on rates of erosion cannot be easily separated from natural rates, unless the natural rates are known. This is a dilemma in many streams because few streams exist that have not been indirectly impacted by land use practices. Thus, the rates of natural processes have not been determined. An example of an indirect effect of man-related impacts is as follows: more runoff from urban development is causing the channel to adjust its geometry, which in turn causes its rate of bank erosion or bed incision to accelerate. Another example would be road construction that has increased the supply of sediment from bare soil surfaces or increased landsliding along road cuts. Subsequently, the mainstem channel adjusts its geometry to accommodate increased sediment load, which in turn causes its rates of bank erosion or bed incision to accelerate. These scenarios exemplify that for most of the sediment volumes that we report here, man-related and natural causes cannot be easily distinguished, and should be considered as “gray” areas.

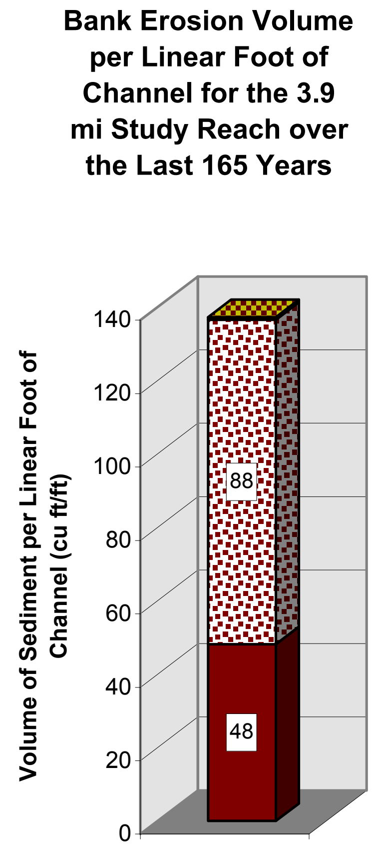
Figure 13. Bank Erosion Volume per Reach

In the Carriger Creek Study Site, different sediment sources include alluvial terrace banks and banks below bankfull, gullies, and canyon slopes. The graph on the left shows the volume per linear foot of channel for each reach. The graph on the right shows the total for the entire Study Site. The sediment volume was divided by length of each reach. This allows reaches of different length to have their relative volumes compared. This also allows us to compare other creeks with different study reach lengths. The volumes represent the total amount of sediment supplied during the last 165 years.

Carriger Creek has 137 cu ft/linear ft of sediment supplied to the channel from its banks, as shown in the right hand graph. This represents a bank supply rate of 0.83 cu ft/linear ft/year. Of this total, the terrace banks supply 64% of the sediment, which is nearly twice the amount from the banks below bankfull. This is because the terrace banks often have greater height than bankfull banks in entrenched channels. The respective volumes of sediment per channel length are 88 cu ft/linear ft and 48 cu ft/linear ft. Although volume of terrace erosion is twice the bankfull amount, the length of eroding terrace banks is nearly equal to the bankfull banks. The amount of sediment supplied from gullies and canyon slopes is minimal in comparison to the alluvial banks. The respective values are 0.1 cu ft/linear ft and 0.5 cu ft/linear ft.

The graph on the left shows that the reaches with the greatest volume of sediment supply are located in the middle of the Study Site which includes Shamrock through Intermittent Reaches. These reaches occur on the alluvial fan where the channel is less entrenched than the upstream and downstream reaches. The reach with the greatest sediment volume is Arnold, accounting for 532 cu ft/linear ft of sediment supplied over the last 165 years (or 3.22 cu ft/linear ft/yr). We expect that this extremely high rate is partly due to the impacts of an earlier undersized bridge constructed at Arnold Avenue and the channel straightening activities. There is also a corresponding and dramatic decrease in riparian vegetation along the alluvial fan where straightening activities were performed below Steelhead Reach. This can be seen on Figure 2b Photo Map. Whether the riparian vegetation below Steelhead Reach was lost before or after the channel straightening was conducted is presently unknown. It is possible that bank erosion rates upstream of the old distributary confluences have also been influenced by the loss of distributaries.





For the entire study reach, there is 137 cu ft of sediment supplied by bank erosion per linear foot of channel

WATERSHED SCIENCES, 2002

Figure 13

Steelhead and Diversion Reaches are also on the alluvial fan, but they have a sharp drop in the amount of sediment supplied to the channel from the banks. Riparian vegetation still occurs along most of their banks. These reaches become more entrenched due to confinement by adjacent canyon slopes.

Figure 14. Volumes of Bank and Bed Sediment Supply per Linear Foot of Channel during the Last 165 years

The volume of sediment per linear foot of channel contributed by bank erosion (shown in a solid red pattern) is compared to the amount supplied by bed incision (shown as a stippled red pattern) for the different reaches. Note that the bank erosion total includes the supply from gullies on the banks. The amounts from the different sources are also compared to the combined total from both sources (shown as purple diagonal lines). This provides a way to visualize how the dominance of different processes varies over the length of the main channel. By plotting the combined total, the locations with the greatest supply of sediment become apparent.

The far column on the right shows the overall amounts of sediment for the entire Study Site. The total amount supplied by bank erosion for the Study Site is 137 cu ft/linear ft of channel length. Bed incision provides 117 cu ft/linear ft. The combined total is 254 cu ft/linear ft. Please note that this does not include bedload or suspended load transported from upstream. This would require either long-term sampling or development of a sediment budget for the whole watershed.

If sediment supply from bed and bank sources along the different reaches is examined, some important patterns emerge. For example, the supply of sediment from bed incision dominates bank erosion in the downstream and upstream reaches. Bank erosion dominates the middle reaches from Shamrock through Intermittent Reaches on the Alluvial Fan Morphologic Zone. The reaches that are dominated by bank erosion also supply the greatest combined total amounts of sediment. Reaches downstream of Shamrock have a greater combined total amount of sediment supply than upstream of Intermittent Reach. This is because downcutting is greater in the downstream reaches than those upstream, as indicated in Figure 5.

Since the total combined sediment supply for the Study Site is about 254 cu ft/linear ft, total long-term rate of supply can be reported as 1.54 cu ft/linear ft/yr. See Table 3 below. Alternatively, we can think of this as a total long-term supply rate of 1,175 cu yd/yr from the Study Reach. Clearly a long-term rates average years of very high or low inputs, so this rate may not be representative of any actual rate in any one year. Short-term rates that are punctuated by land disturbance are much greater than long-term rates. Rates or erosion may be highest after an initial perturbation and then slow at an asymptotic rate, or acceleration of rates may propagate spatially through a channel network. The

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Volumes of Bank and Bed Sediment Supply per Linear Foot of Channel
Since the Time of Nonnative Settlement about 165 Years Ago

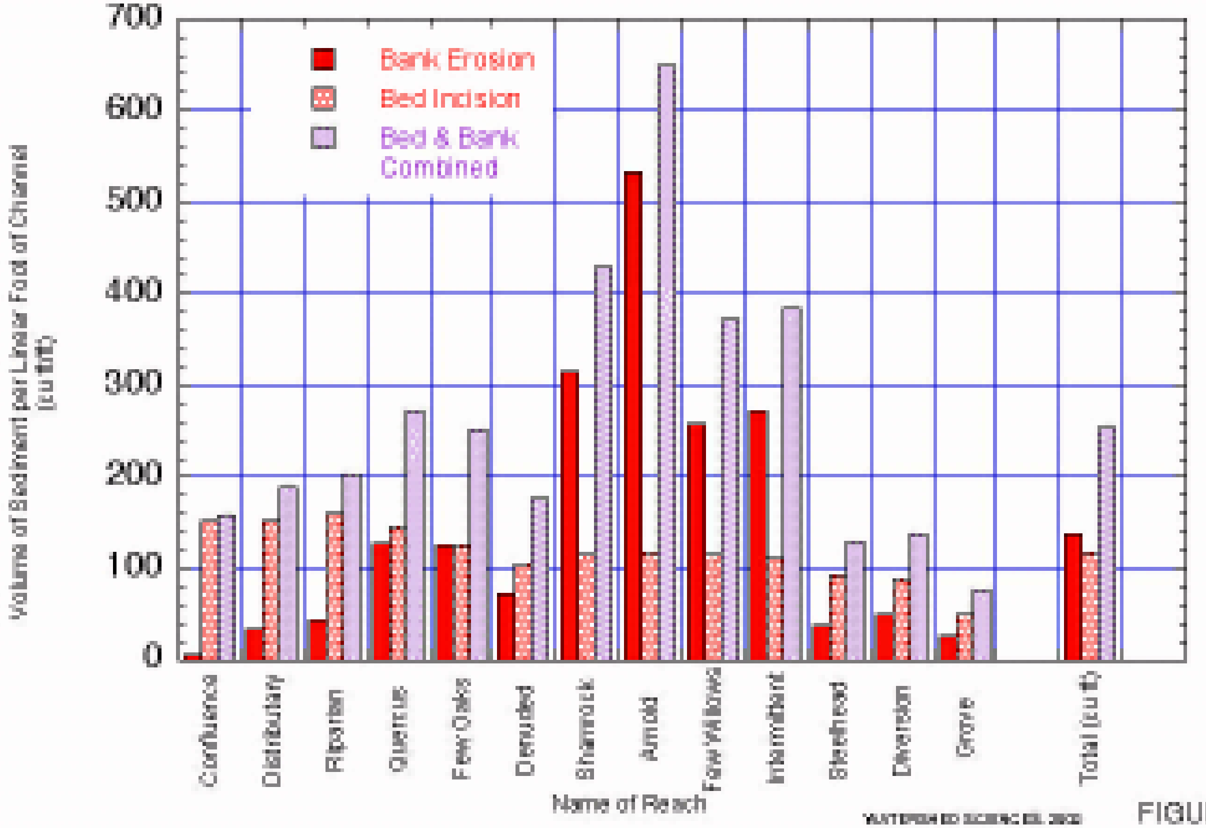


FIGURE 14

individual sediment supply rates for bed and bank are also listed in the table below. A total watershed yield cannot be determined since the rest of the watershed was not quantified.

Table 3. Sediment Supply Rates for Study Site

SOURCE	**Volume in 165 years (cu ft)**	**Volume per linear foot of mainstem channel (cu ft/ft)**	**Long-term rate per linear foot per year (cu ft/ft/yr)**	**Long-term rate for Study Site (cu yd/yr)**
Banks	2,827,439	137	0.83	635
Bed	2,404,237	117	0.71	540
Combined Total	**5,231,676**	**254**	**1.54**	**1,175**

The amount of man related sediment supply that we can directly attribute to man's activities is only 1%. This supply is associated with instream structures such as bridge abutments and floating fences. Yet, we expect that the indirect effects of man probably account for a significant portion of the total supply, perhaps 60%. We consider this a conservative estimate. This amount has been estimated for other watersheds we are working on in the Bay Area. The principal indirect impacts in Carriger Creek have been destruction of tributaries, modification of the riparian zone for agricultural practices, channel straightening, and backwater flooding from instream structures such as bridges.

DISTRIBUTION OF DIFFERENT SIZES OF SEDIMENT ON THE BED SURFACE

Channel gradient, longitudinal curvature, supply of sediment, and downstream sorting causes variations in sediment size over the length of a channel system. Across the width of a channel, variations in sediment sorting may occur from velocity variations caused by flow obstructions. Patches of different-sized sediment can be separated into discrete size classes that can be quantified by conducting pebble counts on the particular patches rather than averaging the particle sizes over the entire bed. By performing pebble counts, where particle diameters are measured in the field, the average particle size (D50) is determined by statistical analysis. Once enough pebble counts are performed on different sediment patches, the D50 size class can be reasonably estimated by eye. Using this method, we have determined that the accuracy is +/- one standard sieve size. The size classes represent the range of standard sieve sizes, which are listed in the legend for Figure 15.

If a single patch of sediment was sorted into a bimodal or trimodal size distribution along the channel bed, we noted two or three D50 values over the appropriate channel length. Similarly, if the bed was laterally sorted into two or three different patches, two or three D50 values would be reported.

The sediment D50 size classes are used to spatially characterize the bed surface of different reaches in a particular channel, as well as to compare the particular channel to other systems. By establishing a continuum of particle size information, it is possible to monitor temporal changes, and to determine the influence of tributary channels that may be contributing abundant fine or coarse sediments to the mainstem channel. Additionally, the availability of fine sediments (smaller than 2mm) and their potential for impacts on fish habitat (spawning gravels and pools) can be crudely assessed. It is important to keep in mind, however, that the bed surface is typically coarser than the subsurface, so fines may have a much larger influence on spawning gravel characteristics.

The distance location for the individual bed classes was recorded. This allowed us to plot their longitudinal distribution. The specific bed characteristics are shown in the Streamline Graphs Appendix.

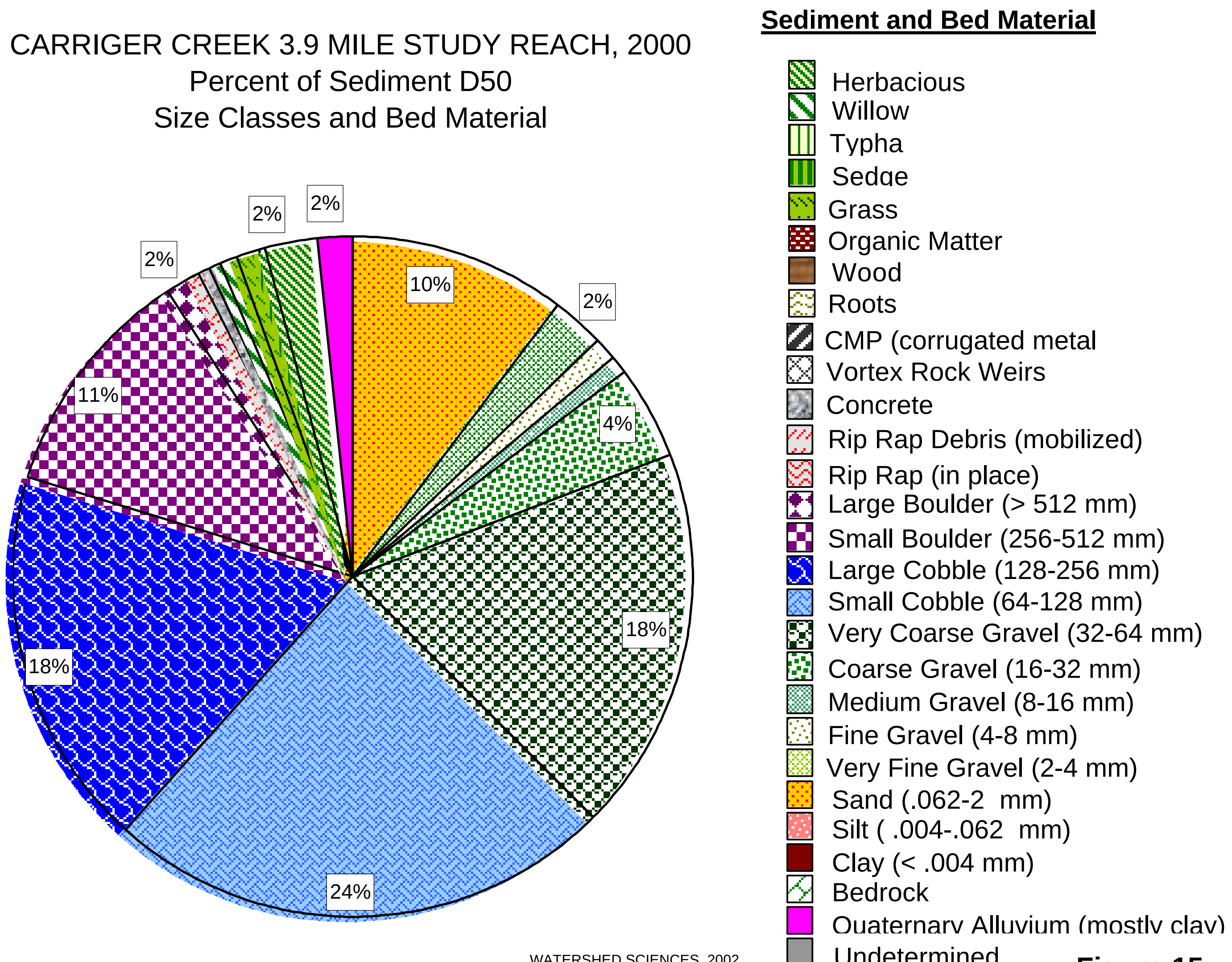
Figure 15. Percent of Sediment D50 Size Classes and Bed Material

For the entire length of the mainstem Carriger Creek Study Site, the dominant D50 size class is small cobble, representing 24% of the total bed classes. Very coarse gravel and large cobbles have an equal but subdominant influence, each representing 18% of the bed surface. Small boulders represent about 11%, and sand represents 10% of the bed surface. All other size classes individually represent less than 4% of the total. A very small percentage of the bed is represented by vegetation, where herbacious and grass vegetation represent the most coverage by any particular flora. A minor amount of the bed has concrete and mobilized riprap debris.

