SAN PEDRO CREEK WATERSHED SEDIMENT SOURCE ANALYSIS

Volume III:
Tributary Sediment Source Assessment

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ABSTRACT

The San Pedro Creek watershed supports steelhead trout (Oncorhynchus mykiss), a federally listed threatened species, despite many years of intensive land use, channel modification, and the current suburban setting. The current condition of tributary sub-basins, including sediment supply, transport, and dominant geomorphic processes, has been identified as a data gap for the management and restoration of the creek and watershed. Building upon a previous study by Collins et al. (2001), this study documents current conditions in three tributary basins.

Data collected in San Pedro Creek on the Sanchez fork, South fork, and Middle fork included: bank and terrace erosion; bank revetment; terrace height above the thalweg; average bankfull width and depth; bed incision; sediment storage; bed grain size distribution; pool location, depth, and an index of pool volume; and large woody debris loading.

Compared to the mainstem, the tributaries are experiencing much greater erosion, dominated by landslide/slump and terrace erosion. Bed incision is also a significant source of sediment, with the tributaries responding to well-documented incision of the mainstem. Sediment storage is significantly less than sediment input, and is dominated by terraces, particularly in Middle fork. Bed grain size reflects underlying lithology of the sub-basin, and is finest in Sanchez and South forks, contributing substantial amounts of fine sediment to the mainstem. The greatest length of bank revetment occurs in Sanchez fork, associated with the residential land use. Sanchez fork offers the poorest steelhead habitat among the tributaries studied mainly because of high entrenchment and length of revetment. Management should focus on increasing the success of bank stabilization, encouraging native vegetation, and decreasing deleterious effects of the residential area on water quality. South fork is dominated by bank and terrace erosion, due to historic channel relocation. A greater number of pools, large woody debris pieces, and channel complexity offers better steelhead habitat. Management should focus on the stabilization of banks. Middle fork provides the best steelhead habitat due to its greater channel stability, larger mean grain size, abundance of pools, wood and riparian vegetation, and low-intensity surrounding land use. Management of this fork as steelhead habitat will likely have the greatest impact on native fishery success in the watershed.

The data collected in this study strives to make a contribution to local stream and land management, as well as to the science of steelhead conservation in California.

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INTRODUCTION AND PURPOSE

San Pedro Creek has been identified by the California Department of Fish and Game (CDFG) as an important habitat for steelhead (*Oncorhynchus mykiss*). The steelhead population of San Pedro (documented back to 1941) is part of the south/central California population of steelhead, which is listed by the Federal government as a threatened species. Land use pressures have resulted in changes in runoff character, excessive channel erosion and incision, channel revetment, grade structures, bridges, and reductions in water quality potentially associated with confined animal facilities, landfills, street and commercial runoff, sewage leaks and illegal discharges. The community-based San Pedro Creek Watershed Coalition (SPCWC), a non-profit (501 (c)(3)) organization, working closely with the City of Pacifica, CDFG and other local environmental management organizations are concerned about the longevity of the steelhead population given past and present land use pressures associated with urbanization and agriculture.

Steelhead are sensitive to changes in many physical conditions often due to increased intensity land use. Changes that have deleterious effects upon steelhead include: increased water turbidity, increased storage of fine sediment, increased embeddedness, increased water temperatures, and degraded water quality. For example, increased water turbidity has been shown to cause avoidance by both migrating adult salmonids (Bjornn, 1978; McCabe et al., 1981; Bell, 1986; Bjornn and Reiser, 1991) and juveniles (Bisson and Bilby, 1982; Sigler et al., 1984; Lloyd et al., 1987); cause habitat effects such as embeddedness and reduced complexity (Bash et al., 2001); affect foraging and feeding (Berg and Northcote, 1985; Newcombe and MacDonald, 1991); and cause physiological effects such as gill trauma and impaired reproduction and growth (Sigler et al., 1984; Bash et al., 2001).

Increased input of sediment can be linked to adjacent land management (Bunte and Macdonald, 1999), and is often manifest as storage of fine sediment in large pool deposits. These deposits decrease pool volumes, increase water temperatures necessary for successful salmonid rearing, and have many other detrimental effects on salmonids (Lisle, 1987; Bjornn and Reiser, 1991; Hilton and Lisle, 1993; Nielsen et al., 1994; Klein, 1997). Increased fine sediment also contributes to greater embeddedness of a channel bed. Embeddedness can cause greater difficulty in adult excavation of redds, and increased mortality of eggs in redds and fry emergence from gravels. Salmonids require adequate grain size distributions of spawning gravels (Kondolf and Wolman, 1993). Levels of fine sediment greater than 14% for < 1 mm and 30% for < 6.35 mm has been shown to correspond with less than 50% survival to emergence for salmonids (Kondolf, 2000). Hydromodification in a watershed can lead to increased transport and modification of bed sediments, potentially affecting the survival of eggs in a redd (Madej and Ozaki, 1996; Orsborn and Ralph, 1995; DeVries, 1997).

Steelhead migration can be reduced or prevented because of changes in seasonal hydrology, grade controls, road bridges and culverts and other temporary or permanent structures such as waterfalls, and debris jams (McEwan and Jackson, 1996). In some areas of San Pedro Creek, channel revetment, grade structures, and bridges are thought to be causing problems for fish migration under certain flow conditions (SPCWC, 2002).

Increased water temperatures associated with loss of riparian canopy, competition for water resources for human uses, or land use impacts of summer flows have also been shown to cause physiological affects such as increased metabolism, altered timing of lifecycle events, and slowed rates of growth (Spence et al., 1996). Not only is egg development highly temperature dependent (Flosi et al., 1998), but adult migration, spawning, and juvenile rearing are also affected by water temperatures (Reiser and Bjornn, 1979). Reduced water quality (Charbonneau and Kondolf, 1991) can significantly affect salmonid populations, in some instances, causing fish kills in an entire creek.

To begin to address these types of concerns, the San Pedro Creek Watershed Assessment and Enhancement Plan was written by the San Pedro Creek Watershed Coalition in collaboration with many Bay Area scientists. The plan documents the current condition, many processes and management efforts in the watershed, and outlines a plan for information gathering and fact finding using scientific assessment of physical, biological and water quality aspects of the watershed, restoration and public education and outreach. In close relation to this current effort, a study by Collins et al. (2001) focused upon the geomorphic character and dominant processes occurring in the mainstem of San Pedro Creek. Significant channel incision up to 16 ft (4.9 m), bank erosion, sediment supply and transport through the fluvial system was shown to affect the functioning and aquatic habitat supplied by the creek. Other past studies include the effects of landslides caused by the January 1982 storm (Howard et al., 1982), and the functioning and effects of sediment on a proposed flood control channel project (USACE, 2000).

Although much previous work has been accomplished in the San Pedro Creek watershed, some data gaps remain. The previous reports and local stakeholders have determined that documentation of the current tributary condition is one of the largest data gaps. An analysis of the tributaries is important because tributary land use and management have been hypothesized as supplying large amounts of sediment to the creek. The amount of sediment supplied and transported through the tributaries may be having a significant impact upon mainstem channel morphology, stability and habitat quality.

This study aims to fill tributary sub-basin data gaps associated with baseline conditions of sediment supply from hillslope input, and bed and bank erosion, as well as sediment storage. This study will also characterize the dominant fluvial geomorphic processes operating in the sub-basins and make specific sub-basin scale recommendations. The data collected will make a contribution to local stream and land management, and to the science of conservation of anadromous fishes in California.

SETTING

The San Pedro Creek watershed flows through the city of Pacifica, in northern San Mateo County, at the most northern extent of the Santa Cruz Mountains (Figure 1). The watershed has an area of 8.2 mi^2 (21.2 km^2), ranging in elevation from 1,898 ft (579 m) at Montara Mountain, to mean sea level. The mainstem of San Pedro Creek is a perennial stream that drains directly to the Pacific Ocean, is approximately 13,800 ft (4,200 m) in length, and is a third order channel (Strahler, 1957). The mainstem is surrounded by the Linda Mar neighborhood of the city of Pacifica, including residential neighborhoods, commercial development, parks, and schools. Five main tributaries contribute to the mainstem, from west to east: Shamrock fork, Sanchez fork, North fork, South fork, and Middle fork. Three of these tributaries were chosen for intensive data collection: Sanchez, South and Middle forks (Figure 2).

Sanchez fork has a drainage area of 0.9 mi^2 (2.3 km^2), and ranges in elevation from 60 ft (18 m) to 1,600 ft (488 m). The lowest 0.5 mi (0.8 km) is surrounded by a residential neighborhood, with the remainder of the sub-basin consisting of open space, including some hiking trails traversing the upper sub-basin. This sub-basin is underlain primarily by Paleocene unnamed sandstone, shale and conglomerate, while the upper portion of the sub-basin is underlain by the granitic rocks of Montara Mountain (Brabb, et al., 1998). These two formations tend to weather into sediment that is sand-sized and finer.

The South fork has a drainage area of 1.1 mi^2 (2.9 km^2), and ranges in elevation from 145 ft (44 m) to 1898 ft (579 m). The entire sub-basin is within the San Mateo County Parks and Recreation system, incorporating recreation areas, open space, and watershed catchment area for the North Coast County Water District. This sub-basin is also underlain by the Paleocene unnamed sandstone and granitic rocks of Montara Mountain.

The Middle fork has a drainage area of 1.3 mi^2 (3.4 km^2), and ranges in elevation from 145 ft (44 m) to 1,400 ft (427 m). This sub-basin is also a part of the County Parks system, and consists entirely of open space area, traversed by a moderate number of hiking trails. The basin is underlain by both Paleocene unnamed sandstone, and Cretaceous to Jurassic Franciscan Complex, locally containing sandstone (greywacke), greenstone, and minor areas of limestone (Brabb, et al., 1998).

METHODS

The methodology is based upon that of Collins et al. (2001), and uses many of the same protocols, descriptors, and classifications. Although many aspects are similar, some minor modifications were made due to the scope and budget of this project. The intention is to allow data collected in the tributaries to be directly comparable to that previously collected in the mainstem by Collins et al. (2001).

Fieldwork in the tributaries of San Pedro Creek occurred during October and November, 2003. Each tributary was continuously walked from the confluence with the mainstem, to an upstream location defined by the likely limit of steelhead habitat (Figure 2). The study reach lengths vary between each tributary, yet each chosen reach captures the lower-gradient portion of the tributary that is both readily capable of responding to changes in sediment flux, and a potential habitat for salmonids.

The data collected included: bank and terrace erosion; bank revetment; terrace height above the thalweg; average bankfull width and depth; bed incision; sediment storage; bed grain size distribution; pool location, depth, and an index of pool volume; and large woody debris loading. Specific methods for each data type will be described below. Telescoping survey rods were used for all in-channel measurements. Distance upstream from the confluence was measured continuously using a HipChain brand metric hipchain (calibrated to 0.1 m). The hipchain has an accuracy of approximately +/- 2%, based upon previous tests and experience. Field flagging was tied every 164 ft (50 m) to allow for re-occupation of the same locations.

For each side of the channel, areas of erosion were categorized as either bank erosion or terrace erosion, depending on the position, below or above, the average bankfull elevation. Bankfull elevation is considered to be the flow equivalent to the 1.5 to 2 year recurrence interval flood, as opposed to the flow that fills the channel to the top of the banks. The field-defined bankfull elevation was based upon regional curves predicting bankfull elevation from drainage basin area and average annual rainfall (Leopold, 1994), as well as field indicators, such as the break in slope between the bank and the floodplain, a small break in the slope of the bank, the elevation of bar tops, a change in vegetation type or density, or presence/absence of moss or leaf litter. Although this measure can be somewhat subjective, professional experience in many other Bay Area streams was used (Brady et al., 2003; Pearce et al., 2003a, 2003b; Pearce et al., 2002) as well as calibration to data collected by Collins et al. (2001). The length, height, distance of retreat, type, cause, and estimated age of erosion was recorded for each bank. Erosion was quantified when average distance of retreat exceeded 0.3 ft (0.1 m). The cause of erosion was assigned, either natural fluvial processes, or directly related to anthropogenic actions or structures. The age of erosion was recorded based upon indicators of erosion including: exposed roots, undercut structures or anthropogenic features, semi-circular scallops associated with mass-wasting, fresh bank faces, and density and age of re-vegetation. Erosion that has occurred over approximately the past 100 years was included, because the methodology relied upon indicators of erosion, and no older indicators were observed.

Bank revetment data included length, position, type and condition of revetment. Revetment condition was divided into good, moderate, or failing. If at least 85% of a structure was functioning as designed, the revetment was rated as good. If 50 - 85% of the structure was functioning, it was rated as moderate, and if less than 50% was functioning, it was rated as failing. If the bank was not classified as either eroding, or revetted, the condition was considered stable.

Approximately every 164 ft (50 m), the bankfull channel width and depth were measured, and an estimate of height of the inner and upper terrace above the thalweg elevation was made. Bed incision was measured opportunistically, where indicators of incision were present, including: undercut structures, tree rooting heights above the bed, and incision into inner fluvial terraces. The total volume of sediment supplied by bed incision was calculated by multiplying bed width by incision height by length of channel between incision indicators.

The average width, depth, length, age, and type of sediment deposits were recorded (methods described in Pearce et al., 2002). Only deposits of > 0.3 ft (0.1 m) in depth, with either length or width >3.3 ft (1.0 m) were recorded. Age (in years since deposition) was estimated by considering deposit elevation relative to the thalweg, the grain size of the deposit, as well as the age, density, and vegetation species growing on the deposit (if present). Deposit types included: active channel deposits, forced bars, alternate bars, lateral bars, point bars, medial bars, pool deposits, slump deposits, and terraces. Active channel deposits are the bed sediment that is ordinarily entrained as bedload, and is routed through the fluvial system in a period of decades. Bar classifications are similar to those used by the Washington State Department of Natural Resources (Washington Forest Practices Board, 1997). This assessment focused upon supplies of sediment that are active, or readily available for transport. Although most of the deposits are within or near the bankfull elevation, the assessment included higher, more stable bars and some inner terraces in the 20 to 50 year age class. Neither terraces nor bars higher than 6 ft (1.8 m) above the thalweg elevation, or with trees 50 - 100 years old were included, because these are considered only available for transport in an extreme flood event. The relative stability, age, and availability of each deposit was evaluated on a case-by-case basis, with an aim to be consistent throughout the three tributaries. The volume of sediment stored in each deposit is summed, giving a total volume of storage for each sub-basin. This total volume estimate is likely a minimum, due to the exclusion of older terraces, and also due to the conservative estimates of deposit depths. However, measurements in each tributary are consistent and provided an accurate estimate of the total volume of sediment that is available in low magnitude, high frequency events.

The channel bed surface grain size distribution was measured, utilizing a pebble count methodology modified from Wolman (1954) and Bunte and Abt (2001). Pebble counts were performed in randomly chosen locations that based upon visual inspection appeared to be representative of the average channel bed. Sampling included counts in pools, riffles, runs, and on bars, with an effort made to sample units in the same proportion as they occur throughout the channel length. The pebble counts utilized a systematic random sampling approach in which a grid was defined by using a tape measure and a survey rod. At each grid node, the size of the intermediate axis (b-axis) of the closest grain was measured. Grains were placed into standard sieve size class categories (<2, 2, 4, 5.6, 8, 11, 16, 22, 32, 45, 64, 90, 128, 180, 256, 360, >360 mm). A total of at least 300 grains in each tributary were measured to produce a statistically robust estimate of the surface distribution. This methodology tends to overestimate the average surface grain size distribution, due to the limitations of selecting a single grain smaller than approximately 8 mm with one's fingertip. Despite this limitation, surface pebble counts are used in many studies, and have produced results within approximately 10% of the true grain size distribution (Brady et al., 2003). In addition to pebble counts, continuous estimated grain size distributions were also noted during data collection, for the purpose of graphically illustrating major changes.

For each pool, the surface dimensions (average width and length) and residual depth (maximum pool depth minus tail-out depth) were measured to the nearest 0.3 ft (0.1 m) (Lisle, 1999). Only pools with a residual depth greater than 0.65 ft (0.20 m) were included. An index of pool volume was calculated as a product of pool length, width, and half of the maximum depth. Pools were then placed in a volume size-class, ranging from < 25 ft^3 - >1600 ft^3 (< 0.7 - >45 m^3). However, it should be noted that actual pool volume, following methodologies of Hilton and Lisle (1993), were not followed due to time constraints. Classification of pool types focused on the mechanism of formation, and include: natural, wood-related, man-related, complex, and multiple (Collins et al., 2001). Natural pools form by natural hydraulic processes, wood-related pools are formed by scour around in-channel wood pieces, and man-related are formed by in-channel anthropogenic structures, or man's activities. Complex pools form by the combination of man-related with either natural or wood-related mechanisms, while multiple pools form by the combination of natural and wood-related mechanisms.

Large woody debris (LWD) pieces were included in the data set if the piece (or the significant roots of live trees) was affecting flow within the bankfull channel. Pieces larger than 0.65 ft (0.20 m) in diameter, and 6 ft (1.8 m) in length were included. Data also include the recruitment process, and whether the piece was directly forming or was associated with a pool.

RESULTS

Bank and terrace erosion

The length of each tributary study reach that is classified as eroding is substantial. Of the total study reach length, 58 % of Sanchez fork (SA), 88% of South fork (SO), and 58% of Middle fork (MI) are eroding (Figures 3 and 4). These percentages are high in comparison to the 37% of the total mainstem length that is classified as eroding (Collins et al., 2001). The total length of measured erosion is divided into four categories: bank, terrace, landslide/slump, and gully erosion. In each tributary, most erosion occurs on the banks and terraces, followed by a smaller percentage of landslide/slump type erosion, and finally by the smallest percentage of gully erosion (Figure 5). As is the case in these three tributaries, highly entrenched channels tend to have equal percentages of bank and terrace erosion, reflecting the entrenched morphology (Collins et al., 2001). South and Middle forks have the largest percentage of total study reach length experiencing landslide/slump erosion in the watershed, with 10% and 8%, respectively, a result consistent with the hypotheses presented by Collins et al. (2001).

The relative importance of each of these four erosion types is determined by normalizing the total erosion volume to the total study reach length. Erosion volume per unit channel length, or linear foot of channel (ft^3/ft), highlights the dominant processes of sediment contribution to the fluvial system (Figure 6). The total amount of sediment contributed to the channel by erosion is 14.6 ft^3/ft in SA, 16.2 ft^3/ft in SO, and 14.1 ft^3/ft in MI. For both SA and MI, landslide/slumps provide the largest volume of sediment, with 6.5 and 8.1 ft^3/ft of sediment, respectively. However, in SO, terrace erosion (7.9 ft^3/ft) dominates, followed by landslide/slumps (6.1 ft^3/ft). Gullies contributed the smallest amount of sediment in all tributaries, ranging from 0.1 ft^3/ft in SO, to 0.6 ft^3/ft in MI.

The estimated age of erosion, based upon indicators, allows inferences regarding the cause of erosion, whether it be a major change in land use, a major flood event, or perhaps just natural background erosion (Figure 7). In general, the 10 to 20 year age class dominates bank and terrace erosion in all three tributaries. Two other age classes, 20 to 50 years, and 5 to 10 years are also substantial, but SA was the only tributary with sizeable erosion in the 1 to 5 year age class. The cause of erosion in each location was assigned; erosion was typically due to natural fluvial processes, but in some instances, it was directly related to land use practices, or individual structures in the channel (Figure 8). A total of 49% in SA, 8% in SO, and 4% of erosion in MI was attributed to anthropogenic activities or structures.

Bank and terrace revetment

The amount of bank and terrace revetment appears to be highly correlated to the surrounding land uses. For example, 13% of the SA study reach length was revetted, in all instances providing protection for houses bordering the channel (Figure 3). This is of similar magnitude to the 20% revetment observed along the mainstem (Collins et al., 2001), which also has a high density of residential neighborhoods adjacent to the channel. In comparison, the primary land use in both SO and MI is park and recreation area, and thus, these tributaries only had 1.8 and 1.2% respectively, of their study lengths revetted.

Partially due to the high entrenchment of the channel, as well as to the proximity of structures to the bank edge, landowners along SA are very concerned about property loss due to bank erosion, and thus, many generations of revetment are observed (Figure 9). In SA, concrete blocks are the dominant revetment type, followed by poured concrete, and wood. In terms of condition, nearly equal lengths of good, moderate and failing revetment were observed, reflecting many generations of installation and design (Figure 10). In SO, poured concrete and riprap were the most common types, with most revetment associated with an old flashdam, and four pedestrian bridges that span the channel. Because the bridges were all fairly new, nearly all observed revetment is in good condition, with only a minor amount in moderate condition. In MI, revetment types include poured concrete associated with an old flashdam structure, and corrugated metal sheets placed along the top of the terrace to prevent water from entering existing gullies. However, the largest portion of revetment was associated with the recently replaced (2001) spanning pedestrian bridge. This location featured geotextile bank fabric and willow stakes on each bank, all of which were in good condition.

Terrace heights

Measures of terrace heights above the thalweg elevation illustrate the degree of incision of the current channel bed. Although measures tend to be highly variable along the study reach length, taken as a whole, a general trend was observed. In SA, only a single location of an inner terrace was observed, 6 ft (1.8 m) above the thalweg (Figure 11). The upper terrace, both right and left sides, was approximately 20 ft (6.1 m) above the thalweg throughout the entire study reach. In SO, a distinct trend was observed in the upper terrace heights, decreasing from approximately 14 ft (4.3 m) near the confluence, to 6 ft (1.8 m) at the top of the study reach (Figure 12). The terrace heights at the confluence reflect the incision by SO, to maintain grade with the mainstem. MI contains many more inner terrace remnants, typically located at 5 ft (1.5 m) above the thalweg (Figure 13). The upper terrace decreases slightly from 20 ft (6.1 m) near the confluence, to 15 ft (4.6 m) at the top of the study reach.

Bankfull width and depth

Bankfull width measured in the field was approximately half the width determined from published regional curves. Field measures indicated an average width of 6.7 ft (2.0 m) in SA, 6.5 ft (1.9 m) in SO, and 8.0 ft (2.4 m) in MI (Figure 14). Based upon the drainage basin areas of these tributaries, the published curves (Leopold, 1994) predict bankfull widths of 15 ft (4.6 m), 15.5 ft (4.7 m) and 16 ft (4.9 m), respectively. This discrepancy could be due to lesser annual rainfall in the basin compared to that used in the curves, a greater infiltration capacity of the soils reducing the immediate runoff to the channel, errors in field identification of the bankfull elevation, or possibly to a period of rapid incision, where all stream energy is directed on the bed. A combination of incision and infiltration capacity are the likely causes of the discrepancy.

Bed incision

Bed incision can be a response to changes in baselevel elevation, amount of sediment and water supplied to the channel (controlled primarily by climate and land use), knickpoint migration, removal of grade control structures, bank hardening, or tectonics. Besides bank and terrace erosion, bed incision can provide a major source of sediment to the channel. Also, with greater bed incision, bank erosion will eventually increase, as the channel makes adjustments to regain a stable cross section by widening. Incision up to 16 ft (4.9 m) in the past 217 years was observed in the mainstem, and was shown to contribute consistently larger volumes of sediment compared to bank erosion (Collins et al., 2001). Smaller amounts of incision compared to the mainstem are evident in each of the tributaries, likely due to smaller drainage basin areas and increased channel slopes. These tributaries are also upstream of the influence of the North Fork tributary, a mostly culverted reach that provides concentrated flows deficient in sediment load to the mainstem, significantly contributing to further bed incision down stream. The total volume of sediment per unit channel length contributed from bed incision was 28.5 ft^3/ft

in SA, 15.9 ft^3/ft in SO, and 21.7 ft^3/ft in MI (Figure 15), compared to incision in the mainstem study reaches quantified by Collins et al. (2001) that ranged from 50 - 200 ft^3/ft. For both SA and MI, bed incision contributed a greater volume of sediment per unit channel length than bank and terrace erosion, but the contribution from each source was nearly equal in SO.

Sediment storage

The amount of sediment storage in a channel reflects the prevailing water and sediment input and transport capabilities, channel gradient, localized supplies of sediment, valley and channel width, and load of large woody debris, among other factors. An assessment of the total volume of sediment that is currently in storage, but is available for transport in each tributary study reach was made. This assessment, when considered along with volumes of sediment input to the fluvial system allow an estimate of sediment flux through the tributary basins.

Although the overall current regime in 2003 was incision, each tributary channel still contained substantial accumulations of sediment in the form of active channel deposits, pool deposits, bars and terraces. The total volume of sediment in storage varied immensely between the three tributaries, with measured volumes of 6,379 ft^3 in SA, 13,348 ft^3 in SO, and 60,219 ft^3 in MI. However, these values can not just be normalized to the study reach length. Bankfull channel width is one of the primary controls on sediment storage in a channel; wider channels have a greater ability to store larger volumes of sediment. Instead, the total volume of sediment is normalized to the average bankfull channel width (BFW). This reveals calculated values of 26.1 ft^3/BFW in SA, 48.1 ft^3/BFW in SO, and 94.3 ft^3/BFW in MI (Figure 16). Upon further inspection, the data reveals that the variability in the normalized values is largely due to the inclusion of terraces. If all terraces are removed from the data set, sediment storage per bankfull channel width becomes 14.1 ft^3/BFW in SA, 25.3 ft^3/BFW in SO, and 30.7 ft^3/BFW in MI.

Terrace deposits comprised 46 -68% of the total volume of sediment storage in each tributary, while active channel deposits comprised 10 -22% of the total (Figures 17-20). Volumes for each individual bar type were quite variable, however, when taken together, all bar types comprised 21 -27% of the total storage volume. Pool deposits were also quite variable, making up 18% of the total storage in SA, but only 1% in both SO and MI.

The estimated age of deposits (in years since deposition) is controlled by the recent major channel forming and modifying flow events. In each tributary, the majority of deposits were in the <1 and the 1 -5 year age classes (Figure 21). If total volume rather than total number of deposits in each age class is considered, a different result was attained (Figure 22). Both SA and SO contained sediment storage volumes that are evenly distributed amongst age classes. However, the storage volume in MI is dominated by the 20-50 year age class, followed closely by the 1-5 year age class. The dominance of the older age class reflects the influence of terraces in the data set. More terraces are preserved, and thus, greater sediment storage occurs in MI because it is a slightly larger sub-basin with a wider valley cross-section, compared to SA and SO.

Bed grain size distribution

The grain size distribution of bed sediment reflects the dominant lithology exposed in the basin, as well as dominant fluvial geomorphic processes and transport ability of the channel. Distributions typically vary along the length of a channel, generally fining downstream, but may respond to inputs of sediment from tributaries or localized sources. In adjacent basins of similar sizes, basin lithology will have a large effect upon grain size distributions. For example, SA and SO, which are both underlain by sandstone and granitic rocks, have 53 and 51%, respectively, of their total surface sediment distribution that is smaller than fine gravel (4-8 mm) (Figure 23). In contrast, MI only has 38% of sediment smaller than fine gravel, reflecting the Franciscan Complex sandstone, greenstone and limestone lithologies underlying the sub-basin. A similar trend was noted for sand-sized sediment particles, comprising 14% in SA, 13% in SO, and 11% of the total in MI. Due to the methodology, surface pebble counts group all sediment that is finer than 2 mm in the sand-sized category. However, differences in the fine sediment texture are evident, and were noted in the field; SA and SO more often contained silt to sand sized fine particles, whereas MI contained mud to silt sized particles (documented in field notes, SFEI). In the mainstem, the average percentage of sediment that is sand-sized or finer (<2 mm) was 22% (Collins et al., 2001) perhaps caused by inputs of fine sediment from other tributaries, urban sources, or different storage characteristics in the upper versus lower reaches associated with gradient. In addition to fewer fines, MI also has a larger percentage of its grain size distribution in the coarse gravel to small cobble range (16 to 128 mm). These variations in each distribution are captured in the calculated median grain size (D_{50}), which is based upon the pebble counts performed in each tributary (Figure 24). D_{50} is 5.2 mm in SA, 4.3 mm in SO, and 11.0 mm in MI.

Pools

Pools are important habitat features for salmonids and other aquatic species because they provide a velocity shelter, deeper and cooler water, and cover for protection from predators. Pools also have an effect upon the sediment flux of a basin, liberating sediment as they are scoured, and temporarily storing sediment in the form of pool deposits. The number of pools measured in each tributary varies, from 15 in SA, 33 in SO, to 76 in MI. When normalized to the study reach length, the number of pools per foot of study reach is 0.010 in SA, 0.018 in SO, and 0.015 in MI. Average pool spacing is 15.3, 8.4 and 8.3 bankfull widths, or one pool every 102, 55, and 66 ft (31, 17, 20 m) in SA, SO, and MI, respectively. This spacing contrasts with the mainstem, where average pool spacing was measured as one pool every 108 ft (33 m) (Collins et al., 2001).

Most measured pools were in the <25, 25-50, and 50-100 ft^3 size classes (Figure 25). No pools in the 400-800, or >1,600 ft^3 class were observed, while only a single pool in the 800-1,600 ft^3 class was observed. This particular pool is located in SA, was associated with a 5.9 ft (1.8 m) diameter culvert that runs underneath a church parking lot, and was hanging approximately 8.2 ft (2.5 m) above the water surface. All other pools in SA were smaller than 50 ft^3, with only two formed by anthropogenic mechanisms (Figures 26 and 27). In SO, all pools are smaller than 400 ft^3. Besides a single man-related pool, all pools were formed either by natural, wood-related or multiple processes (Figures 28 and 29). All pools in MI were smaller than 400 ft^3, and represent a greater range of pool-forming processes. While the majority were formed by natural, wood-related and multiple mechanisms, a total of four pools were either complex or associated with man (Figures 30 and 31). The percentage of pools directly formed by LWD was 6, 18, and 43%, and the percentage of pools that are associated with LWD was 25, 18 and 21% in SA, SO, and MI, respectively (Figure 32).

