Geomorphology of the Walker Creek Watershed:

Prospects for Habitat Enhancement and Sediment Management

Prepared for

Marin Resource Conservation District

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PROJECT SUMMARY

Extensive changes in ecosystem structure and function have been observed in Walker Creek, including dramatic reductions in steelhead and coho salmon populations, excessive erosion and sedimentation, and loss of riparian habitat. These issues have led to regional concern and interest in restoring the health of the watershed's natural resources. Since the 1960s, multiple studies have been completed to assess riparian health and characteristics, steelhead and coho populations, and sediment erosion distribution. Bank stabilization, sediment control, and channel enhancement projects have been implemented throughout the watershed. In 2001 a Watershed Enhancement Plan was developed to incorporate resource management issues and landowner concerns.

This project is part of the larger Walker Creek Watershed Restoration Program. The 76-square-mile watershed drains into Tomales Bay, one of California's richest and most diverse coastal habitats. The watershed is 95% privately owned, consisting predominantly of livestock and dairy ranches. The Walker watershed is also home to steelhead trout and coho salmon, the endangered freshwater shrimp, red-legged frogs, and many other aquatic species. According to the California Regional Water Quality Control Board, San Francisco Bay Region (RWQCB), beneficial uses in the watershed are threatened by sedimentation and nutrients. Tomales Bay is listed as a category 1 watershed according to the State Water Resources Control Board's California Unified Watershed Assessment.

This geomorphic assessment of the Walker Creek watershed continues the process of documenting the environmental status of the watershed. It provides an understanding of the hillslope and fluvial geomorphic processes currently occurring in the watershed and places these processes in a geologic, historic, and landuse perspective. Sediment mobilization, storage, and transport trends through the system are analyzed and described. Channel reaches are morphologically characterized and classified. Most important, a strategy is developed to guide resource managers in prioritizing watershed and channel enhancement projects that will work with natural processes to restore fisheries habitat and effectively reduce detrimental sediment loads.

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INTRODUCTION – BALANCING RESOURCE NEEDS AND CHANNEL CONSERVATION

River systems are often the center of attention in conflict between competing resource needs. Though Walker Creek is a rural agricultural watershed with relatively few demands placed upon its waters, the ecosystem status and management of the riparian resources has often been a contentious subject. With nearly 95% of the 76 square-mile watershed in private ranches, maximizing grazing area and productivity, providing for stock-watering, and maintaining a financially-viable agricultural lifestyle are primary resource needs for landowners in the watershed. Many of these landowners are also interested in restoring historic salmon runs and increasing wildlife habitat. On a regional level, resource management needs include rehabilitating instream habitat for threatened and endangered species, reducing transport of mercury and nutrient laden sediments into the channels and through to Tomales Bay, and improving water quality. Environmental concerns in the Walker Creek watershed include:

- Altered sediment and hydrology from historical and current land use practices.
- Degraded channel and riparian habitats.
- Loss of agricultural land due to bank erosion and gully development.
- Reduced wildlife populations.
- Excessive sedimentation.
- Nutrient contamination.

The Marin Resource Conservation District (MRCD), local landowners, and many other agencies and organizations have been developing and implementing assessment and restoration projects designed to address these concerns. As watershed conditions change and knowledge grows, there is an ongoing need to assess and refine watershed plans and management practices. A solid understanding of watershed assets is as critical to defining enhancement projects that work effectively within the social and natural landscape constraints as is an assessment of resource problems. The following assets in the Walker Creek watershed support ecologically-sound resource-management strategies:

- Large, family-owned agricultural properties.
- Engaged landowners, community, and resource management agencies.
- A responsive, dynamic ecosystem.
- Riparian corridors with few buildings, roads or other infrastructure.
- Naturally recovering channel conditions.

This report on the geomorphology of Walker Creek focuses on the natural channel dynamics and behavior of the catchment, how discrete sections of the channels have responded to similar land use practices, and how these channel sections are likely to respond to current environmental pressures. Guidelines for design-with-nature enhancement projects and ecological restoration priorities are included.

CATCHMENT BACKGROUND AND HISTORY

Physical Setting

The Walker Creek watershed is a major tributary to Tomales Bay in northern Marin County and covers 76 square miles. Tomales Bay, at the northern portion of the San Andreas Fault valley, was formed when sea levels rose after the last ice age and inundated the alluvial plain. The bay is regionally important as a commercial fishery, with oyster, halibut, and herring comprising the bulk of the annual harvest. Water quality issues such as sedimentation, high mercury levels, and diminished fresh water inputs threaten the Bay's ecosystem.

Walker Creek flows from Southeast to Northwest, with four major tributaries entering on its way to Tomales Bay (Figure 1). Elevations range from 1532 feet at Hicks Mountain to sea level at the mouth. Steep hills enclose a narrow alluvial valley along Walker Creek, Salmon Creek, and lower Arroyo Sausal and Chileno Creek. Keys Creek and upper Arroyo Sausal and Chileno Creek traverse broad alluvial valleys surrounded by rolling hills.