The most distinctive elements about the bed of Carriger Creek, when compared to other North Bay creeks of similar size and gradient, is the very low amount of sand and finer sediments, the very low quantity of fine to coarse gravels, and the abundance of cobble to boulder-sized sediment. The amount of sand may be less evident by falling between the interstitial spaces of cobble, but we do not observe that the spaces are filled. Based upon our observations during the walk-through of the upper canyon, the supply of sand and finer sediments from bank erosion does not appear to be as high along the canyon banks because the banks are comprised of mostly coarse sediments. Additionally, the banks are not eroding as severely as those downstream. Sediment size in the banks of the study site was noted at each eroding bank. Carriger has a lower amount of sand than any other channel that we have assessed which includes San Antonio Creek (Sonoma-Marin County boundary), Miller and Novato Creeks (Marin County), Wildcat Creek (Contra Costa County), Crow Creek (Alameda County), and San Pedro Creek (San Mateo County).

We are finding a general correlation between streams with high values of fish habitat (including high numbers of steelhead) to streams with low percentages of

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Percent of Sediment D50
Size Classes and Bed Material



WATERSHED SCIENCES, 2002

Figure 15

sand and finer sediment noted on the bed surface. Generally, the streams with less than 40% sand seem to be supporting steelhead and trout. The streams that we have studied that have greater than 40% sand do not presently support these kinds of fish. This may be coincidental or may be an interesting trend, but more streams need to be analyzed to determine if this is an actual threshold.

Figure 16. Sediment D50 Size Classes and Bed Material for Different Reaches

The general pattern of sediment size classes shows that Carriger Creek fines in its downstream direction and coarsens upstream. Although this may seem to be an obvious finding, we have found that some Bay Area streams have a higher percentage of fine sediment upstream. This is particularly true in some landscapes dominated by earthflow processes, such as the Orinda Formation in the East Bay

The reaches in Carriger Creek that have the highest percentages of sand and finer sediments are located downstream of Few Oaks Reach. Upstream of Few Oaks Reach to Denuded Reach, large cobble becomes the D50 size class and Carriger Creek transitions from its alluvial fan into the alluvial terraces of Sonoma Valley. We expect that the channel gradient decreases significantly through this section. Very coarse gravel starts to dominate the D50 size classes within Distributary Reach, where much of it may be settling out during bankfull flows. Below this reach, beyond the confluence with Felder Creek, smaller-sized gravels probably dominate the channel.

Small boulders become significant as a dominant size class starting at Intermittent Reach. However, both cobbles and boulders are present as part of the size distribution on the Alluvial Fan zone. After the loss of the distributary channels, the main channel entrenched as a result of the more frequent high flows. As it entrenched larger floods could be accommodated that could exert even greater shear stresses on the bed. This explains why boulder to cobble-sized sediment has been transported so far out onto the toe of the alluvial fan. The fact that the banks are composed of finer sediment (sometimes very fine-grained Quaternary Alluvium) than the armored bed, makes the banks much more erodable than the armored bed. Clearly, most of the boulder and cobble-sized material only moves with infrequent flood flows. Yet when this large-sized material mobilizes and armors more of the downstream bed, it induces bank erosion, especially where there is a lack of root strength from riparian vegetation.

Large boulders begin to represent the D50 size class at Steelhead Reach. This is where perennial flow is continuous. In the reaches upstream of and including Steelhead Reach, we find that cobble and boulder bars promote the development of pools.

Patches of vegetation have also been documented on some portions of the active channel bed. The patches coincide with open areas of little riparian

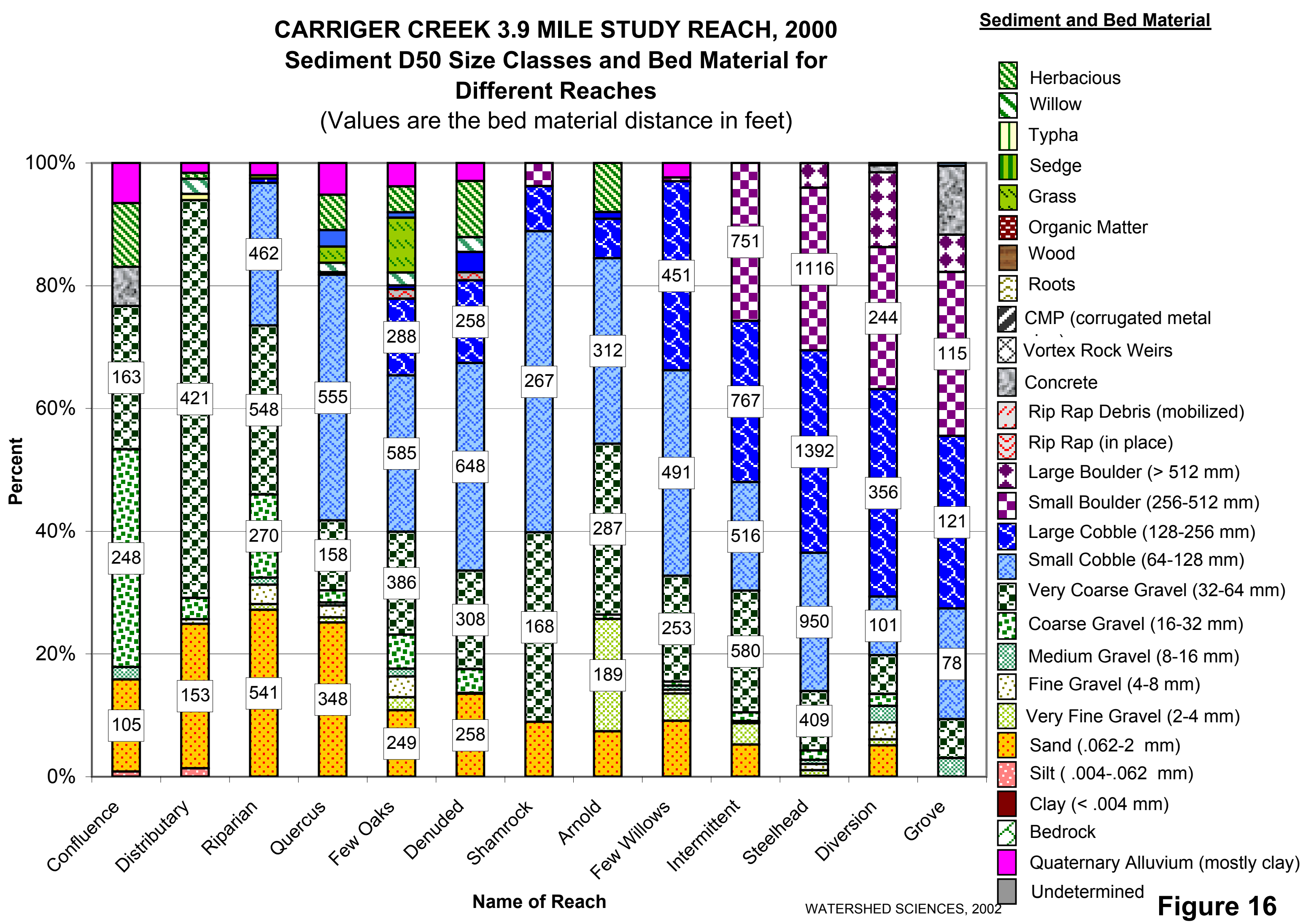

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Sediment D50 Size Classes and Bed Material for Different Reaches
(Values are the bed material distance in feet)
Percent
100%
80%
60%
40%
20%
0%
Name of Reach
Confluence
Distributary
Riparian
Quercus
Few Oaks
Denuded
Shamrock
Arnold
Few Willows
Intermittent
Steelhead
Diversion
Grove
163
248
105
421
153
462
548
270
541
555
158
348
288
585
386
249
258
648
308
258
267
168
312
287
189
451
491
253
751
767
516
580
1116
1392
950
409
244
356
101
115
121
78
Sediment and Bed Material
Herbacious
Willow
Typha
Sedge
Grass
Organic Matter
Wood
Roots
CMP (corrugated metal
Vortex Rock Weirs
Concrete
Rip Rap Debris (mobilized)
Rip Rap (in place)
Large Boulder (> 512 mm)
Small Boulder (256-512 mm)
Large Cobble (128-256 mm)
Small Cobble (64-128 mm)
Very Coarse Gravel (32-64 mm)
Coarse Gravel (16-32 mm)
Medium Gravel (8-16 mm)
Fine Gravel (4-8 mm)
Very Fine Gravel (2-4 mm)
Sand (.062-2 mm)
Silt (.004-.062 mm)
Clay (< .004 mm)
Bedrock
Quaternary Alluvium (mostly clay)
Undetermined
WATERSHED SCIENCES, 2002

Figure 16

canopy, chiefly in the downstream reaches where smaller particle sizes are more abundant along the bed. We find that intermittent reaches heavily influenced by cattle have the highest amount of grass coverage on the bed. This may coincide with the direct input of organic materials (manure) to the bed that becomes compacted and mixed with the substrate through trampling. Grasses can then become established and their affect upon the bed is to reduce its mobility.

SIZE, ABUNDANCE AND DISTRIBUTION OF POOLS

In stable channels, systematic downstream variations in velocity will create pools and riffles at predictable intervals. These intervals relate to the wavelength of the meander, where scour and pool formation is typically found at the outside of bends. Because the sinuosity and wavelength of meanders are related to bankfull discharge and gradient of the channel, the minimum expected spacing of pools is usually predictable (Leopold, 1994). For example, in sand or gravel dominated channels of low gradient and well-defined meanders, the expected pool spacing is 5-7 times the bankfull width. This is generally the case for a Rosgen Stream Class “C” type channel. In steep, coarser-bedded step-pool channels, pool spacing is often 2-4 bankfull widths, typical of a Rosgen Stream Class “B” channel. The number of pools in a channel can be much higher than the predicted value when there are flow obstructions of LWD or bedrock, for example. Low pool spacing means that there are a large number of pools per unit length, often a good indication that the channel exceeds the number of pools that would be available if spacing was just based upon curvature alone. It also means more potential habitat for fish. When pool spacing is greater than the expected values, meaning a low number of pools per unit length, the channel may be in an unstable form, adjusting to changes in supply or transport of water and sediment.

Only pools greater than 1 ft deep for the low flow condition were documented for this analysis. Maximum pool depth for the low flow condition was measured by subtracting the water depth, at the pool tail-out, from the maximum depth in the pool. Pool volume was determined by multiplying the average width and length for the low flow condition by 1/2 the maximum depth. The occurrence of pools in Carriger Creek below Steelhead Reach was documented twice. This is because pools in the downstream reaches were first measured during the summer between June and mid-September, while pools upstream of and including Steelhead Reach were measured in early fall after mid-September. Because flow nearly dried up downstream of Steelhead Reach, we re-measured maximum low flow depth again in early fall. Thus, two quantities of pools for the different time intervals are reported for the reaches downstream of Steelhead. Pool volumes were not re-measured in these downstream reaches, so their volumes are only reported for the summer interval. The location of each pool was documented by recording its distance station. The specific pool location, volume, and maximum depth can be viewed by looking at the Streamline Graphs Appendix.

Figure 17. Number and Percent of Different Pool Volume Classes, June-September, 2000

The total number of pools for Carriger Creek during the summer season was 76. This decreased to 32 pools by fall when pools below Steelhead Reach had their depths re-measured and only 7 out of the 32 pools below Steelhead Reach remained. Over the length of the Study Site, pool spacing changed from one pool per 271 ft of channel length to 644 ft by mid September. Values for both summer and fall are greater than the expected spacing of 5 to 7 bankfull widths, which would be from 160 ft to 225 ft. The 76 pools measured during summer formed 50% of the pools in two volume classes, 400-800 cu ft and 800-1600 cu ft. About 13% were greater than 1600 cu ft volume. Pools of small volume, less than 50 cu ft, represented only 10% of the total.

By fall, the pools upstream of Intermittent Reach were the most important pools for several reasons. They had high numbers of steelhead trout, their volumes and depths were adequate for habitat, water quality appeared good, and riparian shading maintained cool temperatures. Many of the pools downstream of Steelhead Reach, even during the summer season, did not appear to support as many fish. Temperatures seemed elevated, riparian shade was missing, water appeared stagnant in some pools, cattle disturbance was frequent in some, and several pools had algal blooms and fetid odors.

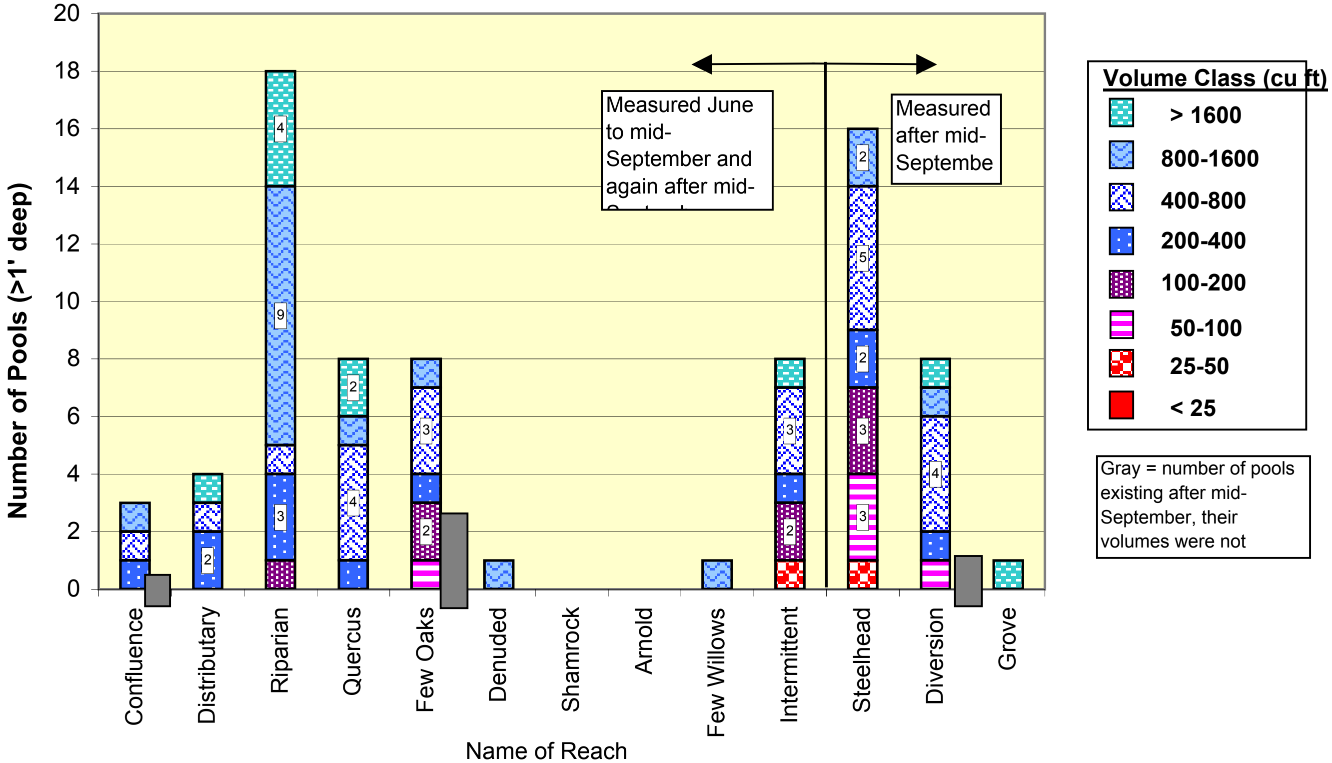
Figure 18. Number of Pools per Volume Class per Reach at Two Different Times of Year

The total number of pools for the two time intervals of summer and fall are shown for the reaches below Steelhead. The first column shows the number of pools divided into volume classes for summer. The second column, when it appears, is shown in gray. It only shows the number of pools below Steelhead Reach for the fall season, not the volumes because they were not re-measured. When a gray column is not shown for these reaches, it indicates that pools greater than 1 ft deep did not exist by fall. The upstream Steelhead, Diversion, and Grove Reaches were only measured during the fall season, so their volumes are shown for this season. During this time most of the pools for the Study Site are located upstream of Intermittent Reach, which is where the greatest number of pools existed in the 400-800 cu ft volume class. This is where many steelhead trout were observed.