Large woody debris (LWD)

Similar to pools, the number of LWD pieces in each tributary varied widely, from 10 in SA, 79 in SO, to 175 pieces in MI. In the 13,795 ft (4,205 m) of mainstem channel surveyed, a total of 198 LWD pieces were measured, with an average spacing of one piece every 70 ft (21.3 m) (Collins, et al., 2001). In the tributaries, average spacing is one piece every 164 ft (50 m) in SA, 23 ft (7.0 m) in SO, and 29 ft (8.8 m) in MI. Wood loading is calculated as 3.8 m^3/km in SA, 20.1 m^3/km in SO, and 18.9 m^3/km in MI, and is fairly low compared to other Bay Area creeks (Pearce et al., 2003a; 2003b; Brady et al., 2003). Recruitment mechanisms are also variable, with all recruitment types (except aggraded) represented in SO and MI (Figures 33-36). All 10 LWD pieces in SA are in the "other" recruitment category, because the mechanism could not be determined, however, most of these pieces are likely recruited from bank erosion and float. Bank erosion and leaning are the most important recruitment processes in the mainstem (Collins et al., 2001). In the tributaries recruitment is more evenly distributed, likely due to lesser management, removal and accessibility to the tributaries in comparison to the mainstem.

DISCUSSION

The collection of data was focused upon gathering information regarding the current status of sediment input and storage in three tributaries of San Pedro Creek. The goals of this tributary sediment assessment include: 1) identifying locations of excessive sediment contribution to the fluvial system, 2) quantifying the amount of sediment being supplied through bank erosion and mass wasting processes, 3) estimating the amount of sediment currently in storage in the creek, 4) establishing baseline conditions, and 5) assisting the completion of a watershed-scale sediment budget. The following section addresses these goals by discussing the findings for each tributary, focusing on sediment input and storage, and the management implications based upon the data.

Sanchez fork

Of the three tributaries, Sanchez fork (SA) is the most urbanized, confined, and revetted (Figure 47). SA is highly dynamic, and is currently responding to encroachment of the neighborhood, locations of poorly designed revetment, and incision of the mainstem. The negative effects of the surrounding residential area, and many generations of revetment are clearly evident (Figures 37 and 38); of the three tributaries, SA has the largest length of revetted banks (13%), and also the largest portion of erosion in the 1-5 year age class (20%). Much of the study area contained invasive cape ivy, which tends to kill established riparian vegetation, while offering little to no protection from scour on the banks. Throughout the study reach, many locations of poorly designed or failing revetment were observed, often causing increased erosion on the opposite bank or immediately downstream. In addition, 58% of the length is classified as eroding; half of this amount can be directly attributed to anthropogenic structures or activities. Every gully location occurs as a result of a culvert or modified drainage pattern directly associated with the surrounding residential area (Figures 39 and 40). The location of one gully and landslide/slump (located approximately 25 m downstream of a small tributary confluence joining on the right bank, near the upper limit of surveyed channel) may be related to drainage modifications associated with the abandoned Coastside Boulevard, based upon position and size and input of sediment contribution to the creek. Further field-checking should confirm the linkage between gullies heading on the abandoned road and connectivity with the fluvial system.

SA contributes the largest total volume of sediment per unit channel length (43.2 ft^3/ft), yet has the least volume of total sediment storage, when including terraces (26.1 ft^3/BFW) or when excluding terraces (14.1 ft^3/BFW). SA is one of the sources of fine sediment that is delivered to San Pedro Creek. This tributary has a relatively small D_{50} (5.2 mm), with a large proportion of fine sediment in its distribution, and 18% of its total sediment storage composed of fine-grained, annually mobile pool deposits.

SA is narrow and highly entrenched, as evidenced by the terrace heights above the thalweg elevation, and lack of inner terraces. Because of the cross-sectional morphology of this entrenched channel, the percentage of bank erosion and terrace erosion is nearly equal. When the toe of the bank is destabilized by fluvial erosion processes, the entire bank and terrace slope becomes unstable, allowing large contributions of sediment from the terrace to enter the fluvial system. Although this reach of channel does not contain large hillslope-derived landslides that are directly connected with the fluvial system, many large slump blocks comprising the entire bank and terrace height are evident. These slump blocks are only 5% of the total eroding length, but because of the height of the banks and terraces, this erosion type contributes the highest volume of sediment per unit channel length. The slumps are probably partially caused by the suburban development, especially due to watering and runoff from lawns, the weight of houses loading the banks, and modified drainage patterns adding storm runoff directly into the creek. SA has likely incised in response to incision on the mainstem; 28.5 ft^3/ft of sediment is estimated to have been contributed by bed incision. However, many current structures on the channel bed appear to be relatively stable, including the culvert under Rosita road, a concrete flashdam (Figure 37), and a poured concrete bed and wall.

Because the valley width of Sanchez fork is relatively narrow, removing all of the hardscape revetment, and replacing it with banks that are laid-back and planted with biotechnical revetment (reshaping the channel cross-section to a more stable form) does not appear to be a viable option. Better coordination between landowners on adjacent banks and immediately up and downstream of revetment projects should increase the success of each project, and reduce the amount of fluvial work that is merely shifted from one project location to another unrevetted location. Areas of current revetment could be improved by replacing the failing revetment (often concrete blocks that are falling into the channel) with either biotechnical revetment or more stable, larger pieces that have been designed to work with the adjacent conditions.

This tributary provides only poor habitat for salmonids and other aquatic species. Limiting factors include poor habitat complexity, migration barriers and likely degraded water quality. Overall, SA does not include many pools, especially large enough for salmonid rearing, or many LWD pieces to provide complexity, cover, or trap spawning gravels. In addition, a few partial migration barriers exist, dependent upon discharge, including the concrete box culvert under Rosita Street, and the old flashdam structure 669 ft (204 m) upstream of the confluence (Figure 37). The large culvert under the church parking lot, 984 ft (300 m) upstream of the confluence is an absolute migration barrier because the culvert is approximately 8.2 ft (2.5 m) above average winter baseflow water elevation (Figures 41 and 42). The pool at the base of this culvert is large, but is significantly diminished by the substantial pool deposit of silts and muds. Although measures of water quality are beyond the scope of this study, casual observations reveal large amounts of trash in the channel, and compromised water quality, likely due to suburban runoff.

South fork

Portions of the South fork (SO), especially downstream of Brooks tributary, have been highly modified, due to channel relocation for the John Gay trout farm (in operation during the 1950's until 1962). The channel was shifted to the east side of the valley, and pinned to the valley wall by a levee (J. Davis, pers. comm.). This sub-basin is supplied with, and is capable of transporting large volumes of water and sediment, as evidenced by the 1962 flood and debris flow that destroyed the trout farm (Collins, et al., 2001).

The effects of channel relocation are most evident in the length of study reach that is classified as eroding (Figure 48). 88% of the total length is classified as eroding, while only 10% is classified as stable, and 2% as revetted. The overall current process is channel incision and widening, as the channel makes adjustments in its geometry to regain a stable cross-sectional morphology. Because the current channel is relatively narrow (Figure 43), with approximately 6.5 ft (2 m) vertical banks, during flood events, work done by the channel is focused on the bed, banks, and terrace banks above bankfull channel elevation.

Like SA, SO has a nearly equal percentage of bank and terrace erosion length, due to its entrenched morphology. This erosion is primarily in the 10 to 20 and 20 to 50 year age classes, suggesting that this erosion is chronic. However, unlike the other two tributaries where bed incision is greater than total bank erosion, SO contributes nearly equal proportions of sediment from bed incision and total bank erosion. Greater bank and terrace erosion, and lesser bed incision likely reflect the modified channel morphology, highlighting the location where most channel adjustments are currently being made. Landslides/slumps are of secondary importance for sediment contribution to the fluvial system. SO only contains a few hillslope-derived landslides (from hillslopes on the eastern side of the channel) that directly enter the channel, and bank slumps, where the entire bank and terrace height has failed. However, despite SO having the largest length of channel classified as eroding (88%) amongst the three tributaries, SO contributes the smallest total volume of sediment per unit channel length (32.2 ft^3/ft).

Most of the channel contains well-vegetated banks, and a stable riparian corridor, so planting additional vegetation to increase bank stability will likely not make a significant difference. Cape ivy is also a problem in this sub-basin, but small areas of eradication appear to be effective. Solutions designed to slow bank erosion would involve the removal of the levee, and/or widening of the channel and modification of the banks, to a more stable cross-sectional morphology. This would be a major restoration project that may not make a dramatic difference in the volume of sediment supplied through bank and terrace erosion, or quality of salmonid habitat. A cost-benefit analysis may show that this restoration may not be financially viable, or even deemed necessary by local stakeholders.

SO has a moderate amount of total sediment storage, with terraces excluded from the data set (25.3 ft^3/BFW), and a more substantial amount when terraces are included (48.1 ft^3/BFW). Like SA, SO is a source of fine sediment delivery to San Pedro Creek, because it is underlain by the same lithologies, and has the same fine-grained surface sediment characteristics. Despite the abundance of fine sediment, and a greater number of pools, SO only stores 1% of its total sediment as pool deposits. These deposits do not appear to significantly reduce the volume of pools.

Although the channel is still adjusting to past modifications, effects of current land use and anthropogenic actions are not directly causing major changes in the tributary. For example, four pedestrian bridges, a visitor center, and a trail are all located along the creek, yet only 1.8% of the study reach length is revetted, and only 8% of the measured erosion is directly attributable to man. All of the erosion attributed to anthropogenic sources is associated with scour around the hardened banks that support the bridges, runoff entering the channel at the bridge locations, and trails that lead to the channel forming gullies.

SO provides moderate to adequate habitat for salmonids. The channel has perennial flow, no migration barriers (up to the North Coast Water District barrel and pump, 2,958 ft (902 m) upstream of the confluence with the mainstem), an adequate number of pools of large volume, a third of which are associated with LWD pieces, and a good total number of LWD pieces to provide cover and complexity. However, the limiting factor is likely the fine sediment size distribution that would affect spawning success. Also, because the channel is relatively narrow, water velocity during flood flows may be high enough to scour excavated redds. Although, likely not a limiting factor, water diversions, especially during drought years, could be a stressor for any oversummering salmonids in this sub-basin.

Middle fork

The Middle fork (MI) is the most pristine of the three tributaries, containing the most channel complexity, channel stability, sediment storage, and potential salmonid habitat. Amongst the three tributaries, MI has the highest percentage of study reach length that is classified as stable (41%) (Figure 49). This tributary has a wider valley cross-section, allowing more lateral adjustment by the fluvial system, and more terraces to be preserved. However, the channel is also relatively entrenched, limiting the amount of lateral movement, and tending to increase terrace erosion (Figure 44).

MI contributes a moderate total volume of sediment per unit channel length (35.8 ft^3/ft), with landslides/slumps contributing the largest volume per unit channel length. Although all recent landslide or slump locations are included in the erosion data set, many other locations of older landslides and slumps were not included. These older landslides/slumps were typically 2-5x larger than more recent mass-movements, are likely hundreds of years old, and are not currently liberating sediment.

Besides contributions from landslides/slumps, this fork also receives sediment from bank erosion and gully erosion. Compared to the other two tributaries, MI has the lowest contribution from bank erosion (4.3 ft^3/ft), and the highest contribution from gully erosion (0.6 ft^3/ft) (Figures 45 and 46). The locations of gullies most often relate to areas where drainage from adjacent trails, or past agriculture, has funneled runoff into the channel. Agriculture-related gullies tend to be much larger, and contribute a greater volume of sediment in comparison to trail-related gullies.

The proportion of fine sediment contributed to San Pedro Creek is less in MI than in SA or SO. Due to the lithologies that underlie the sub-basin, MI has a larger bed surface D_{50} (11.0 mm), with a larger proportion of coarse-grained sediment in its distribution. Because MI does not have as much fine sediment, most pools do not contain significant fine pool deposits.

In spite of the moderate total sediment contribution to the fluvial system, MI has the largest volume of total sediment storage per bankfull channel width (94.3 ft^3/BFW). The wider valley cross-section allows more sediment deposition, and preservation of terraces, which account for most of the storage volume. When terraces are included in the data set, total storage is over 3x higher than when terraces are excluded.

Historic land uses likely had a large impact on MI, including modification of adjacent terraces for agriculture, stream crossings, water diversions, grazing and agricultural runoff, land use-related gully development, and straightening or ditching of the channel. One location of a flashdam structure was observed approximately 4,275 ft (1,303 m) upstream of the confluence. Although now abandoned, the structure continues to have an effect on the channel, by forming a localized grade control, limiting the amount of bed incision that can occur upstream of this point.

Compared to historic land uses, current land use does not have as large an impact on MI. Currently only a very small portion of the length is revetted (1.2%), and only 4.2% of all measured erosion is directly attributable to anthropogenic activities. Although many stakeholders believe that the trail system in this sub-basin is contributing significant amounts of sediment to the channel, there was no substantial evidence found to support this belief. These concerns are legitimate, in the sense that trail runoff is often linked to the formation of gullies and increased erosion. However, it does not appear that the runoff and associated erosion is directly routed to the creek. Whatever small amount of sediment that is contributed from trails, is largely overshadowed by the contribution from largely naturally-occurring landslides/slumps and terrace erosion.

The best spawning and rearing habitat provided by the tributaries of San Pedro Creek is in the Middle fork, because of the number of pools, LWD pieces, more appropriately sized spawning gravel, volume and stability of spawning gravel, and greater channel complexity and stability. In a few pools, young-of-the-year fish were observed, possibly steelhead trout/rainbow trout. Because current conditions are adequate to support steelhead trout and because the adjacent land will likely remain designated open space, management of MI for steelhead trout is a viable option for helping the population recover in San Pedro Creek.

CONCLUSIONS

For three tributaries of San Pedro Creek, Sanchez fork (SA), South fork (SO), and Middle fork (MI) data was collected regarding inputs of sediment and storage of sediment in the fluvial system. The data highlights the location, type, and volume of sediment input or storage, focusing on the geomorphic process involved. This data set provides baseline conditions for 2003, which can be utilized for comparison with a future assessment of channel condition.

The current dominant process occurring in the tributaries of San Pedro Creek is incision, and channel widening through bank and terrace erosion, as well as through landsliding and slumping. Landsliding is a naturally occurring process (probably enhanced by the ongoing effects of historical land management) in the tributary sub-basins, and over hundreds of years, is likely the largest contributor of sediment to the channel. In all cases, the total volume of sediment in storage per bankfull channel width is 1.5-7x less than that contributed by either bank erosion or bed incision. Landslides/slumps and terrace erosion provide the most sediment per unit channel length to the creek. Gully erosion provides the least amount of sediment per unit channel length, but is typically related to an anthropogenic structure or land use activity, whereas the cause of the other erosion types are not as clear. Terraces provide the greatest volume of sediment storage, followed by active channel deposits, forced bars, and lateral bars. Pool deposits are only substantial in SA.

SO has the greatest length of banks classified as eroding, MI has the greatest length classified as stable, and SA has the greatest length revetted. The greatest amount of erosion that is directly attributable to anthropogenic structures or activities occurs in SA. Surface grain size distributions are finer in SA and SO, compared to MI, reflecting the different lithologies underlying each sub-basin. MI contains the greatest number of pools and LWD pieces, with the closest average pool spacing, and the second closest average wood spacing. Because of these factors, along with perennial flow, good riparian vegetation, and surrounding low-intensity land use, MI appears to represent the best potential salmonid habitat of the three tributaries.

Management implications drawn from this data set include:

- Future bank stabilization projects in SA should be better coordinated between land-owners to ensure greater success. When appropriate, biotechnical stabilization methods should be utilized rather than hardscape revetment.
- Especially in SA, the riparian corridor should be managed to encourage native flora, and to support natural wood recruitment. An increase in wood recruitment, and water quality will increase potential habitat value.
- Efforts to eradicate invasive cape ivy should be considered, especially in SA and SO. Without control of this invasive, much of the native vegetation is in jeopardy. The cape ivy could potentially kill much of the bank and riparian vegetation, substantially reducing bank stability and resistance to erosion.
- Restoration of SO, modifying current channel cross-sectional morphology from a narrow channel to a wider channel, could reduce the amount of bank and terrace erosion, and consequent contribution of sediment to the fluvial system.
- In MI, contributions of sediment from trail runoff do not appear to be significantly affecting the creek. However, control of trail runoff will prevent the formation of new hillslope gullies, or the aggravation of existing gullies.
- Management of MI as steelhead trout habitat will encourage the success of the native fishery in San Pedro Creek.

REFERENCES

Bash, J., Berman, C., and Bolton, S., 2001. Effects of turbidity and suspended solids on salmonids. Report by Center for Streamside Studies, University of Washington prepared for the Washington Department of Transportation. 74 pp. http://depts.washington.edu/cssuw/Publications/Salmon%20and%20Turbidity.pdf (June 2003).

Bell, M.C., 1986. Fisheries handbook of engineering requirements and biological criteria. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Fish Passage Development and Evaluation Program, Portland, Oregon.

Berg, L. and Northcote, T.G., 1985. Changes in territorial, gill-flaring and feeding behavior in juvenile coho salmon (Oncohynchus kisutch) following short term pulses of suspended sediment. Canadian Journal of Fisheries and Aquatic Sciences, v. 42, p. 1410-1417.

Bisson, P.A. and Bilby, R.E., 1982. Avoidance of suspended sediment by juvenile coho salmon. North American Journal of Fisheries Management, v. 4, p. 371-374.

Bjornn, T.C., 1978. Survival, production, and yield of trout and chinook salmon in the Lemhi River, Idaho. Idaho Department of Fish and Game. Federal Aid to Fish Restoration Project F-49-R. 57 pp.

Bjornn, T.C., and Reiser, D.W., 1991. Habitat requirements of salmonids in streams. In: Meehan, W.R. (ed). Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19. pg. 83-138.

Brabb, E.E., Graymer, R.W., and Jones, D.L., 1998. Geology of the onshore part of San Mateo County, California: A digital database. U.S. Geological Survey Open File Report 98-137. Map scale 1:62,500.

Brady, R.H. III, Pearce, S., McKee, L., Overton, S., and Striplen, C., 2003. Fluvial geomorphology, hydrology, and riparian habitat of La Honda Creek along the Highway 84 transportation corridor, San Mateo County, California. A technical report of the Watershed Program, San Francisco Estuary Institute (SFEI), Oakland, California. SFEI contribution no. 78.

Bunte, K. and Abt, S.R., 2001. Sampling frame for improving pebble counts accuracy in coarse gravel-bed streams. The Journal of the American Water Resources Association, v. 37, p. 101-1014.

Bunte, K., and MacDonald, L.H., 1999.Sacale considerations and the detectability of sedimentary cumulative watershed effects. National Council for Air and Stream Improvement, Technical Bulletin 776. Research Triangle Park, North Carolina.

Charbonneau, R.B., and Kondolf, G.M., 1991. Land use conversion as a source of contaminants. Proceedings of the conference "Protecting drinking water". University of California Water Resources Center Report No. 76. pg. 41-56.

Collins, L., Amato, P., and Morton, D., 2001. San Pedro Creek geomorphic analysis.

DeVries, P., 1997. Riverine salmonid egg burial depths: review of published data and implications for scour studies. Canadian Journal of Fisheries and Aquatic Sciences, v. 54, pg. 1685-1698.

Flosi, G., Downie, S., Hopelain, J., Bird, M., Coey, R., and Collins, B., 1998. California salmonid stream habitat restoration manual, 3rd edition. State of California, Department of Fish and Game, Inland Fisheries Division.
Hilton, S. and Lisle, T.E., 1993. Measuring the fraction of pool volume filled with fine sediment. Res. Note PSE-RN-414. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, California. 11 pp.
Howard, T.R., Baldwin, J.E., and Donley, H.F., 1982. Landslides in Pacifica, California, caused by the storm. In: Ellen, S.D., and Wieczorek, G.F., (eds.). Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay Region, California. U.S. Geological Survey Professional Paper 1434. p. 163-183.
Klein, R.D., 1997. Critically annotated bibliography to support EPA's sediment TMDL protocol. Review Draft of June 11, 1997. Prepared by Tetra Tech, Inc. under EPA Contract #68-C3-0303. EPA Region 9, San Francisco, California.
Kondolf, G.M., 2000. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society, v. 129, p. 262-281.
Kondolf, G.M., and Wolman, M.G., 1993. The sizes of salmonid spawning gravels. Water Resources Research, v. 29, pg. 2275-2285.
Leopold, L.B., 1994. A view of the river. Cambridge, Massachusetts, Harvard University Press. 298 pp.
Lisle, T.E., 1987. Overview; channel morphology and sediment transport in steepland streams. In: Beschta, R.L., Blinn, T., Grant, G.E., Ice, G.G., and Swanson, F.J. (eds). Erosion and sedimentation in the Pacific Rim, Proceedings of the Corvallis symposium. International Association of Hydrological Sciences, Publication 165. Wallingford, U.K. pg. 287-297.
Lisle, T.E., 1999. Channel processes and watershed function. In: Taylor, R.N. (ed). Proceedings of a workshop: using stream geomorphic characteristics as a long-term monitoring tool to assess watershed function. Humboldt State University, Arcata, California. p. 4-14.
Lloyd, D.S., 1987. Turbidity as a water quality standard for salmonid habitats in Alaska. North American Journal of Fisheries Management, v. 7, p. 33-45.
Madej, M.A., and Ozaki, V.L., 1996. Channel response to sediment wave propagation and movement. Redwood Creek, California, USA. Earth Surface Processes and Landforms, v. 21, pg. 911-927.
McCabe, G.T., Coley, T.C., Emmett, R.L., Muir, W.D., and Durkin, J.T., 1981. The effects of the eruption of Mt. St. Helens on fishes in the Columbia River Estuary. Estuaries, v. 4, p. 247.
McEwan, D., and Jackson, T.A., 1996. Steelhead Restoration and Management Plan for California. California Department of Fish and Game, Inland Fisheries Division. Sacramento, California. 244 pp.
Newcombe, C.P. and MacDonald, D.D, 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management, v. 11, p. 72-82.
Nielsen, J.L., Lisle, T.E., and Ozaki, V., 1994. Thermally stratified pools and their use by steelhead in Northern California streams. Transactions of the American Fisheries Society, v. 123, pg. 613-626.
Orsborn, J.F., and Ralph, S.C., 1995. An aquatic resource assessment of the Dungeness River system: Phase II- physical channel analysis, hydrology, and hydraulics, and

Phase III- fisheries habitat survey. Prepared for the Jamestown S'Klallam Tribe, Sequim, Washington.

Pearce, S., O'Connor, M., Grossinger, R., and McKee, L., 2002. Napa River sediment TMDL baseline study: geomorphic processes and habitat form and function in Soda Creek. San Francisco Estuary Institute, Oakland, California. SFEI contribution no. 63. 100 pp.

Pearce, S., O'Connor, M., McKee, L., and Jones, B., 2003a. Channel geomorphology assessment: A component of the watershed management plan for the Carneros Creek watershed, Napa County, California. A Technical Report of the Regional Watershed Program. San Francisco Estuary Institute, Oakland, California. SFEI contribution no. 67. 58 pp.

Pearce, S., O'Connor, M., McKee, L., and Jones, B., 2003b. Channel geomorphology assessment: A component of the watershed management plan for the Sulphur Creek watershed, Napa County, California. A Technical Report of the Regional Watershed Program. San Francisco Estuary Institute, Oakland, California. SFEI contribution no. 68. 60 pp.

Sigler, J.W., Bjornn, T.C., and Everest, F.H., 1984. Effects of chronic turbidity on density of steelheads and coho salmon. Transactions of the American Fisheries Society, v. 113, p. 142-150.

SPCWC, 2002. San Pedro Creek Watershed Coalition. Davis, J., Matuk, V., Wilkinson, N., and Chan, C. (eds). San Pedro Creek Watershed assessment and enhancement plan. Prepared for the California Department of Fish and Game.

Spence, B.C., Lomnicky, G.A., Hughes, R.M., and Novitzki, R.P., 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057, Management Technology, Corvallis, Oregon.

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

USACE, 2000. San Francisco District Projects, San Pedro Creek, Section 205, Project Manager Eric Bluhm. www.USACE.army.mil/projects/sanpedro.html

Washington Forest Practices Board, 1997. Standard methodology for conducting watershed analysis.

Wolman, M.G., 1954. A method of sampling coarse bed material. American Geophysical Union, Transactions, v. 35, p. 951-956.

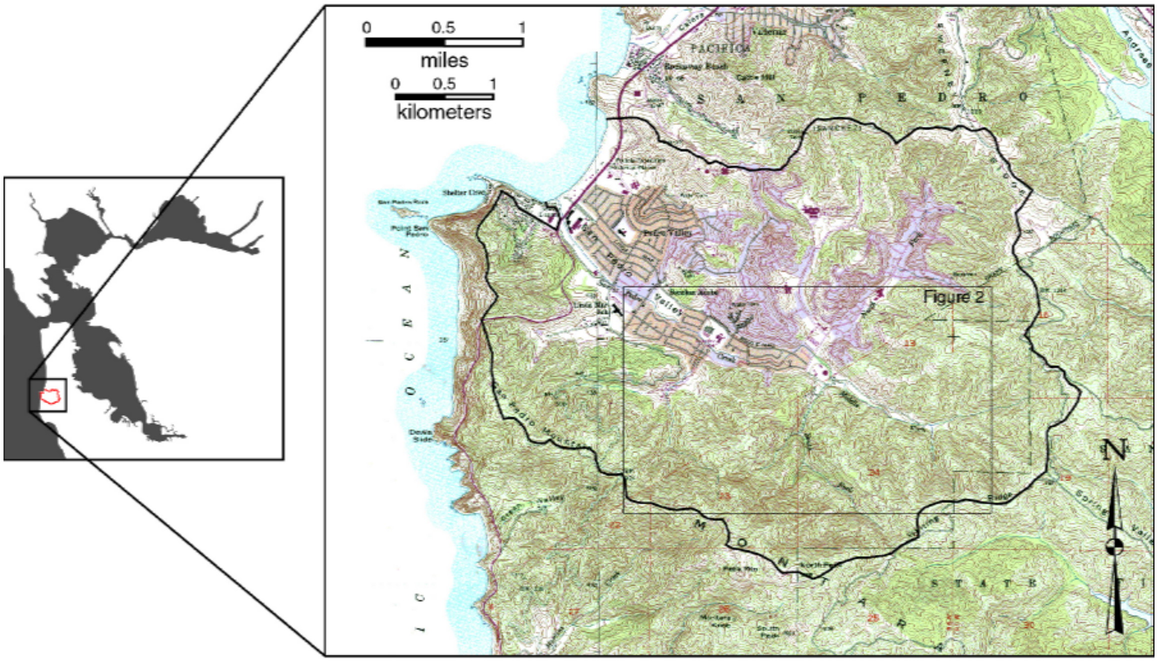

Figure 1. Location of the San Pedro Creek watershed, San Francisco Bay Area, Northern California. Watershed boundary is shown by heavy black line. Area of Figure 2 is inset.

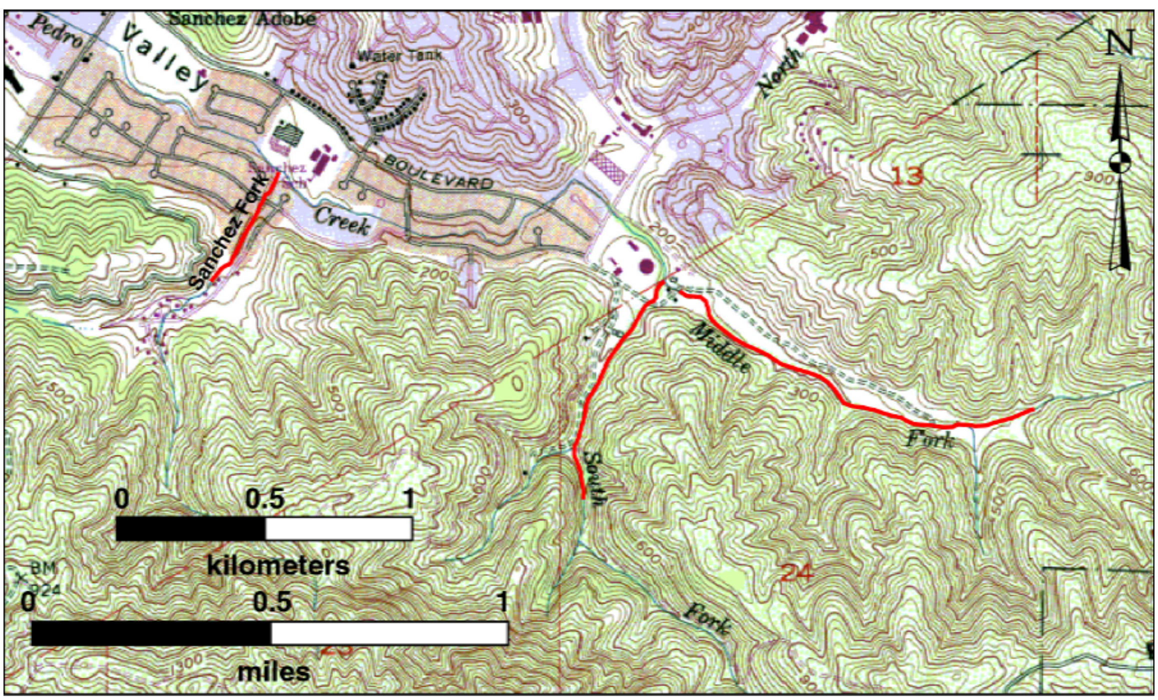

Figure 2. Location of the three tributary study reaches (highlighted in red).