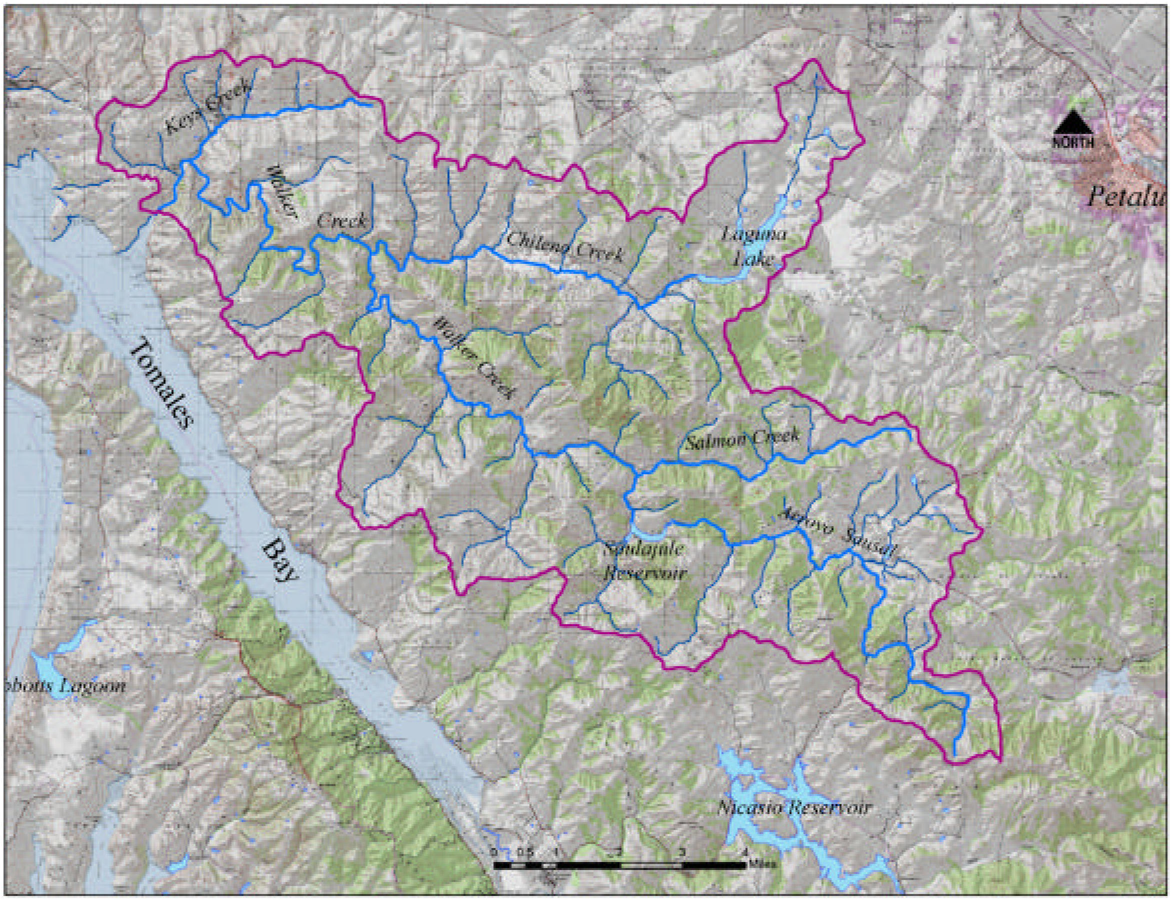

Figure 1. *Walker Creek watershed.*

Tectonic activity has been a primary force in shaping the landscape of coastal Marin County and the Walker Creek watershed. The dominant underlying geology of Walker Creek watershed is the Jurassic-Cretaceous Franciscan formation (Figure 2). It is composed of folded, sheared, and metamorphosed sedimentary and volcanic rocks from the Jurassic and Cretaceous Periods (150-100 million years ago [mya]). The ranges were formed when seafloor sediments and rocks were pulled into a deep, marginal trench and then accreted onto the edge of the continent, as the Pacific Plate was subducted under the North American Plate. About 40 mya, after the period of subduction ended, the accreted sediments experienced periods and discrete locations of uplift or subsidence (Alt and Hyndman, 1975). In the northern part of the watershed (Keys Creek), the Pliocene Wilson Grove (formerly Merced) formation overlies the Franciscan formation. The Wilson Grove formation was deposited during a period of subsidence and is composed of marine derived sandstones and conglomerates that are poorly indurated and cemented.

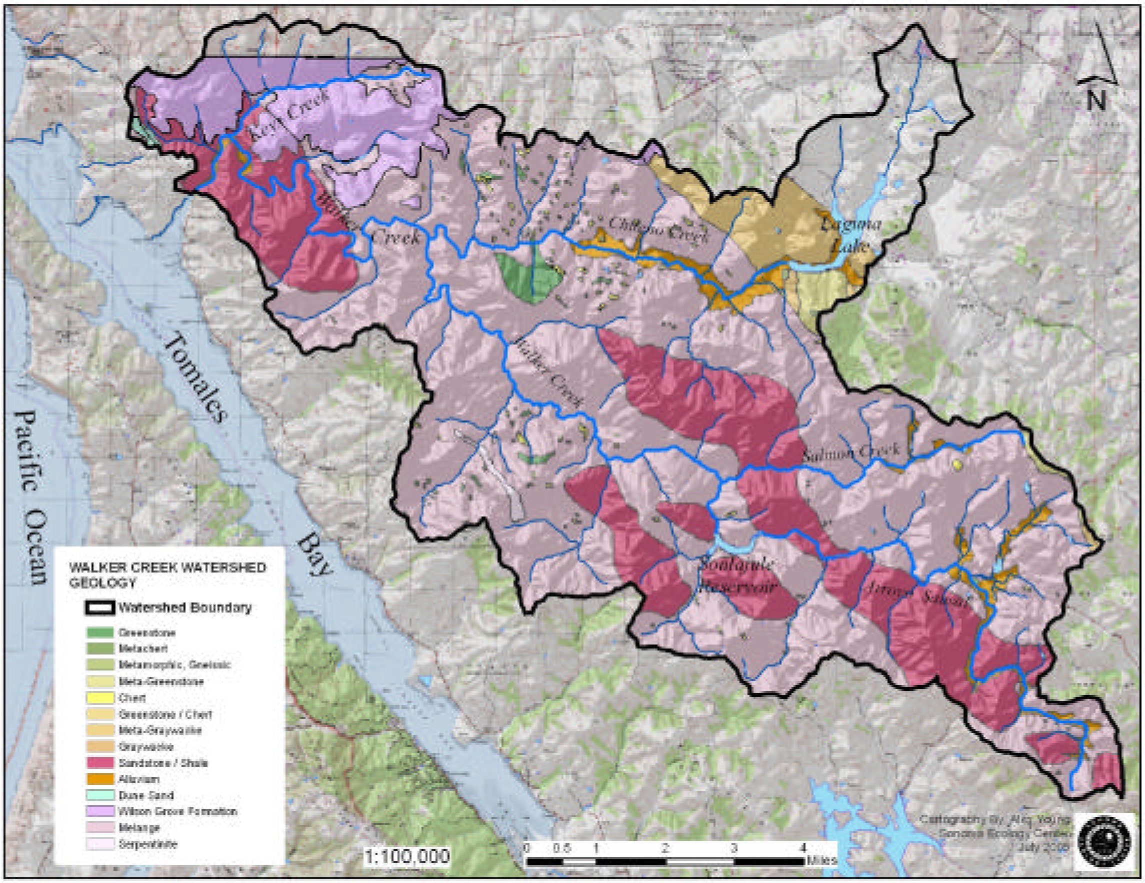

Figure 2. *Geology of the Walker Creek watershed.*

Soils in the watershed are those commonly associated with the Franciscan and Wilson Grove formations and generally follow the geologic boundaries. The Steinbeck and Los Osos associations are loamy soils prone to erosion through sheetwash and gullying, especially where vegetation has been removed or compromised by high grazing pressure (Soil Conservation Service, 1967).

Four vegetation types are predominant in Walker Creek – annual grassland, coastal shrub, oak-bay woodland, and riparian woodland. Coastal shrub is found in drainages on all slope aspects, while the oak-bay woodland is primarily on the steeper, north-facing slopes. Riparian woodland, while relatively scarce throughout much of the watershed during the last century is now found extensively along mainstem Walker Creek and the lower reaches of the perennial tributaries. Prior to

European settlement, it is thought that woodland vegetation types had a more extensive distribution in Walker Creek, including evergreen trees and redwoods in the high valleys and north facing slopes (Zumwalt, 1972). However, there is some dispute as to if redwoods were present in the watershed other than the uppermost portions of Arroyo Sausal. The extensive annual-dominated prairies seen today were historically located primarily on the hillsides and ridgetops and were composed of native, perennial bunchgrasses.

Fisheries

Historically, Walker Creek had abundant steelhead and Coho salmon runs. As in many other coastal watersheds, it is said that 90 to 100 years ago it was difficult to drive a horse and buggy across the stream at the height of the winter run because of the numbers of fish in the shallow water (Worsely, 1972). Many long-term residents of Marin County reported adult steelhead migrating nearly 25 miles up Walker Creek to spawn in the headwaters of Arroyo Sausal (Kelley, 1976). In addition to steelhead and Coho salmon, Pacific lamprey, California roach, threespine stickleback, sculpins, mosquitofish, and bluegill have been found in Walker Creek (Emig, 1984).

It appears that both steelhead and Coho populations declined gradually after the 1930s. By as early as the mid-1950s very few steelhead were caught by anglers at the lower end of Walker Creek (Kelley, 1976). In 1975 a comprehensive investigation of steelhead and silver salmon populations was performed by Kelley (1976). Small numbers of steelhead young-of-the-year were found in all viable habitat areas in the watershed, but only 8 Coho were found near the confluence of Chileno and Walker Creek. Multiple factors have been cited as contributing to the population declines, including high rates of bank erosion, sedimentation of pools and riffles, loss of riparian shade leading to high water temperatures, lack of summer flows, reduced winter baseflows, pollution, and blocks to habitat access. These habitat alterations, combined with fishing pressures have led to the likely extirpation of native coho and only a remnant steelhead population in Walker Creek.

Efforts to increase fish populations have focused on both habitat restoration and restocking. Erosion reduction, riparian revegetation, riparian fencing, and stream-flow augmentation projects have been implemented throughout the watershed to improve instream habitat. Steelhead and coho salmon fingerlings have been planted on several occasions, and in 2004 eighty adult coho broodstock were released.

Historical Settlement and Watershed Conditions

Tomales Bay attracted early settlers to its shores with its diversity of seafood, climate, and peaceful living conditions. The first humans to inhabit the Tomales Bay and Walker Creek watersheds were the Coast Miwok, who arrived in the area approximately 5,000 to 8,000 years ago (Tomales Bay Watershed Council, 2003). In general, the lifestyle of the Coast Miwok did not put much pressure on the watershed in terms of natural resource use or alteration of physical characteristics. According to historic archeological data, most of their activities consisted of hunting and gathering and trading with neighboring tribes for the few essentials that weren't available (Treganza in Tomales Bay Watershed Council, 2003). However, they are now known to have actively managed their environment (grassland extent and composition) through fire. Large scale physical adjustments in the watershed probably occurred as a result of storms, earthquakes, climatic changes and other physical, natural activities rather than from land-use during the pre-historic time period.