During summer, Riparian Reach had the greatest number of pools downstream of Steelhead Reach. By fall, all pools greater than 1 ft deep disappeared in Riparian Reach. Below Few Oaks Reach, the summer spacing of pools was less than 5-7 bankfull widths. This is because of riparian vegetation along the eroding stream banks, as discussed earlier. By fall, there is simply not enough flow to support these pools. The loss of surface water flow through these reaches is likely caused by a number of reasons including: lack of recharge of the ground-water table; diversion of water; local water consumption by cattle; increased evaporation from lack of riparian shade; channel geometry; and deposition of

CARRIGER CREEK 3.9 MILE STUDY REACH, JUNE - SEPTEMBER 2000
Number of Pools per Volume Class per Reach at Two Different Times of Year

Pool spacing per linear foot of channel from June to September is shown in top box at reach name; bottom box shows number of pools after mid-September. Where a gray column appears within an individual reach, an adjusted number of pools is plotted for the time period following mid-September for reaches downstream of Steelhead. Reaches above Steelhead were initially measured after mid-September.



233	163	111	173	287	1915	0	0	1465	365	264	132	430
0	650	0	0	766	19 5	0	0	0	1460	264	132	430

WATERSHED SCIENCES, 2002

Figure 18

sediments that armor the bed from pool scour. Further investigation would be required to determine the magnitude and importance of each of these causes of diminished surface flow. Undoubtedly, they all have a synergistic and cumulative effect.

We can consider two hypotheses regarding flow on the lower alluvial fan of Carriger Creek. In Hypothesis One we suggest that historically, Carriger Creek Study Site could have flowed year-round, maintaining its pools throughout summer and fall seasons. A thorough ground-water study, including historical well levels could show changing trends in the groundwater table along the alluvial fan and in the local Sonoma Valley alluvial terrace. According to the Ground-Water Master Plan for the Valley of the Moon Water District, the Fowler Creek Road area within the Sonoma Valley has a groundwater depressions where ground-water extraction is exceeded by ground-water recharge (Luhdorff and Scalmanini, 1998). They report that the water level has declined by 200 ft indicating that water level is now below sea level. If the historical channel had perennial flow, pool spacing was probably less than 5-7 bankfull widths. This is because there would have been a continuous riparian corridor lining both banks, thus the channel width was narrower than is today, therefore more LWD was available to become hung-up between the riparian vegetation to produce scour pools. Additionally, if most of the channel was a Rosgen Stream Class B-type channel, the pool spacing would be expected every 2-4 bankfull widths. If it transitioned to a C-type channel the pool spacing would have been 5-7 bankfull widths based upon the meander curvature. The LWD would have created pools in areas other than the outside meander bends.

In Hypothesis Two the lower alluvial fan of Carriger Creek may have typically dried out during late fall as groundwater along the Carriger fan may have spread out and dropped down to a lower ground-water level of the Sonoma Valley. Perhaps, perennial flow was regained below the transition zone between the alluvial fan and the Sonoma Valley alluvial terrace in Riparian Reach or at the confluence of Felder Creek. In the Ground-Water Master Plan of the Valley of the Moon Water District, a subsurface geologic cross section of the Sonoma Valley and alluvial fan of Carriger Creek is shown to have a fault separating the Sonoma Volcanics on the west side of the Valley from the Glen Ellen Formation (sands and gravels). The projection of this fault across the Carriger alluvial fan is near the transition from Steelhead Reach, which has perennial flow, to Intermittent Reach. It might be possible that some of the groundwater flow from Carriger Canyon is laterally diverted along this fault.

CAUSES OF POOLS

During field inspection, the specific and/or dominant causes producing scour and pool formation were identified to determine how pools formed and how they influence a particular stream or stream reach. Specific causes were grouped into five general categories called Natural, Wood-related, Man-related, Multiple and

Complex. Natural pools include those pools that form by natural hydraulic processes associated with flow at bends, natural bars, narrow constrictions, or bedrock abutments. Wood-related pools are caused by scour associated with LWD, tree trunks, roots, or debris jams. The Man-related category includes pools caused by man-made structures or by man's activities in the channel. For example, if a pool forms around a large piece of riprap that has been transported from its original placement, the pool is still characterized as Man-related. Other Man-related pools include backwaters that form behind structures such as check dams or pools that form around bridge abutments. If there were several contributing causes that included a Man-related cause with either a Natural or a Wood-related cause, the pool was classified as Complex. For example, a pool at the outside edge of a bend that also has a concrete abutment from a retaining wall associated with it might be caused by the combined effect of both Natural and Man-related causes. If the combined causes were Natural and Wood-related, the general category would be called Multiple. An example would be roots causing scour at an outside bend.

Figure 19. Pool Depth per Reach from June to Mid-September

Maximum pool depths at intervals of 1 ft size classes for the low flow condition are shown for the summer season, June to mid-September. The 1-2 ft depth category had the greatest number of pools, 32 out of 76, representing about 42% of the total. The second highest number of pools was in the 2-3 ft category, representing 33% of the total. The 4-5 ft category had a couple more pools than the 3-4 ft class. Only three pools existed in the greater than 5 ft depth class, two were from the Man-related category and one was from the Natural category. The deepest pool was 8.3 ft. It formed from scour downstream of a small dam. Within the Natural category of pool causes, 55% were in the 1-2 ft depth range, while 29% were in the 2-3 ft depth class. For Wood-related pools, 38% were in the 2-3 ft depth class and 31% were in the 1-2 ft class. Wood-related pools had more pools in the 3-4 ft and 4-5 ft depth classes than any other cause.

Figure 20. Number of Pools per Volume Class and Their Associated Causes between June and Mid September

During the summer season, June to mid September, natural causes formed 45% of the 76 pools that were greater than 1 ft deep. 29% were formed from Wood-related causes, 16% were Man-related, 9 % had Multiple causes, and 1% had Complex causes.

When volume class is used to stratify pools, we note that the 400-800 cu ft volume class had the most pools. Man-related pools were only found in the three larger volume classes, with 50% of them exceeding the largest volume class of greater than 1600 cu ft. For this largest class, 60% of the pools were Man-related. Natural and Wood-related causes were minimal, but pools with multiple causes were second most abundant. This indicates that exceptional conditions are usually needed to create pools of such size. Pools in the smallest volume

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000 Pool Depth per Reach from June to mid September					
Reach	1' - 2'	2' - 3'	3' - 4'	4' - 5'	>5'
Confluence	2	1	0	0	0
Distributary	1	1	1	0	1
Riparian	3	8	4	1	2
Quercus	2	3	0	2	1
Few Oaks	4	4	0	0	0
Denuded	0	0	0	0	1
Shamrock	0	0	0	0	0
Arnold	0	0	0	0	0
Few Willows	0	1	0	0	0
Intermittent	5	3	0	0	0
Steelhead	12	2	1	1	0
Diversion	5	2	0	0	1
Grove	0	0	0	1	0

Pool classes based upon maximum depth subtract pool tail-out de

WA

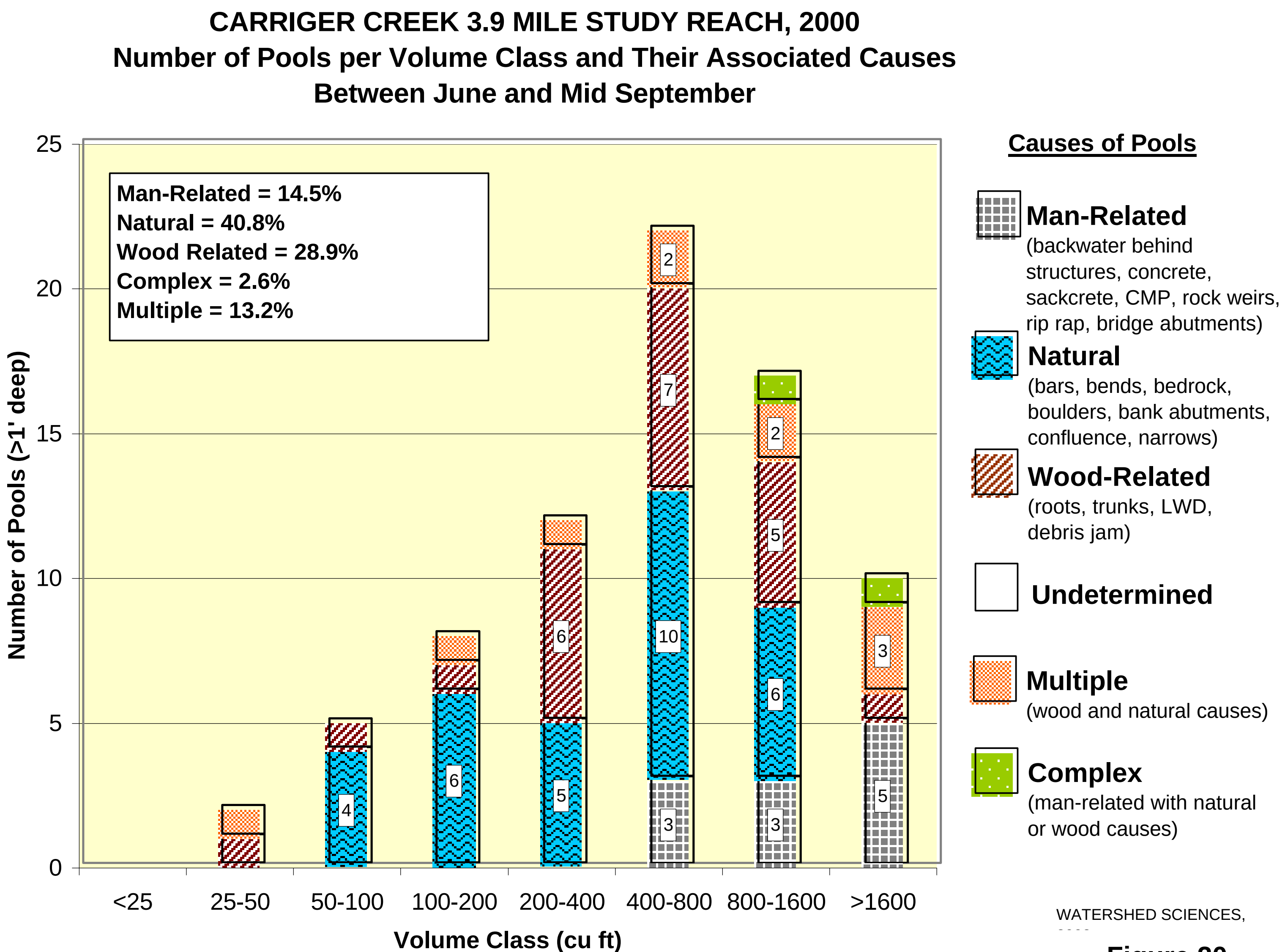

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Number of Pools per Volume Class and Their Associated Causes
Between June and Mid September
Man-Related = 14.5%
Natural = 40.8%
Wood Related = 28.9%
Complex = 2.6%
Multiple = 13.2%
Number of Pools (>1' deep)
0
5
10
15
20
25
<25
25-50
50-100
100-200
200-400
400-800
800-1600
>1600
Volume Class (cu ft)
4
6
5
6
3
10
7
2
3
6
5
2
5
3
Causes of Pools
Man-Related
(backwater behind structures, concrete, sackcrete, CMP, rock weirs, rip rap, bridge abutments)
Natural
(bars, bends, bedrock, boulders, bank abutments, confluence, narrows)
Wood-Related
(roots, trunks, LWD, debris jam)
Undetermined
Multiple
(wood and natural causes)
Complex
(man-related with natural or wood causes)
WATERSHED SCIENCES,

Figure 20

category of 25 cu ft were not found. Pools from 25-50 cu ft were only formed by Wood-related and Multiple causes. Pools with Multiple causes were distributed throughout all the volume classes greater than 25 cu ft, but they comprised the lowest percentage of the four general categories, except for Complex for which there was only one pool.

If just the spacing of pools formed by Natural causes were considered for Carriger Creek, then the spacing would be one pool per 605 ft of channel length. This is greater than the 5-7 bankfull width spacing that would place a pool within every 1322 ft to 182 ft. This indicates that the channel is not presently adjusted to its discharge and sediment load. It may also reflect the impact of armoring as well as reduced water table elevation.

Clearly, Wood and Man-related causes are important mechanisms in Carriger Creek in its present day form. Indeed, Wood-related causes are as equally important as Natural causes for maintaining summer pools that have volume classes greater than 200 cu ft. Within the Wood-related category only 13% of the pools are formed by LWD, the others are formed by roots of riparian trees, tree trunks and debris jams. Roots of riparian trees growing along the banks caused 70% of Wood-related pools. Hence, erosion of banks that have exposed tree roots is presently an important component for pool formation, but ironically, the pools and trees are threatened by the fact that the banks are eroding. Although some LWD is available within the active channel bed in some of the reaches, it is not presently an important pool-forming mechanism within Carriger Creek Study Site.

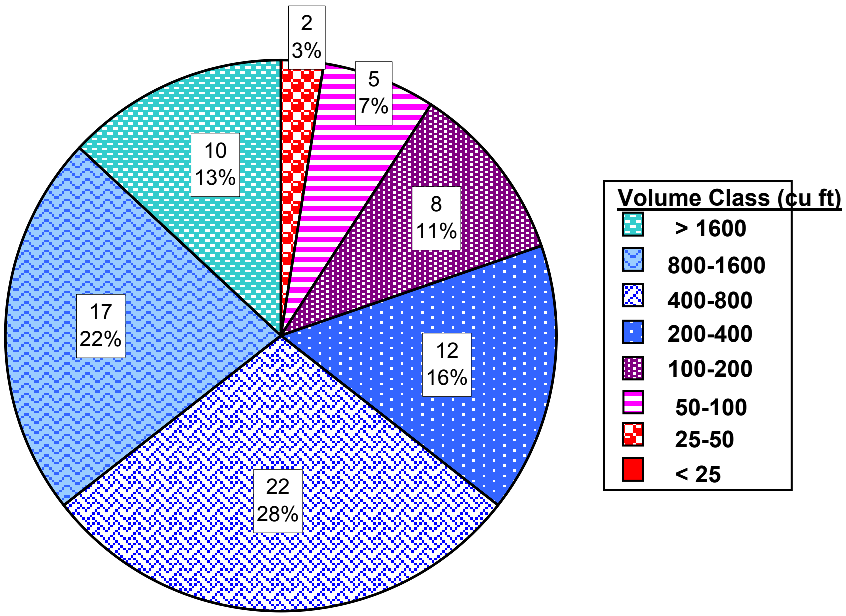
The abundant coarse sediment of large cobbles and boulders that armor the bed from scouring during bankfull flows is partially why the woody debris is ineffective for pool scour. Over-widened banks, that prevent the wood from being caught and hung-up in the channel may be another important factor. Only three debris jams were identified as causes contributing to pool formation along the entire Study Site. They were located in extreme downstream and upstream reaches where the channel was narrow and entrenched. The Distributary and Riparian Reaches were the only sections of channel where single elements of LWD had the potential to scour pools greater than 1 ft depth. This is because the sediment size did not exceed the D50 size class of small cobbles and the channel was more entrenched.

Figure 21. Pool Spacing and Pool Causes Stratified by Reach for Two Different Time Periods

The amount, spacing, and causes of pools stratified by reach for two different time periods, summer and fall, are shown in Figure 21. The importance of Wood-related causes for maintaining pools from summer to fall diminishes with time. This is because the pools downstream of Denuded Reach that were formed by Wood-related causes dried up by fall or became less than 1 ft deep. In the

CARRIGER CREEK 3.9 MILE STUDY REACH, JUNE - SEPTEMBER
Number and Percent of Different Pool Volume Classes (pools >1' deep)

(In each white box, number on top is the number of pools from June to mid September; number on bottom is the percent of pools per size class)



Total number of pools from June to mid- September: 76
Total number of pools after mid- September: 32
Mean pool spacing between June and mid- September: 271 feet

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Fig

reaches upstream of Intermittent Reach, Wood-related causes were not the dominant pool forming mechanism. Those that were Wood-related were not associated with LWD. They were mostly formed by scour beneath roots of live trees. Instead, Natural and Complex factors were more important in reaches upstream of Few Willows.