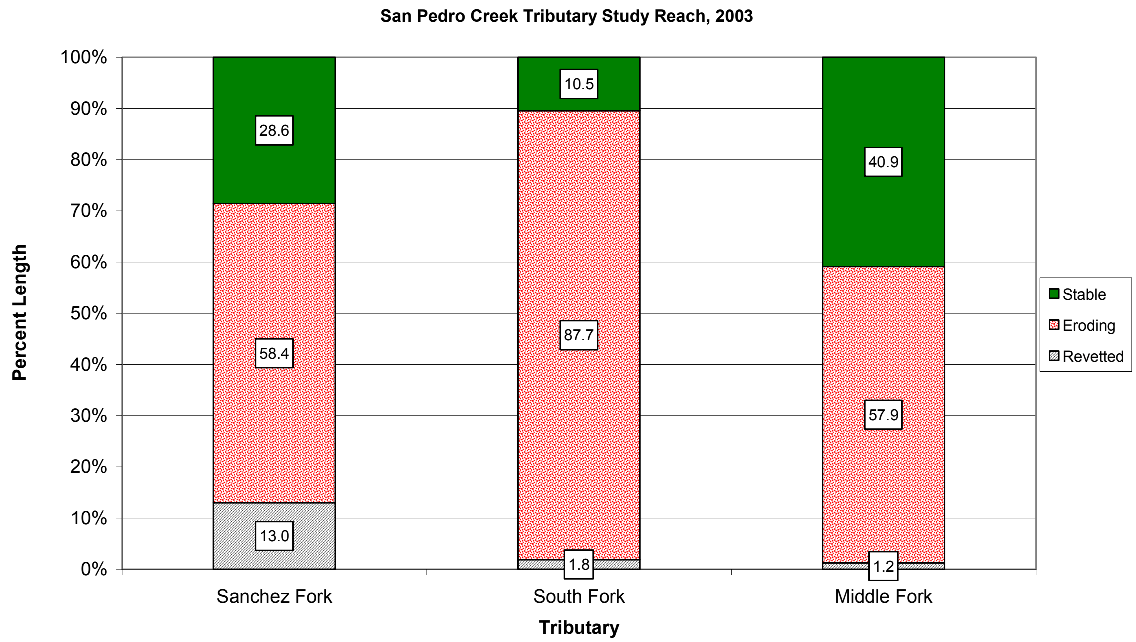

Figure 3. Percent of bank condition, right and left banks combined.

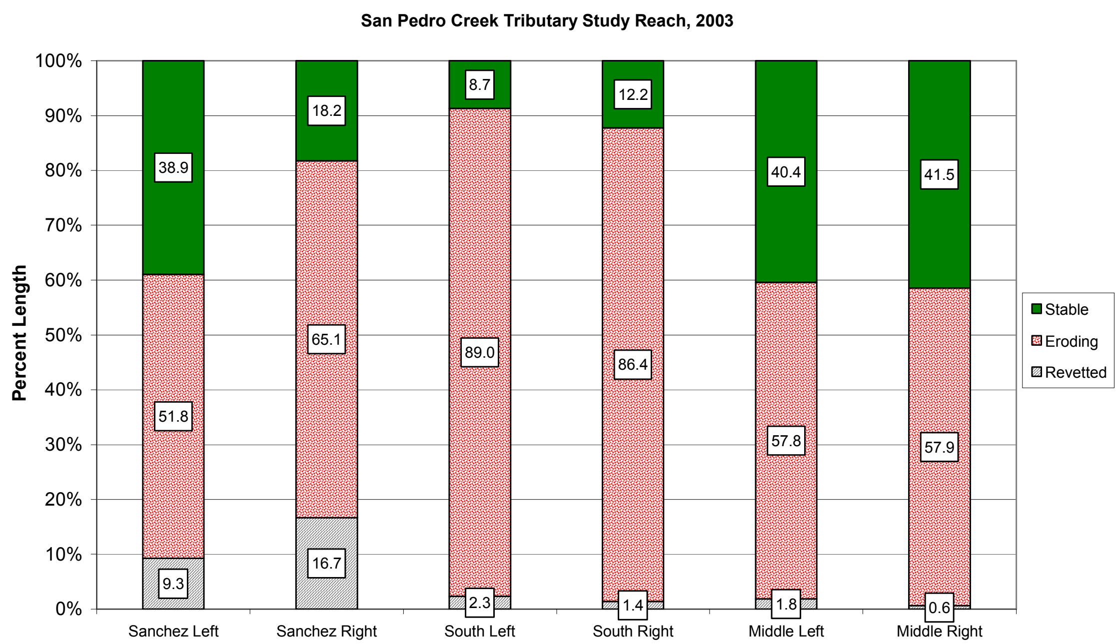

Figure 4. Percent length right and left bank conditions.

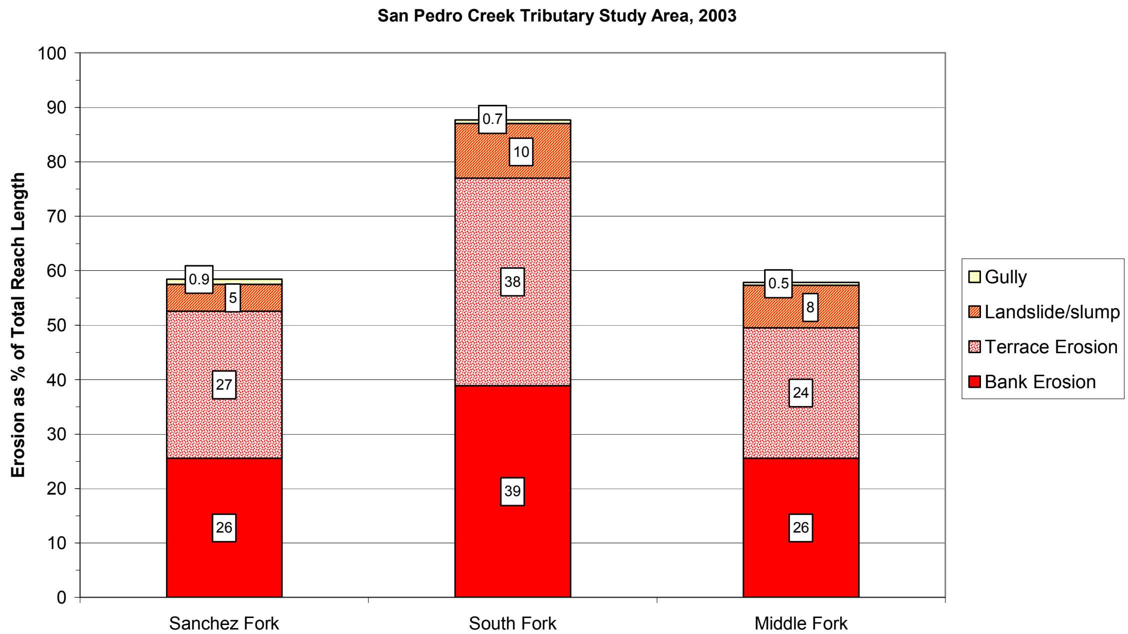

Figure 5. Length of erosion, measured as a percentage of the total study reach length.

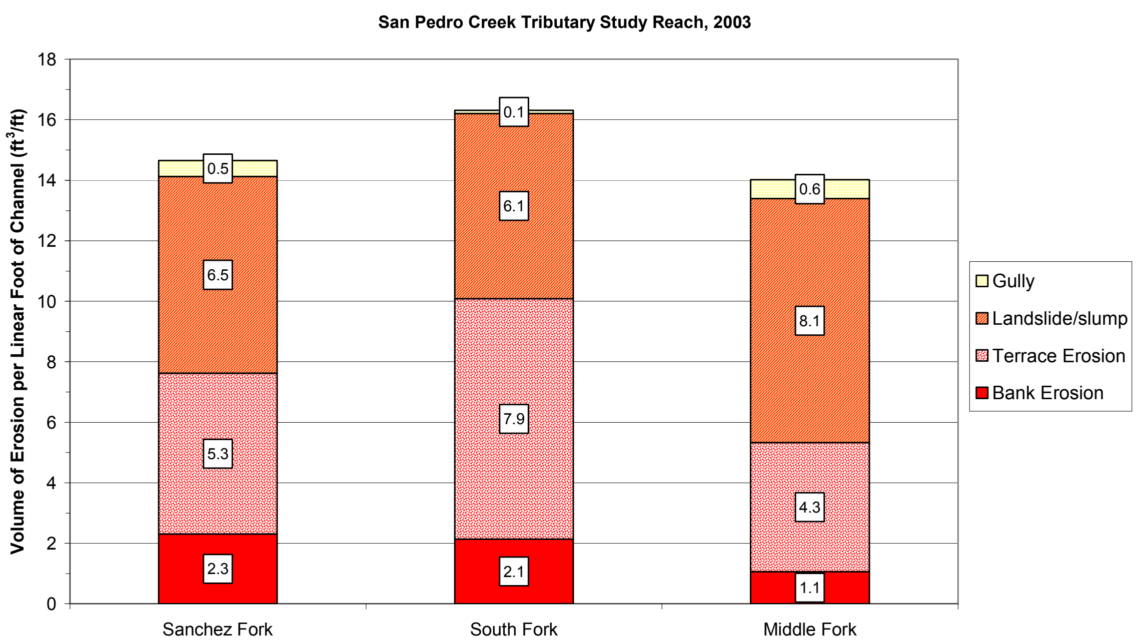

Figure 6. Erosion volume per linear foot of channel.

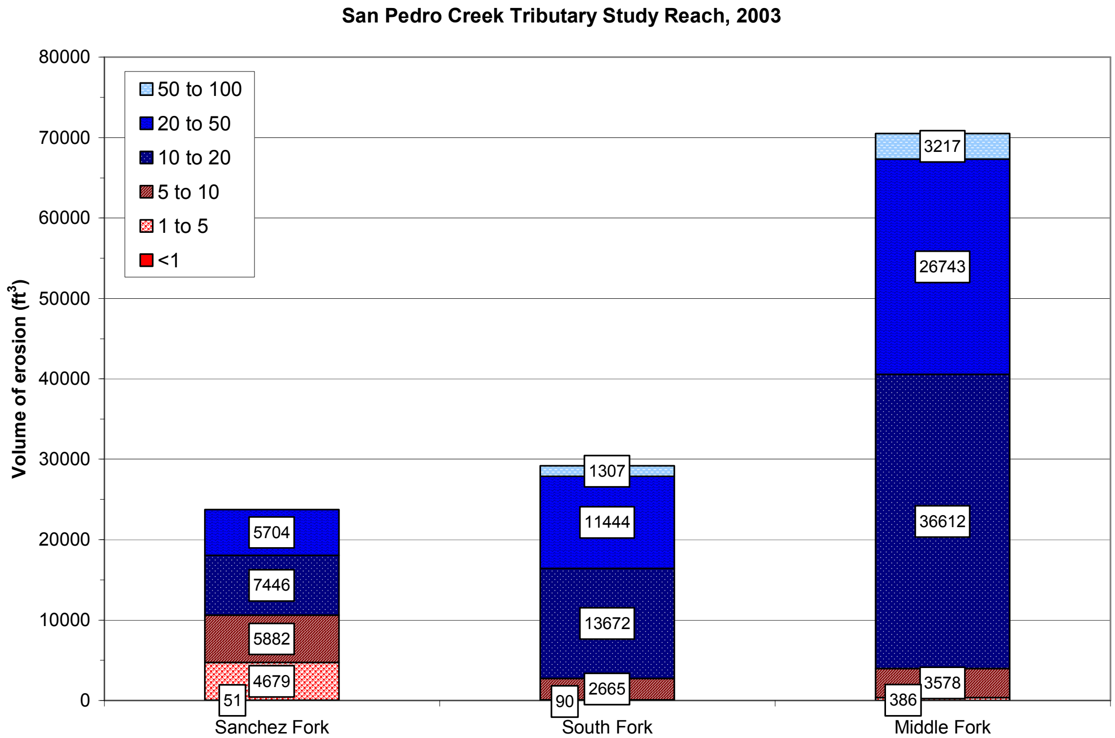

Figure 7. Volume of erosion measured in each age class, from <1 year up to 50-100 years.

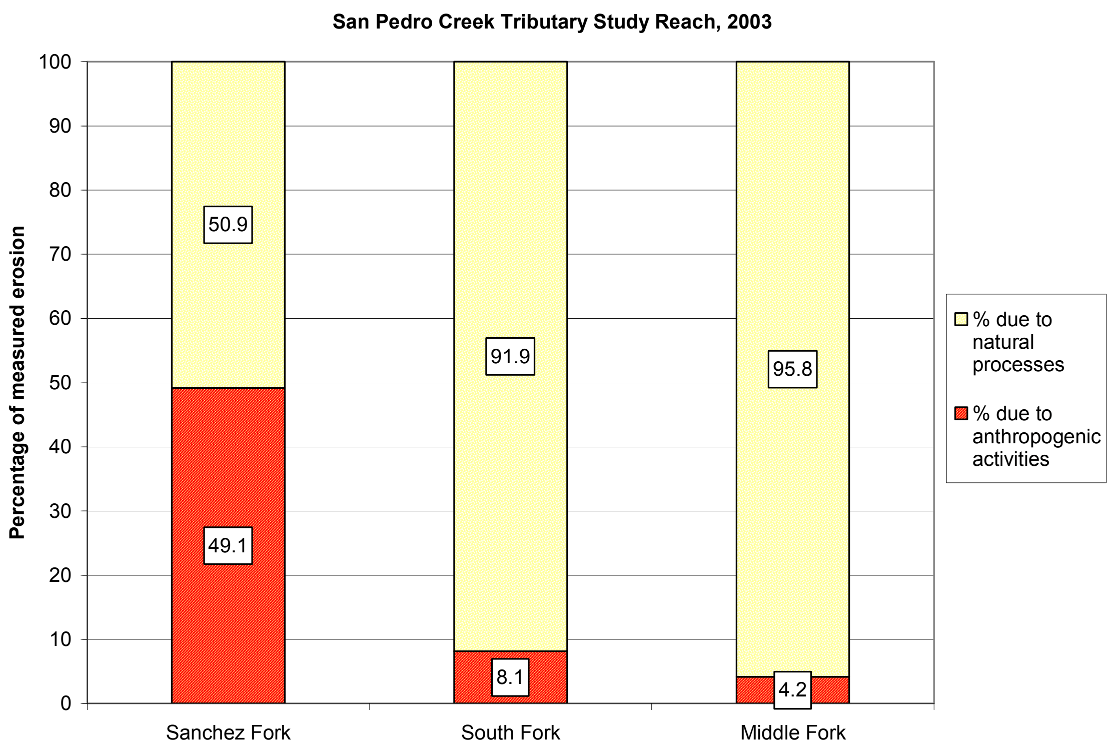

Figure 8. Causative mechanism of measured erosion.

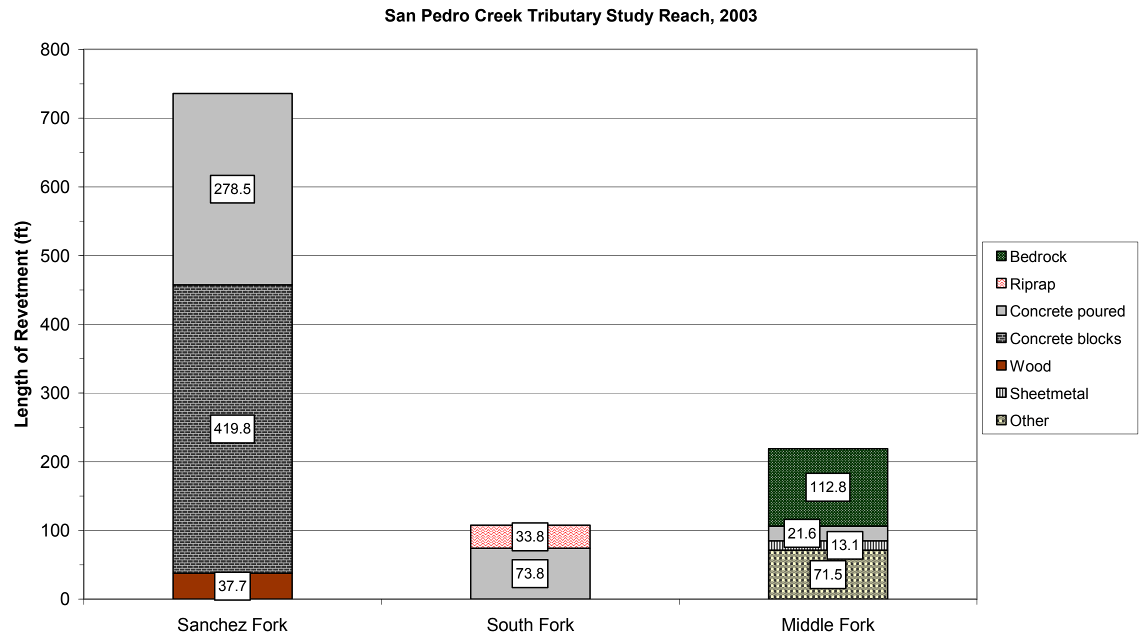

Figure 9. Total length of different revetment types, right and left banks combined.

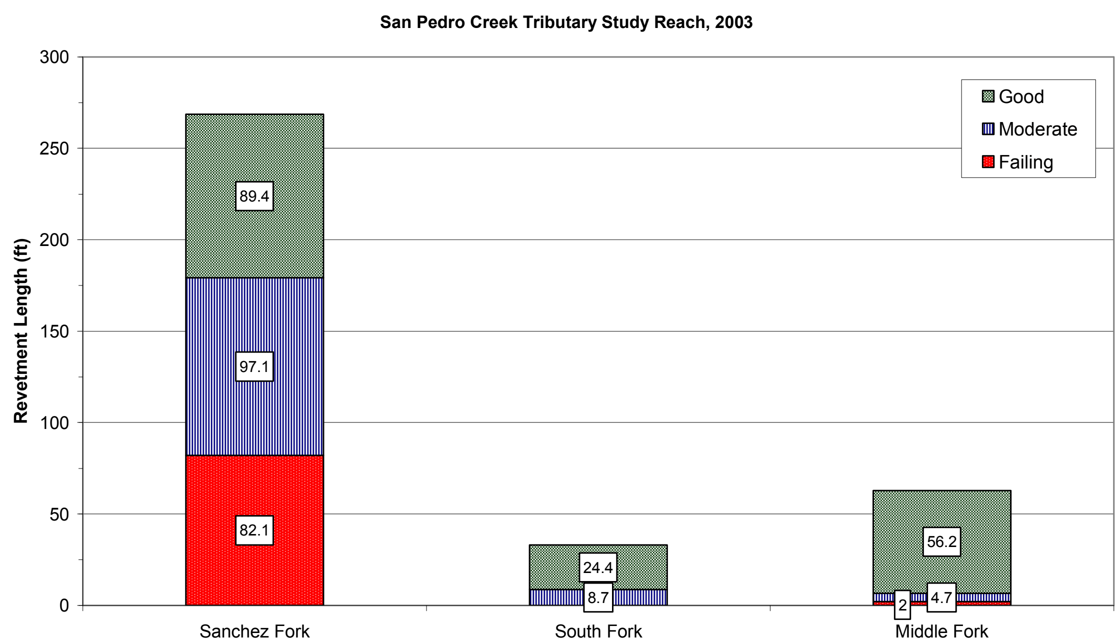

Figure 10. Revetment condition.

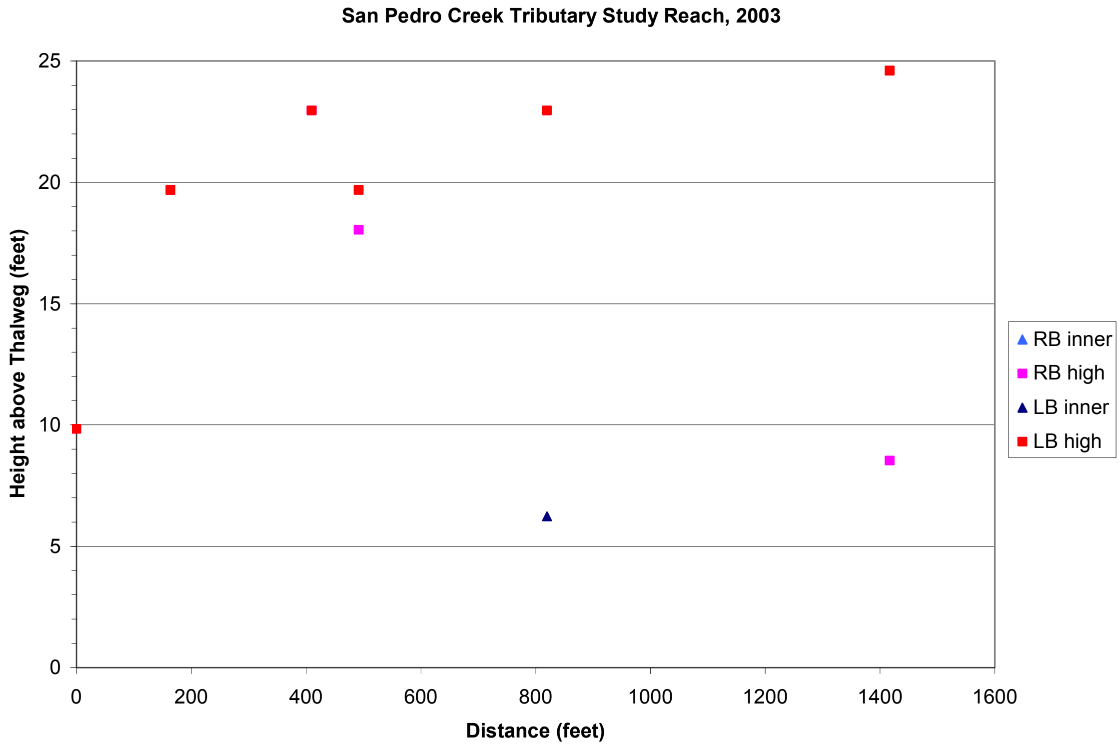

Figure 11. Terrace heights relative to the thalweg in Sanchez fork. RB= right bank, LB= left bank.

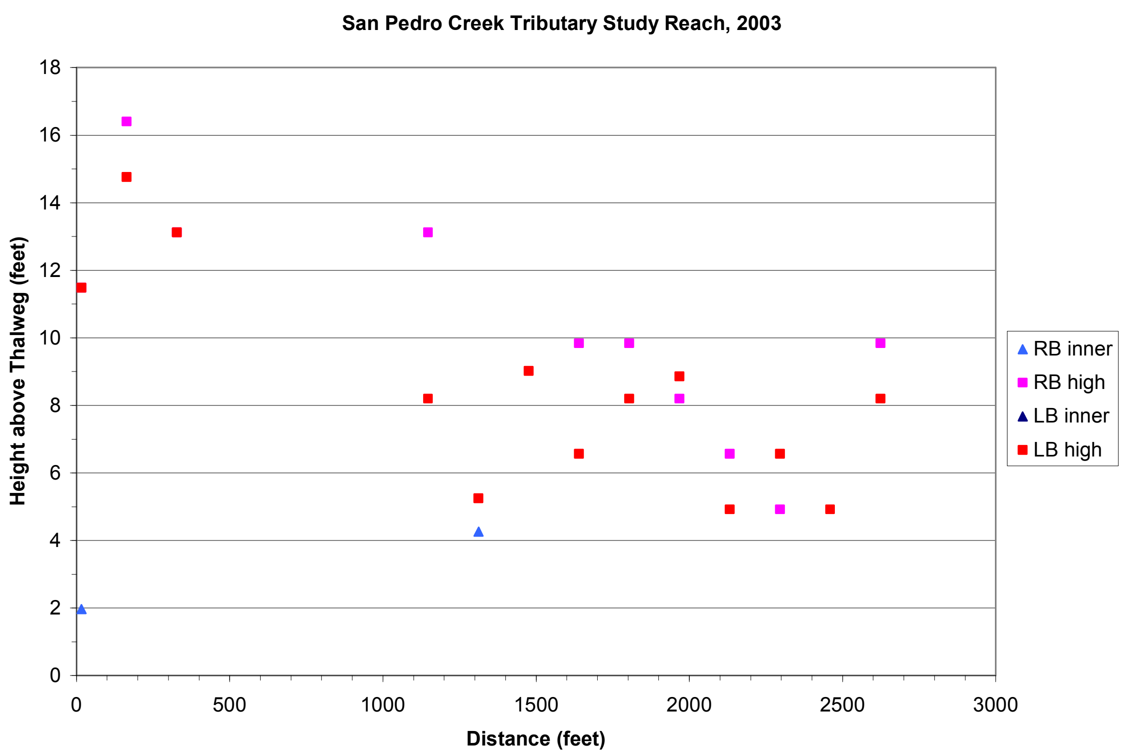

Figure 12. Terrace heights relative to the thalweg in South fork. RB= right bank, LB= left bank.

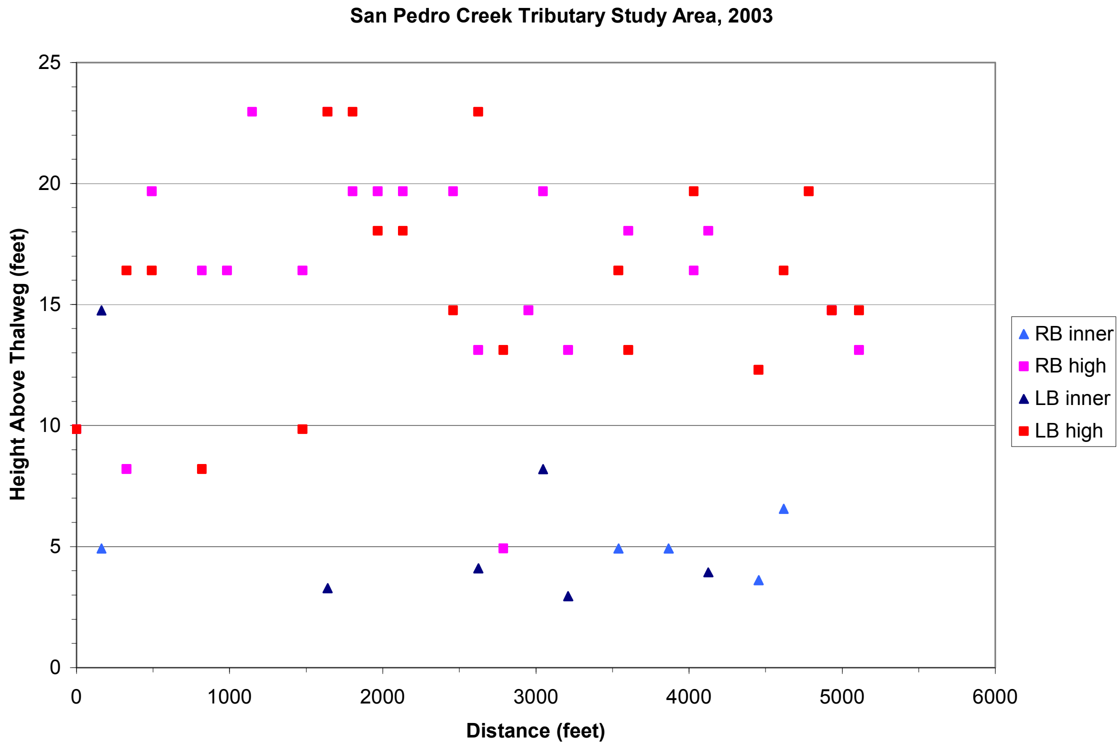

Figure 13. Terrace heights relative to the thalweg in Middle fork. RB= right bank, LB= left bank.