The peaceful, low-impact lifestyle of the Coast Miwok did not last long after the discovery of the region by Russian and Spanish explorers. "The early 1800's saw the end of the Coast Miwok way of life. The occupation of the territory by Mexico and subsequent land grants, the construction and operation of Mission San Rafael and its shepherding/enslavement of many of Marin's indigenous people, and of most consequence, the introduction of the small pox virus effectively displaced … this tribe (Tomales Bay Watershed Council, 2003, p. 35)."

Late 1700s-1800s

The late 1700s brought exploration of the area, and settlements began to be built in the Tomales Bay and northern Marin County region. These Spanish, Russian, and American settlers had a much different lifestyle than the Coast Miwok, and their intensive land-use practices altered watershed conditions. The Spanish brought cattle to the Tomales Bay region in the early 1800s, and accounts indicate that over 8,000 head of livestock were in the area by 1850 (Collier and Thalman, 1996 citing Bancroft's History of California). The American influx in the 1850s brought potato farming, sheep grazing, and more dairy farms (State Coastal Conservancy, 1984).

Soil and the climate conditions in the Keys Creek and Chileno Creek valleys of the Walker Creek watershed were excellent for potatoes, and potato farms began to flourish on the low hills and fertile valleys (UCCE, 1995). With the success of potato farming and a navigable creek, towns were quickly built to enhance trade opportunities. Shallow barges were able to travel upstream to what is now the town of Tomales, load potatoes and other goods, and go to San Francisco (Figure 3).

Figure 3. *Depiction of John Keys' schooner at the docks in Tomales. This vessel was used to ship potatoes, grain and dairy between Bodega Bay, Tomales, and San Francisco between 1850 and 1876. Painting by Richard Shell, date unknown. (From www.krisweb.com courtesy of Northbay Savings Bank and the Tomales Regional History Center)*

Intensive farming and ranching practices in these upper valleys caused severe erosion and subsequent sedimentation in the creek channels, eventually hindering the shallow bottom barges from reaching the docks without dredging. Riparian vegetation clearing and channel straightening was performed to prepare land for agriculture and livestock. These practices increased both the erosivity of flood flows, the transport capacity of the streams, and the volume of sediment eroded from stream bed and banks. Additionally, potato fields were usually plowed in March, planted in May, and then plowed again after the fall harvest. The timing of these crops and plowing caused high volumes of silt to run off these fields and into the creeks during the heavy fall and winter rainstorms.

As siltation problems worsened in Keys Creek and lower Walker Creek, it was necessary to continuously move the wharfs downstream. By 1870 the docks were relocated to Ocean Roar at the mouth of Walker Creek and then to the northeastern shore of Tomales Bay in Hamlet in 1875. A study by Wehraftig and Wagner (1972) focused on the rate of erosion required to fill the lower channel of Keyes Creek from the period of 1852 to 1902. Their rough calculations determined that the rate of erosion was 2,000 tons per square mile per year (Tomales Bay Watershed Council, 2003).

1900s

Potato farming, initially extensive in the northern valleys of the Walker Creek watershed, started to diminish in distribution and intensity in the late 1800s, but did not entirely disappear until the 1940s. In addition to potatoes, barley, oats, and hay were commonly cultivated as cash crops throughout the watershed until the late 1940s. As the demand for potatoes declined and the quality grasslands became renowned, many farmers transitioned to dairy ranching. Butter and cheese became the staple products of the region in the early 1900s. Dairies were the primary agricultural land-use in the watershed until the 1950s. During this period few ranches were cross fenced, so the dairy cattle would roam the hillsides and riparian areas throughout the year, returning to the barn on well-worn trails twice daily. Hillside scarring and gullying from this period is still evident. High intensity grazing near barns contributed to sediment and nutrient loading in the nearby streams (Figure 4).

Figure 4. *The Respini Dairy on Salmon Creek circa 1900-1920. (From www.krisweb.com courtesy of the Tomales Regional History Center)*

After 1950 many of the ranchers switched their livestock from dairy cattle to beef cattle, cross-fenced their property, and implemented seasonal rotational grazing (lowlands grazed in the summer and uplands in the winter). Sheep ranching was also extensive until the 1980s. With the introduction of supplemental feeding, ranchers have increased their herd sizes and field rotation practices. Overall the amount of sediment derived from pasture land has decreased since the early 1900s' dairying practices. However, large amounts of fine sediment are still entering the system from surface runoff, especially from pastureland that is adjacent to waterways with free access to creek banks.

Crop farming and grazing practices led to eradication of the native perennial grasses in the watershed and introduction of annual grasses from Southern Europe, North Africa, and Australia (State Coastal Conservancy, 1984). Introduction of nonnative plant species can alter the hillslope and channel hydrology. Native perennial grasses create a dense mat that reduces the amount of surface erosion, increases infiltration, and retains soil moisture. The nonnative annual grasses do not provide as much protection from surface erosion, causing the mulch layer to wash away and exposing the soil to rainsplash induced erosion. Without the grass mulch and thick thatch to slow the water down, rainfall is less likely to infiltrate the soil, thus increasing sheet flow and erosion of fine-grained topsoil from the hillsides. The volume of water supplied from the hillsides is greater, and the travel time to the tributaries shorter in the heavily grazed, annual grasslands. This ultimately leads to higher flood flows and shorter timing from rainfall to peak flow during the winter storm events, reduced infiltration and soil moisture retention, increased fine sediment input into the waterways, and diminished winter and summer baseflows.

Dramatic changes in channel form and behavior continued to occur throughout the watershed as a result of landuse impacts. Haible (1980) documented that during the 60 years between 1915 and 1975 the channels in the upper watershed incised 5 to 8 feet while the lower reaches of Walker Creek, above the Highway 1 Bridge, aggraded approximately 4 feet. Infilling and narrowing of the estuary has continued over the past 100 years (Figure 5 and 6). Extensive tidal flats have developed and have been slowly extending seaward to cover several kilometers at the mouth (Figure 7). Conversations with long-term residents in the watershed indicate that the primary incision documented by Haible (1980) occurred prior to 1950.

Figure 5. *Photo circa 1900-1919 of boating in Walker Creek near the train trestle and Ocean Roar. Channel is now approximately half the width seen in this photo. (From www.krisweb.com courtesy of the Tomales Regional History Center)*

Figure 6. *Highway 1 crossing at lower Walker Creek circa 1920. View is looking upstream. Note extensive fine-grained sediment deposits on both banks and in the channel at lower right. (From www.krisweb.com courtesy of Tomales Regional History Center)*