The effects of LWD may be less important in these upstream reaches because the dominant particle size on the bed tends to be boulder and large cobble. From upstream and including Intermittent Reach, large cobble and small boulder D50 size classes dominate the channel bed. About 42% of the pools in these reaches are formed by Natural causes, mostly forced pools from bars. 21% of the pools were Man-related. The woody debris would have to be very large or compiled into a debris jam to produce scouring in such an armored bed. One debris jam was found to create such scour. The lack of pools through the Shamrock and Arnold Reaches can be explained by a combination of the following characteristics: recharge to ground-water table, moderate to large D50 size classes, scant riparian vegetation (thus no overhanging roots), over-widened banks that cannot entrap floating LWD, and minimal recruitment of LWD.

DISTRIBUTION AND TYPE OF LWD

Large woody debris (LWD) plays a major role in the form and function of streams. It can increase the number of pools to greater than that predicted for a given sinuosity. It can add diversity, cover and structure to pools, or it may trap gravels that may be of adequate size for spawning purposes. Large amounts of LWD can increase the length of time that sediment stays in storage throughout a channel network. Without LWD, sediment transport rates can become accelerated because storage and residence time is decreased due to the lack of the sediment trapping effect. In the past, LWD has been considered by some to be a negative stream asset, particularly urban ones, because it can become trapped at bridges or forms natural debris jams that create backwater floods. Consequently, landowners and flood control agencies have commonly practiced LWD removal causing many streams around the Bay Area and North Coast to become depleted of LWD. Some agencies, such as California Department of Fish and Game, and US Fish and Wildlife Service have now developed programs to place LWD back into streams.

To assess the amount of LWD in a stream, its average spacing can be determined, just as for pools. The species of wood that are being supplied and the processes by which wood is recruited can also be assessed to determine future trends. This provides a unique mechanistic picture for individual streams and gives us the ability to determine if the rates or processes that supply LWD have been altered by land practices.

As per the other features quantitatively assessed along Carriger Creek, the location of LWD was recorded relative to its position along the centerline tape. Its location, as well as the location of debris jams, is plotted on the Streamline Graphs in the Appendix. To be included in the data set, the minimum diameter of the LWD had to be at least 8 in and it had to be within the active channel bed or intersecting usual bankfull flows. Trees or brush leaning or hanging below bankfull with diameters less than 8 in, but functioning as LWD by producing scour were also counted and categorized to be leaning or bent into flow. For example, clumps of willows or trees with dense branches that have been pulled into the flow can often create significant scour pools as well as important cover for fish.

Figure 22. Number and Percent of Different LWD Types

This pie chart shows the number and percent of different vegetation species that contributed LWD in Carriger Creek. The total number of LWD elements was 117. This represents a spacing of 176 ft. Willows were the dominant species supplying wood. They represented 48% of the total amount of LWD. Oaks represented 20%, alders represented 14%, and ash represented 6%. The high amount of LWD that is from oak trees reflects the instability of terrace banks since many of the older trees grow at this surface. The loss of remaining oaks is of increasing concern. In total, other species that included bay, big leaf maple, buckeye, and eucalyptus represented 11% of the LWD. Lumber was determined to represent 1% of the supply.

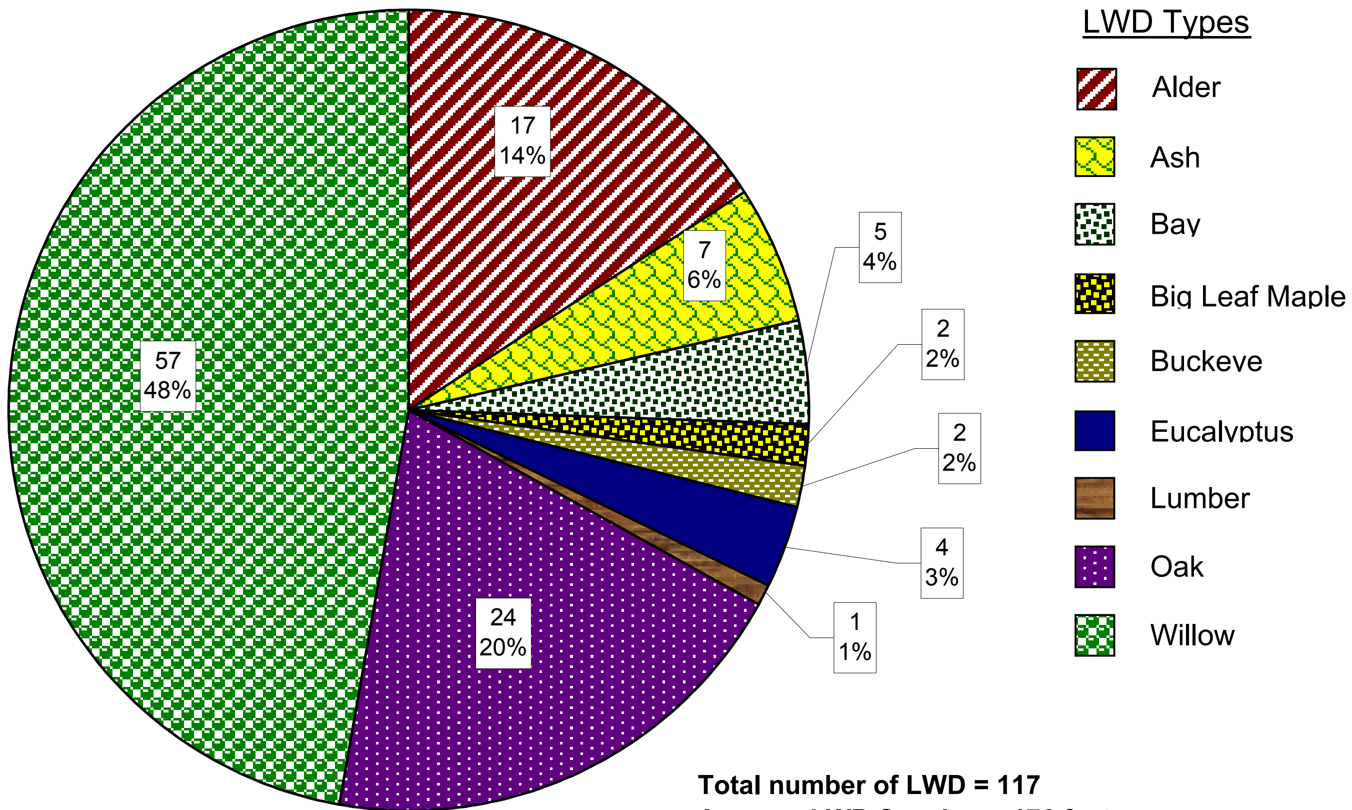
An obvious change since historical times is the input of nonnative species and lumber. However, this is only a minor component of LWD in Carriger. We do not expect that the types of native species have changed greatly over time, but perhaps the size of the LWD supplied from willow and alder has changed. Most of the LWD we observed from these species was not very large in diameter. In fact, the age distribution of willow, alder, ash, and big leaf maple growing along the low inner banks was young, most having established themselves during this century. The density and maturity of old growth riparian vegetation that is on the higher terrace banks can be assumed to be much greater before the onset of channel adjustments that caused the banks to erode and the trees to fall into the channel during the last 165 years. As wood was supplied to the channel, much of it was inadvertently pulled out to minimize potential backwater floods at downstream bridge and floating fence crossings. We have observed numerous tree stumps modified by chain saws after they fell into the channel.

Figure 23. Number of LWD Types per Reach

If we look at the distribution of different species comprising LWD over the reaches, Steelhead Reach has the largest quantity of LWD, about 34 individual elements. Intermittent and Riparian Reach have similar amounts, 23 and 22, respectively. Distributary and Few Oaks Reaches have 16 and 10 respectively, while Diversion, Grove, Denuded and Confluence all have less than 5 each. Quercus, Shamrock and Arnold do not have any LWD. In general, the reaches

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Number and Percent of Different LWD Types

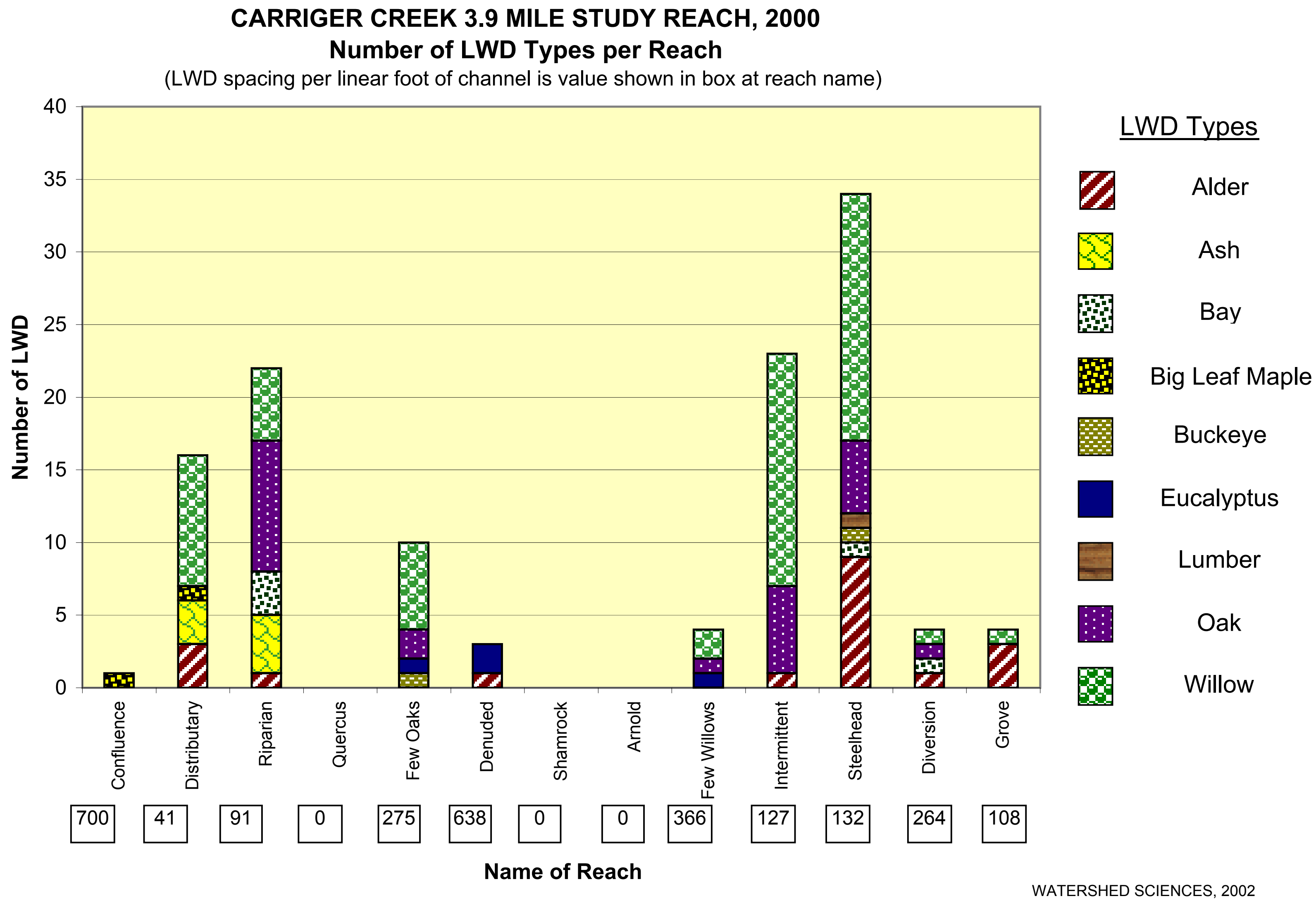
(Top value in the white boxes is the number of LWD species, bottom value is the percent of LWD species)



Total number of LWD = 117
Average LWD Spacing = 176 feet

WATERSHED SCIENCES, 2002

Figure 22


CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Number of LWD Types per Reach
(LWD spacing per linear foot of channel is value shown in box at reach name)
Number of LWD
40
35
30
25
20
15
10
5
0
Confluence
Distributary
Riparian
Quercus
Few Oaks
Denuded
Shamrock
Arnold
Few Willows
Intermittent
Steelhead
Diversion
Grove
700
41
91
0
275
638
0
0
366
127
132
264
108
Name of Reach
LWD Types
Alder
Ash
Bay
Big Leaf Maple
Buckeye
Eucalyptus
Lumber
Oak
Willow
WATERSHED SCIENCES, 2002
Figure 23

with the most amount of LWD also have the greatest amount of riparian vegetation lining their banks.

The spacing of LWD is listed for each reach in the white boxes below the reach name. Although Steelhead Reach has the greatest number of LWD, it does not have the lowest spacing. Distributary and Riparian Reaches have the lowest spacing. The spacing on Distributary Reach is lower than riparian. We expect that this is because the bankfull width is slightly narrower and it is easier for the LWD to be caught between the banks. Also, there are well-vegetated inset terraces along these reaches that contribute to the amount of vegetation that can actually lean into or get dragged down by flood flows. These mechanisms contribute to conditions that create scour pools.

The distribution of the type of LWD species along the length of the channel does not now show a distinct pattern at this point, except that ash species seem to be concentrated at the downstream end of the creek.

Figure 24. Debris Jam Characteristics

Debris jams in Carriger Creek totaled 13. This created an average spacing of 1,585 ft. From this total, 10 were partly across the channel, 2 had been modified and mostly removed, and only 1 completely crossed the channel.

We expect that historically the channel had a greater number of debris jams which were adding to the structure and diversity of pool habitats. The reasons that pools are not as abundant today are that: 1) the LWD gets removed or modified by man; 2) the channel is much wider than it used to be, therefore it is less probable that it will catch between banks; 3) there is less riparian vegetation to be recruited into the channel; and 4) there is less channel length due to the loss of distributaries. Only 3 of the debris jams caused pools to form that were greater than 1 ft deep during the summer season.

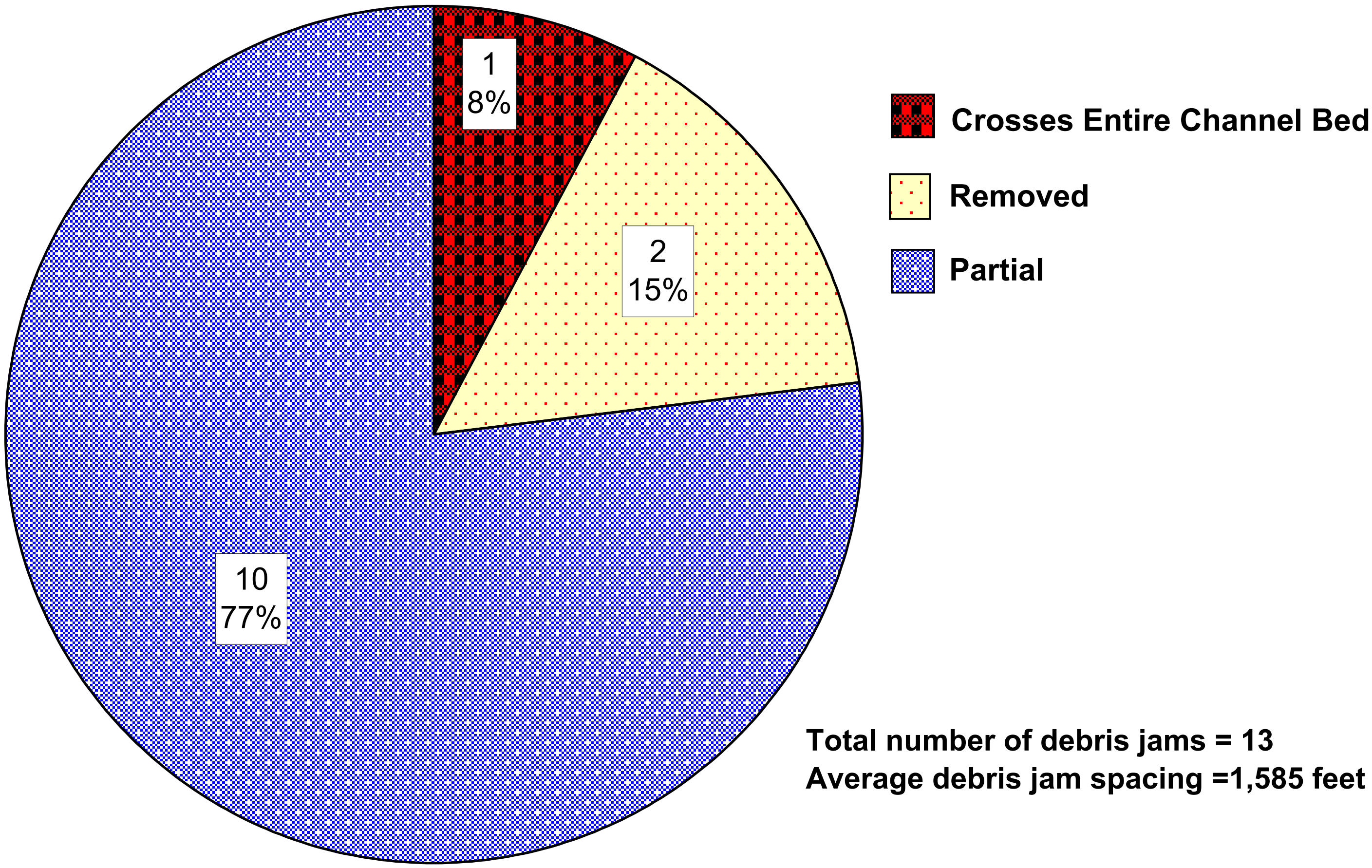
HOW WOOD ENTERS THE CHANNEL

The processes that supply wood to the channel need to be identified if an understanding of the recruitment and loss of wood to the system is desired. How LWD was supplied to the channel was determined when possible. If the cause could not be established, we recorded the wood as float, meaning that it floated to present position. Several categories of LWD recruitment were devised. They include:

- Bank erosion (lateral migration and undermining);
- Landslides;
- Rammed (uprooted and ripped form banks by the large floating debris);
- Bent or leaning into the flow (functioning as LWD even though diameter may be less than 8 in);
- Gravity (falls from windthrow, disease, or is hit by another tree);

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Debris Jam Characteristics

(Top value is the number of debris jams; number on bottom is the percent of debris jams)



Total number of debris jams = 13
Average debris jam spacing =1,585 feet

WATERSHED SCIENCES, 2002

Figure 24

- Aggraded (deposited sediment has filled around the tree trunk incorporating it into the active bed); and
- Human-induced (lumber or stumps, for example, discarded into the creek).