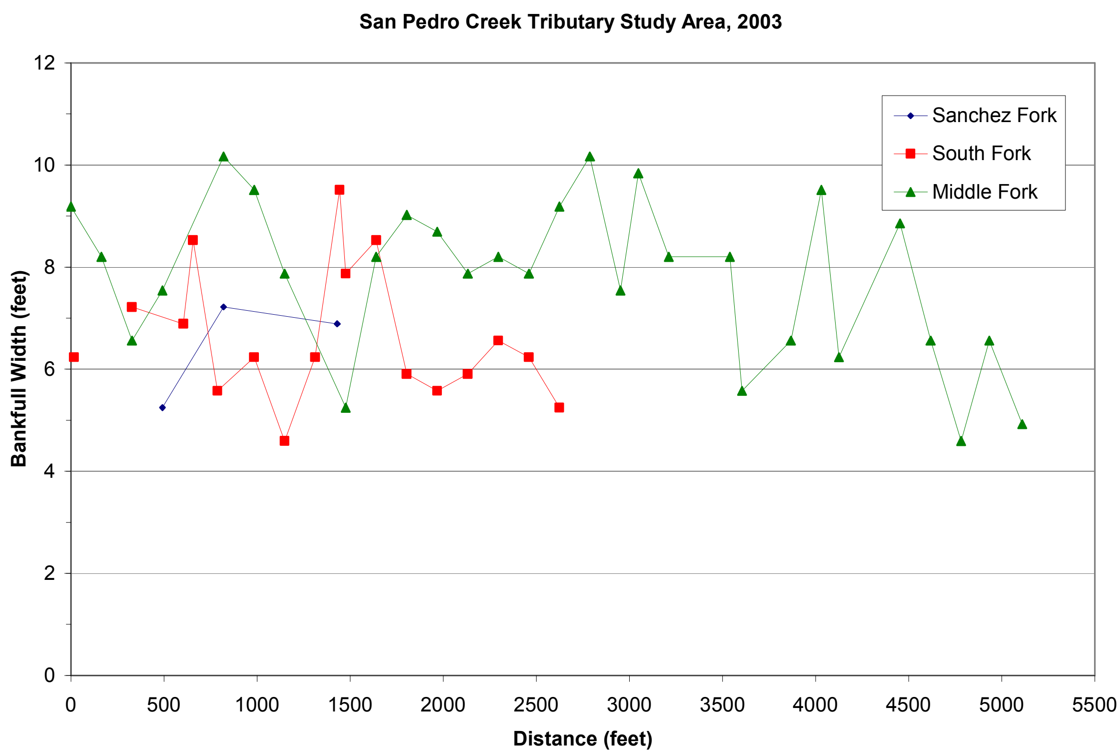

Figure 14. Measured bankfull widths.

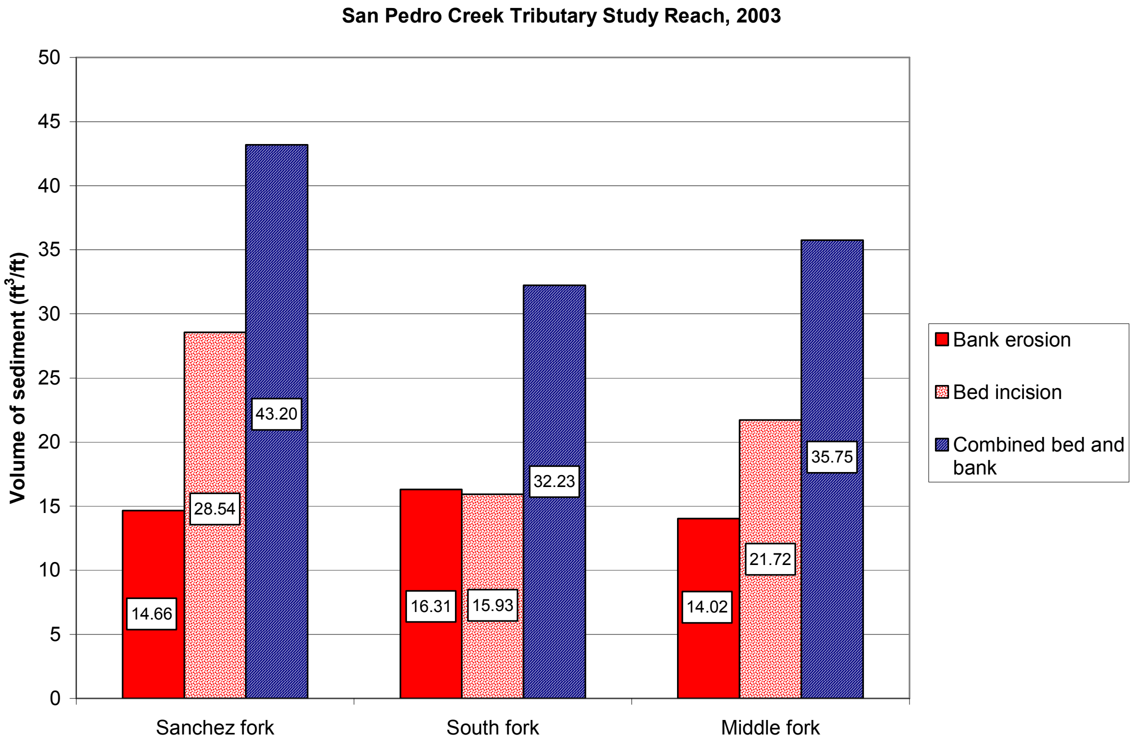

Figure 15. Volume of sediment contribution per unit channel length from the bed, bank, and bed and bank combined.

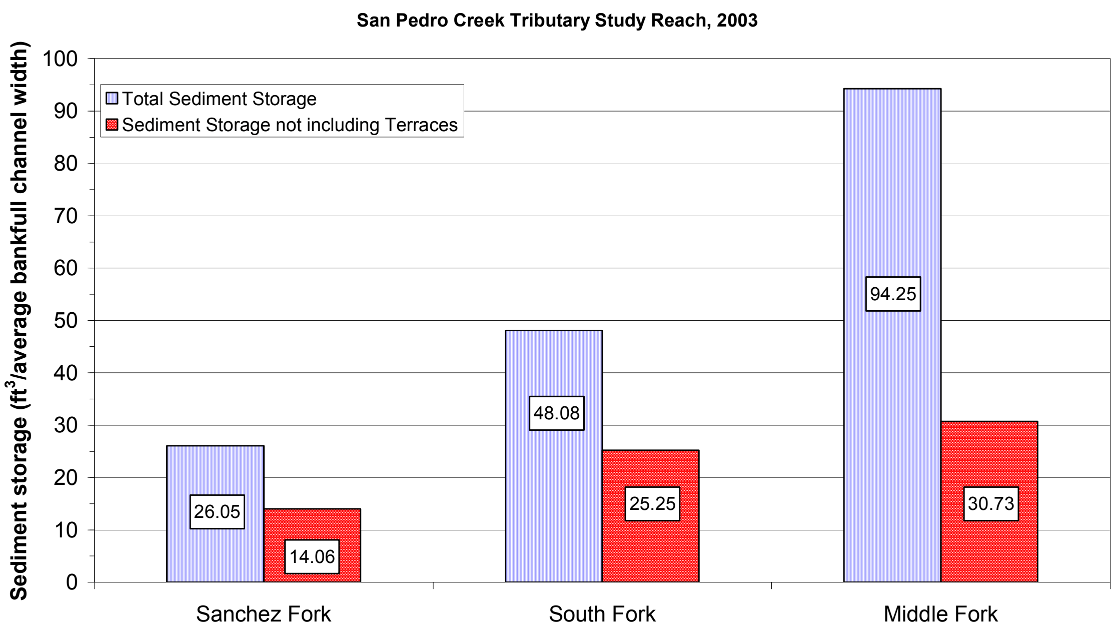

Figure 16. Volume of sediment storage per average bankfull channel width.

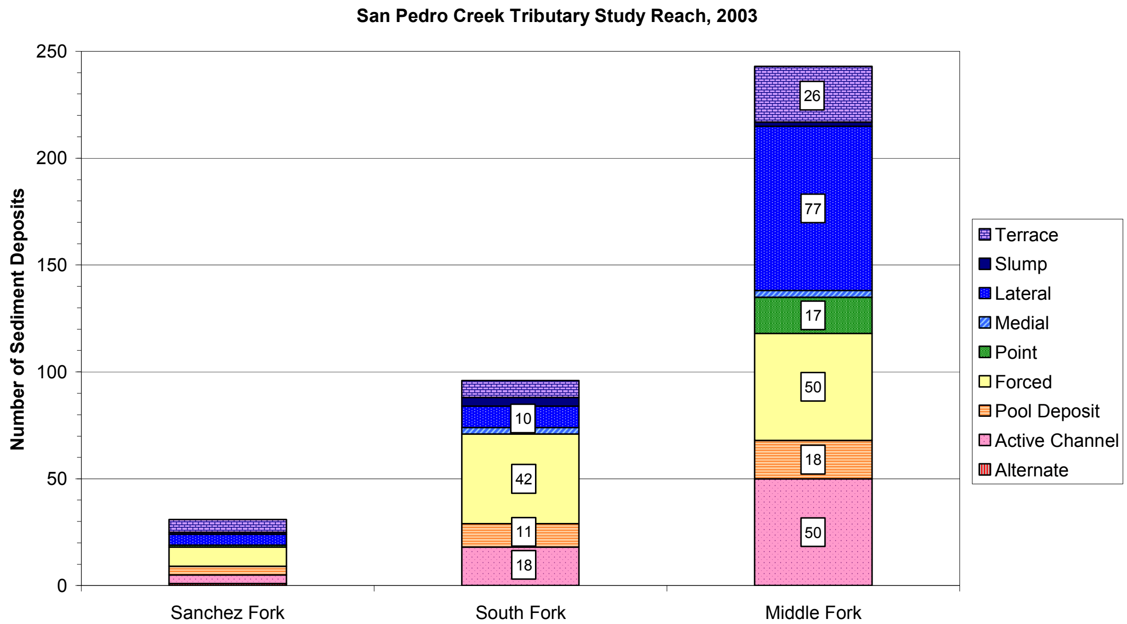

Figure 17. Number and type of sediment deposits.

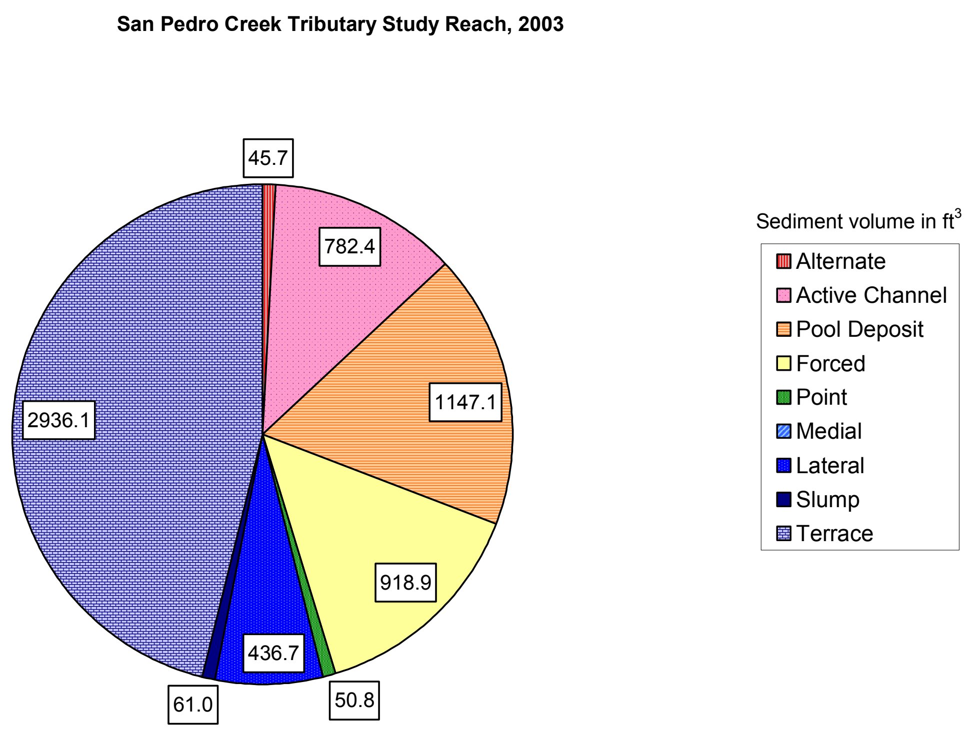

Figure 18. Type and volume of sediment storage in Sanchez fork.

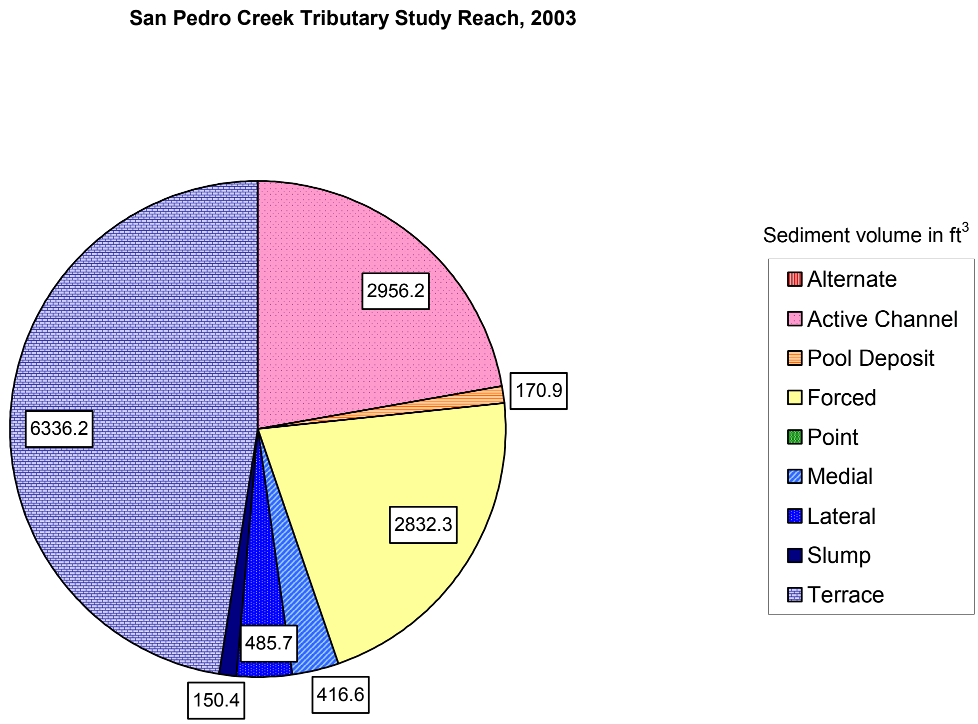

Figure 19. Type and volume of sediment storage in South fork.

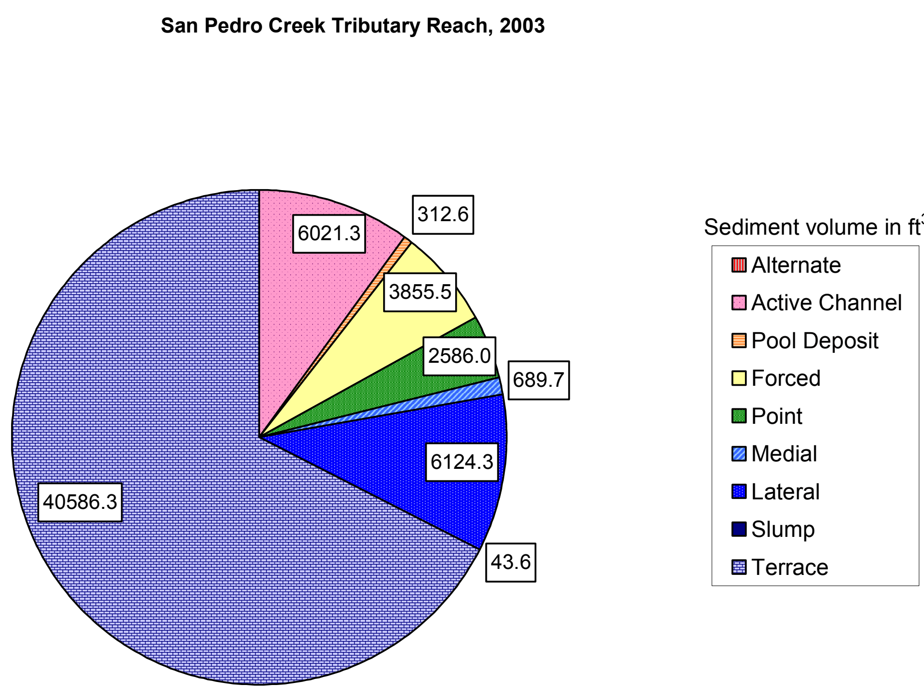

Figure 20. Type and volume of sediment storage in Middle fork.

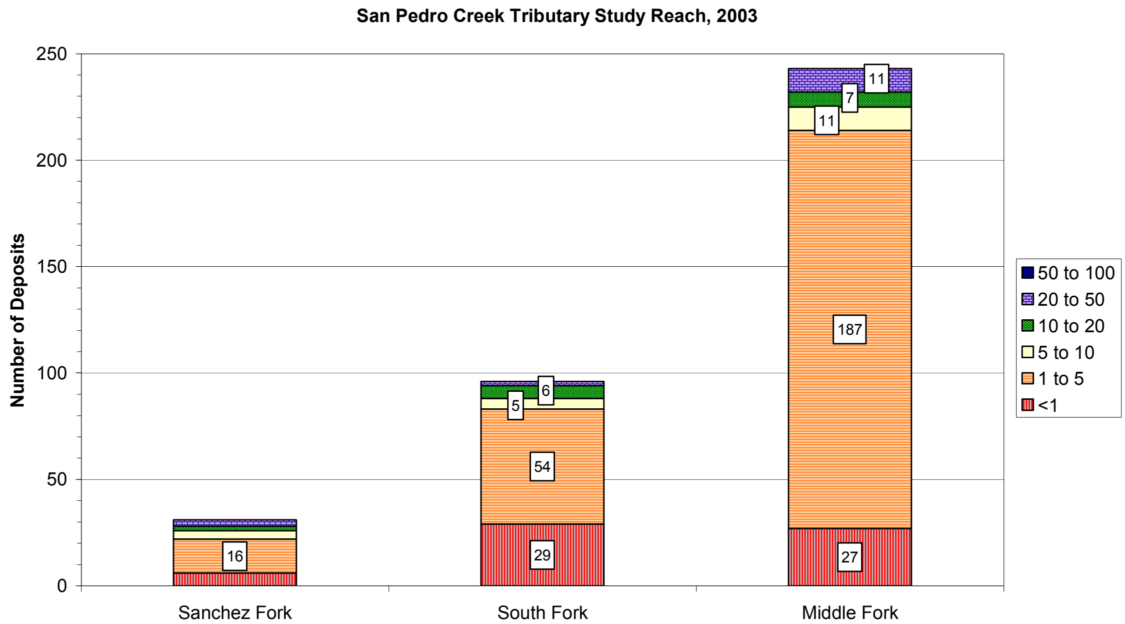

Figure 21. Number and age class of sediment deposits.

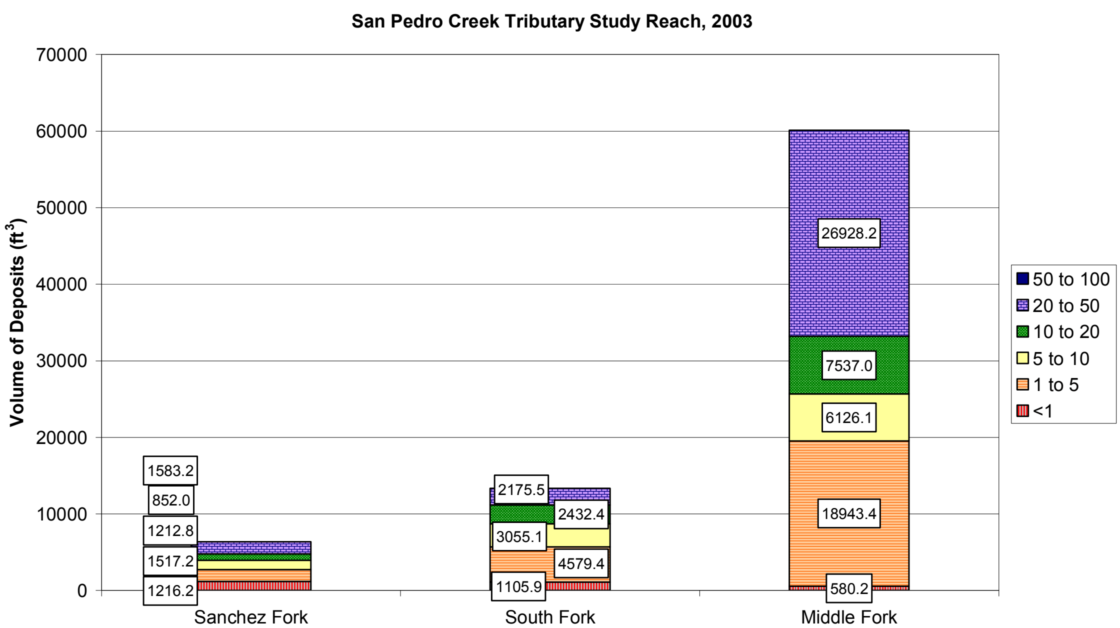

Figure 22. Volume and age class of sediment deposits.

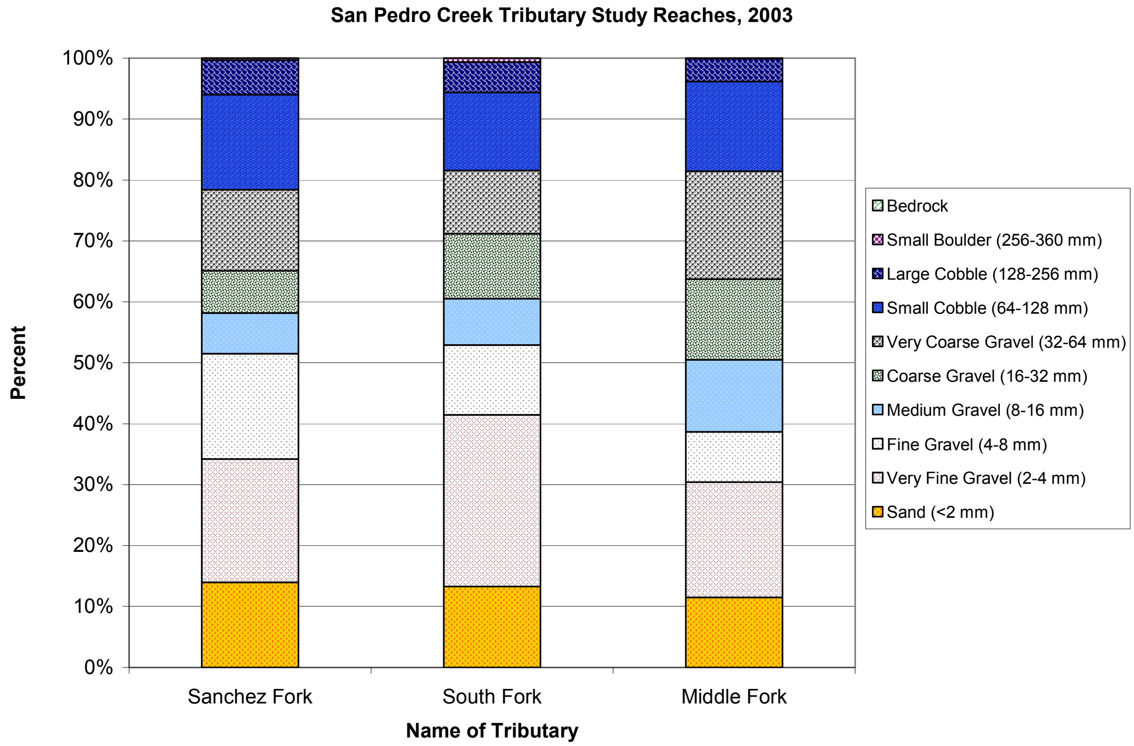

Figure 23. Percentage of surface sediment in each grain size class.

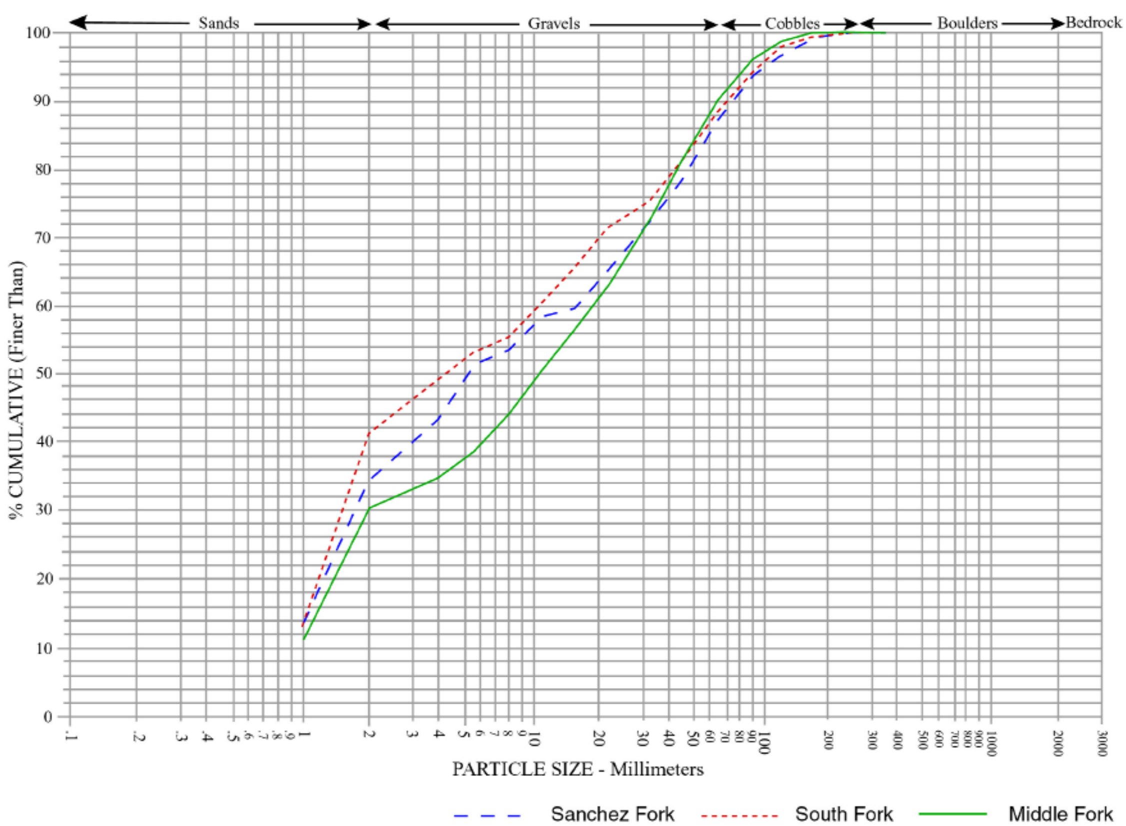

Figure 24. Surface particle size distribution curves. Salmonids utilize framework grain sizes 18-100 mm (Kondolf and Wolman, 1993).

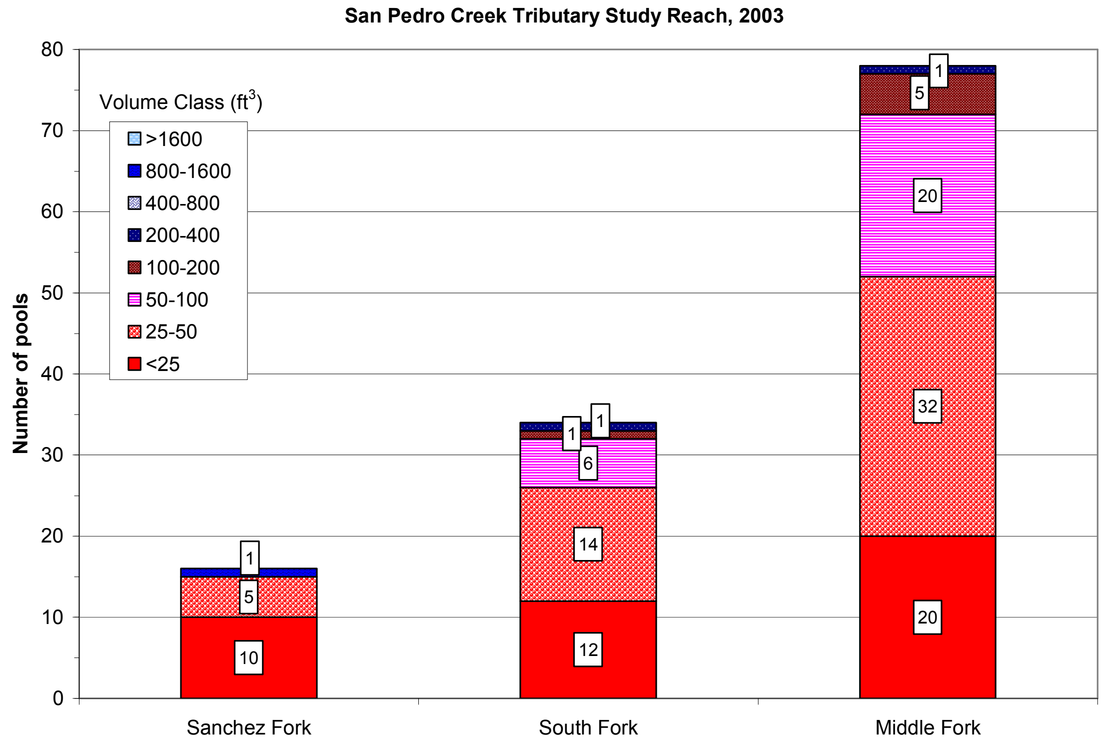

Figure 25. Number of pools per volume class.