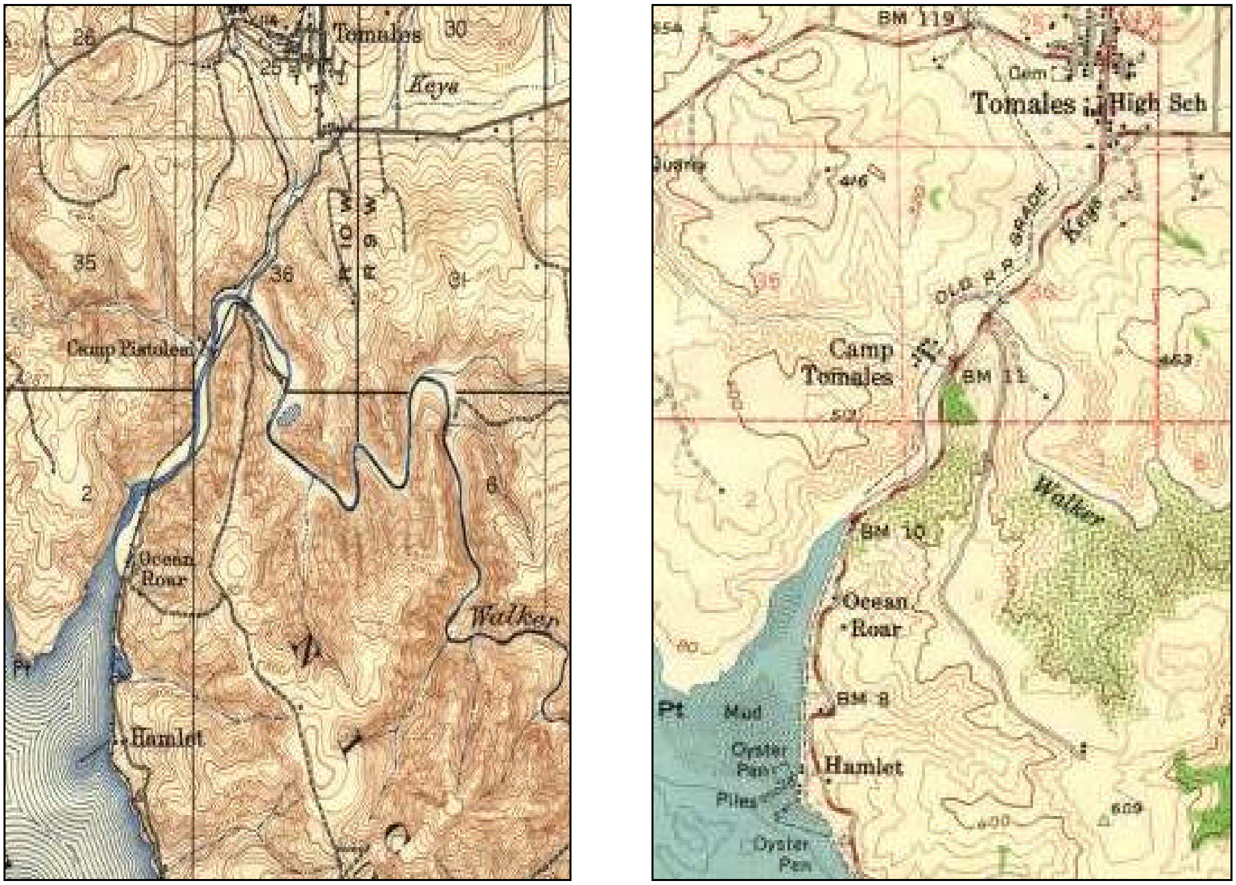

Figure 7. *Comparison maps of the mouth of Walker Creek. The 1916 map on the left shows the mouth open and a wide channel up to the confluence of Keys Creek. By this date Keys Creek was completely aggraded and non-navigable. The 1954 map on the right shows the sediment deposits at the mouth of Walker Creek and the narrowing of the creek to the highway 1 crossing. (USGS Maps courtesy of the Earth Sciences and Map Library, University of California, Berkeley)*

Besides sediment production and grassland degradation, ranching and dairy farming introduced new problems, such as fecal coliform, to the creek, which affected water quality. According to Zumwalt, (1972) "Most dairy feed barns, corrals and milk barns have historically been constructed close to watercourses to ease the job of disposing of the enormous accumulation of animal wastes. One hundred to four hundred cows confined to a small area for twelve hours or more each day produce mountains of manure. In the days when the ranchers located their installations in this fashion there was little thought of using the manure on the land." Water quality in the streams was also affected in the early to mid-1900s by localized farming practices in the Chileno Creek subwatershed. "Up until 1991, local landowners pumped water out of Laguna Lake in the summer so that the lake bed could be farmed. Due to thermal pollution and high ammonia levels the landowners have had to discontinue the practice of pumping this water into Chileno Creek (UCCE, 1995, p.42-43)."

Mercury was extracted at four primary locations in the Walker Creek watershed beginning in the 1940s: the Cycle and Franciscan Mines which drain to Arroyo Sausal, the Chileno Valley mine which drains to Chileno Creek, and Buena Suerta (Gambonini mine) which drains to Salmon Creek (California Regional Water Control Board, 1995 in Tomales Bay Watershed Council, 2003). The mines shut down by 1970, but their activity produced mercury laden sediments that are still traveling through the system. "Mercury continues to pose a long-term threat to downstream reaches of Walker Creek and Tomales Bay and further remediation is warranted" (Whyte, 2003 in Tomales Bay Watershed Council, 2003). Remediation efforts to control the discharge of mercury-laden mine wastes were blown out in large storms in 1981-82, 1990, and 1997-98, releasing many tons of mercury rich suspended sediments into Walker Creek. Concerns surrounding the mercury deposits and their effects on the ecosystem of Tomales Bay have led to the development of a mercury TMDL.

Other significant landuse activities include gravel mining at multiple locations on mainstem Walker, and the construction of the Soulajule Dam on Arroyo Sausal. An earthen dam impounding 670 acre feet of water was first constructed across Arroyo Sausal in the 1960s by a private landowner. This dam effectively blocked over half of the watershed's historic spawning grounds from migrating coho salmon and steelhead (Tomales Bay Watershed Council, 2003). Soon after the construction of this small dam, upstream landowners noted, and complained about, the dramatic decrease in winter migration of steelhead into the headwaters of Arroyo Sausal (Jones, 1969). A larger dam was constructed in 1980 at the same location. Built by MMWD, Soulajule dam impounds 10,570 acre feet of water for supplying water to the municipalities of Marin County. Most of the captured water is pumped as needed over the hills to the Nicasio Reservoir.

On January 4, 1982 the flood of record occurred in the Walker Creek watershed. This flood is generally considered to have been a 100 year storm event for northern Marin and Southern Sonoma Counties. The impacts of the flood were extensive. Shallow landslides appeared throughout the watershed, gullies were reinitiated and flushed out, and widespread bed and bank erosion occurred. Large amounts of sediment was mobilized throughout the channel network, scouring upstream reaches, depositing sizeable gravel bars in the middle reaches, and aggrading the lower reaches near the mouth. On February 2, 1998 a significant flood took place, contributing to gully widening and headcut development and movement. Remnant effects of the 1982 and 1998 floods are still visible throughout the watershed in active gully growth and in-channel knick point migration.

Summary of Impacts and Channel Conditions

Intensive land-use practices, in conjunction with highly erosive soils and heavy winter rainfall events have led to extensive landscape changes and ecosystem degradation in the Walker Creek watershed. The primary landscape alterations over the last 200 years have been: 1) gully formation and migration in upland grasslands; 2) arroyo development in first order tributaries and incision of 2nd and 3rd order creeks; 3) extensive sedimentation of the lower reaches of Walker and Keys Creek; 4) alteration of both hillslope and channel hydrologic regime; 5) reduction of channel structure and instream habitat; 6) excessive fine sediment intrusion; and 7) critical decline of the salmonid populations.

Periods of incision and aggradation are a natural process in the Walker Creek watershed. Haible (1980) postulates that the alluvial fill in Walker Creek, Salmon Creek, and Arroyo Sausal valleys was deposited during a 4000 year period from 5,000 Before Present (BP) to 1,000 BP. Several old channel elevations—terraces in the—alluvium can be seen throughout these reaches. In 1915 the floodplain was approximately 5 feet above the present-day floodplain and, on average, 12 feet below the high terrace. This historic floodplain is now an inset terrace. It is unknown whether the incision process from the high terrace to the historic floodplain was gradual or occurred in short, discrete periods like the recent incision.

The pronounced period of gully formation, arroyo development, and channel incision in the 1800s and early 1900s appears to be a result of removal of riparian forest, changes in upslope vegetation composition, and direct impacts from agriculture, grazing, and trail formation. Channel development and incision has led to loss of productive rangeland, lowering of the water table, and increased sediment loads in the system. The increased sediment loads have caused channel aggradation in the low gradient portions of the watershed and loss of channel form throughout the system (siltation of pools and riffles).