Figure 25. Number of LWD Types per Recruitment Process

Historically, we believe that Carriger Creek had lower bank erosion rates than present day, so the dominant LWD recruitment processes along the alluvial banks may have been gravity and ramming by floating debris. If they were not dominant, their dominance may have been at least comparable to the contribution from bank erosion. We believe that land use activities have caused a shift in rates and processes by which LWD has been and will be recruited in the future. Unless riparian vegetation is encouraged along the reaches where presently there is minimal growth, and given that many of the remaining mature trees will be lost relatively soon from bank erosion unless they are protected, the future supplies of large wood along the middle reaches will continue to decline.

Figure 26. Percent LWD Recruitment Process

About 64% of the wood quantified in Carriger Creek floated to its current position. Of the processes that we could verify, 15% can be directly attributed to bank erosion. Based upon our field observations, this process probably provides most of the wood counted as “float”. Another 12% can be attributed to leaning or bent into the flow, 8% are recruited by aggradation of the bed, and 1% of the recruitment was human-induced.

The way that LWD is lost from a channel system is also of interest. In channels that are not highly entrenched, deposition of LWD onto the floodplain or terraces during floods can remove wood from the active channel bed. As a channel becomes entrenched, there is a greater chance that the LWD will be stored in the system. Its removal would become dominated by mechanical breakdown or by floating through the system. The fact that man is mechanically removing much of the LWD that is of large size, limits the potential for many additional pools to form in Carriger Creek. The way wood is predominantly lost from the system has also changed since historical times. When the channel was less entrenched, much of it probably floated out onto the floodplain. That mechanism is now rare.

CHANNEL STABILITY AND ROSGEN STREAM CLASSIFICATION

We have used a broad-brush approach to the Stream Classification System developed by Rosgen (1996). We have attempted to identify different channel morphologies along the Study Site to identify reaches that are presently in an unstable form. This classification system has been used by some land managers to develop restoration strategies. For explanation of the Classification System, see Rosgen (1996) and the Stream Classification diagram in the Appendix.

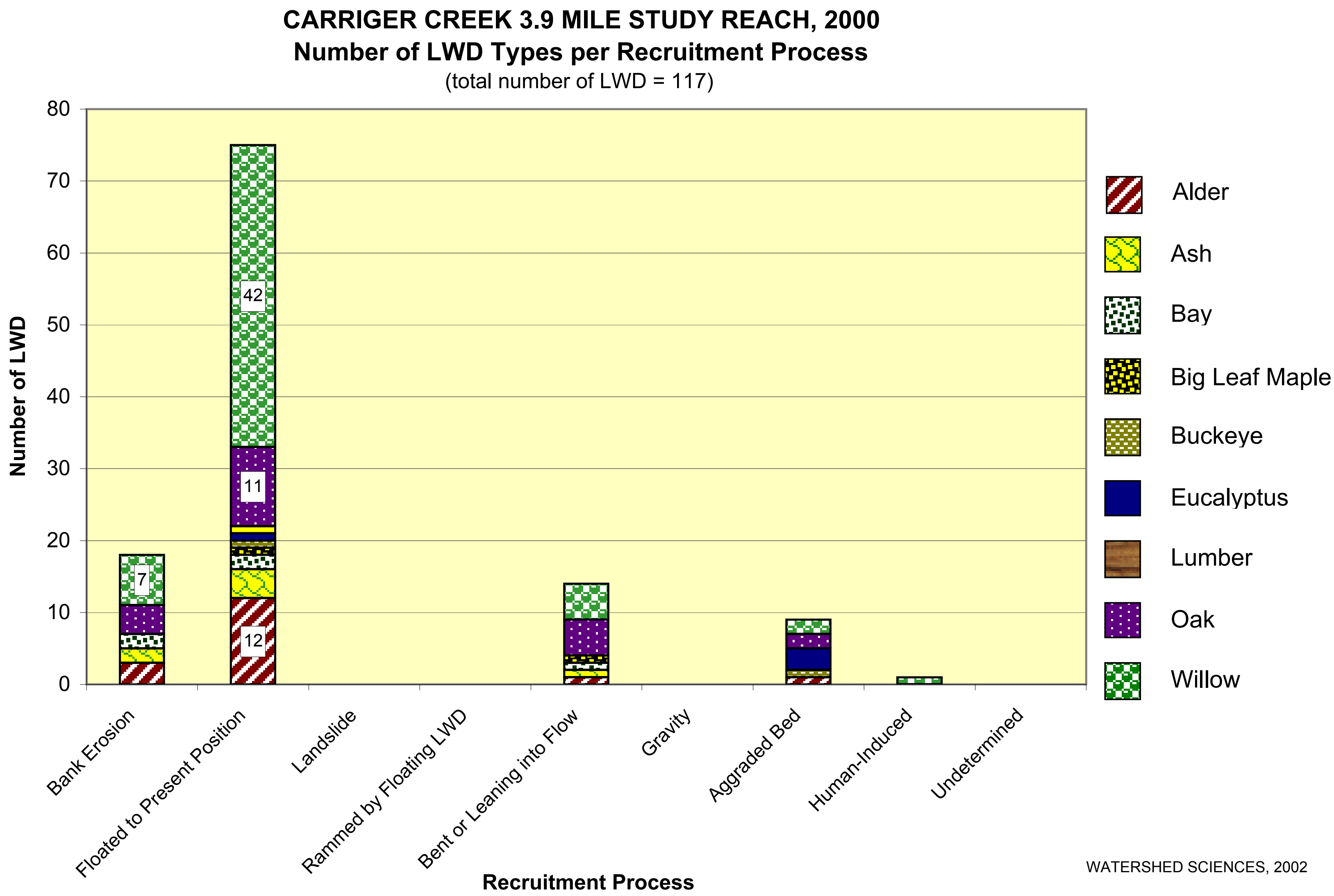
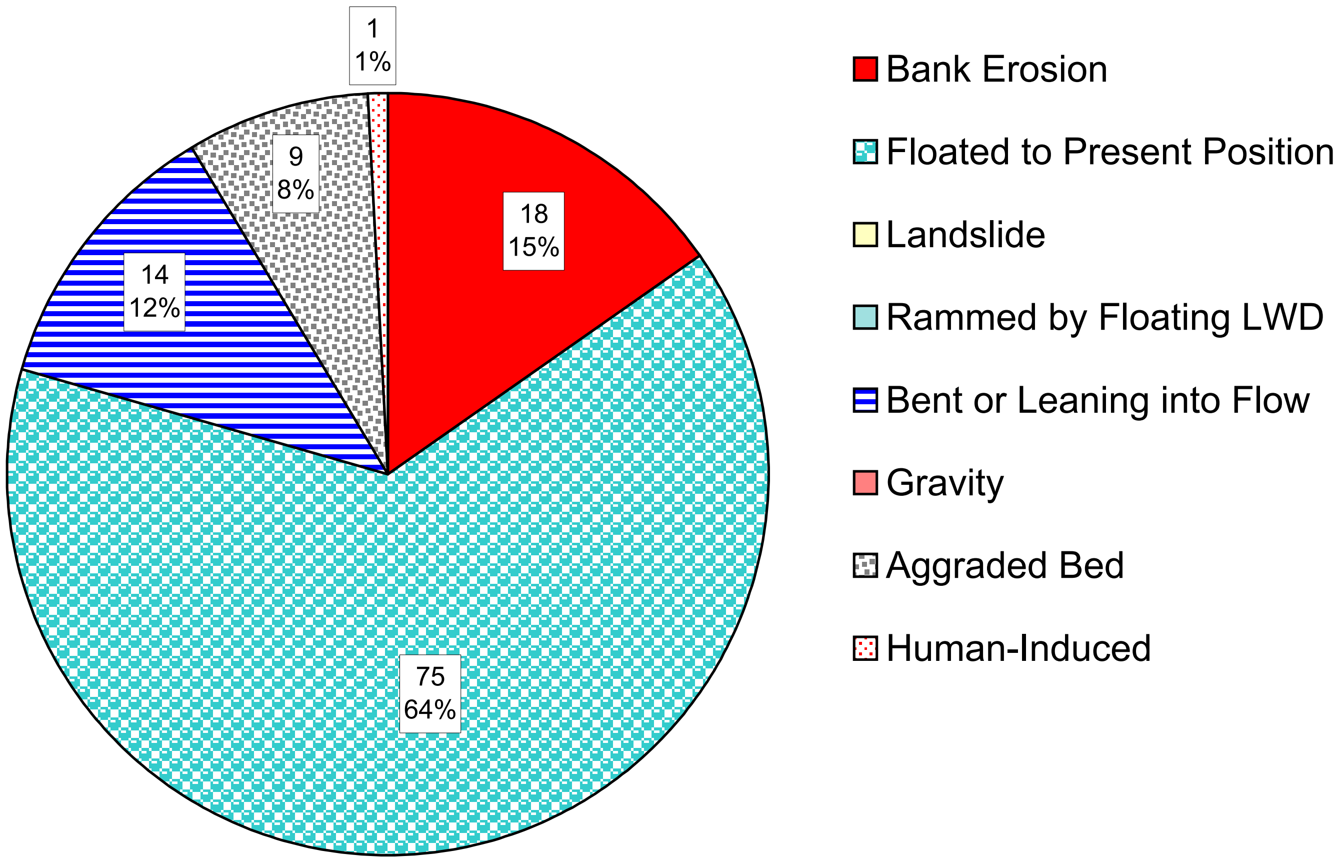

CARRIGER CREEK 3.9 MILE STUDY REACH, 2000
Number of LWD Types per Recruitment Process
(total number of LWD = 117)
Number of LWD
0
10
20
30
40
50
60
70
80
7
42
11
12
Bank Erosion
Floated to Present Position
Landslide
Rammed by Floating LWD
Bent or Leaning into Flow
Gravity
Aggraded Bed
Human-Induced
Undetermined
Recruitment Process
Alder
Ash
Bay
Big Leaf Maple
Buckeye
Eucalyptus
Lumber
Oak
Willow
WATERSHED SCIENCES, 2002

Figure 25

Figure 26 **CARRIGER CREEK 3.9 MILE STUDY REACH, 2000**
Percent LWD Recruitment Process

(Top number is the amount of LWD per process, bottom value is the percent of LWD per process)



WATERSHED SCIENCES, 2002

Figure 26

Classification is based upon 4 stream parameters: entrenchment ratio, width/depth ratio, sinuosity and gradient. We did not measure sinuosity or stream gradient in the field. Instead, we have only used entrenchment and width/depth ratios to depict stream stability. A brief description of the Stream Classes (after Rosgen 1996) that were present in the study site follows in Table 4 below. Note that we have modified the threshold for the width depth ratio that helps establish the stream class.

Table 4. Modified Rosgen Stream Classification

Stream Type	Entrenchment Ratio (+/-0.2)	Width/Depth Ratio (+/- 3.0)	Description
B	1.4 – 2.2	>10	Pool/riffle dominated channel with moderate gradient, moderate entrenchment, and stable banks, planform and profile
C	>2.2	>10	Pool/riffle and point bar dominated channel, slightly entrenched, with low gradient and well defined floodplain
E	>2.2	< 10	Pool/riffle, stable narrow and sinuous channel, slightly entrenched with low gradient and accessible floodplain.
F	<1.4	>10	Pool/riffle channel that is wide, unstable and highly entrenched with low gradient. Laterally unstable with high bank erosion rates.
G	<1.4	<10	Highly entrenched “gully-like’ channel with moderate gradient that is deeply incised causing high bed incision rates and bank instability.

After Rosgen (1996) with modified thresholds for this project.

For the purposes of this report and for the qualities we have found in other Bay Area channels, we have slightly modified the width/depth threshold from 12 to 10. We have also slightly modified its degree of error for defining the different stream classes. Rosgen cites the threshold to be 12, with an error of +/- 2.0. Based upon discussions with him about Bay Area streams and our measured field conditions, we have decided to use a threshold of 10 +/- 3.0.

The Table 4 above shows that channel instability is the general characteristic of F and G type reaches. G channels tend to be in a predominant downcutting mode. F channels are predominantly widening their banks. B, C and E channels have greater stability. It is important to recognize that a channel can change from one stream type to another. A stable B channel may have been in a G form, for example, until it achieved an appropriate geometry to move its water and sediment.

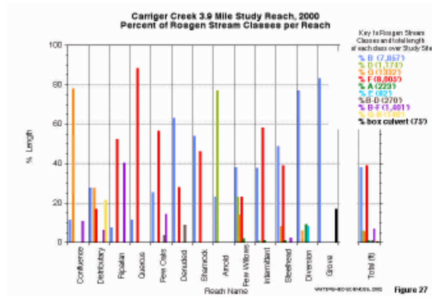

Carriger Creek 3.9 Mile Study Reach, 2000
Percent of Rosgen Stream Classes per Reach
% Length
100
80
60
40
20
0
Key to Rosgen Stream Classes and total length of each class over Study Site
% B (7,857')
% D (1,174')
% G (1332')
% F (8,805')
% A (223')
% E (82')
%B-D (270')
% B-F (1,401')
% G-B (140')
% box culvert (75')
Confluence
Distributary
Riparian
Quercus
Few Oaks
Denuded
Shamrock
Arnold
Few Willows
Intermittant
Steelhead
Diversion
Grove
Total (ft)
Reach Name

Figure 27

Figure 27. Percent Rosgen Stream Classes per Reach

We have plotted the percent that a particular Rosgen Stream Class represents each reach. Our purpose is to show how much of the channel can be considered as relatively stable, the general tendencies in channel morphology, and how morphology changes along the length of the Study Site. We have grouped some of the classes together into what we call a transitional state, where the morphology is either too indistinct or changing from one class to another. This graph can be used to prioritize where restoration efforts could be applied.