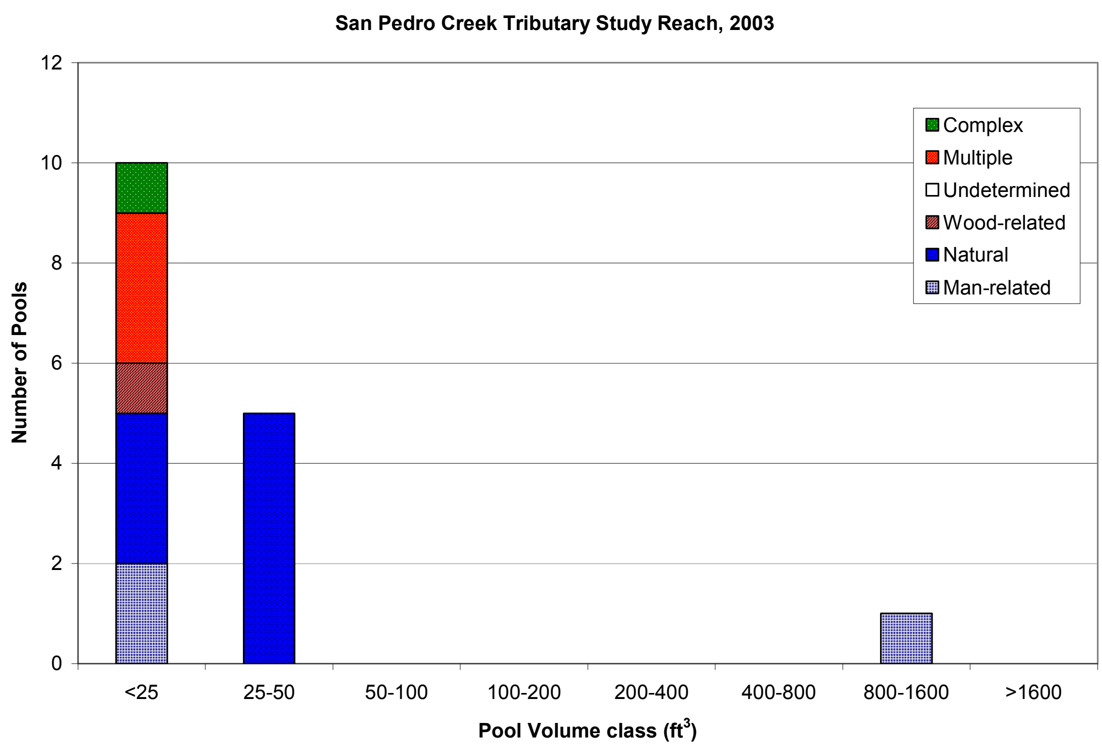

Figure 26. Number of pools and associated causative mechanism in Sanchez fork.

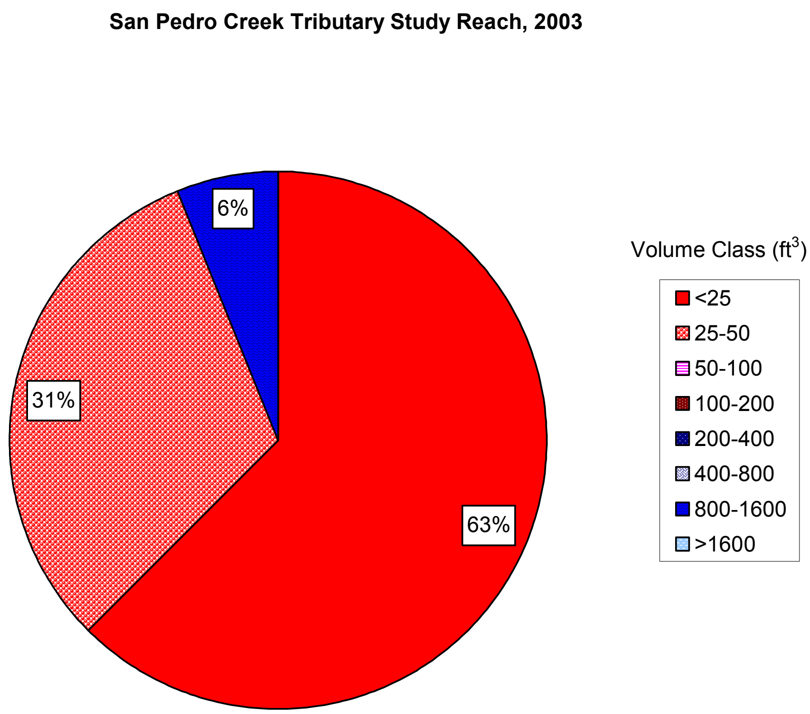

Figure 27. Percent of pool volume classes in Sanchez fork.

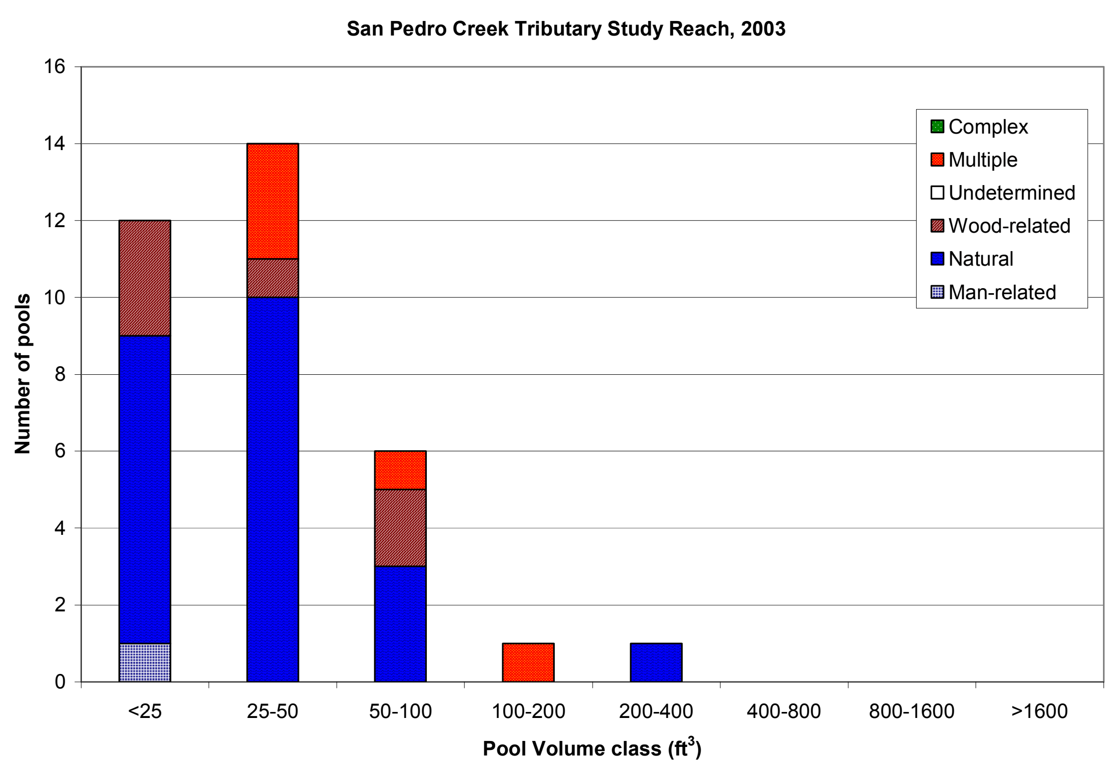

Figure 28. Number of pools and associated causative mechanism in South fork.

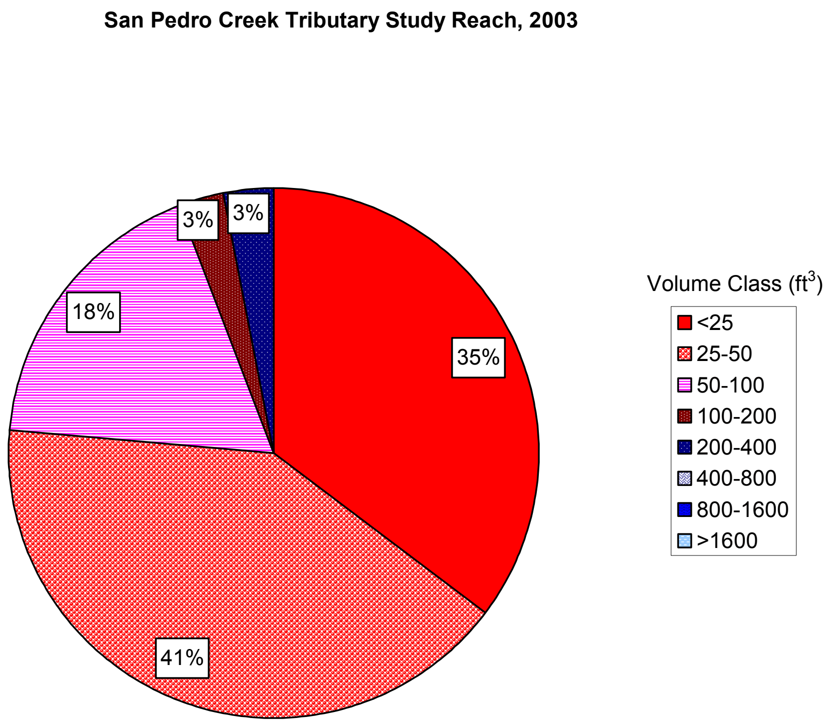

Figure 29. Percent of pool volume classes in South fork.

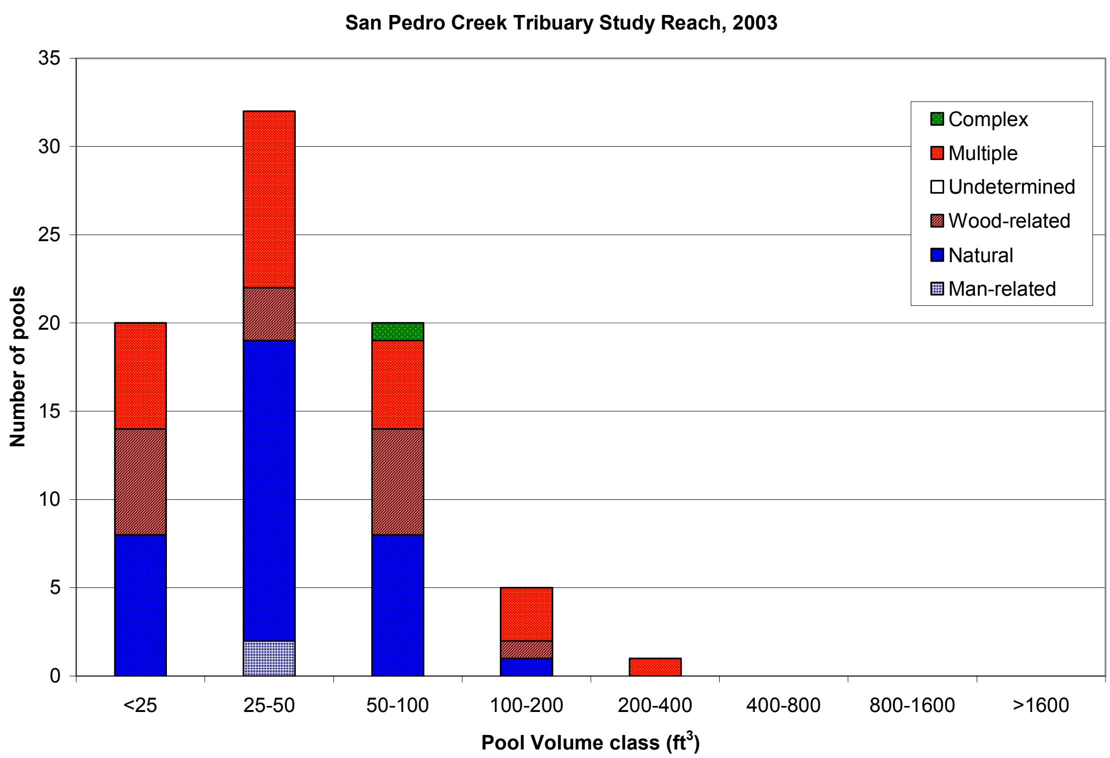

Figure 30. Number of pools and associated causative mechanism in Middle fork.

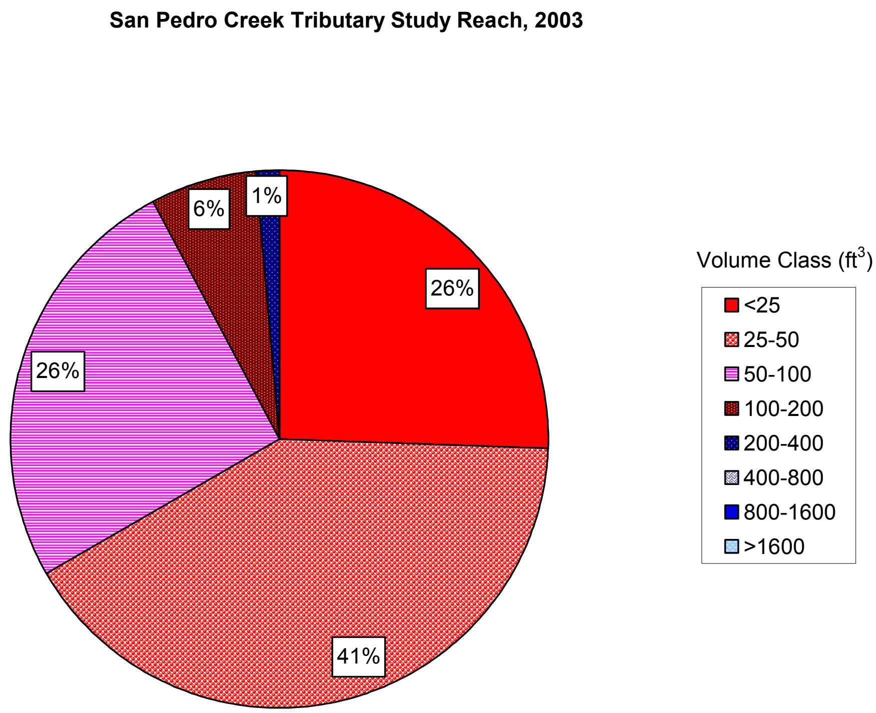

Figure 31. Percent of pool volume classes in Middle fork.

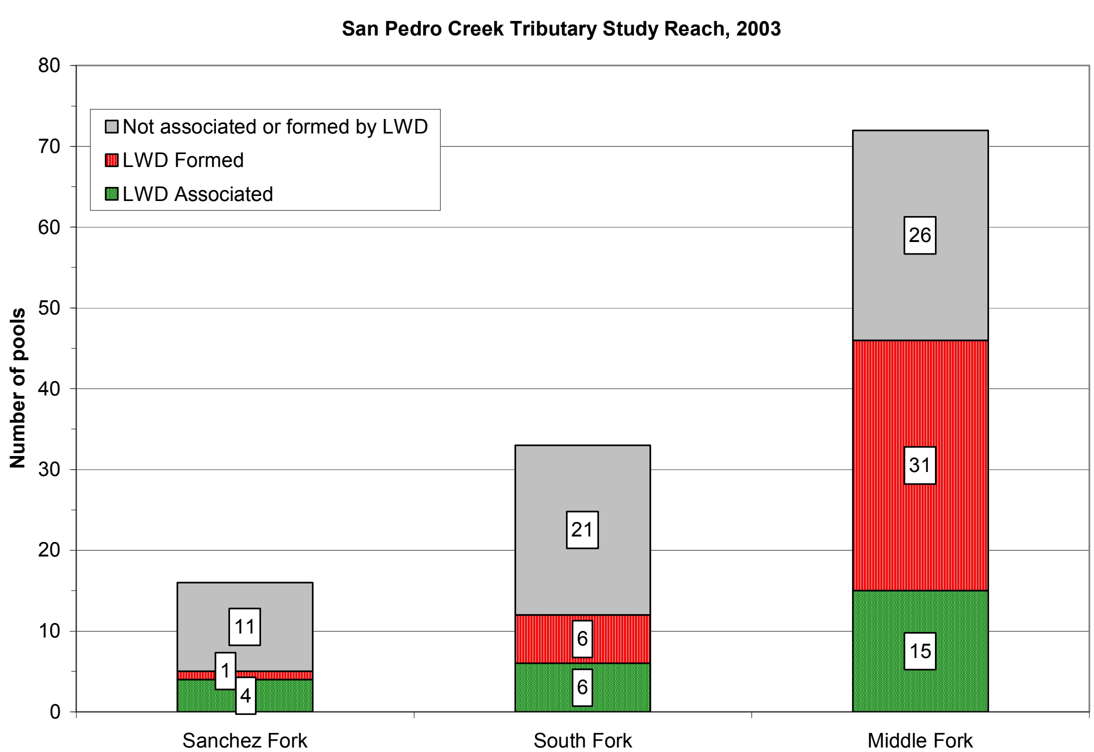

Figure 32. Number of pools directly formed by or associated with large woody debris (LWD).

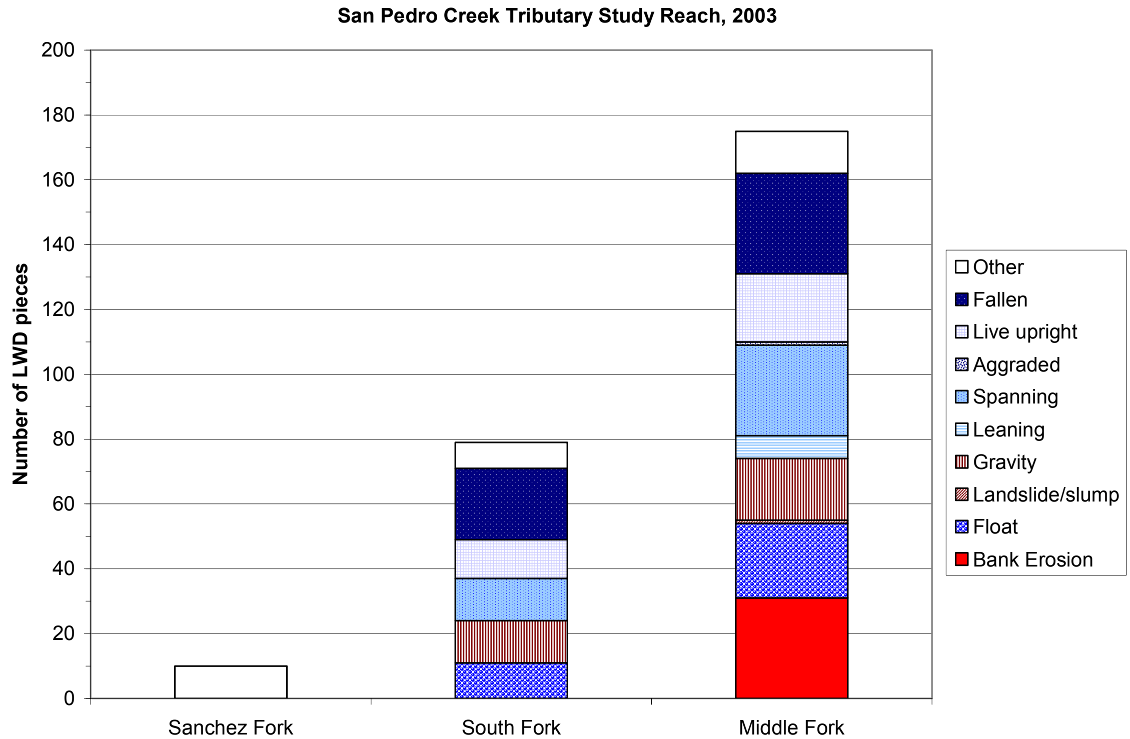

Figure 33. Number of large woody debris (LWD) pieces per recruitment process.

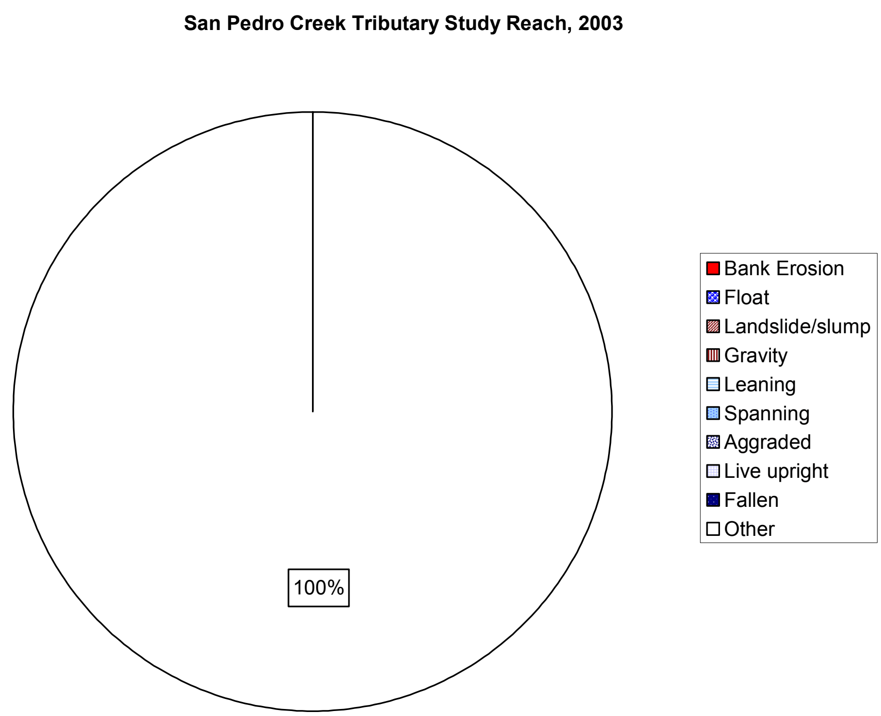

Figure 34. Percentage of each large woody debris (LWD) recruitment process in Sanchez fork.

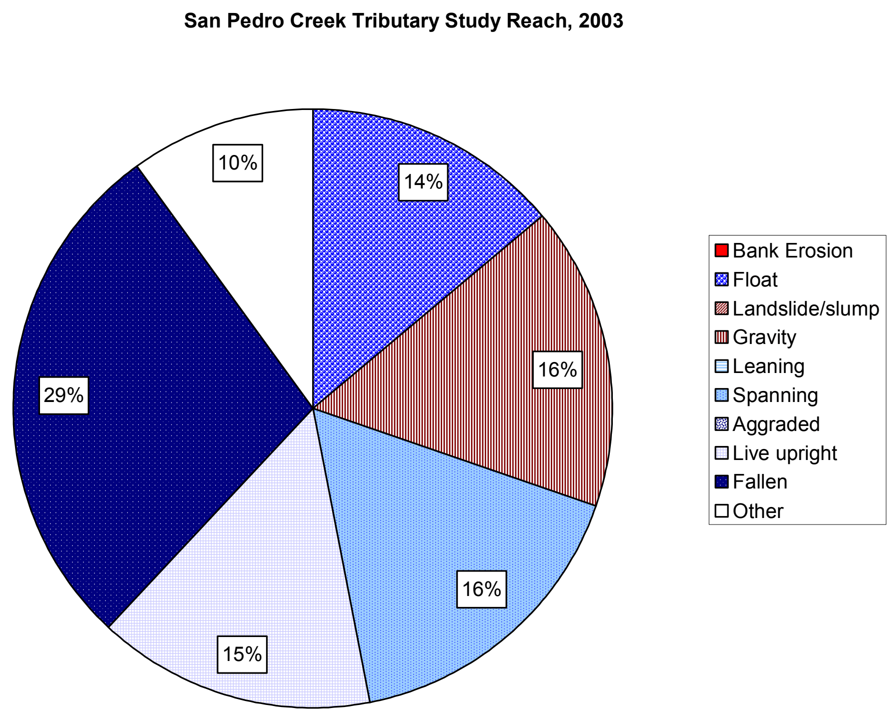

Figure 35. Percentage of each large woody debris (LWD) recruitment process in South fork.

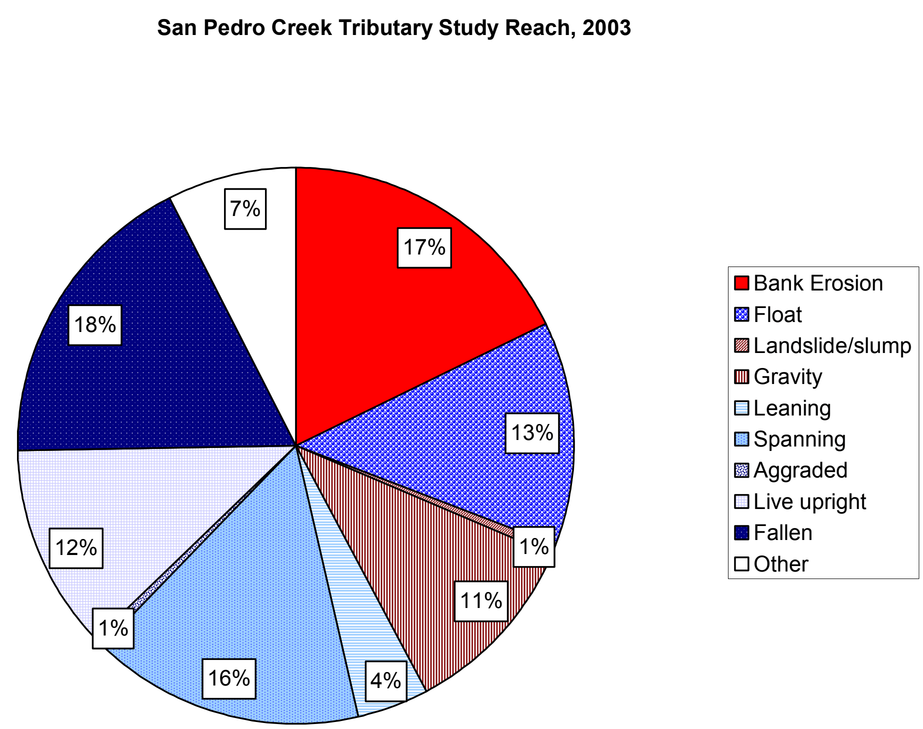

Figure 36. Percentage of each large woody debris (LWD) recruitment process in Middle fork.

Figure 37. Photograph of concrete flashdam located on Sanchez fork, 669 ft (204) m upstream of the confluence.

Figure 38. Photograph of a large chunk of concrete fallen from the bank, and significantly affecting flow in Sanchez fork 157 ft (48 m) upstream from the confluence.

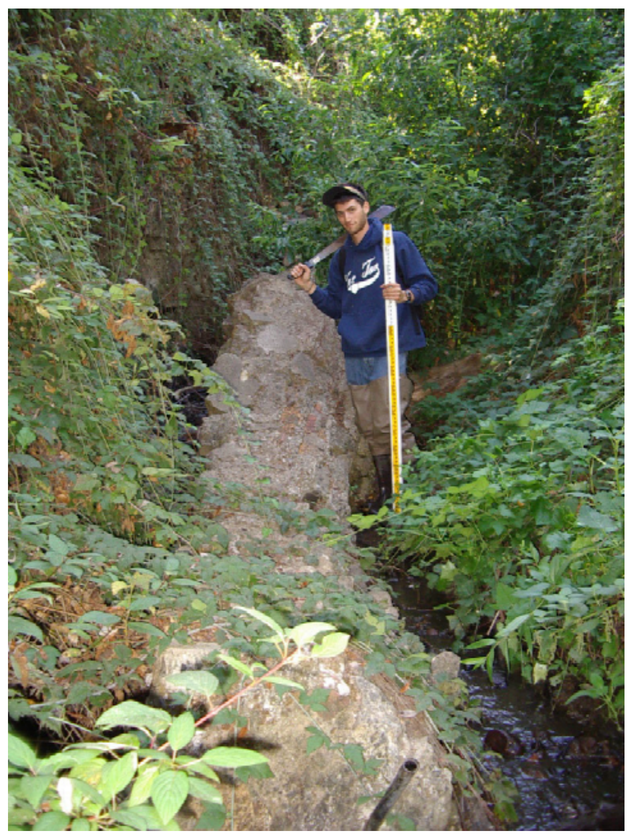

Figure 39. Photograph of a failing culvert in Sanchez fork, located 1,283 ft (391 m) upstream of the confluence.

Figure 40. Photograph of failing culvert in Sanchez fork 1,316 ft (401 m) upstream of the confluence.

Figure 41. Photograph of the large culvert under the church parking lot and associated plunge pool in Sanchez fork, 984 ft (300 m) upstream of the confluence. This pool contains a large fine-grained pool deposit.

Figure 42. Photograph of the upstream edge of the large culvert in Sanchez fork, 1.109 ft (338 m) upstream of the confluence.

Figure 43. Photograph of a particularly narrow reach of South fork.

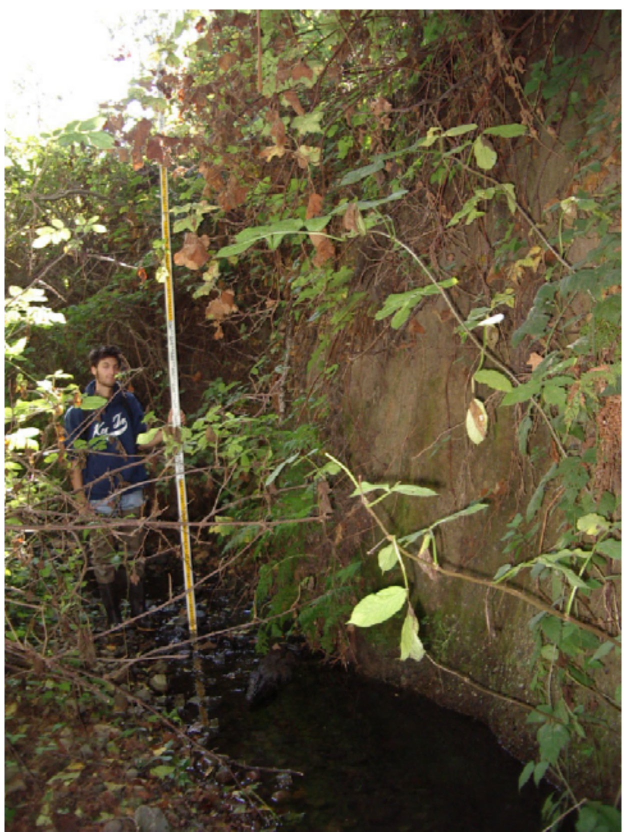

Figure 44. Photograph of a nearly vertical bank in Middle fork. These features are often found along the study reach length.