WATERSHED ANALYSIS METHODS

A preliminary watershed analysis was performed by mapping geology, soils, channel slopes, valley width, stream order, and landuse practices. With this information, combined with a general understanding of channel morphology throughout the watershed, a number of channel reaches with similar geomorphic characteristics were distinguished. Collection of detailed morphology data and analyses of historic air photos provided additional information to further refine and delineate the similar reaches. The resultant channel reach types and locations were based on valley characteristics (width and slope), sediment dynamics (erosional, depositional, or transport dominated), channel features (degree of entrenchment and channel planform), stream order (1st order, ephemeral gullies versus 2nd and 3rd order perennial streams), and historic channel behavior.

Reference study sites were selected within each geomorphic channel reach type for detailed morphologic description and analysis. These sites and the channel reaches were then classified by planform geometry, channel morphology, and evolutionary stage. Appropriate channel enhancement actions for habitat restoration and sediment management are then based on the understanding of channel dynamics and processes occurring in each reach, as derived from this analysis.

Reference Sites

Two reference sites were typically established and sampled for each of the delineated geomorphic channel reach types. Within each reach type the 'A' site was chosen as representative of a dynamic equilibrium condition with developed channel features (stable) within that reach, and an additional site (B) showing signs of disequilibrium or lack of well-developed channel features (unstable). Site locations were chosen from analysis of aerial photographs, site visits, the presence of historic restoration projects, and access permission.

At each reference site, channel features were surveyed and measured to characterize the average channel morphometry and sediment distribution. Using a total station to collect topographic data, an average of five cross sections per site was surveyed, including riffle, pool, and run features. From this data, channel and floodplain dimensions were determined (bankfull width and depth, channel area, and floodplain width), as well as planform characteristics such as sinuosity and valley slope. Additionally, a detailed longitudinal profile of the thalweg was surveyed to determine remnant pool depths and channel slope.

Sediment Sampling

Sediment size distribution data was collected on riffle gravel bars and floodplain features. A surface particle size distribution (Wolman count) was performed at a riffle feature in each reference reach and bulk subsurface samples were collected at a riffle feature and floodplain deposit. The channel bed surface- and subsurface-size distribution analysis was used to characterize differences between and within the geomorphic channel reach types.

Channel Classification

The classification of channels can range from simple planform description to more complex morphological analysis that includes cross-sectional geometry, slope, and bed-material size distribution. Channel-adjustment based classifications have recently been developed that are based on fluvial processes and adjustment trends. Additionally, the stages of evolutionary response typically seen in river systems affected by aggravating landuse practices, flow regulation, and altered sediment dynamics are outlined by a model of channel evolution.

In this study, multiple classification schemes were used to describe the geomorphic reach types. Rosgen's (1996, 1998) stream classification method was used to morphologically compare the channel reaches. Reference site channel measurements were used in this classification, and include bankfull width, mean depth, width-depth ratio, maximum depth, width of flood-prone area, entrenchment ratio, channel materials, slope, and channel sinuosity. Comparison of the Rosgen stream classes found within a geomorphic reach type may indicate a direction of channel adjustment towards a stable planform and morphology. Two process-based classification schemes were also used to define the *state* of the channels adjustments to system perturbations. Downs' (in Downs and Gregory, 2004 and Thorne et al, 1997) classification system is based on linking observed trends in channel behavior such as aggradation, degradation, channel shifting, bar development, and bank erosion to the physical processes driving the adjustments. The channel evolution model first developed by Schumm et al. (1984) for incised channels and modified by Hupp and Simon (1991, in Downs and Gregory, 2004) provides insight into the response *stage* an incised channel is currently in, and the future expected behavior as the channel system relaxes into a new dynamic equilibrium. The later two classification methods use interpretive judgment based on field observations, historical channel and landuse data, and understanding of process-form relations.

CHANNEL REACH ASSESSMENTS

Six primary channel-reach types were delineated and named (Figure 8, Table 1). The type names describe the characteristic channel environment and dominant sediment behavior.

Table 1. *Geomorphic Reach Types and their distribution throughout the Walker Creek watershed. Also see Figure 9.*

Reach Type #	**Name**	**Location**
1	Alluvial Valley Transfer/Deposition Zone	Keys Creek, Chileno Creek, Upper Salmon Creek, Middle Arroyo Sausal (Hicks Valley)
2	Incised Transfer Zone	Lower Salmon Creek, Lower Arroyo Sausal
3	Inset Floodplain Exchange Zone	Middle and Upper Walker Creek
4	Valley Transfer Zone	Lower/Middle Walker Creek
5	Tidal Deposition Zone	Lower Walker Creek
6	Upland Gully Source Areas	Throughout watershed

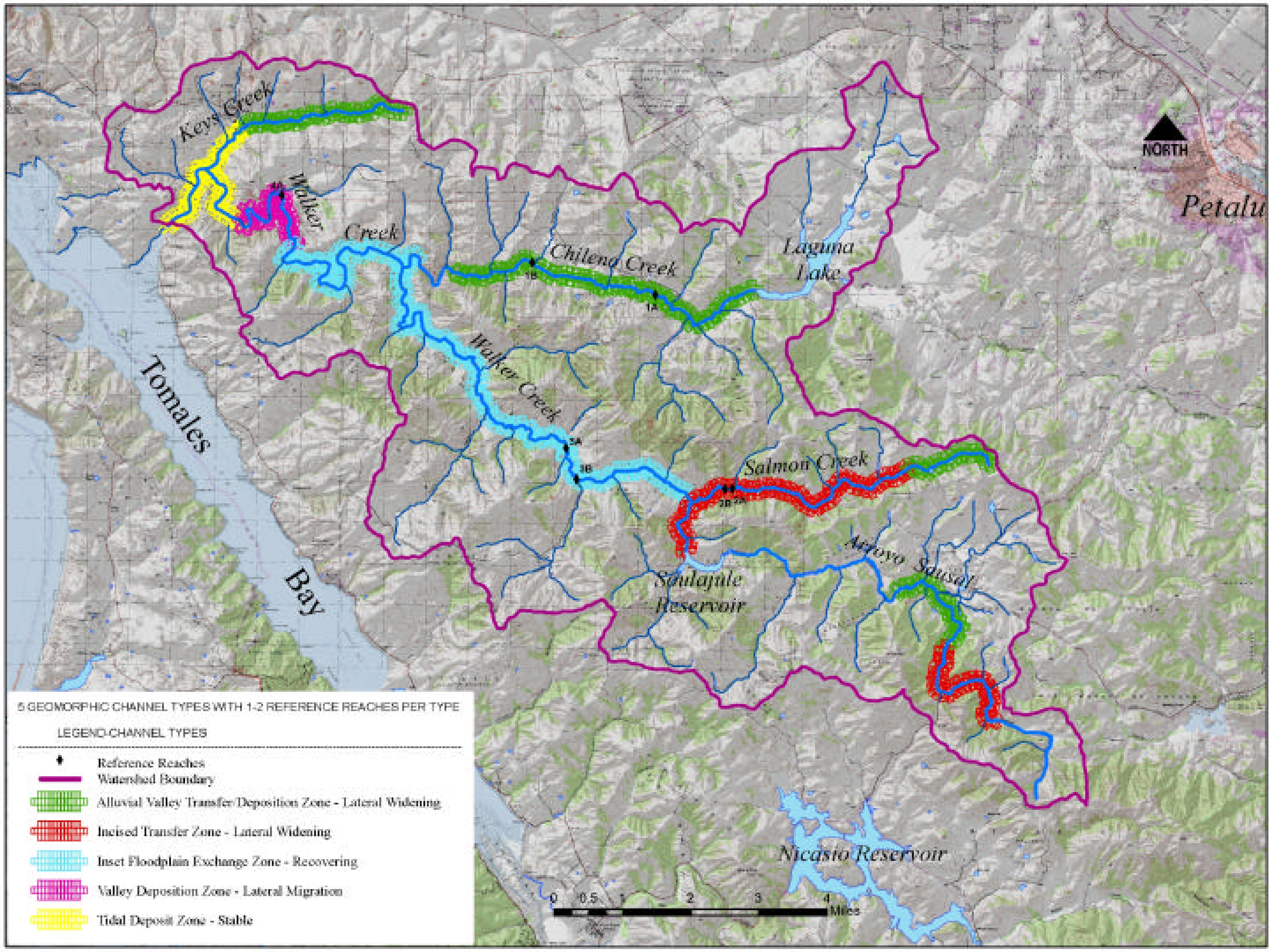

***Figure 8**. Delineation of geomorphic channel Reach Types throughout the watershed.*

#1 - Alluvial Valley Transfer/Deposition Zone

Channel Reach Type #1 is found in the broad alluvial valleys of Keys Creek, Chileno Creek, and Arroyo Sausal (Figure 8). The creeks in these locations are incised into fine-grained alluvial sediment with a straight to slightly meandering channel pattern (Figure 9). It appears that sections of the main channels and their tributaries may have been straightened and channelized.