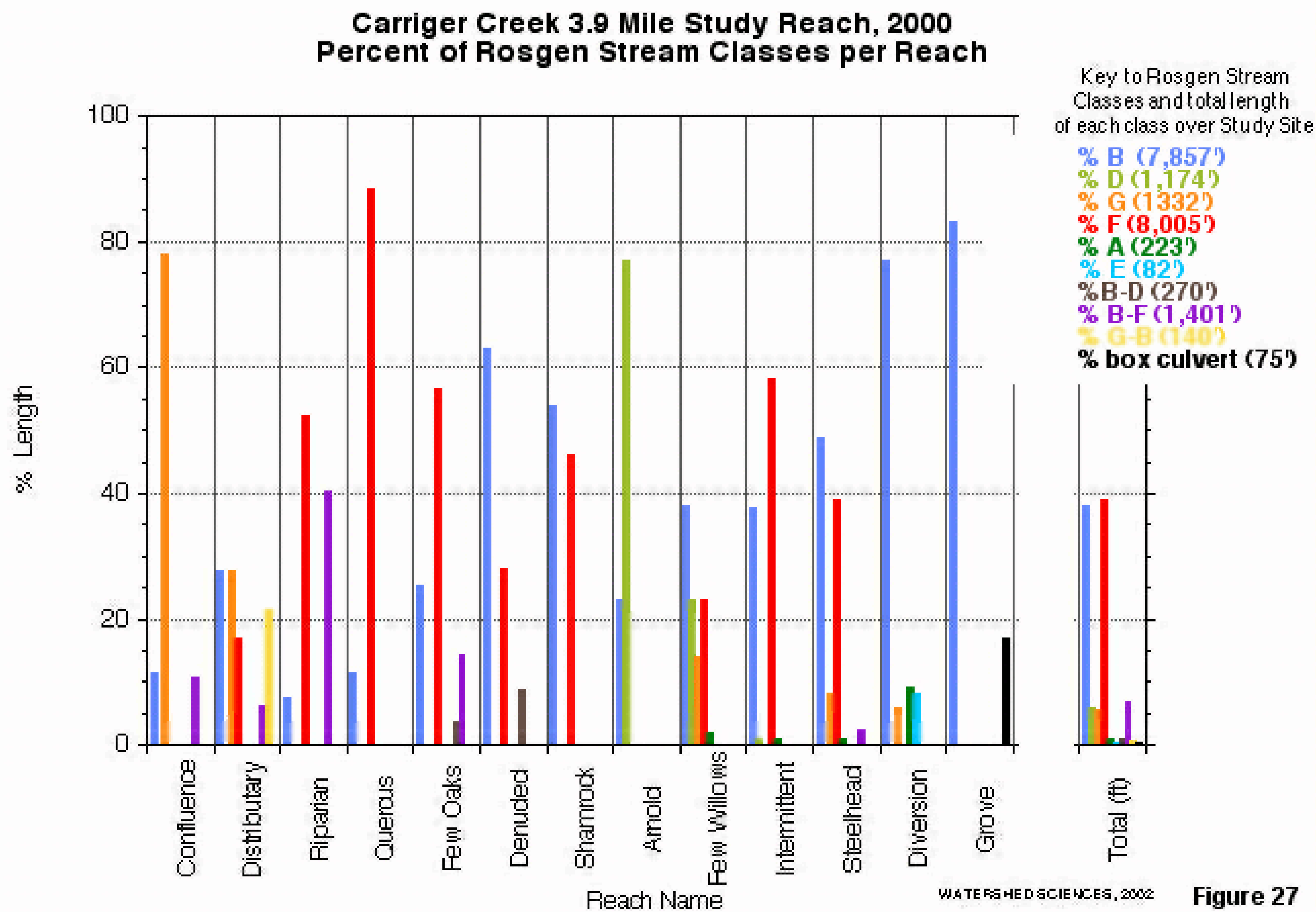
In the downstream Confluence Reach, the channel is predominantly a G type channel. This is substantiated by our estimates of incision versus bank erosion. Distributary Reach is essentially transitional to the upstream Riparian, Quercus, and Few Oaks Reaches that are dominated by F type characteristics where bank erosion predominates, making the channel over-widened. Quercus Reach is the reach with the greatest length of F type channel, 88%. However, the total sediment supply from bank erosion is small compared to the amount from Arnold Reach, which has had at least two bankfull widths of erosion over the long term. Denuded and Shamrock Reaches indicate that B and F reaches are dominant, but that slightly more of the total length has presently achieved a stable B form after extensive bank widening. Arnold Reach is still in a highly unstable F form where historical channel straightening activities had taken place. At Steelhead Reach, the channel starts to become dominated by B type characteristics, finally changing to 100% B channel at Grove Reach.

The columns on the far right show the summary characteristics for the entire Study Site, where 46% of the channel is an F class, 39% is B, 6% is a G, and the rest is in transitional forms. Based upon the data, if we simply combine the F and G reaches, a minimum at least 52% of the channel has an unstable form that will potentially continue to cause negative impacts to stream resources.

Figures 28a-e. Stream Classes by Reach and Longitudinal Profile

We have plotted the extent of the different Rosgen Stream Classes by their distances along the Study Site. We have incorporated the gradient derived from topographic maps and the total amount of sediment supply per linear foot of stream for the 165-year period of interest. The purpose of this graph is to show where the channel types occur so that potential restoration efforts can be planned on a site-specific basis. Please note that a longitudinal profile of the bed, water surface and terrace gradients was later developed for the reaches upstream of distance station 9000 ft (upper portion of Shamrock Reach). These profiles and their Associated Rosgen Stream Classes are shown in the Appendix as Figures 5a-l.

For some restoration projects, it is useful to compare the geometric parameters of unstable reaches to those of the stable reaches. For example, cross sections



Carriger Creek 3.9 Mile Study Reach, 2000
Percent of Rosgen Stream Classes per Reach
Key to Rosgen Stream Classes and total length of each class over Study Site
% B (7,857')
% D (1,174')
% G (1332')
% F (8,005')
% A (223')
% E (82')
% B-D (270')
% B-F (1,401')
% G-B (140')
% box culvert (75')
% Length
100
80
60
40
20
0
Confluence
Distributary
Riparian
Quercus
Few Oaks
Denuded
Shamrock
Arnold
Few Willows
Intermittent
Steelhead
Diversion
Grove
Total (ft)
Reach Name
WATERSHED SCIENCES, 2002

Figure 27

Carriger Creek 3.9 Mile Study Reach
Rosgen Stream Classes by Reach and Longitudinal Profile

NOTE: Reported sediment supply for the different reaches is for local contribution from bank erosion and bed incision over a 165 year period.

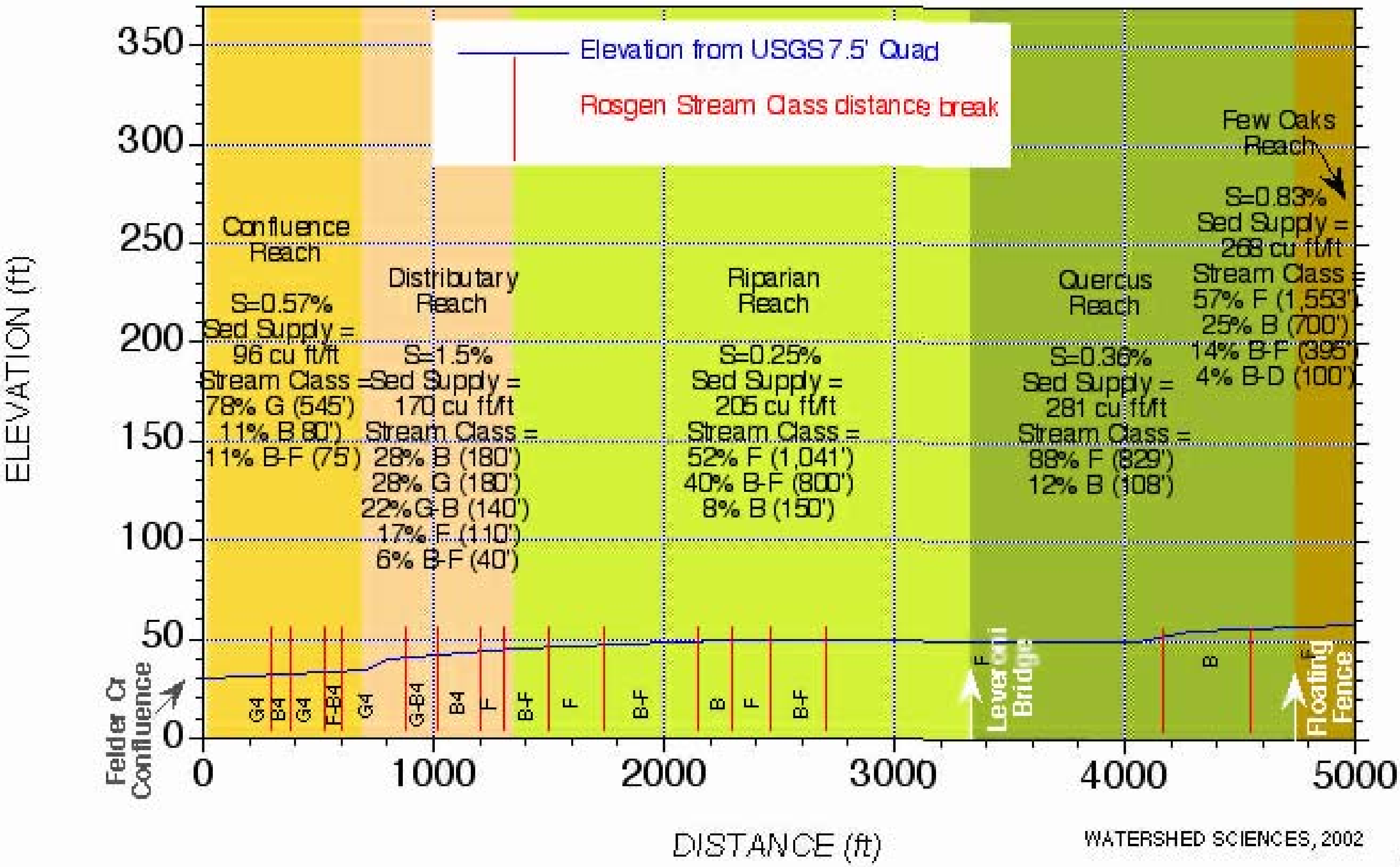


Figure 28

Carriger Creek 3.9 Mile Study Reach
Rosgen Stream Classes by Reach and Longitudinal Profile

NOTE: Reported sediment supply for the different reaches is for local contribution from bank erosion and bed incision over a 165 year period.

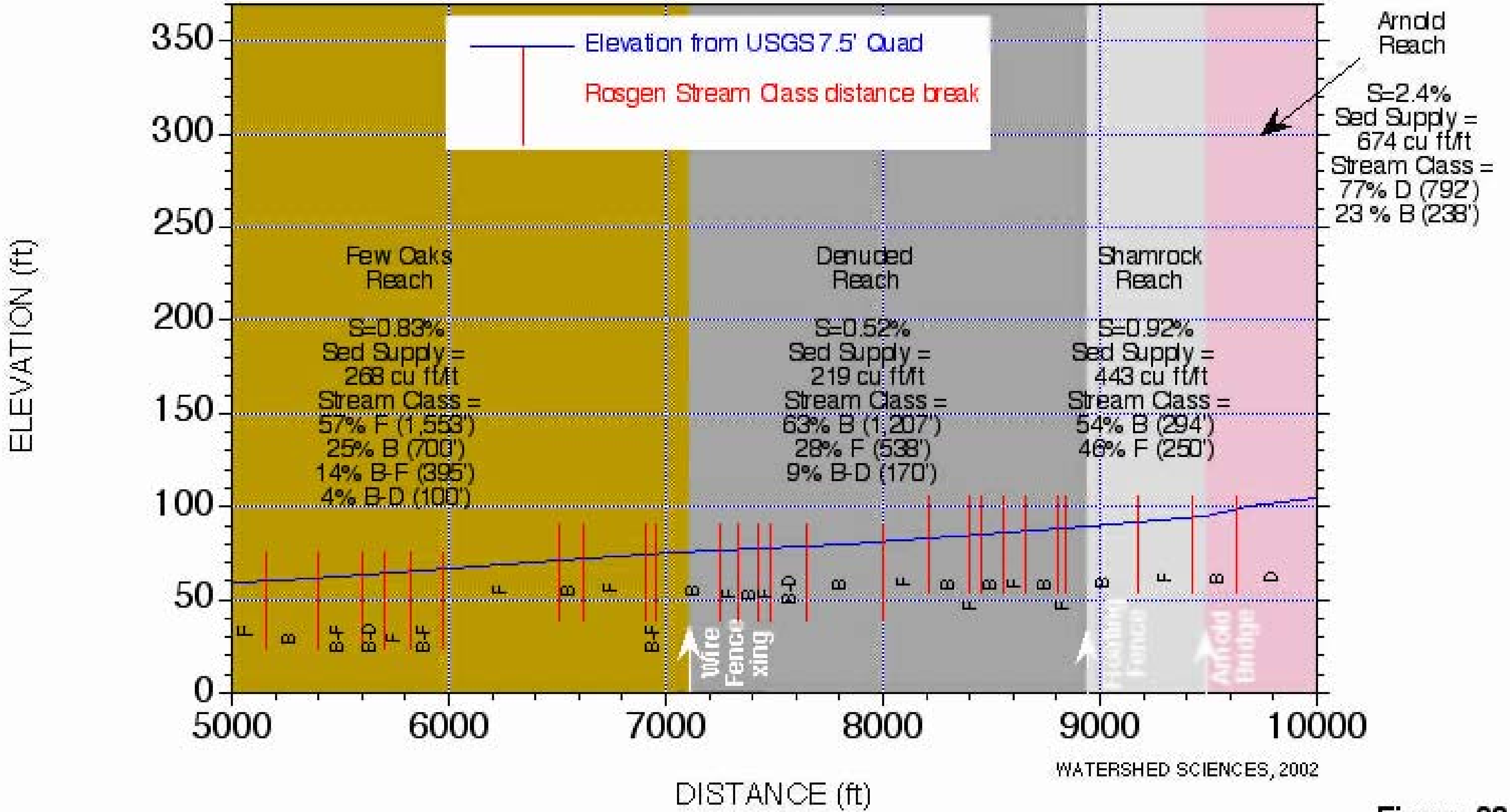


Figure 28b

Carriger Creek 3.9 Mile Study Reach
Rosgen Stream Classes by Reach and Longitudinal Profile

NOTE: Reported sediment supply for the different reaches is for local contribution from bank erosion and bed incision over a 165 year period.