Figure 45. Photograph of an undercut bank and exposed alder roots in Middle fork. This condition was commonly found throughout the study reach length.

Figure 46. Photograph of gully erosion on the right bank of Middle fork

Streamline Graphs Legend

Bank revetment

o	Other
c	Concrete
rrp	Rip Rap Debris
w	Wood
rrd	Riprap/concrete debris
cmp	Corrugated Metal Pipe
rw	Rock Wall
cms	Sheet Metal
br	Bedrock bank

Bed grain size

Boulder
Cobble
Gravel
Sand
Silt
Bedrock

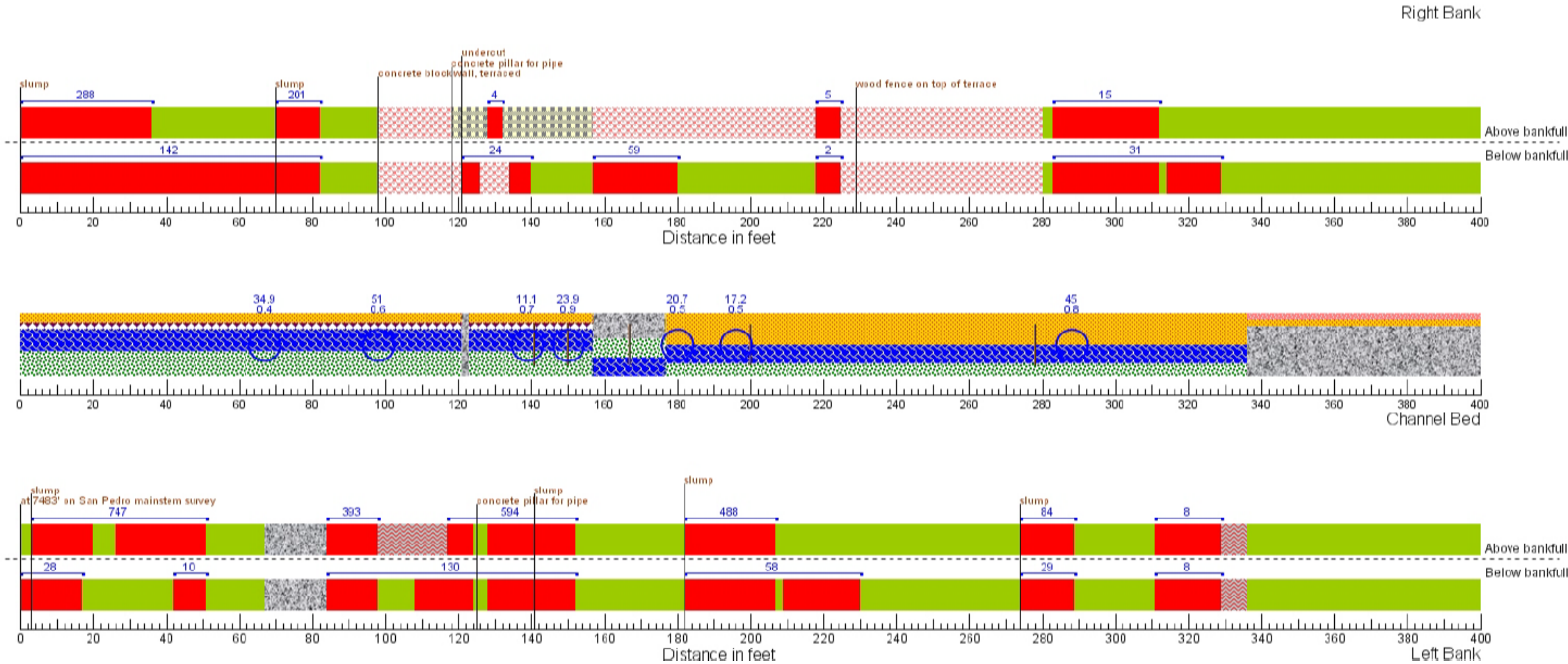

Figure 47. Streamline graph of the Sanchez fork study reach. The reach begins at the confluence with San Pedro Creek, and extends 1,640 ft (500 m) upstream. Section 0 to 400 ft.

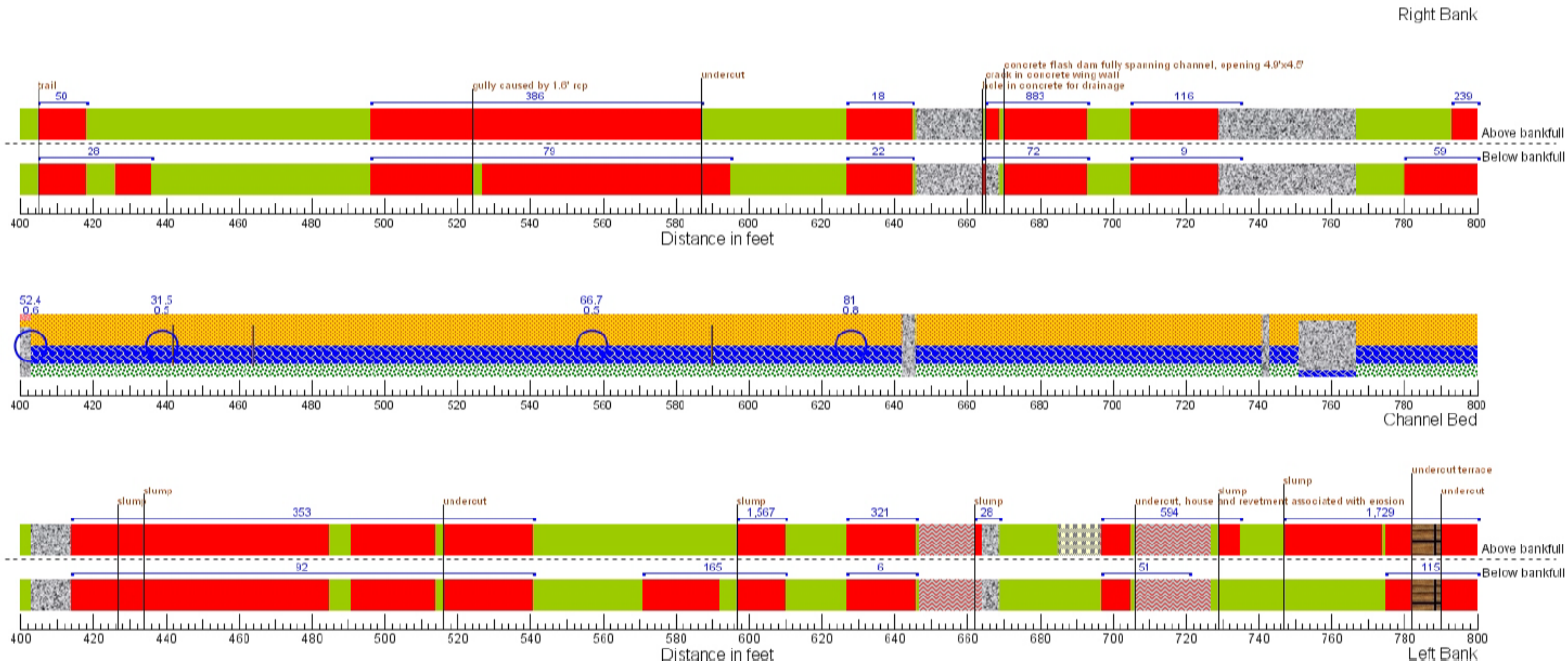

Figure 47. Streamline graph of the Sanchez fork study reach. Section 400 to 800 ft.

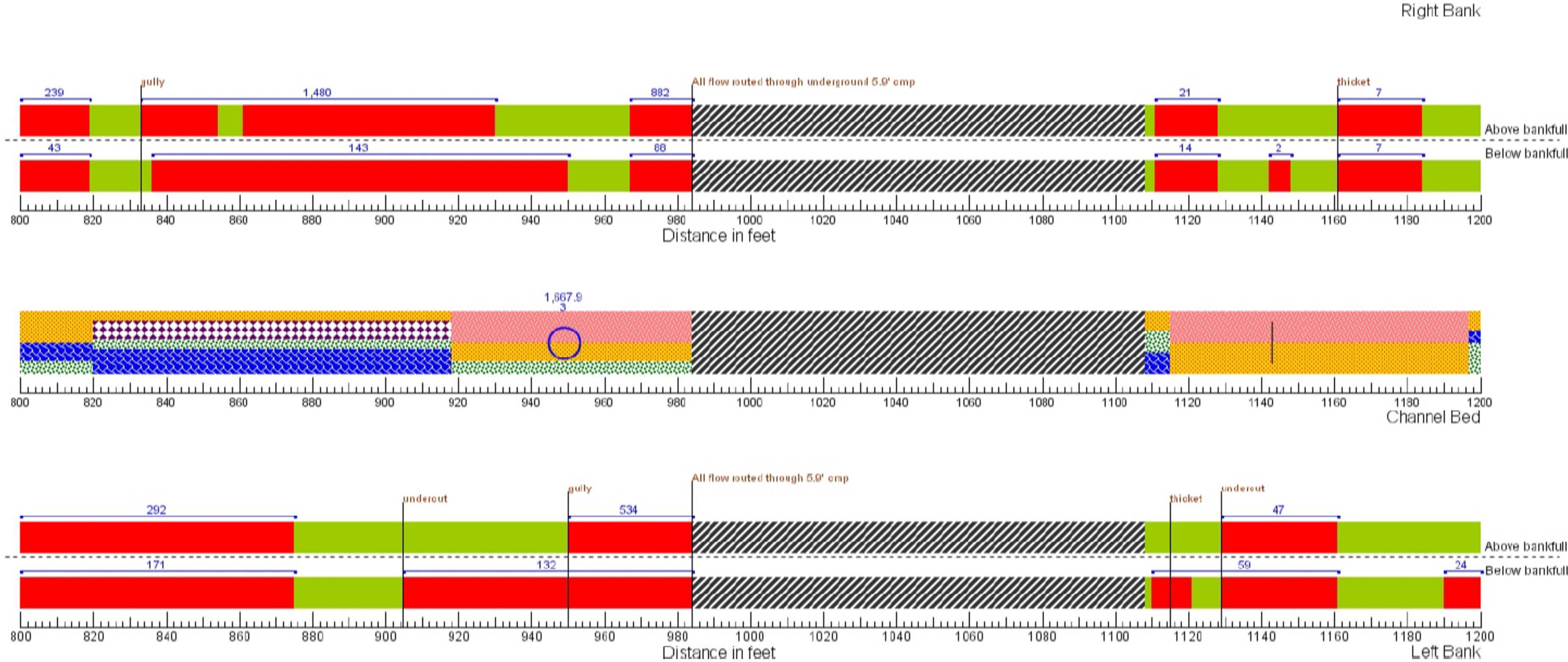

Figure 47. Streamline graph of the Sanchez fork study reach. Section 800 to 1200 ft.

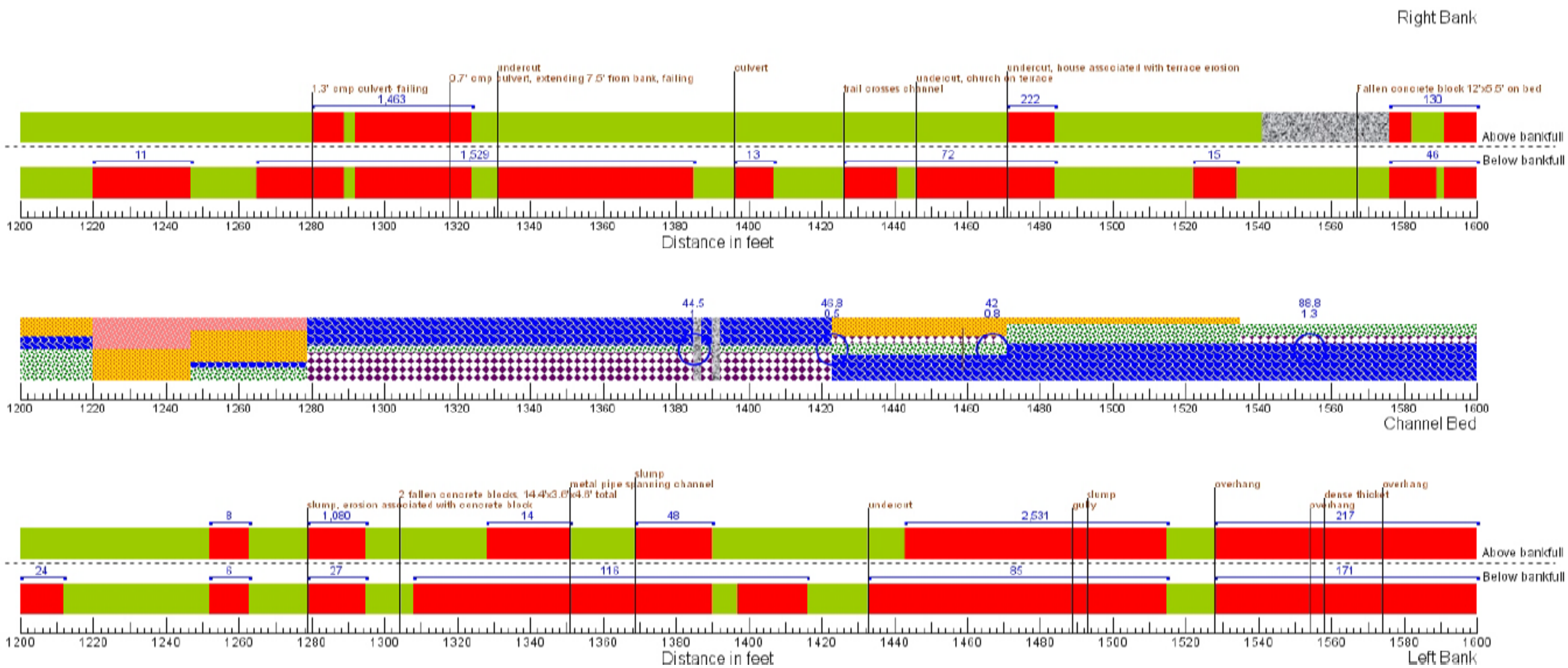

Figure 47. Streamline graph of the Sanchez fork study reach. Section 1200 to 1600 ft.

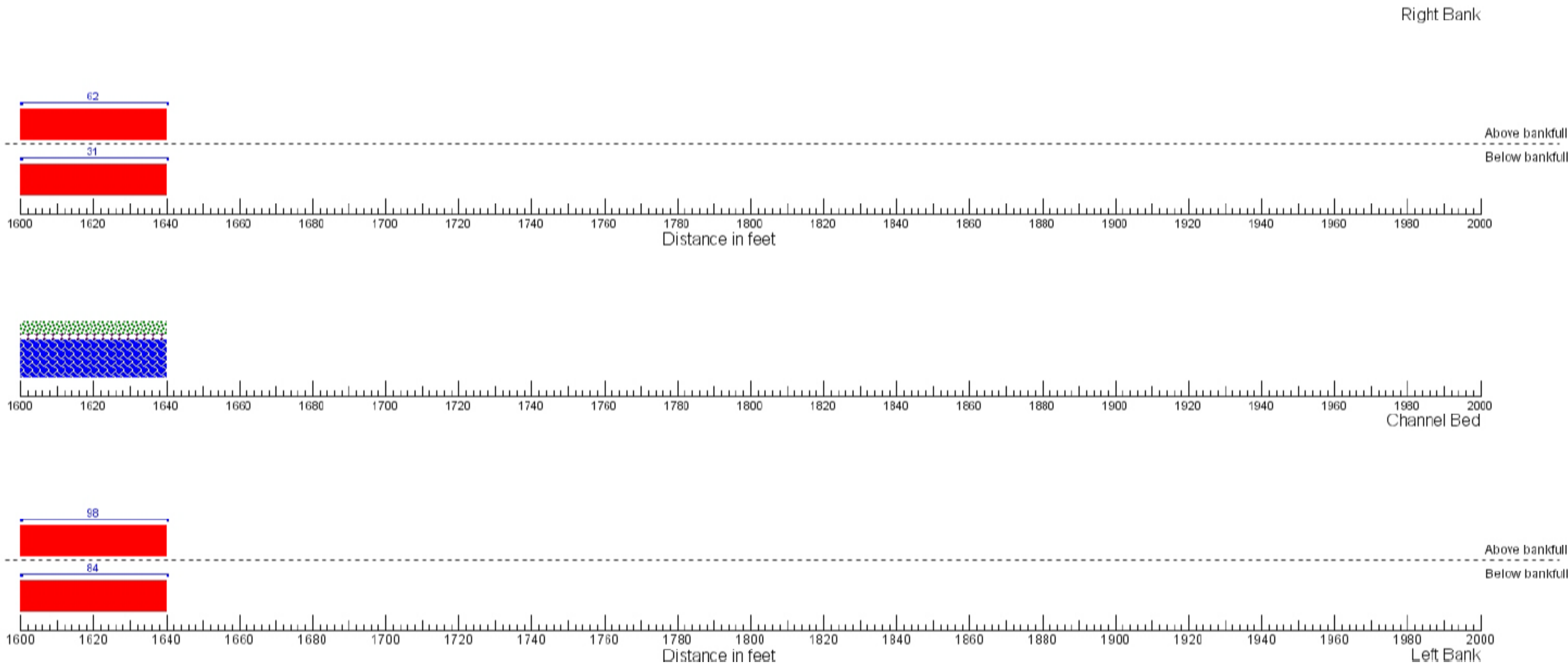

Figure 47. Streamline graph of the Sanchez fork study reach. Section 1600 to 2000 ft.

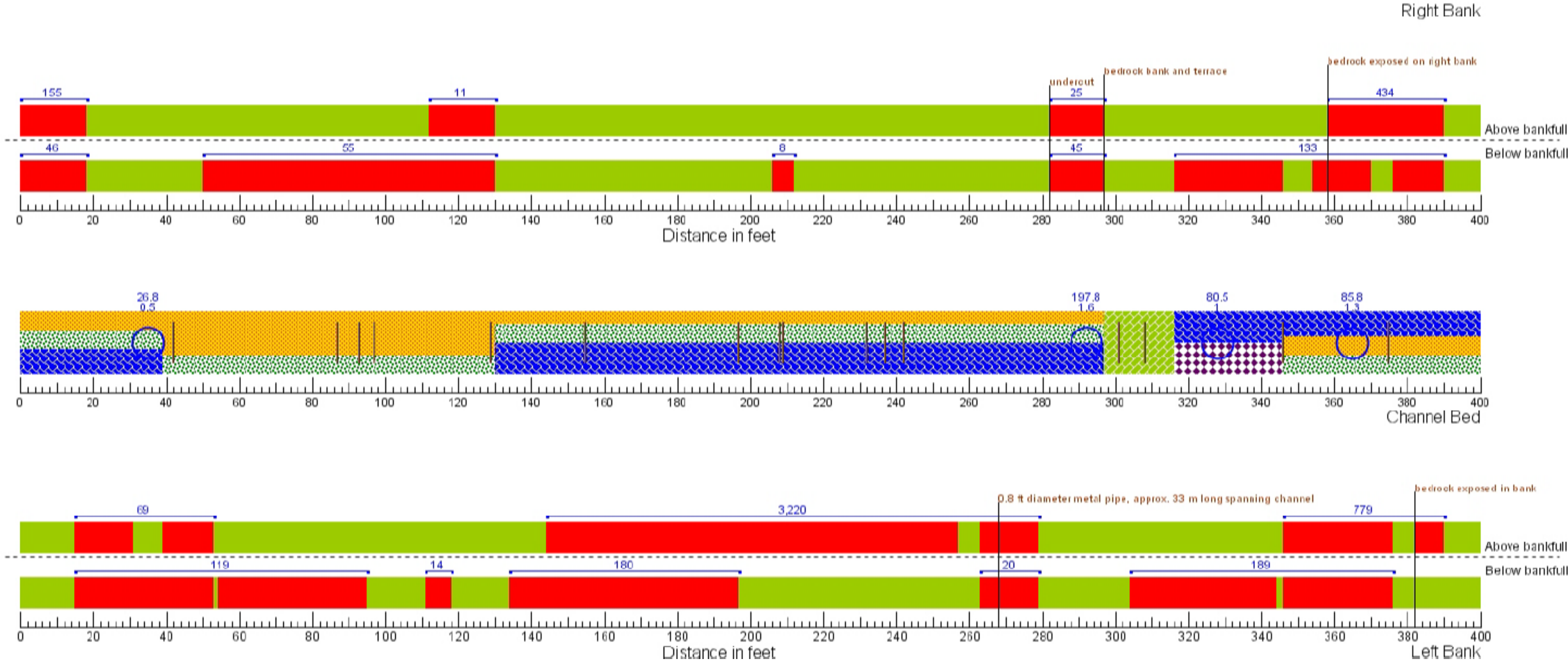

Figure 48. Streamline graph of the South fork study reach. The reach begins at the confluence with San Pedro Creek, and extends 2,956 ft (901 m) upstream to the North Coast Water District pump and barrel. Section 0 to 400 ft.

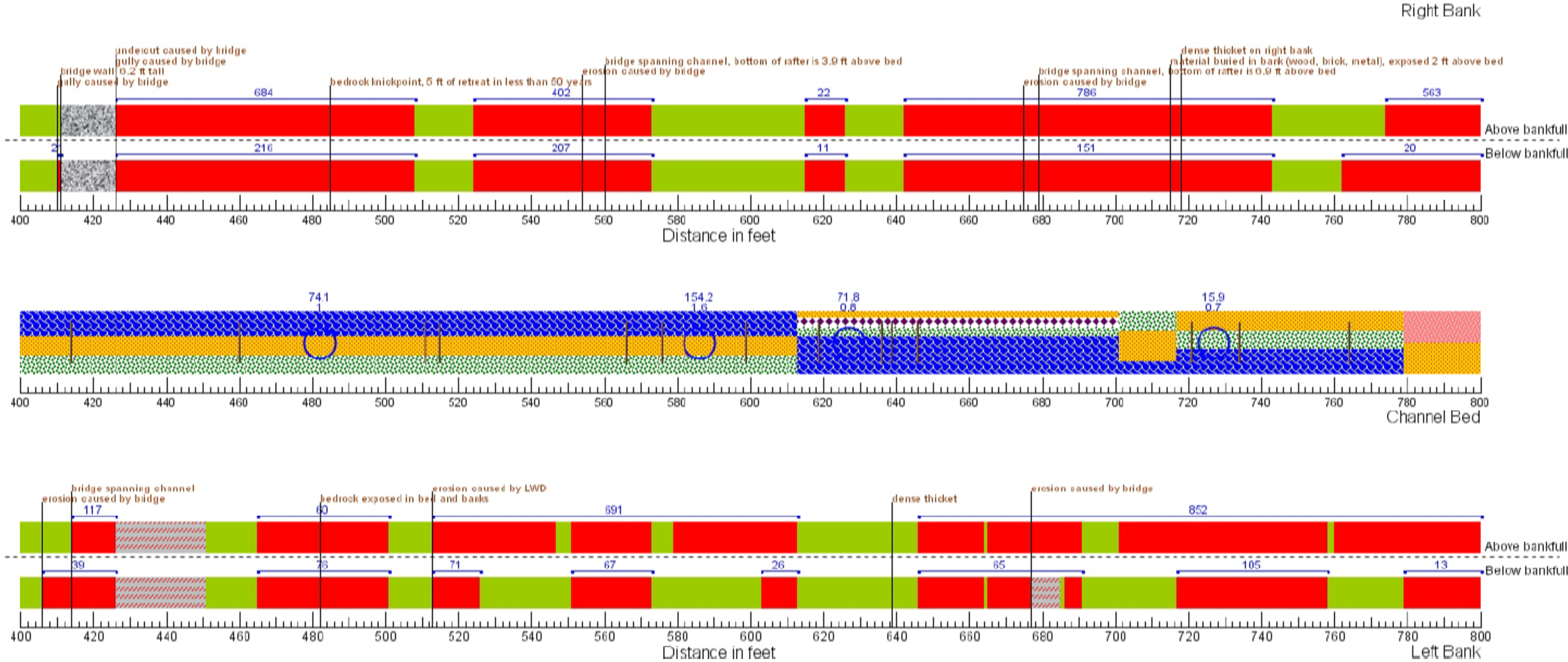

Figure 48. Streamline graph of the South fork study reach. Section 400 to 800 ft.

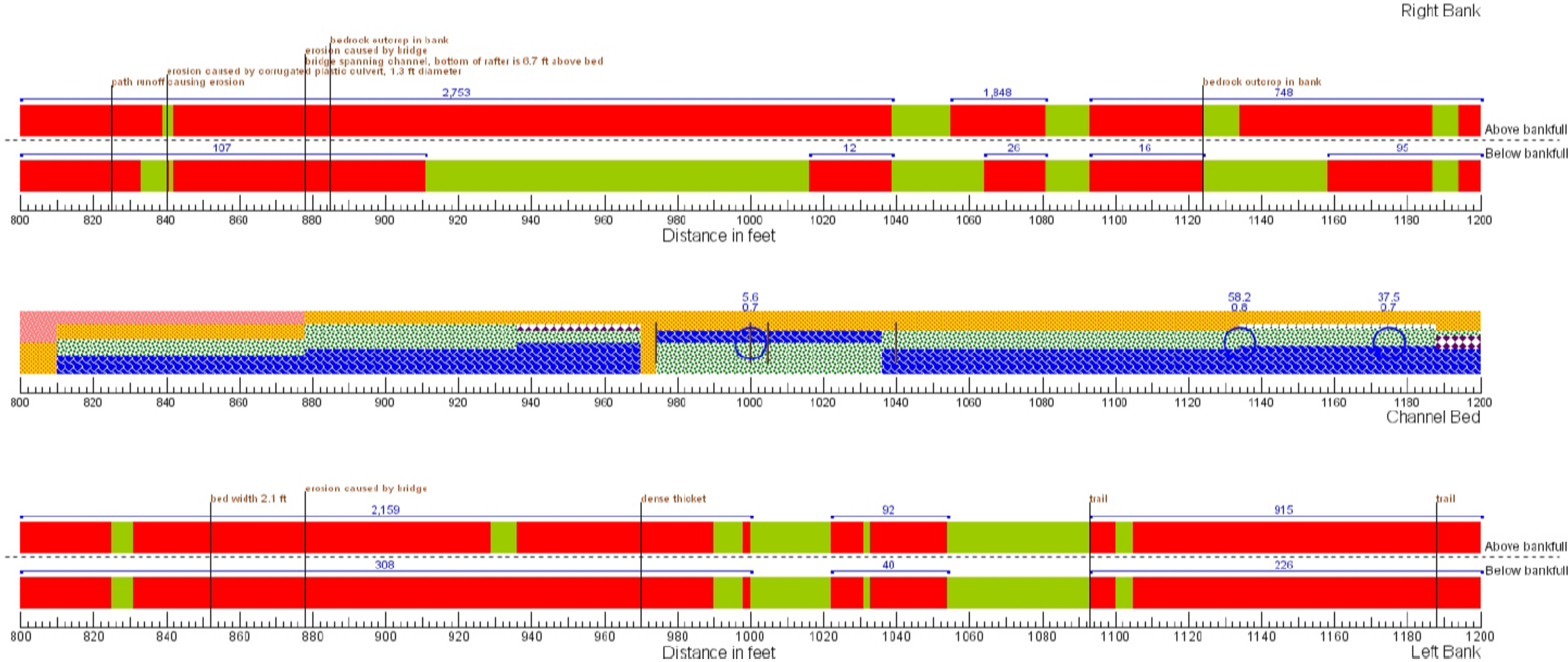

Figure 48. Streamline graph of the South fork study reach. Section 800 to 1200 ft.