Figure 9. *An example of the Alluvial Valley Transfer/Deposition Zone shown with Chileno Valley looking upstream. Straightened reach in lower left of photograph with black arrow pointing to possible original channel course. Blue circles indicate reference site locations.*

Prior to European settlement and associated landscape modifications it is likely that the creeks flowed through a wide, thickly vegetated riparian zone. The majority of the sediment produced in this valley was stored in alluvial fans at tributary mouths or on the floodplain. The channel planform may have been either a single thread, sinuous channel or a multi-threaded, anastomosed channel.

Riparian vegetation removal, channelization, increased sediment delivery, and altered flood hydrology led to rapid incision through general bed degradation and headcutting. It is likely that incision of the perennial channels initiated gully development and headcut migration in the 1st order drainages. The gully systems in these alluvial valleys were fully developed by 1942. Large, active gravel bars and areas of bank erosion are clearly visible in aerial photos from 1942 and 1984. By 1998 the gravel bars appear to have stabilized and active bank erosion has decreased significantly (Figure 10).

Figure 10. *Reference site location on Chileno Creek showing in-channel sediment changes between 1942 (left) and 1998 (right).*

Reference Sites

Two reference sites were chosen in Chileno Creek to represent the range of channel forms seen in the Alluvial Valley Transfer/Deposition Zone reach type. The A—stable, dynamic equilibrium—site is located in the middle of the valley (upper circle in Figure 9, Figure 10). This stretch of Chileno Creek is wider and more sinuous than many sections of channel upstream and downstream. Additionally, exclusionary fencing was installed and riparian planting occurred at the 1A reference site in 1996, and is thus well vegetated with willows and upland shrubs.

This site and other similar stretches were labeled the entrenched, meandering form, and are characterized by the following features:

- Meandering channel within incised banks.
- Alternating inset floodplains and point bars.
- Well defined pool-riffle structure.
- Riparian vegetation stabilizes and enhances in-channel features, promotes sediment deposition.
- Stable knick-zones in vegetated reach.

The B – unstable, adjusting – site, at the lower end of Chileno Valley may have been straightened and channelized, or is a naturally occurring straight channel form (lower circle in Figure 9, Figure 11). The majority of channels in this Reach type fall into this entrenched, straight form. The following features are characteristic of this form:

- Narrow, incised channel.
- Alternating, low gravel bars.
- Few, widely spaced pools that become disconnected in summer.
- Small, intermittent floodplain strip (formed by bank slumping).
- Little to no riparian vegetation.
- Erosion on selective alternate banks.

Figure 11. *An example of the straight channel form in the Alluvial Valley Transfer/Deposition Zone. View is looking downstream at site 1B during winter base flow.*

Channel form comparisons indicate that the gradient through both reference sites is low (0.003). Figure 12 illustrates the differences in channel cross section form. Entrenchment and width-to-depth ratio is high in the straight type and moderate in the meandering type.

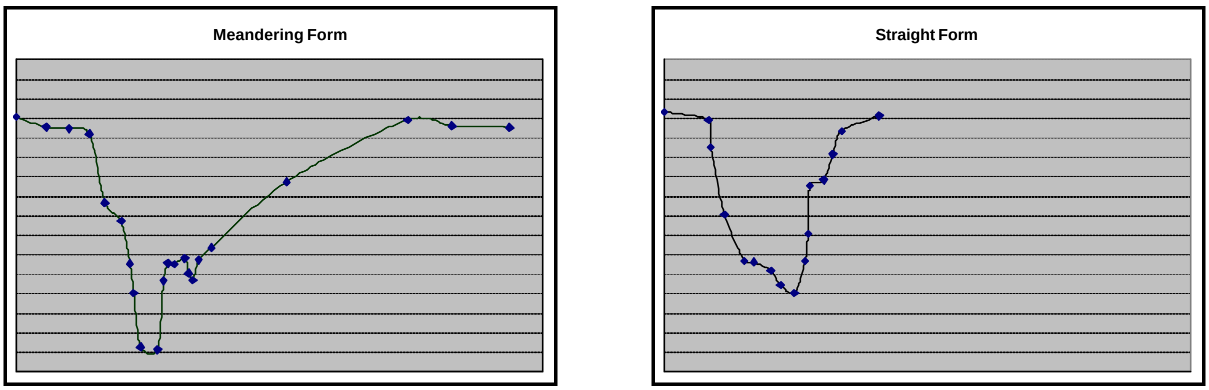

Figure 12. *Comparison of typical cross sections in the meandering and straight channel forms in Reach Type 1 – the Alluvial Valley Transfer/Deposition Zone. Note differences in active channel and floodplain widths, as well as channel depths.*

Classification

Table 2. *Classification of channel forms in the Alluvial Valley Transfer/Deposition Zone reach type.*

1A - Meandering Form	**1B - Straight Form**

• Rosgen Classification
  o C5 channel (transitioning)
  o Slightly entrenched, well-defined meandering
  o Phankuch channel stability - good
• Downs Classification
  o R – recovering (vegetated), s – stable
• Channel Evolution Model
  o Stage 6 – quasi-equilibrium
	• Rosgen Classification
	  o F5 channel
	  o Entrenched, meandering, laterally unstable
	  o Phankuch channel stability – good
	• Downs Classification
	  o s – stable, m – lateral migration
	• Channel Evolution Model
	  o Stage 4/5 – degradation, aggradation and widening

Channel Dynamics, Sediment Distribution, and Habitat Features

The channels in the Alluvial Valley Transfer/Deposition Zone appear to be transferring the sediment entering the system. Gravel bars throughout the reach are composed of fine gravels and coarse sand, and appear stable. Channel migration is minimal, and the limited bank erosion occurs primarily on alternating banks.

Establishment of riparian vegetation in the entrenched channel leads to development of well-defined channel features such as pool-riffle complexes, inset floodplains, and high-flow side channels. Dense, woody vegetation in an incised channel both concentrates flow to scour pools and sorts riffle gravels as well as slowing overbank flows for deposition of fines on the floodplain. This process increases flow differentiation, leading to the creation of the complex habitat structure necessary for a healthy stream system.

Re-establishment of a continuous, complex riparian corridor in Reach Type 1 may lead to general aggradation within the incised channel, returning the system to its pre-development sediment storage function. Flood heights and duration may increase in the lowlands bordering the channel with in-channel vegetation growth and sediment aggradation. Flooding in this type of environment redeposits fine sediment and nutrients on the floodplain, slows flow velocities for reduction of downstream bank erosion and flooding, and increases important over-wintering habitat for steelhead and coho salmon.

#2 - Incised Transfer Zone

Salmon Creek and Upper and Lower Arroyo Sausal are grouped into Reach Type #2 (Figure 8). This Reach Type is generally characterized by narrow, deeply incised channels with mature riparian vegetation (Figure 13). These sections are steeper than most in the watershed and have a higher percentage of coarse material in the bed. The planform ranges from straight to moderately sinuous.