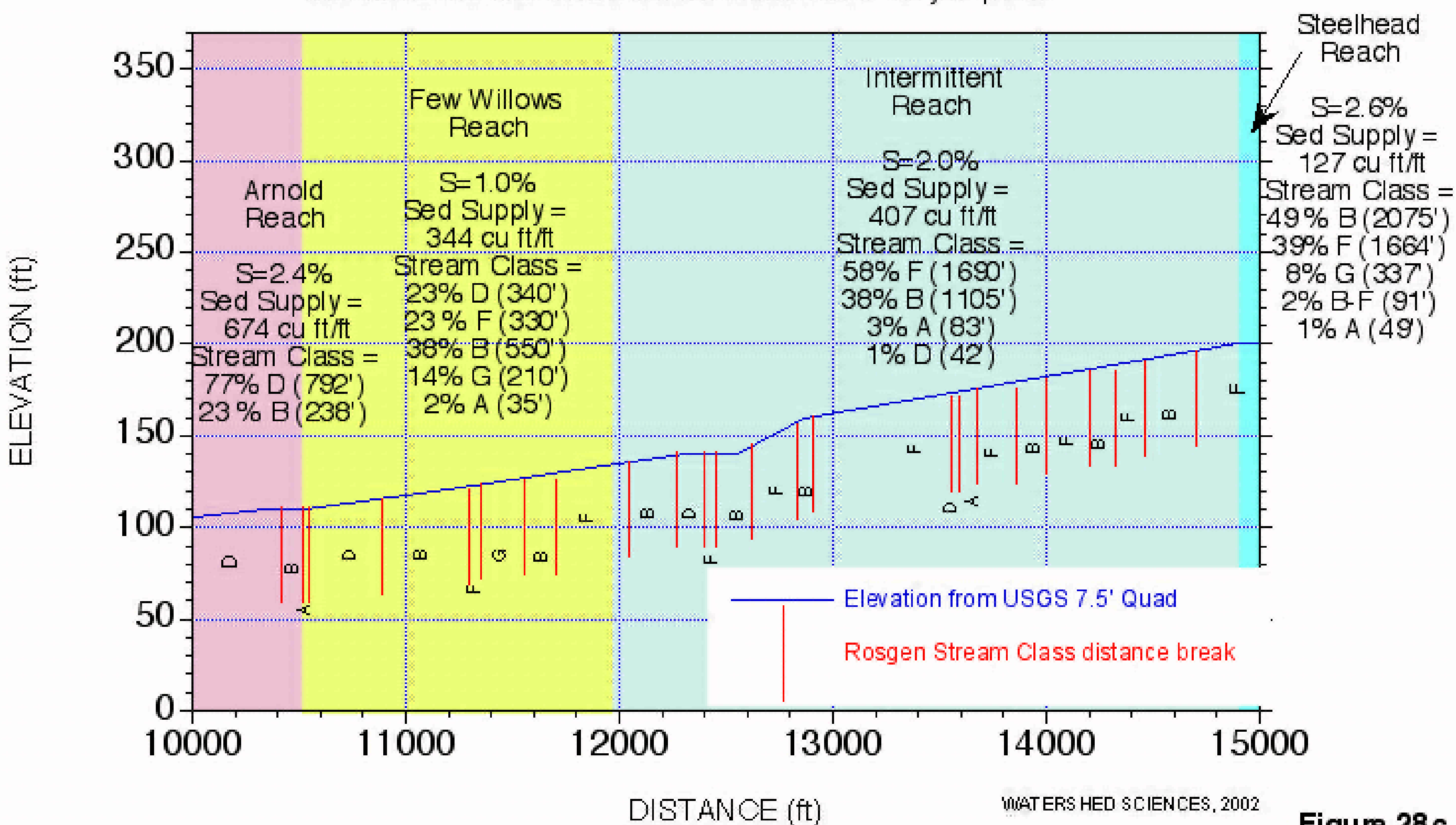


Figure 28c

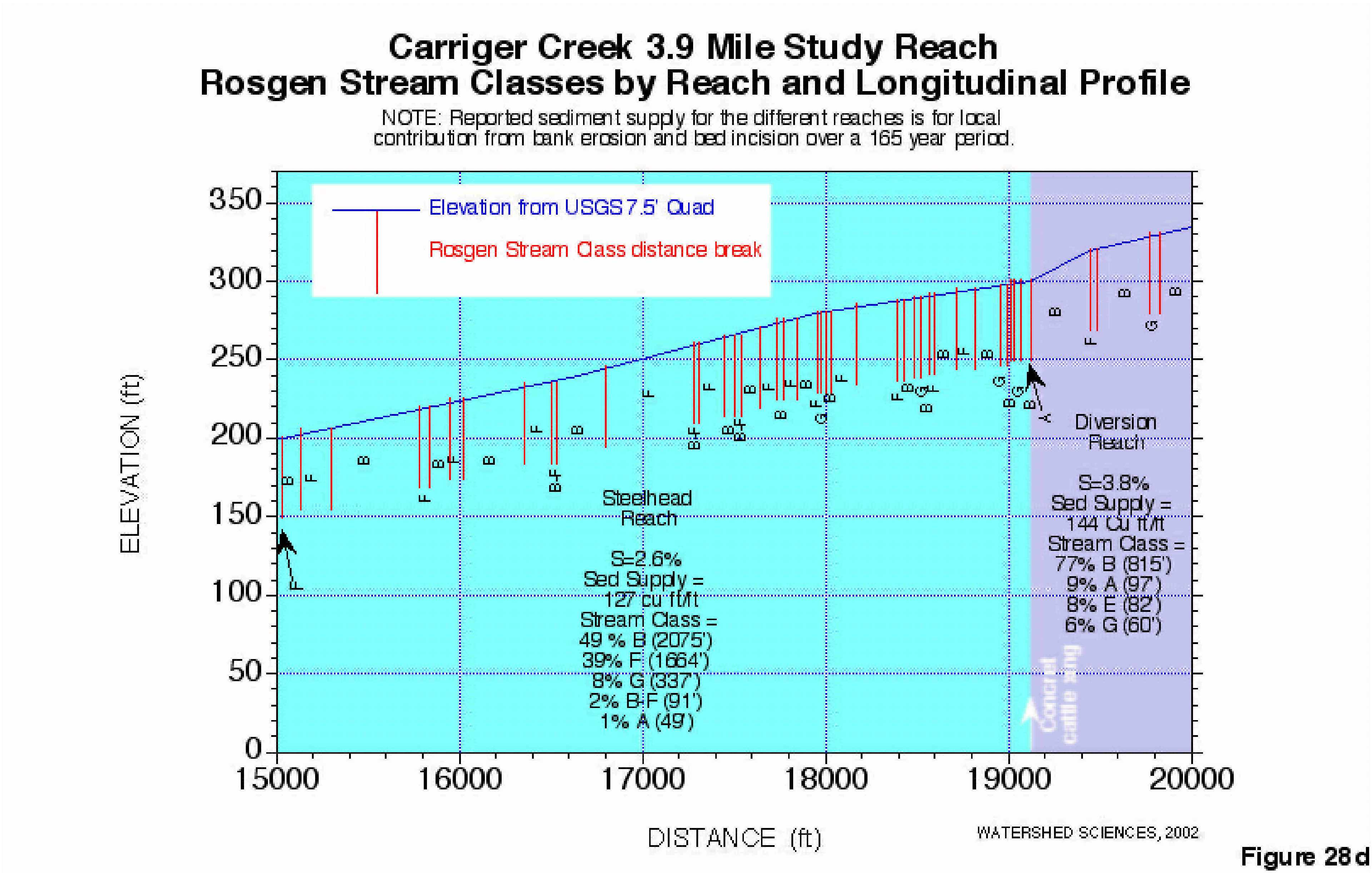

Carriger Creek 3.9 Mile Study Reach
Rosgen Stream Classes by Reach and Longitudinal Profile
NOTE: Reported sediment supply for the different reaches is for local contribution from bank erosion and bed incision over a 165 year period.
Elevation from USGS 7.5' Quad
Rosgen Stream Class distance break
ELEVATION (ft)
DISTANCE (ft)
Steelhead Reach
S=2.6%
Sed Supply = 127 cu ft/ft
Stream Class =
49 % B (2075')
39% F (1664')
8% G (337')
2% B-F (91')
1% A (49')
Diversion Reach
S=3.8%
Sed Supply = 144 Cu ft/ft
Stream Class =
77% B (815')
9% A (97')
8% E (82')
6% G (60')
Concrete cattle xing
WATERSHED SCIENCES, 2002

Figure 28d

Carriger Creek 3.9 Mile Study Reach
Rosgen Stream Classes by Reach and Longitudinal Profile

NOTE: Reported sediment supply for the different reaches is for local contribution from bank erosion and bed incision over a 165 year period.

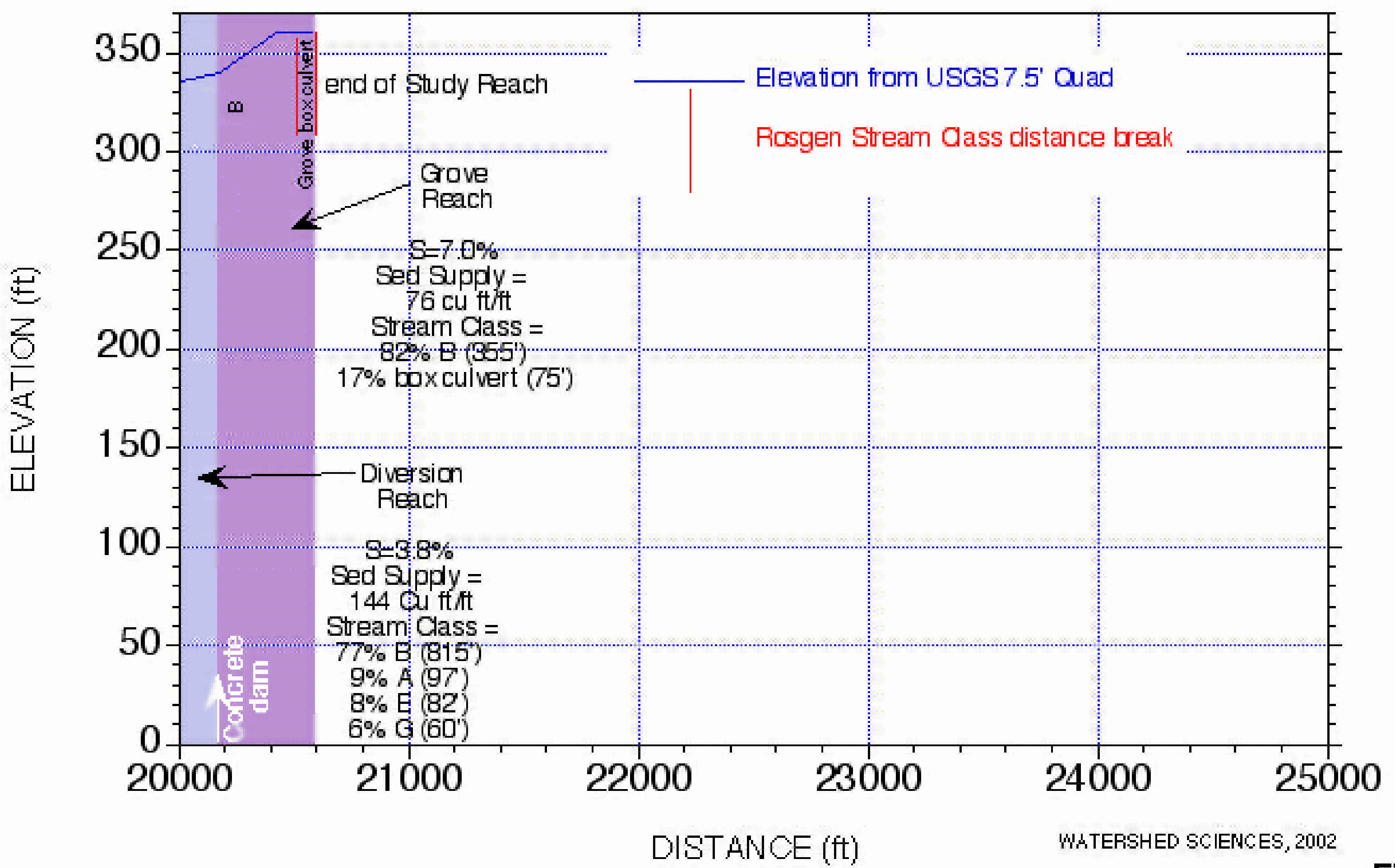


Figure 28e

could be surveyed in similar gradient reaches of F versus B type channels. This could be done if potential plans called for reconfiguring the channel into a more stable form in order to reduce property loss or minimize sediment supply. This graph exemplifies how reference channel characteristics can be sought for certain slope and sediment size regimes. We caution that a true field survey of channel gradient is required for detailed restoration planning (see Appendix Figures 5a-l).

The reaches with the highest sediment supply may not necessarily correlate with the reaches of greatest percentage of unstable stream class, as demonstrated in the comparison between Quercus and Arnold Reaches. This is because in its present condition, much of the channel may have already undergone adjustments in hydraulic geometry and may now be in a stable form. The graphs only allow assessment of present status, not past behavior.

A PICTURE OF CONDITIONS ALONG THE STUDY SITE

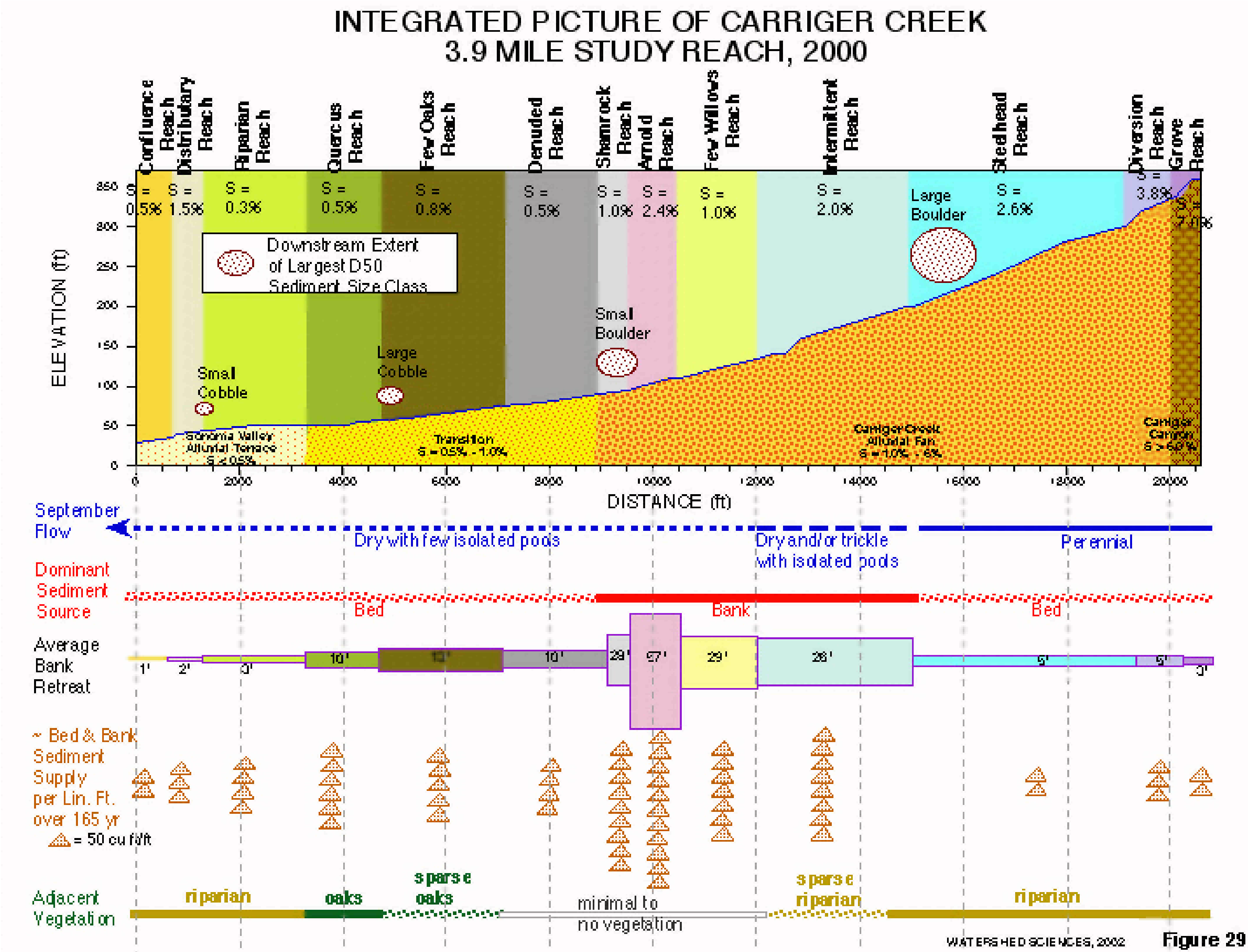
Figure 29. The Integrated Picture

An integrated picture of some of the important physical characteristics is shown in this diagram. It depicts some of the channel parameters that we have quantified along the length of Carriger Creek Study Site. It shows:

- The stream gradient (derived from USGS quads) of the reaches and the morphologic zones;
- The downstream extent of the largest D50 sediment size classes;
- The distribution of flow during mid-September;
- The dominant sediment source of bed versus bank;
- The average bank retreat;
- The volume of bed and bank sediment supply per linear foot of channel for the 165 year period; and
- The extent of adjacent vegetation.

As the graph demonstrates, most of the bank retreat and sediment supply occurs on the reaches in the alluvial fan that are armored by boulders, and lacking riparian vegetation. The lack of vegetation is compounded by a cause and effect relationship with bank erosion, i.e., bank erosion can cause loss of adjacent riparian trees. The greater the amount of vegetation lost to the channel, the less the added cohesion from roots, hence higher rates of bank erosion. Additionally the draw down from the lowered ground water table in the Fowler Road area makes it difficult for vegetation to recover along the reaches that dry out.

Alluvial fans tend to be morphologic features that are formed by streams that are often in an unstable state. Changes in climate can cause a channel to braid back and forth across the fan as it builds upward or alternatively, become entrenched


INTEGRATED PICTURE OF CARRIGER CREEK
3.9 MILE STUDY REACH, 2000
Confluence Reach
Distributary Reach
Riparian Reach
Quercus Reach
Few Oaks Reach
Denuded Reach
Shamrock Reach
Arnold Reach
Few Willows Reach
Intermittent Reach
Steelhead Reach
Diversion Reach
Grove Reach
S = 0.5%
S = 1.5%
S = 0.3%
S = 0.5%
S = 0.8%
S = 0.5%
S = 1.0%
S = 2.4%
S = 1.0%
S = 2.0%
S = 2.6%
S = 3.8%
S = 7.0%
Downstream Extent of Largest D50 Sediment Size Class
Small Cobble
Large Cobble
Small Boulder
Large Boulder
Sonoma Valley Alluvial Terrace S < 0.5%
Transition S = 0.5% - 1.0%
Carriger Creek Alluvial Fan S = 1.0% - 6%
Carriger Canyon S > 6.0%
ELEVATION (ft)
DISTANCE (ft)
September Flow
Dry with few isolated pools
Dry and/or trickle with isolated pools
Perennial
Dominant Sediment Source
Bed
Bank
Bed
Average Bank Retreat
1'
2'
3'
10'
13'
10'
29'
57'
29'
28'
5'
5'
3'
~ Bed & Bank Sediment Supply per Lin. Ft. over 165 yr
= 50 cu ft/ft
Adjacent Vegetation
riparian
oaks
sparse oaks
minimal to no vegetation
sparse riparian
riparian
WATERSHED SCIENCES, 2002
Figure 29

at the fan head and redistribute sediment at the fan toe. We hypothesize that the high amount of instability that is presently observed, especially in reaches adjacent to and including Arnold, has been augmented by 1) land use practices that have caused the destruction of distributaries; 2) construction of Arnold Bridge that historically may have had a much smaller capacity; 3) channel straightening activities that reportedly occurred upstream of the bridge; 4) draw down of the water table by 200’ in the Fowler Road area ; and 5) the removal of wide riparian buffers for expansion of agricultural fields. Based upon historical climate data that we studied for Wildcat Creek in the East Bay Area, there are no indications that climate has changed beyond its range of normal variation within the last two hundred years (SFEI, 2001). We expect that subsequent changes in channel geometry (over-widened bed and banks) have also contributed to the loss of perennial flow during autumn drought in some of the upper reaches of the study site.