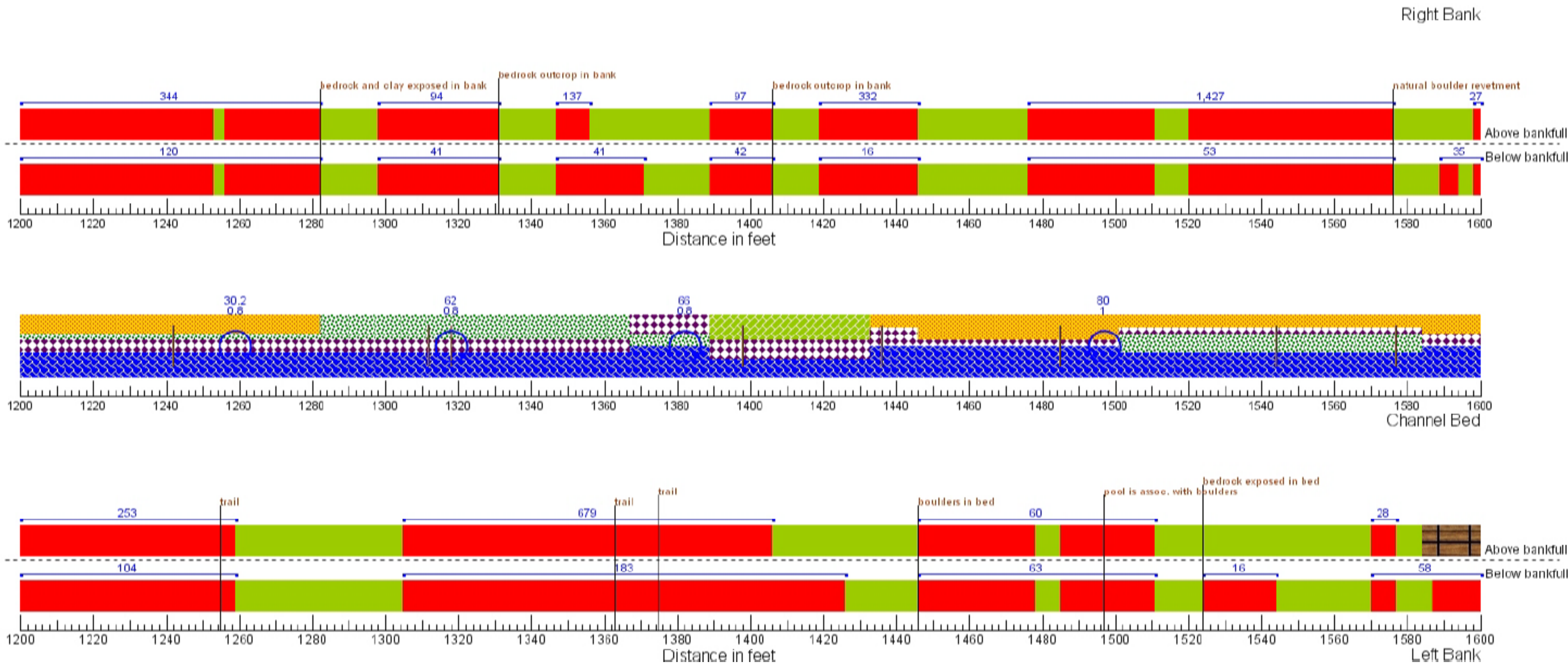

Figure 48. Streamline graph of the South fork study reach. Section 1200 to 1600 ft.

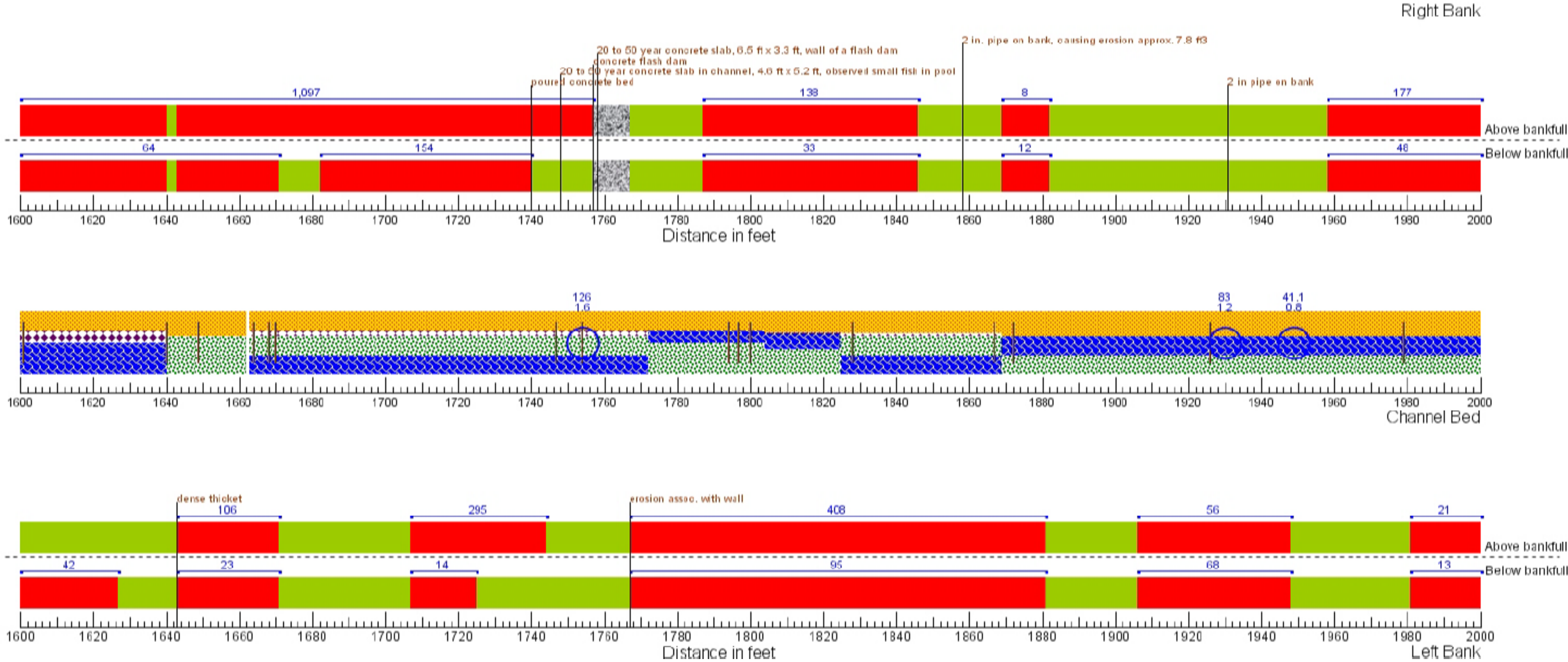

Figure 48. Streamline graph of the South fork study reach. Section 1600 to 2000 ft.

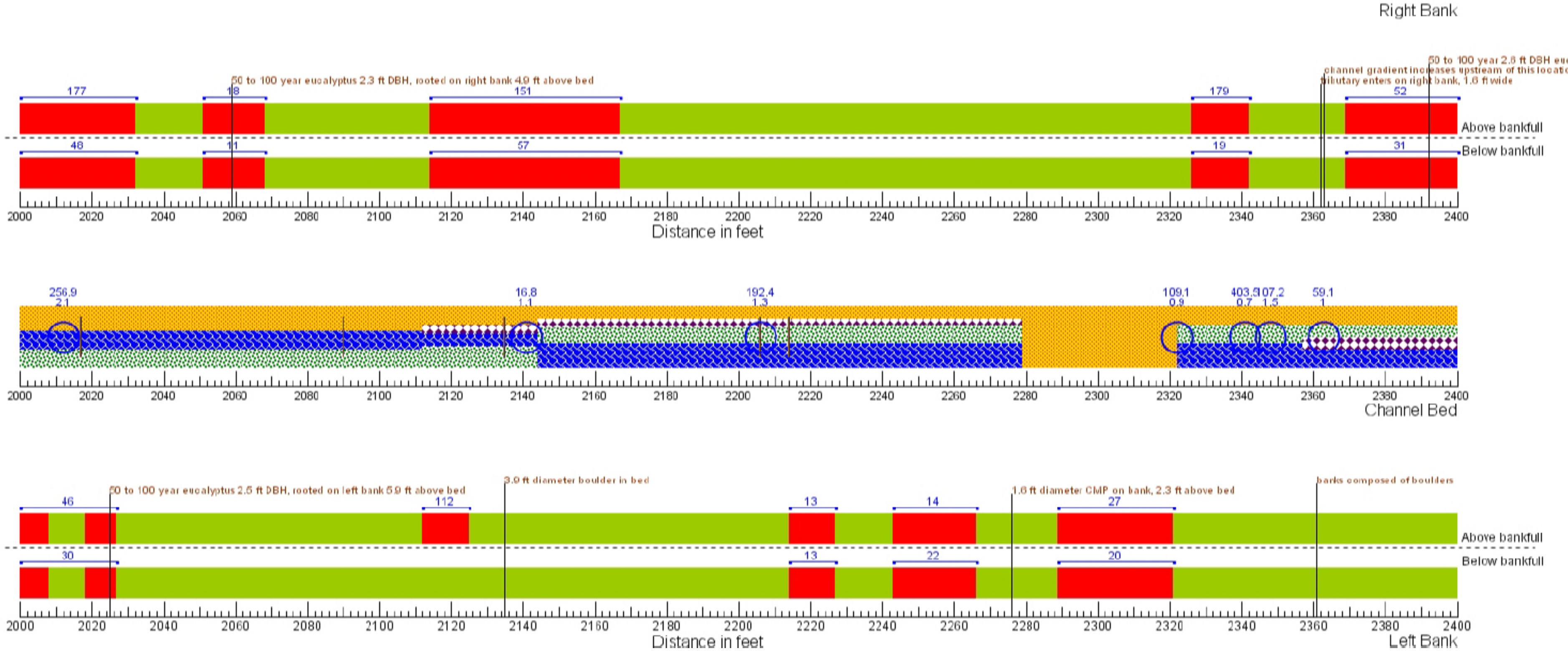

Figure 48. Streamline graph of the South fork study reach. Section 2000 to 2400 ft.

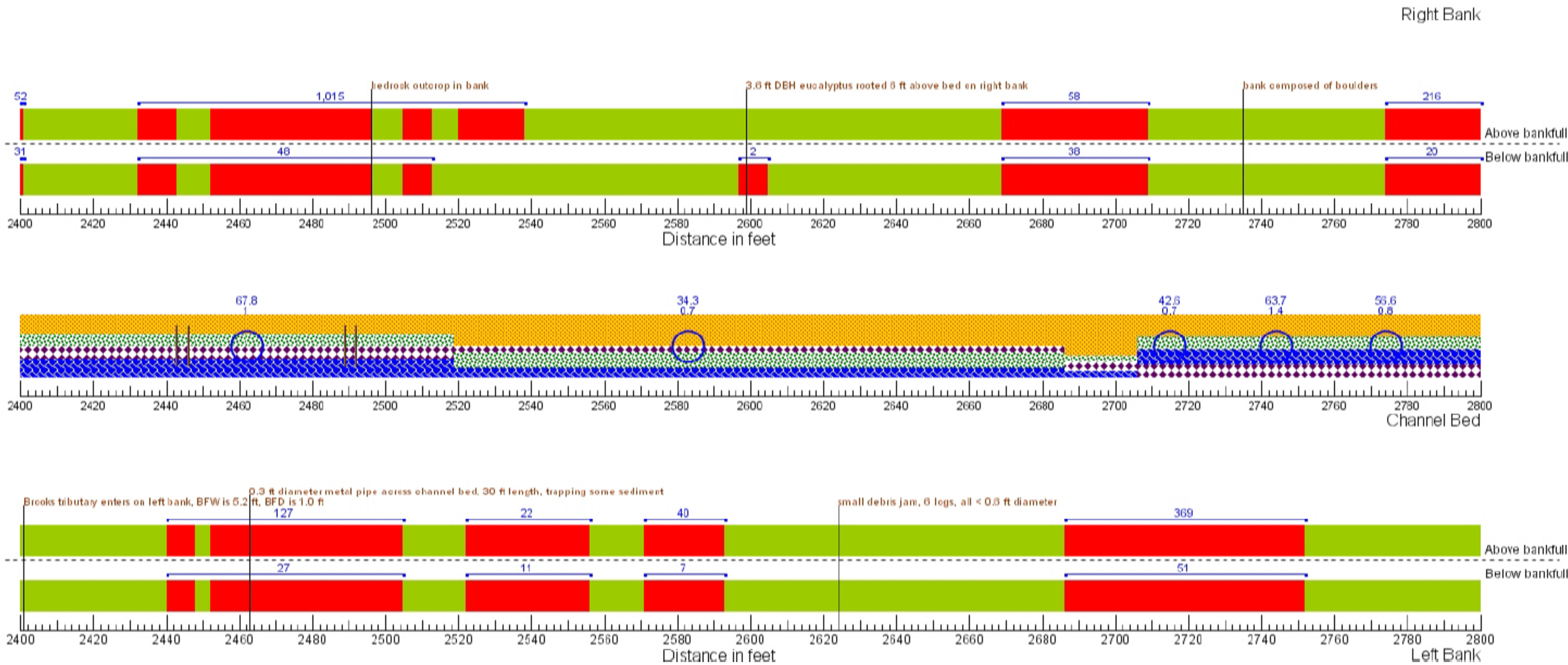

Figure 48. Streamline graph of the South fork study reach. Section 2400 to 2800 ft.

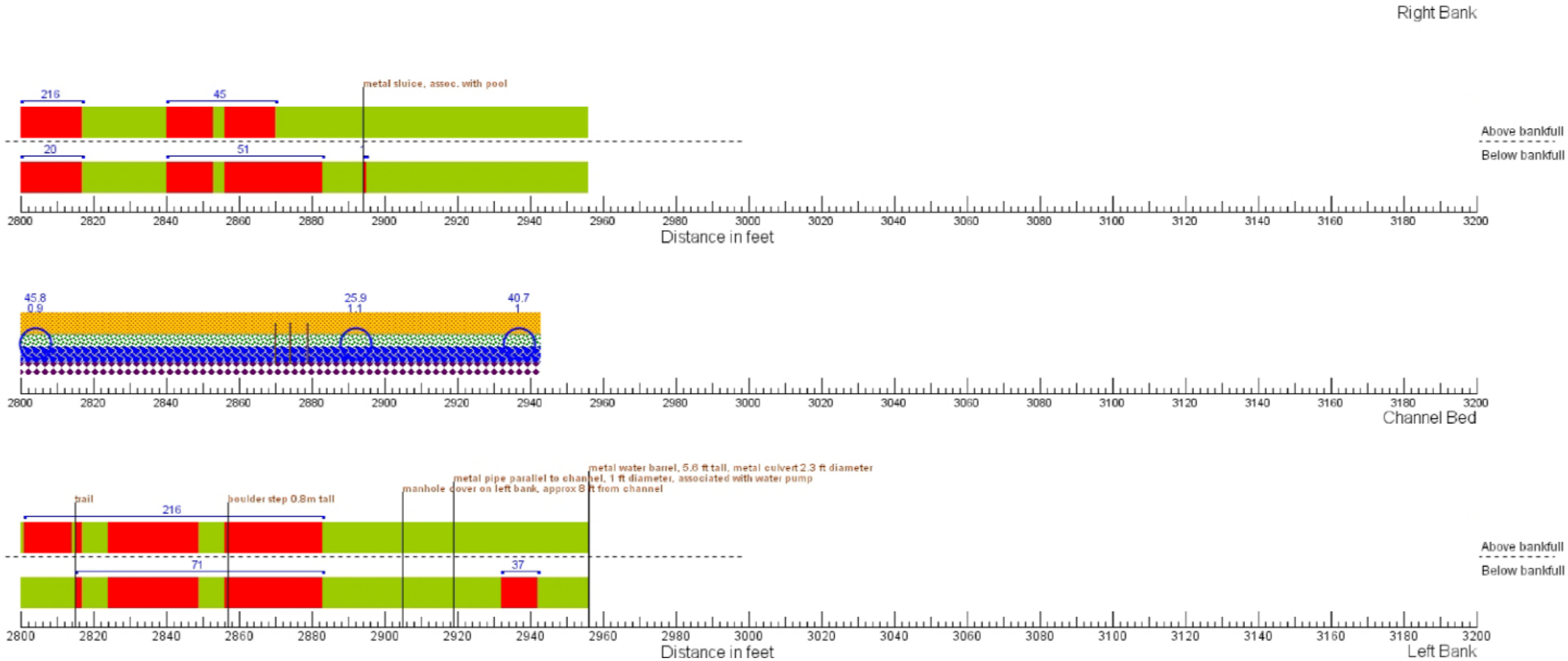

Figure 48. Streamline graph of the South fork study reach. Section 2800 to 3200 ft.

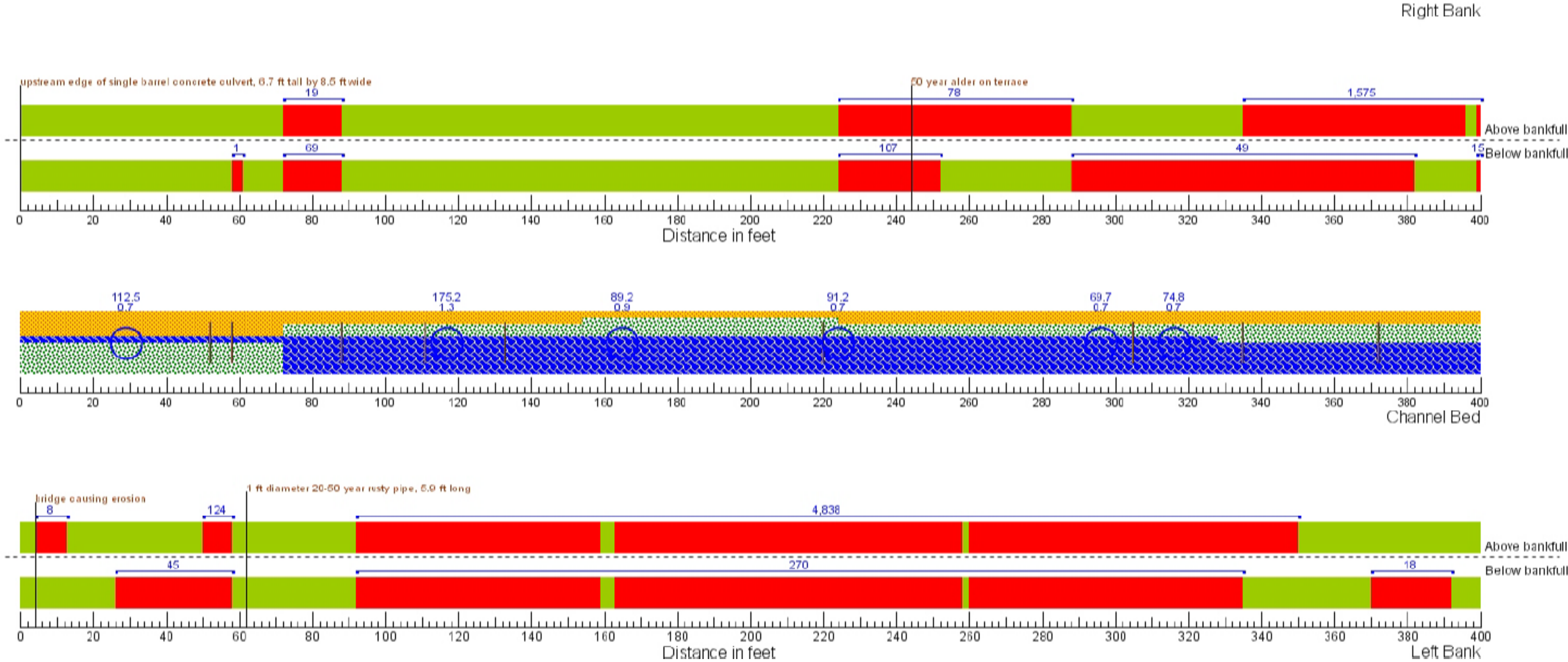

Figure 49. Streamline graph of the Middle fork study reach. The reach begins at the upstream edge of the single barrel concrete culvert bridge near the horseshoe pit, and extends 5,112 ft (1,558 m) upstream, corresponding to the end of the pedestrian trail. Section 0 to 400 ft.

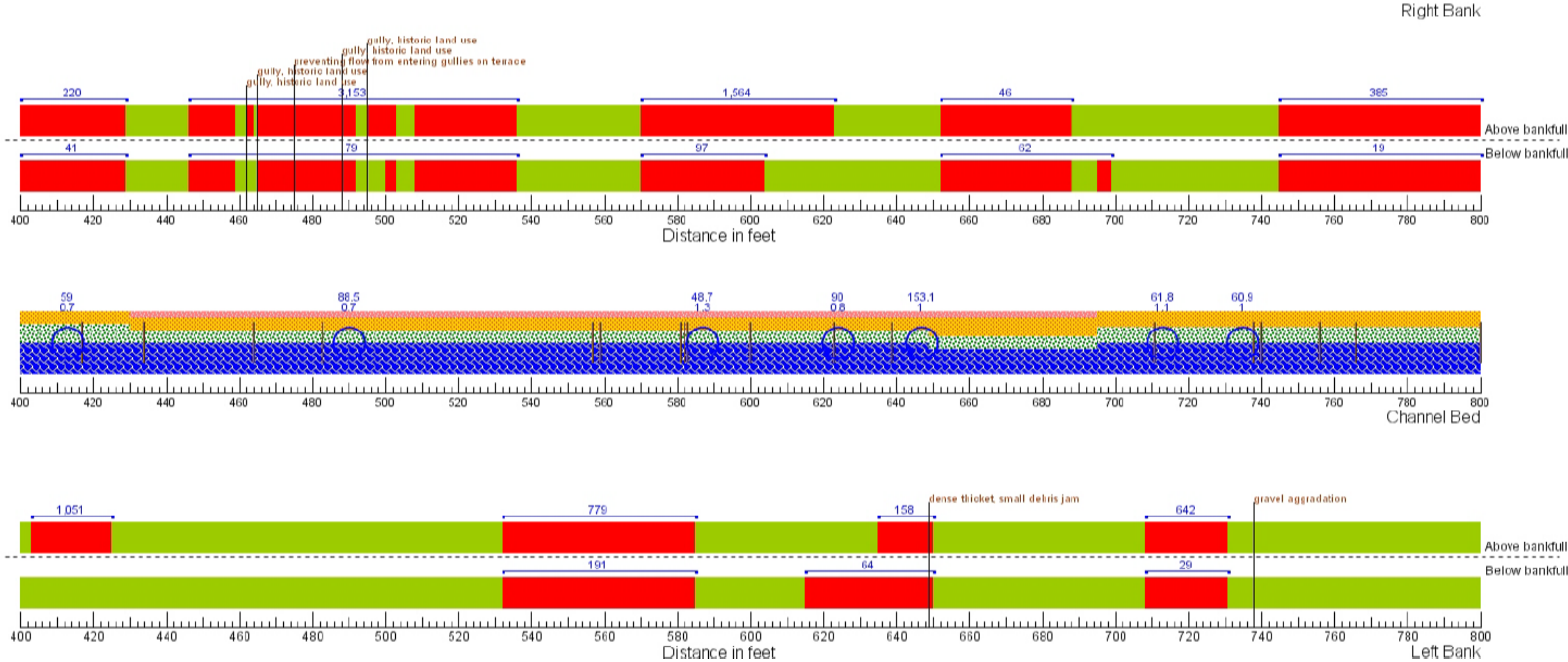

Figure 49. Streamline graph of the Middle fork study reach. Section 400 to 800 ft.

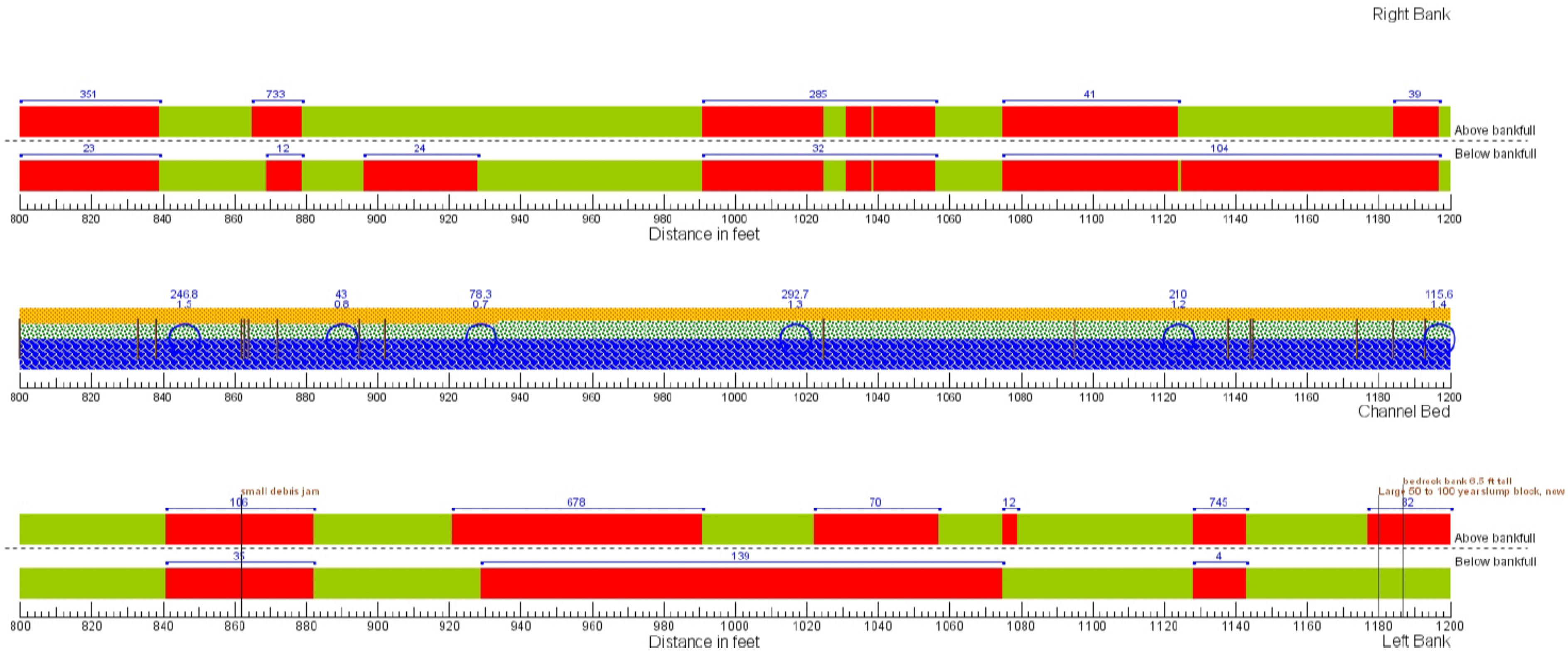

Figure 49. Streamline graph of the Middle fork study reach. Section 800 to 1200 ft.

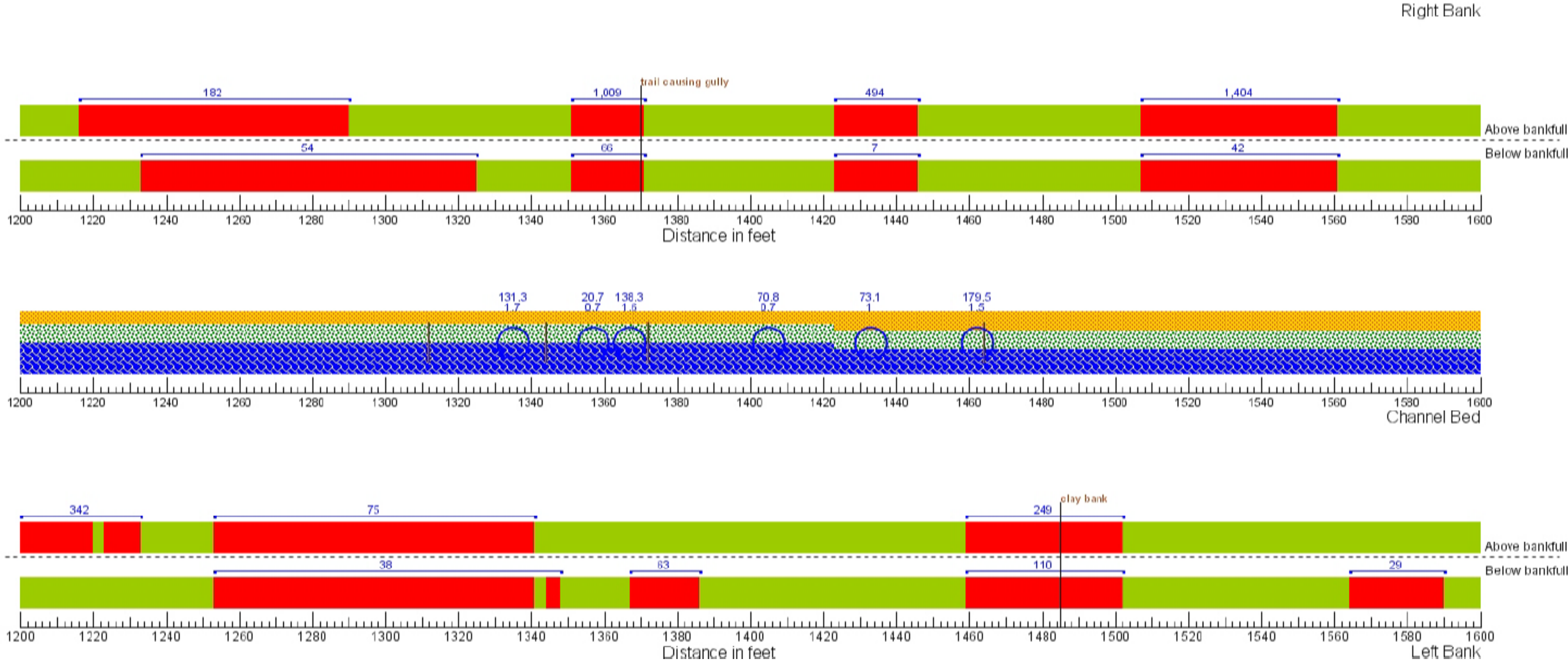

Figure 49. Streamline graph of the Middle fork study reach. Section 1200 to 1600 ft.