Figure 13. *An example of Reach Type 2 – Incised Transfer Zone. Middle Salmon Creek shown in photo with flow from lower left to upper right.*

As in other areas of the watershed, these narrow valleys were cleared for grazing and cultivation, though this probably occurred later than in the alluvial valleys of Chileno and Keys Creeks. According to long-term residents of the watershed, in 1915 the channel floodplain was stable at approximately 5 feet below the valley flat. In the following 60 years, the channel incised 5-8 feet to its present elevation (Haible, 1980). Aerial photos from 1942 and 1984 show areas of active bank erosion and sediment deposition throughout this Reach. By 1998 it appears that bank erosion has decreased (Figure 14). Sections of channel that lack riparian vegetation show signs of chronic erosion along the over-steepened banks. Active knick zones are moving up the channel.

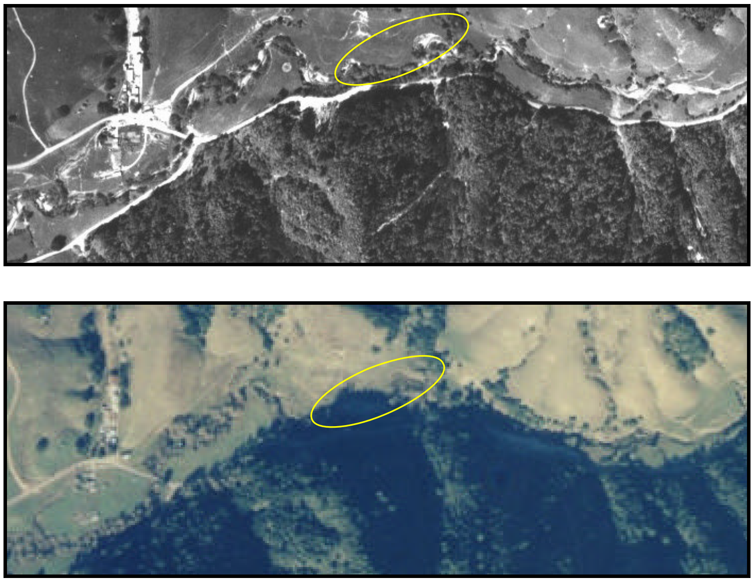

Figure 14. *1984 (upper) and 1998 (lower) aerial images of lower Salmon Creek showing typical sediment and bank changes in the Incised Transfer Zone. Yellow ovals indicate the location of the reference sites for Reach Type 2.*

Reference Sites

As was seen in Reach Type 1, the Incised Transfer Zone Reach exhibits two channel types. Site 2A represents the entrenched, meandering channel form found at locations within this Reach type that have undergone channel widening. The reference site was a chronic meander bend erosion site until the late 1980s when, under the instigation of the MRCD, an inset floodplain was built using a reinforced willow wall, exclusionary fencing was installed, and willow and alder were planted. Subsequently the channel has migrated to the other side of the channel bottom and deposited a wide, complex floodplain (Figure 15). The following features are characteristic of the meandering form of Reach Type 2:

- Moderately sinuous channel pattern.
- Inset floodplains and point bars.
- Well developed pool-riffle sequences.
- Deep pools associated with root wads and debris jams.

Figure 15. *Example of channel and floodplain in the 2A reference site. Flow is from right to left with constructed willow wall in the far background across grassy floodplain.*

The 2B reference site represents the other extreme of channel form in the Incised Transfer Zone Reach. In many sections of this Reach the channel is narrowly confined by steep banks, and riparian vegetation is limited to the edges of the inset terrace (Figure 16). Characteristic channel features of this entrenched, straight form include:

- Incised channel.
- Riffle/run dominated.
- Alternating coarse gravel bars.
- Few, small inset terrace remnants.
- Shallow, widely-spaced pools.

Figure 16. *Example of entrenched, straight channel type. Flow is away from the camera.*

Stream gradient through the reference sites is low (0.008). Figure 17 illustrates the differences in channel cross section form. Entrenchment and width-to-depth ratio is moderate-high in the straight type and moderate in the meandering type.

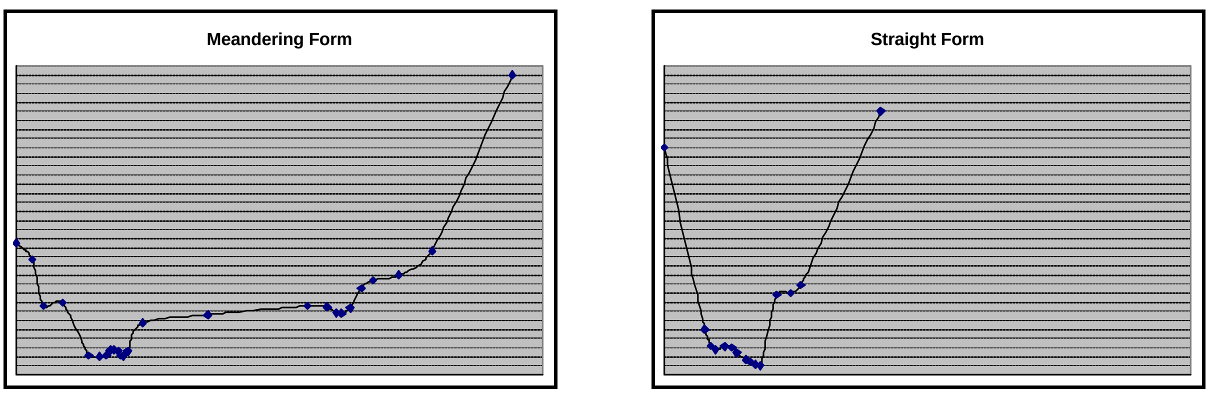

Figure 17. *Comparison of typical cross sections in the meandering and straight channel forms in Reach Type 2 – the Incised Transfer Zone. Note differences in active channel and floodplain widths, as well as channel depths.*

Classification

Table 3. *Classification of channel forms in the Incised Transfer Zone reach type.*

2A - Meandering Form	2B - Straight Form
• Rosgen Classification o C4 channel o Slightly entrenched, well-defined meandering o Phankuch channel stability - good • Downs Classification o R – recovering (vegetated), m – lateral migration • Channel Evolution Model o Stage 5-6 – aggradation and widening to quasi-equilibrium	• Rosgen Classification o B4c channel o Entrenched, riffle dominated, laterally unstable o Phankuch channel stability – poor • Downs Classification o M – Lateral Migration • Channel Evolution Model o Stage 4-5 – degradation, aggradation and widening

Channel Dynamics, Sediment Distribution, and Habitat Features

Channels in Reach Type 2 typically function as sediment transfer zones with little net aggradation or degradation occurring. Discrete bank erosion sites like that shown in Figure 18 are chronic sediment sources. Channel widening through bank erosion is the natural process associated with the channel evolutionary stage seen in the Incised Transfer Zone Reach. Rapid incision leads to destabilization of channel banks, especially in areas with minimal woody riparian vegetation to stabilize the banks. This process combined with reduced sediment loads from improvements in land use practices and gully erosion-control naturally initiates channel widening through meander bend migration. Channel widening, if combined with grazing control and riparian vegetation establishment, will lead to complex channel feature development and sediment storage.

Figure 18. *Characteristic terrace/bank erosion in Channel Reach Type 2 – Incised Transfer Zone. Flow is away from the camera.*

The bed material in this Reach is generally coarser (coarse gravel and cobble) than other portions of the watershed, and thus provides the greatest potential spawning material. Fine sediment intrusion and lack of channel structure (defined pools and riffles) limits the fisheries habitat value. Areas that have widened and support mature riparian vegetation provide spawning and rearing habitat.

#3 - Inset Floodplain Exchange Zone

The majority of the Walker Creek mainstem is typed as the Inset Floodplain Exchange Zone – channel reach type #3 (Figure 8). A broad, active floodplain is inset into high, Holocene terraces (Figure 19). Dense riparian woodland has established itself throughout most of this Reach since the mid 1980s. Knick zones appear to be moving up the system. Channel avulsions are common and multiple side channels are present in most sections. High mid-channel gravel bars are remnant from the 1982 flood.