SUMMARY CONCLUSIONS AND HYPOTHESES

1. Over an estimated 165-year period in the Carriger Creek Study Site, fluvial erosion along 81% of the length of the banks (76% eroding banks + 5% revetted) has supplied 635 cu yd/ yr of sediment to the channel network. Bed incision occurring over 100% of the Study Site length has supplied 540 cu yd/yr. The total long-term combined sediment supply rate of the bed and banks has been 1,175 cu yd/yr. This can also be reported as a yield of 301 cu yd/yr/mi from the channel source. It does not include fluvially transported sediment from the upstream watershed. We consider this rate to be greatly accelerated above the rate of supply that existed prior to settlement of non-indigenous peoples. The amount of retreat of the eroding banks has ranged from about 1.5 ft to 56 ft, the latter representing over two-bankfull widths of bank loss since about 1835. The maximum amount of bed incision observed has been about 8 ft, representing nearly three bankfull depths of incision. Average incision is closer to two bankfull depths.

2. The channel has widened and deepened as a result of several instream and adjacent land use impacts. The instream impacts include 1) the destruction of distributary channels that used to subdivide Carriger Creek into three separate channels (all the flow below Arnold Bridge is now directed into the previous southern distributary); 2) the construction of the original Arnold Bridge that caused backwater flooding and had insufficient capacity for transporting water an sediment during flood events; and 3) the channel straightening activities that were conducted for flood control upstream of Arnold Bridge. The most significant adjacent land use impacts include the minimization and clearing of a once wider riparian corridor for increased acreage of crop fields and pasturelands, and the destruction of willows from grazing pressures in and along the channel. The removal of wide riparian buffers along agricultural fields has lead to significantly increased rates of bank erosion.

3. Following the destruction of distributaries when Carriger Creek became a single thread channel, the hydraulic geometry had to adjust to increased flows that established a cycle of bank erosion, bed incision, and movement of very large boulder to cobble-sized sediment into the newly incising Carriger Creek bed. We call this an “incision and armored aggradation sequence” that has been exacerbated by the loss of riparian vegetation. If Sonoma Creek has also incised its bed during the last 165 years, then it could also be driving some bed incision in Fowler and Carriger Creeks. We suggest that channel incision is being driven by both in situ incision from more flow contained in the channel after the distributaries were destroyed, and from headward propagation of incision initiated by base level lowering at the Sonoma Creek confluence. In the reaches above Arnold Reach, steepening of the stream gradient from channel straightening activities may have also initiated incision.

4. It is presently unclear how much the channel incision in the Study Site might also be influenced by potential increases in runoff upstream of the Study Site. Based upon our upstream reconnaissance above the Study Site, between the box culvert at Grove St. Bridge and the culvert at Grove Extension, several miles upstream, the amount of incision appears to be less than that observed at the Study Site, but whether recent incision is pervasive, extending all the way to the waterfall below Grove Extension, has not been determined. Without further study of the whole watershed, the impacts of suburban development cannot be adequately assessed. Our impression is that increased impervious surfaces have not been significant enough to cause substantial change in runoff. Residential development in the watershed in not dense and the volcanic soils probably have high infiltration rates. We did observe that culverts at road crossings were causing incision downstream of concentrated flow and poorly designed outfalls, but these observations do not indicate increased runoff.

Along the lower alluvial fan and Sonoma Valley below Leveroni Bridge, we did not see abundant evidence of increased surface flow from the vineyard and crop lands. This is probably because the land is fairly flat. We did see numerous cattle trails into the creek on portions of the fan between Leveroni Bridge and Arnold Bridge that probably function as ephemeral channels that transport fine sediment from the uplands directly to the channel. If conversion of land to vineyards occurs on the steeper uplands, there could be increases in both runoff and fine sediment supply, especially if ground cover is minimized. Increases in runoff are associated with loss of interception by plants.

Although there is a history of cattle ranching in the canyon portion of the watershed, extent and magnitude of grazing activities is not clear without further historical research. Our initial impression about the soils of the canyon and alluvial fan area is that they are not very erodable or responsive to typical soil surface erosion impacts associated with grazing. Because the soils are very rocky and porous, trampling and loss of infiltration are less likely to occur. Grazing has contributed to the loss of riparian vegetation, increased bank erosion rates and channel widening which have lead to declines in base flow and degradation of water quality.

Further study would be required to establish whether local tectonic uplift or extreme runoff events may be contributing to some proportion of natural downcutting. The rates of the latter two factors would be considerably less than the recent downcutting rates observed in the Study Site. We do not consider that climate has changed beyond the range of normal variation within the last two hundred years, therefore it is also ruled out as a factor contributing to accelerated erosion rates.

5. Carriger Creek is dramatically different upstream of Steelhead Reach than it is downstream. Upstream there is clear perennial flow during the seasonal drought. Juvenile steelhead are abundant in this part of the creek, indicating that water quality must be relatively good. In contrast, excessive bank erosion along some downstream reaches has degraded the quality of habitat and diminished available flow for fish. Loss of available flow has been partly caused by creating an extremely wide cross sectional area and subsequent armored aggradation of the bed surface with large cobble and boulders. Surface flow is converted to subsurface flow in many of the over-widened reaches. Below Steelhead Reach, the flow is intermittent and there are only a few isolated pools. Below Arnold Reach, the few pools are notably of poor water quality, as indicated by turbid water color, fetid odors, and algal blooms. This downstream area may also be affected by the decreased water table in the Fowler Road area.

6. Without better development of the historical picture of Carriger Creek, the previous amount of perennial flow cannot be estimated. We think that historically Carriger Creek may have had perennial flow through its distributaries to a Fowler and Sonoma Creek. Mature riparian vegetation can occasionally be found growing at the elevation of the Sonoma Valley flat along the banks of remnant distributaries. Downstream of Arnold Bridge only relatively young riparian vegetation is found growing on inset low elevation benches below the level of the valley flat. This is another indication that the water table has dropped and that the trees need to have their roots close to the water table to become established. The fragments of distributary channels that we found are not highly entrenched.

More thorough study should be conducted to determine historical groundwater levels throughout Sonoma Valley and the early conditions of Sonoma Creek, to test the hypothesis that wells, reservoirs, and diversions have influenced the availability of perennial flow to Carriger Creek and perhaps many other tributaries. The influence of channel incision along Carriger Creek, along with well pumping and consumptive agricultural uses in the valley, has contributed to local water table draw down near the channel banks. During low flow conditions reaches below Steelhead Reach may now be functioning as “losing” reaches rather than “gaining” reaches in terms of total discharge. In general we expect that base flow has diminished while peak flows downstream of Steelhead Reach may have increased.

7. Several of the reaches downstream and upstream of Arnold Bridge have few if any riparian trees. The loss of woody vegetation has caused a loss of root strength in the banks, causing the banks to be more erodable and contributing to extreme channel widening. This widening has caused the channel to straighten its meanders, and increase stream gradient and water velocity. We have observed that along many of the vineyards and pasturelands, the riparian corridor is often only as wide as one tree. Before fields were cleared for agricultural practices, a much wider riparian zone probably existed, perhaps as wide as three or more trees on each side. By diminishing the riparian zone to a narrow corridor, the buffer to bank erosion that is created by the added cohesion from root strength of trees is lost. Essentially, the removal of riparian buffers along agricultural fields has lead to increased and unchecked rates of bank erosion in some portions of Carriger Creek.

8. The reaches near Arnold Bridge on the lower alluvial fan are still highly unstable. This instability may continue as a result of the incision and armored aggradation sequence, where large floods mobilize boulders and cobble that cannot be mobilized during bankfull flows. Bankfull flows subsequently erode into fine-grained banks and then incise into the unarmored bed until another flood occurs. This explains the “cross-channel stair-stepped morphology”. It also explains why patches of fine-grained Quaternary clays are interspersed with veneers of boulders and cobble.

9. In the farthest downstream reaches where the gradient is flatter and the bed has not been armored by coarse sediment, the channel assumes a narrower width between its terrace banks and becomes much more deeply entrenched than the middle reaches. At the upstream reaches near the apex of the alluvial fan, the channel is also more deeply entrenched than in the middle reaches. This has caused the supply of sediment from bed incision to exceed that from bank erosion at the upstream and downstream ends of the Study Site. The apex of alluvial fans is a common area of natural instability and should be regarded as such in any future planning efforts.

10. The number of pools through the overall Study Site during autumn drought is considered very low. Pool spacing is within the expected realm only for Distributary and Diversion Reaches. Most of the pools in Carriger Creek have natural causes but wood contributes to forming 30% of them.

11. LWD is most abundant in the channel where there are reaches with riparian vegetation. We expect the recruitment of LWD to diminish through the Study Site until bank erosion rates are decreased and until sufficient maturity of existing riparian vegetation is gained. Accelerated bank erosion must be reduced in order to give time for trees to take hold and grow in the sections of bank that are devoid of riparian trees. Recruitment of LWD is primarily from bank erosion processes. This mechanism was probably much less important in the past.

12. After many years of relative stability, landowners along the Intermittent Reach upstream of Arnold Bridge have observed very recent bank retreat and changes in channel configuration during the 1990's. Some of these landowners have also experienced recent flooding of their properties. We conclude that the channel may be just starting to undergo a new period of destabilization. This could be a lag time response to the downstream "straightening" activities. Overall, the classification of the Study Site into different Rosgen Stream Classes shows that currently over 52% of the channel length has an unstable geometric form of F and G classes.

13. Land use changes during the last 165 years have greatly increased rates of sediment production in Carriger Creek, particularly downstream of Steelhead Reach. Without a complete watershed analysis, we cannot quantify the total sediment supply from different sources nor de we feel that conditions on the alluvial fan can be extrapolated to conditions in the canyon. Because most of the changes that we have discussed have been instigated by instream changes caused by man during the last 165 years, we conservatively project that at least 60% of the sediment supply from the Study Site has been caused by anthropogenic influences that have caused destabilization of the bed and banks. Most of these man-made changes have occurred within the channel (plowing of distributaries, undersized bridge, and channel straightening).

14. The very low percentage of sand found on the channel bed surface is attributed to: 1) the volcanic nature of the canyon that has produced an abundance of rounded cobble to boulder-sized rocks (their rounding may be more associated with explosive volcanic events and weathering than from alluvial processes); 2) the low percentage of fines in the bank materials throughout most of the canyon zone; and 3) the lack of surface erosional features in the soils. It is also possible that land use activities in the canyon have not been heavy-handed or extensive. Without further study, this impression is tentative. We do not find that sand and finer-sized sediments have impaired pool or spawning habitat within the study reach. Bank erosion along the lower alluvial fan has contributed to a supply of sand and finer-sized sediment to the channel, most of which is transported out of the Study Site. Its downstream impact upon downstream reaches of Fowler and Sonoma Creek, including the tidal reaches has not been assessed.

RECOMMENDATIONS

1. Protect the upper watershed. The creek in the canyon has abundant ecological value that should be conserved.
2. Consider restoration of the system of distributary channels across the alluvial fan. Natural distributaries formerly prevented the concentration of flow that now erodes the single remaining channel. This restoration will reduce the risk of floods in downstream Sonoma Creek and increase in-stream ecological values.
3. Where possible, reshape the channel to create a stable cross section; use biotechnical methods of bank stabilization or use boulder veins to direct flow away from eroding banks. A narrower width-to-depth relationship may restore perennial flow in some portions of the creek and minimize migrational barriers to fish that get trapped in isolated pools.
4. Restore the riparian forest on the alluvial fan to reduce future bank erosion, to create a renewable source of LWD for in-stream habitat enhancement, and to minimize increases in water temperature that can be fatal to fish. This will require fencing cattle out of the riparian zone.
5. Investigate methods for restoring the groundwater table in order to increase summer/fall base flow.
6. Increase the amount of LWD from existing sources by not removing LWD ,unless it threatens a structure or causes backwater flooding at bridges.
7. The longitudinal profile of the mainstem channel should be surveyed to establish future monitoring stations within stable reference reaches (Rosgen B-type channels) and unstable reaches (Rosgen F- and G-type channels) that will show differences and in dimensions and profile. It will also allow correct delineation of local reach gradients. This information can also be used to develop design standards for restoration. Realistic projections of the extent of backwater floods associated with past and present bridges should also be determined.
8. A full watershed analysis could be performed as well as bed load sampling and stream gaging. In this way a sediment budget could be developed. The upper watershed would have to be assessed for sources of sediment. Their linkage to land use and in-stream management activities should be assessed as per the downstream Study Site. This could lead to protecting or enhancing the ecological values in the canyon. It is important that these values be sustained.
9. The historical ecology of the watershed should be described, including native land use practices, patterns of historical land use change, and the chronology of local development, including diversions, impoundments, and engineered stream crossings. Such a perspective would improve everyone’s ability to direct management initiatives and to understand the relationships between land use and watershed conditions.

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GLOSSARY

Aggradation	The long-term process of building up a surface by deposition of sediment.
Alluvial fan	An outspread cone-shaped, gently sloping mass of alluvium deposited by a stream due to a rapid change in slope or valley width.
Alluvium	Stream deposits made by streams on river beds, flood plains, or fans that may include boulders, gravels, sands, silts, and clays.
Anastamosing	A stream channel that branches and joins again at the main channel.
Armoring	Coarse sediment on the channel bed surface that does not usually move at bankfull discharges.
Bankfull	The incipient elevation of the water surface of a stream as it begins to flow onto its floodplain. The flow may have a recurrence interval of about 1.3 t 1.7 years.
Confinement	The relationship between valley width and bankfull width.
Cross section	The geometry of a river channel or other fluvial feature usually measured at right angle to the bank.
D50	Median grain size of sediment measured at a location being described. The particle size is measured along the intermediate axis.
Degradation	The long-term lowering of a surface by erosive processes, especially by flowing water.
Deposition	The short-term laying down of material previously entrained in flowing water as a result of a decrease in the energy needed for transport.
Entrenchment	The down cutting of a stream into its floodplain alluvium or bedrock that causes a reduction in the rate of lateral migration and an increase in contained flood waters.
Entrenchment ratio	The floodprone width divided by the bankfull width.
Floodplain	A flat bench or plain at the edge of the banks that floods an average of every 1.5 years.
Floodprone	Description of an area that is likely to be inundated during storm flow that lies within the channel banks or floodplain.
Floodprone width	Floodprone width is the measured width between the banks at twice the maximum bankfull depth.
Incision	The short-term process of down-cutting which, if occurring at a faster rate than deposition, may eventually lead to permanent degradation of a channel bed.
Lateral migration	The action of a stream swinging from side to side, impinging against and eroding its banks.

Longitudinal profile	The elevation of the streambed relative to its distance along its valley.
Large Woody Debris (LWD)	For the purposes of this project, large woody debris is wood greater than 8in diameter and is supplied to the stream from adjacent trees.
Planform	The outline of a shape viewed from above.
Revetment	Any type of retaining structure which increases bank stability e.g., riprap, concrete, wire mesh.
Rosgen Stream Class	A system of stream classification that defines streams by their morphology.
Sediment budget	The quantitative description of sources, sinks and riverine transport. Taking into account the errors associated with the definition and quantification of each of the terms, the sum of all the terms will add to zero. This represents the conservation of mass.
Sediment rate	Transport, accumulation, or erosion of a volume or mass of sediment expressed per unit time.
Terrace	A relatively level bench or step-like surface that was constructed by a river and represents an abandoned floodplain.
Thalweg	The deepest point of a channel at any given cross-section. A thalweg profile is a survey of the deepest point in the channel bed.
Watershed	Area defined by a topographic drainage divides within which water from rainfall flows toward a common point.
Width / depth ratio	The relationship between the width of the channel and the depth of the channel at bankfull stage.

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APPENDIX

Figure __. Streamline Graph Key

Figure __. Streamline Graphs

Figure __. Rosgen Stream Classification System