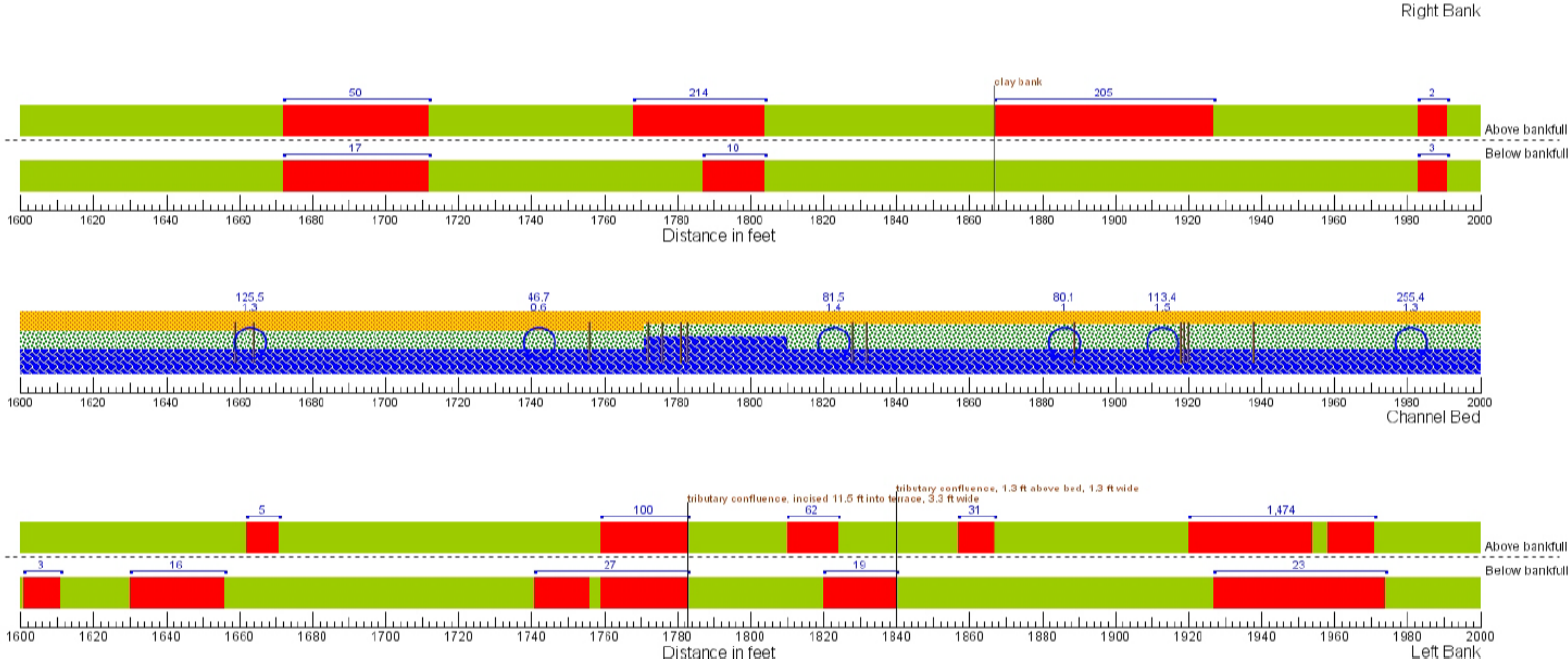

Figure 49. Streamline graph of the Middle fork study reach. Section 1600 to 2000 ft.

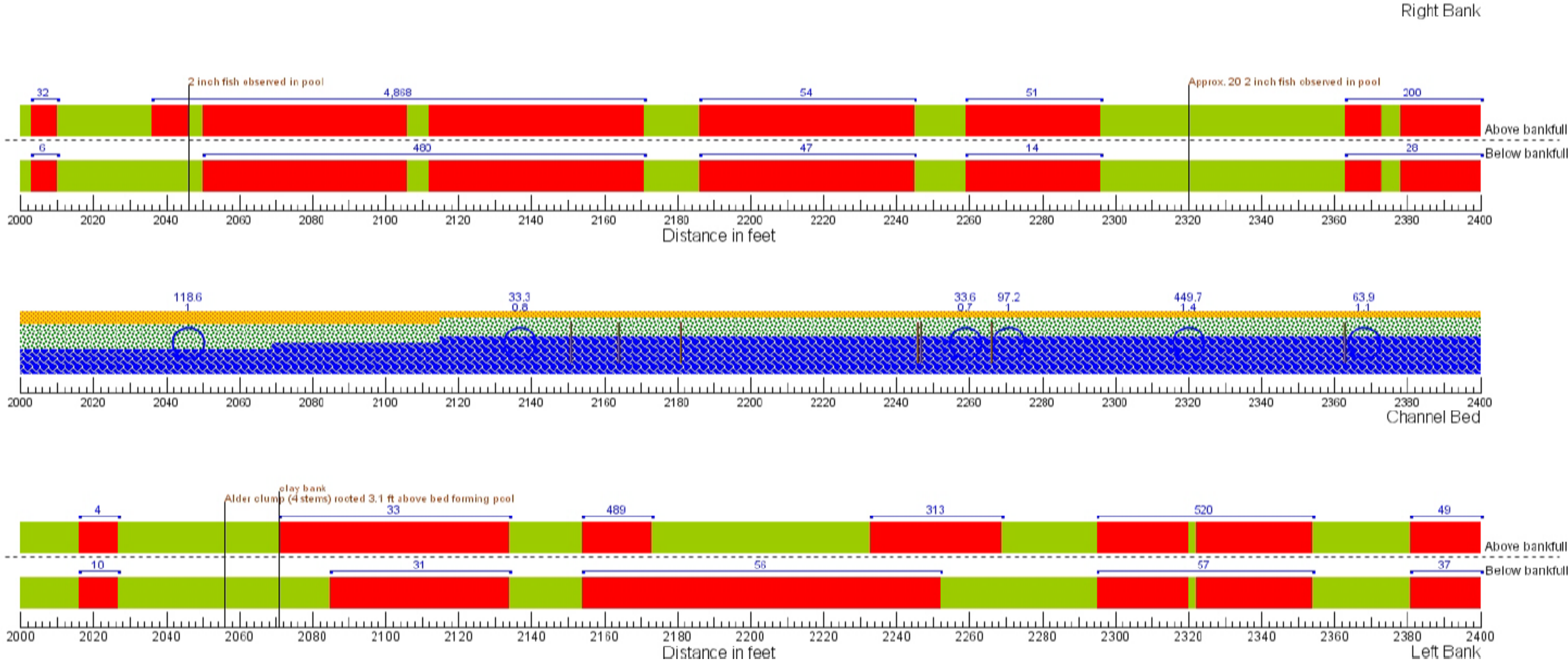

Figure 49. Streamline graph of the Middle fork study reach. Section 2000 to 2400 ft.

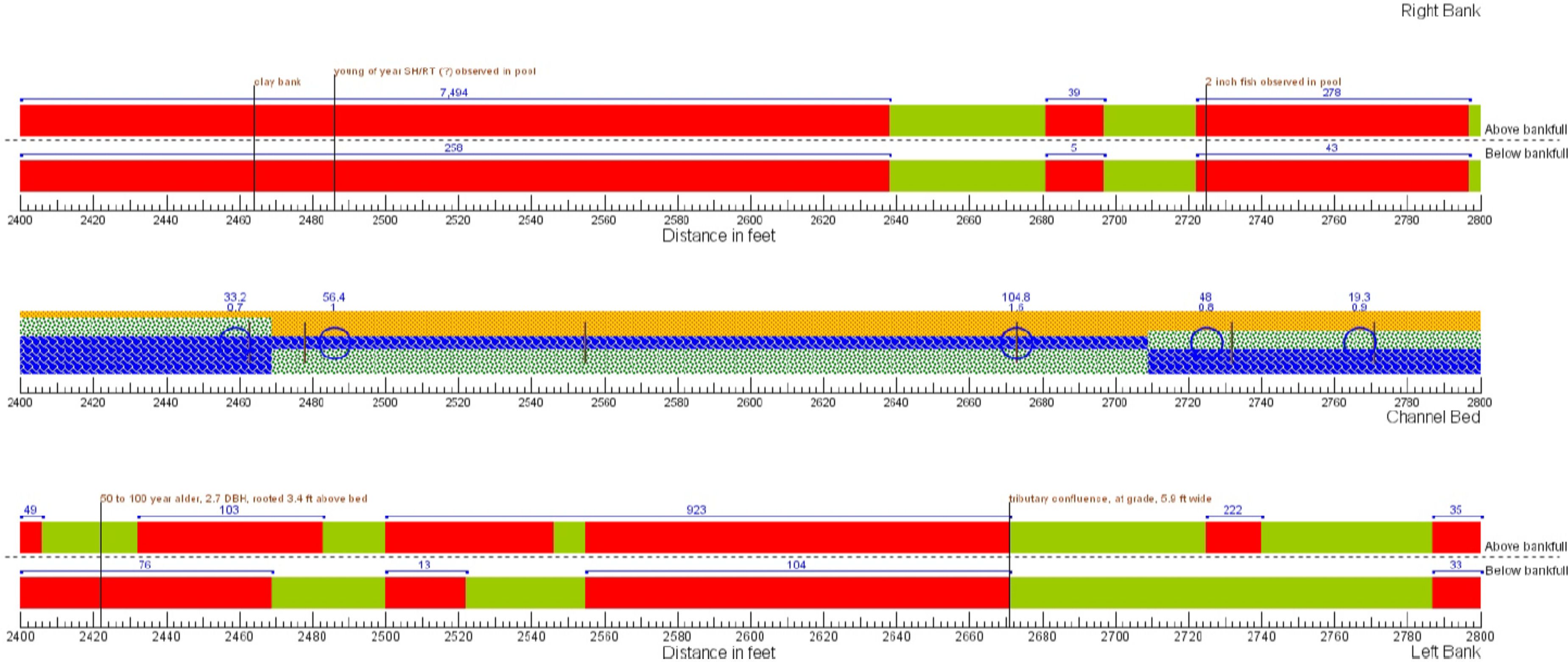

Figure 49. Streamline graph of the Middle fork study reach. Section 2400 to 2800 ft.

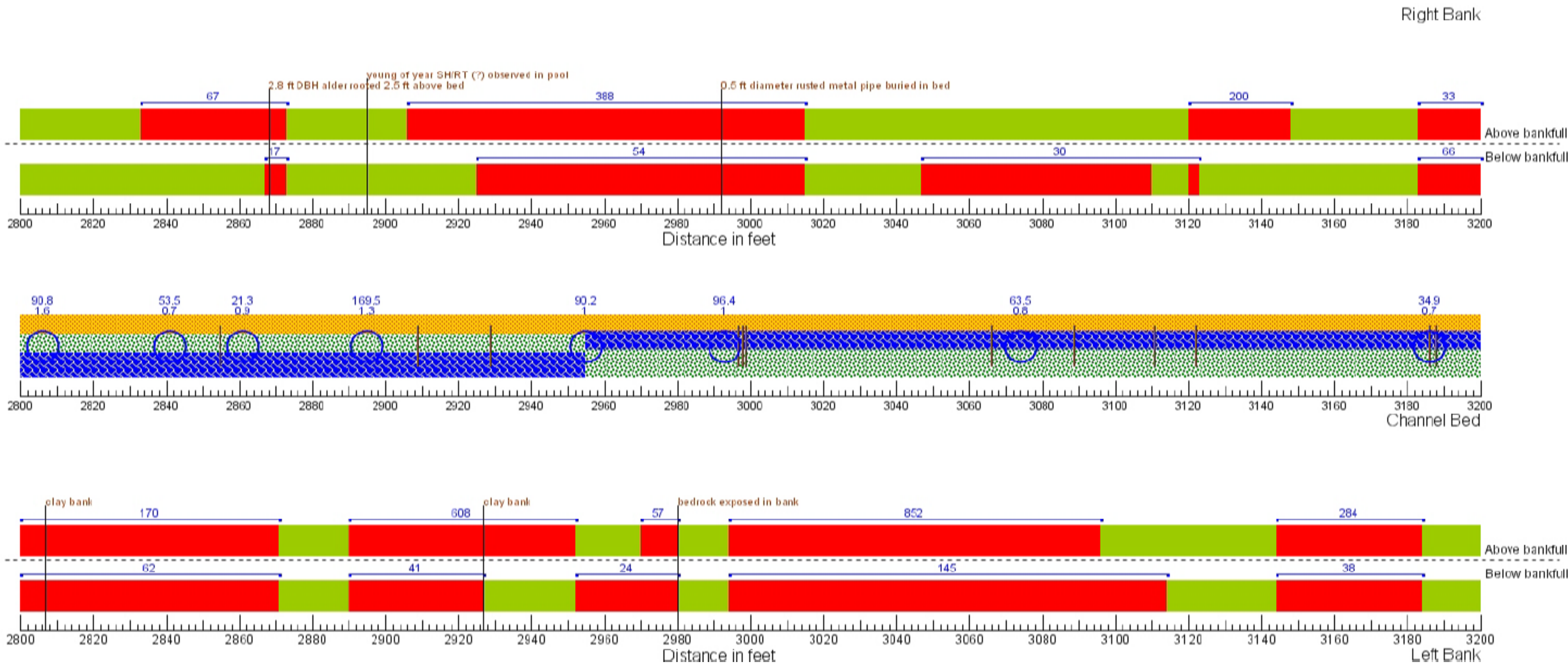

Figure 49. Streamline graph of the Middle fork study reach. Section 2800 to 3200 ft.

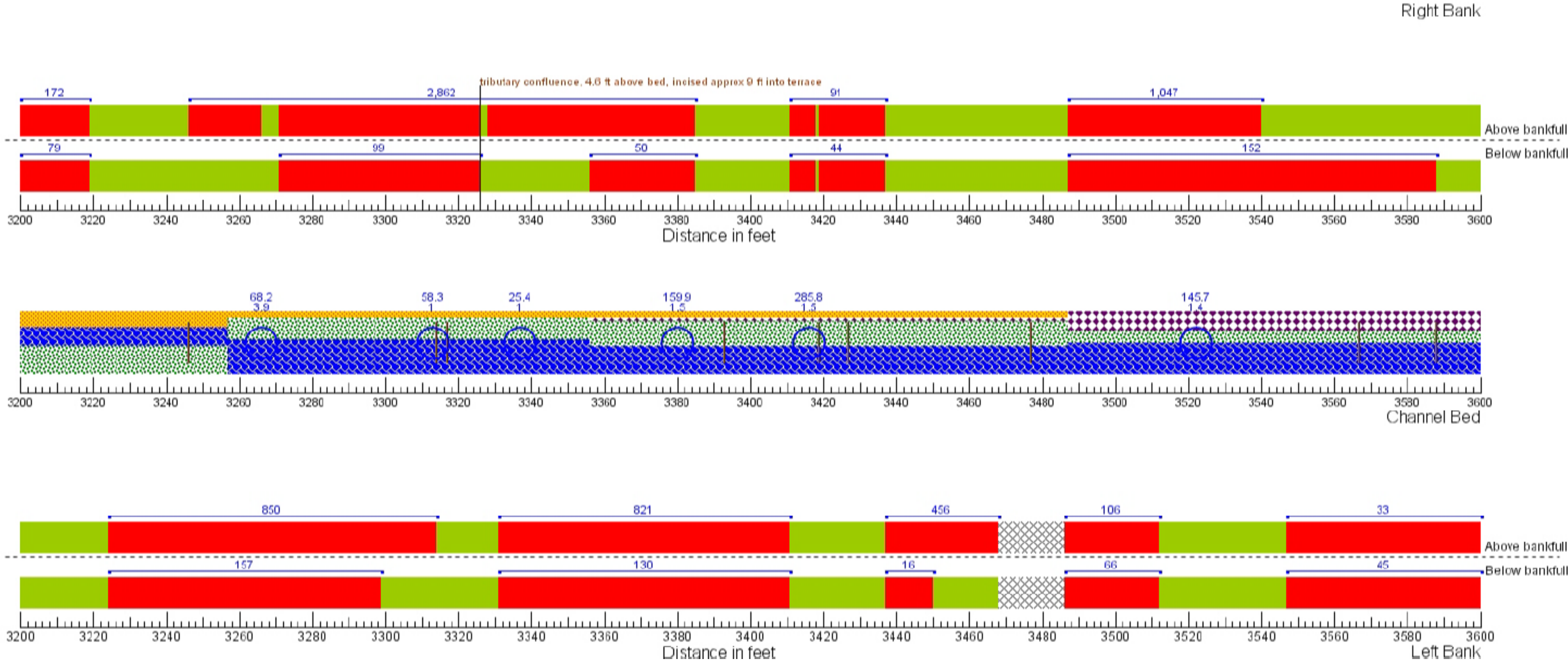

Figure 49. Streamline graph of the Middle fork study reach. Section 3200 to 3600 ft.

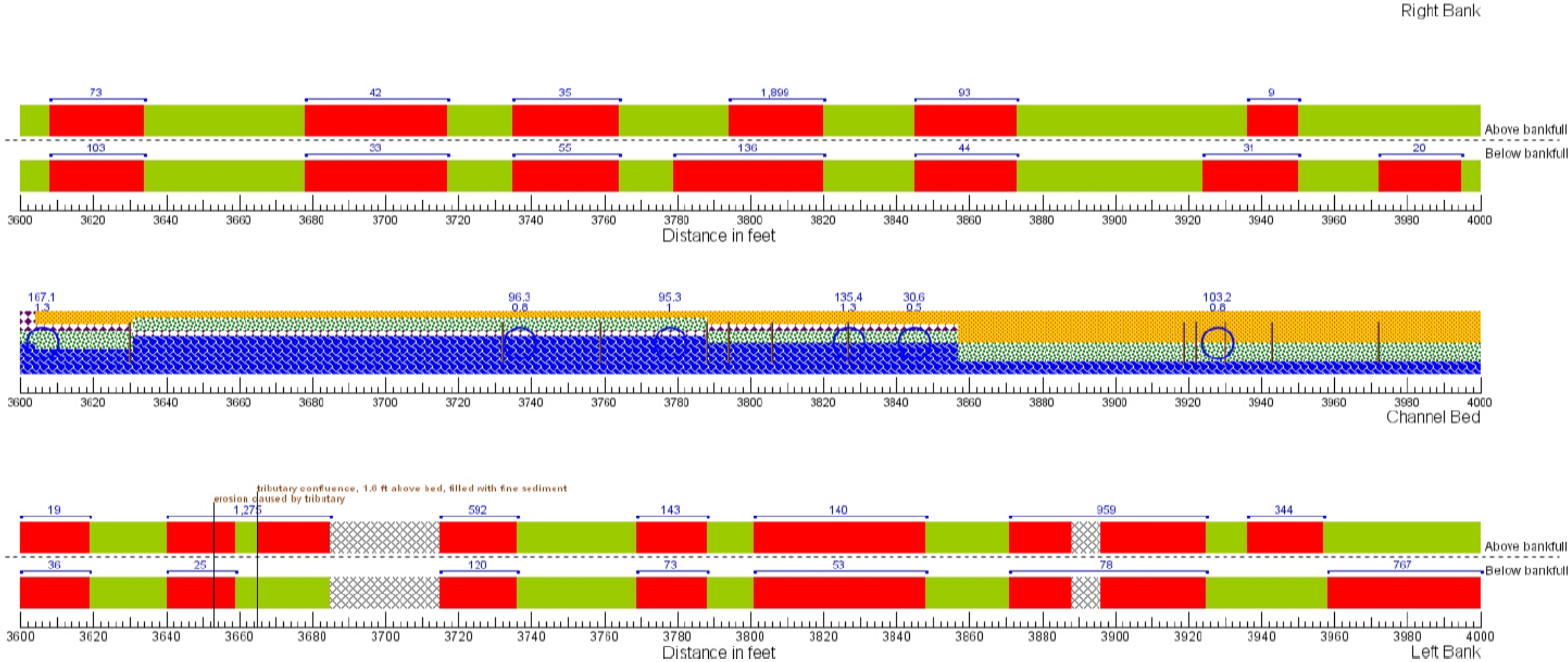

Figure 49. Streamline graph of the Middle fork study reach. Section 3600 to 4000 ft.

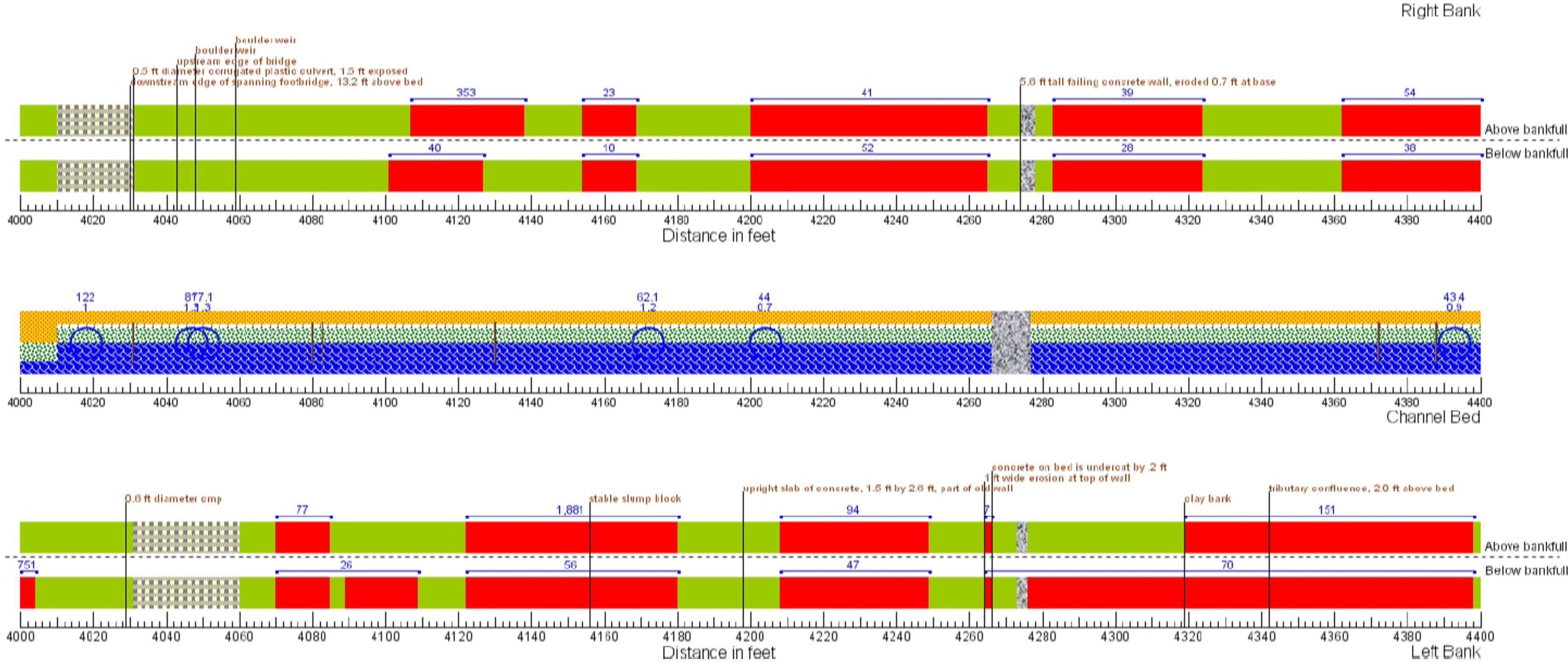

Figure 49. Streamline graph of the Middle fork study reach. Section 4000 to 4400 ft.

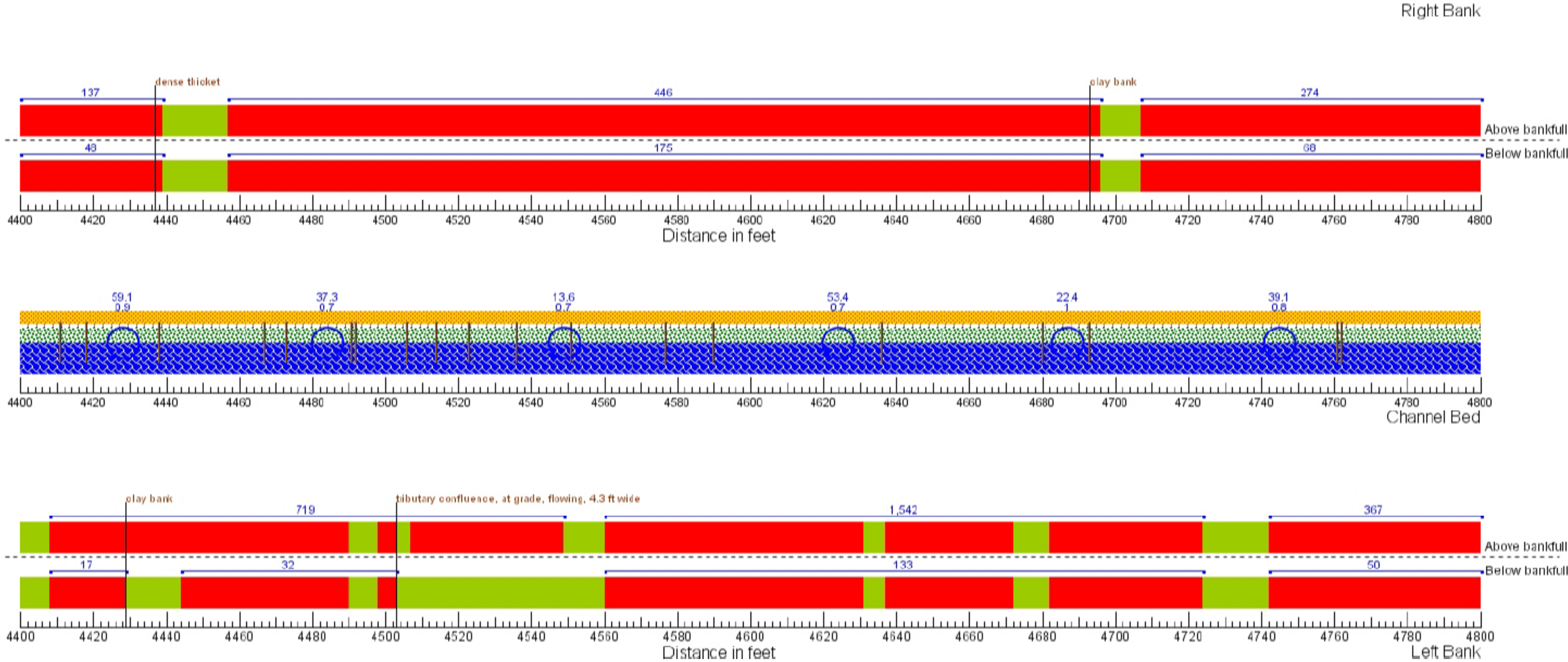

Figure 49. Streamline graph of the Middle fork study reach. Section 4400 to 4800 ft.

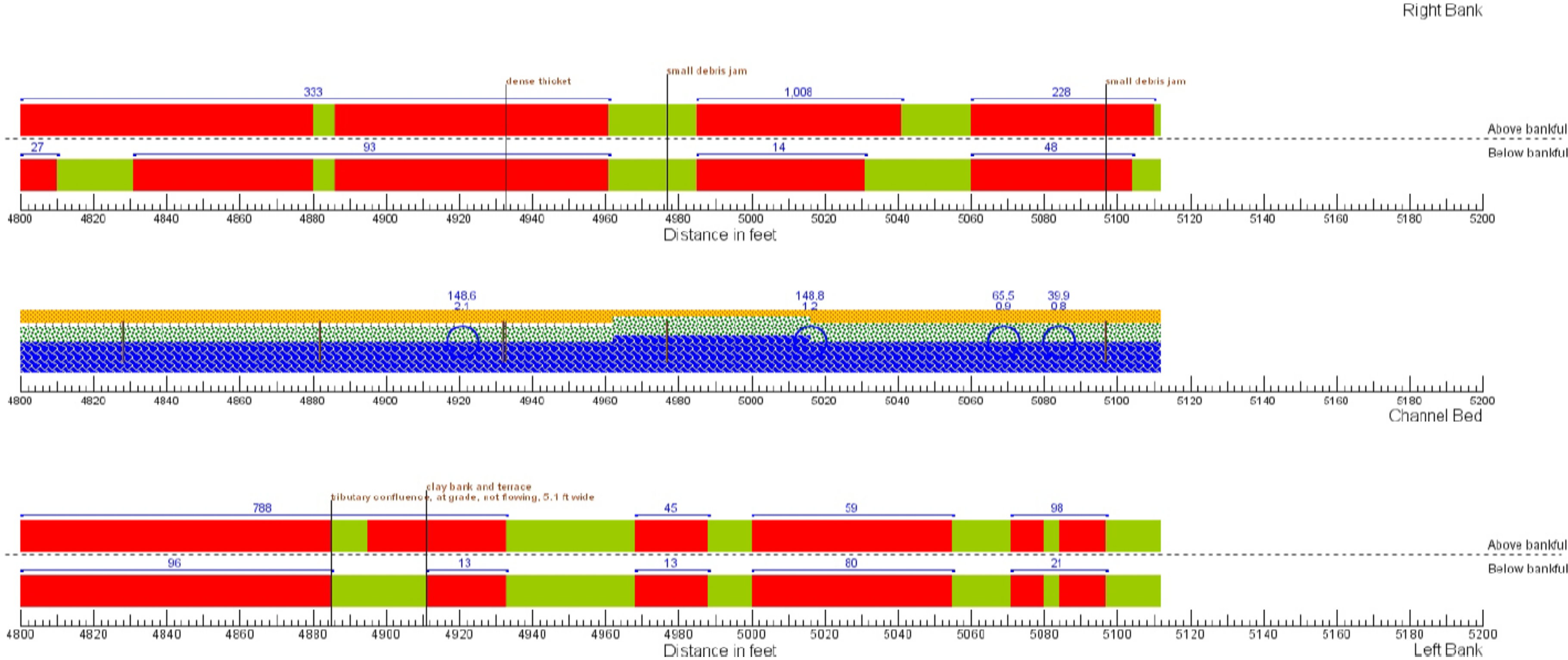

Figure 49. Streamline graph of the Middle fork study reach. Section 4800 to 5200 ft.