Figure 19. *Upper Walker Creek mainstem as an example of the Inset Floodplain Exchange Zone channel reach type. Flow is from left to right.*

Air photos of the Walker Creek watershed (1942, 1950p, 1984, 1988p, and 1998) show dramatic changes in sediment volume, transport, and depositional features in mainstem Walker Creek. In 1942 the active channel area was wide and unvegetated. Large alternating gravel bars filled the active channel bottom (between incised terraces) and the low flow channel planform was straight with sharp transitions across the alternating bars (Figure 20). By 1984 mainstem Walker and lower Chileno Creek showed a narrowing of the active channel bottom with woody riparian vegetation establishment. However, large gravel bars still dominated the floodplain, and terrace erosion and floodplain widening had occurred in several locations since 1942. By 1998 the channels appear to have stabilized. Very few large gravel bars are visible in upper mainstem Walker and lower Chileno Creek. Thick riparian vegetation fills the floodplain from the confluence of Salmon Creek and Arroyo Sausal down to the Brazil property.

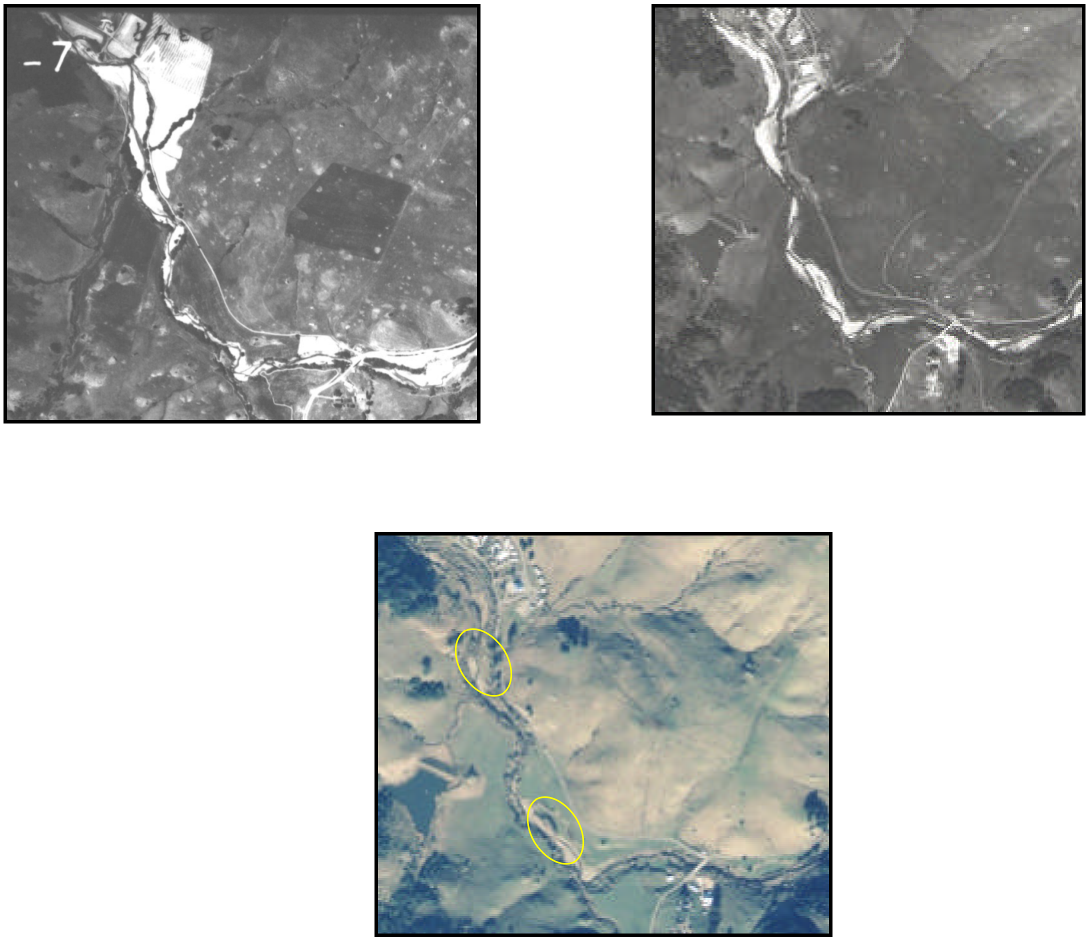

Figure 20. *Comparison aerial photos of upper Walker Creek to illustrate the channel changes that occurred over a 55 year period. Note terrace erosion and gravel bar development between 1942 (upper left) and 1984 (upper right). Riparian development and increased channel sinuosity is seen in the 1998 photo (lower). Reference sites shown by yellow circles.*

Reference Sites

Three reference sites were surveyed in Reach Type 3 to confirm that a single channel type is present throughout the Inset Floodplain Exchange Zone. The range of features seen in this Reach is shown in Figure 21. Characteristic channel features include the following:

- Wide, active-channel zone inset into Holocene terraces.
- Riparian forest continuous throughout Reach.
- Primary channel is moderately sinuous with active gravel point bars.
- Multiple overflow channels across width of floodplain.

- Pools associated with bedrock outcrops and debris jams.
- Depositional floodplain with gravel grading to fines.
- Knickzones and channel avulsions common.

Figure 21. *Typical channel and floodplain features in the Inset Floodplain Exchange Zone.*

Classification

Table 4. *Classification of channel forms in the Inset Floodplain Exchange Zone reach type.*

Reach Type 3

• Rosgen Classification
  o C4 channel
  o Slightly entrenched, meandering
  o Phankuch channel stability - good

- Downs Classification
  - R – recovering ,
    d – depositional
- Channel Evolution Model
  - Stage 6 – quasi-equilibrium

Channel Dynamics, Sediment Distribution, and Habitat Features

This Reach has historically been very dynamic with active gravel bars across the wide floodplain and extensive erosion of the Holocene terraces. Haible (1980) documented that the elevation of the floodplain degraded 5 to 8 feet between 1915 and 1975. Comments from long-term residents of the watershed indicate that the majority of this incision occurred prior to 1950. The active channel subsequently widened dramatically in many areas between the 1940s and early 1980s. Barren, active gravel bars extended across the active floodplain width during this dynamic period.

Reduced grazing pressures combined with altered peak storm events and sediment loads from Soulajule Dam have allowed a dense riparian forest to re-establish throughout most of the Reach. Coarse and fine-grained sediment is deposited on the floodplain, forming complex features. Sediment is temporarily stored in this Reach and remobilized by knick zone migration and channel avulsions. Although the channel in this reach is near dynamic equilibrium conditions, it is still responding to the complex and ongoing adjustments occurring throughout the watershed.

Reach Type 3 provides over wintering, rearing, and spawning habitat. Fine sediment intrusion into pools, riffles, and runs is still an issue. Deep pools are available near bedrock outcrops and debris jams. The spacing and depth of pools is likely to increase as woody debris is added to the system.

#4 - Valley Transfer Zone

A short reach of lower Walker Creek above the tidal zone (approximately 2 miles upstream of the confluence of Walker and Keys Creek) is typed as the Valley Transfer Zone – channel reach type #4 (Figure 8 and 22). Broad, flat terraces border the channel. These terraces are 5-6 feet above the active channel and are equivalent to the high Holocene terraces found in the upstream reaches 20-30 feet above the channel bed. The terraces are composed of fine-grained overbank deposits that form vertical banks on the outside meander bends. Low elevation point bars dominate the active channel width. Little riparian vegetation is found in this Reach.

Figure 22. *Overview of the Valley Transfer Reach. Development of a sinuous channel and meander bend migration has occurred since 1984, eroding terrace pasture land. Flow is from left to right.*

Historically the channel planform was similar to that seen in Reach Type #3—straight low-flow channel with large alternating gravel bars (Figure 23). However, unlike the upstream reaches, the Valley Transfer Zone has not uniformly stabilized with riparian vegetation. The broad, active gravel bars have narrowed and stabilized with a riparian strip along disconnected sections of the valley edge. The low-flow channel planform appears to be transitioning to a sinuous pattern. Development and migration of meander bends have cut into the Holocene terrace, forming steep, actively eroding banks and fine-grained, low-elevation point bars.

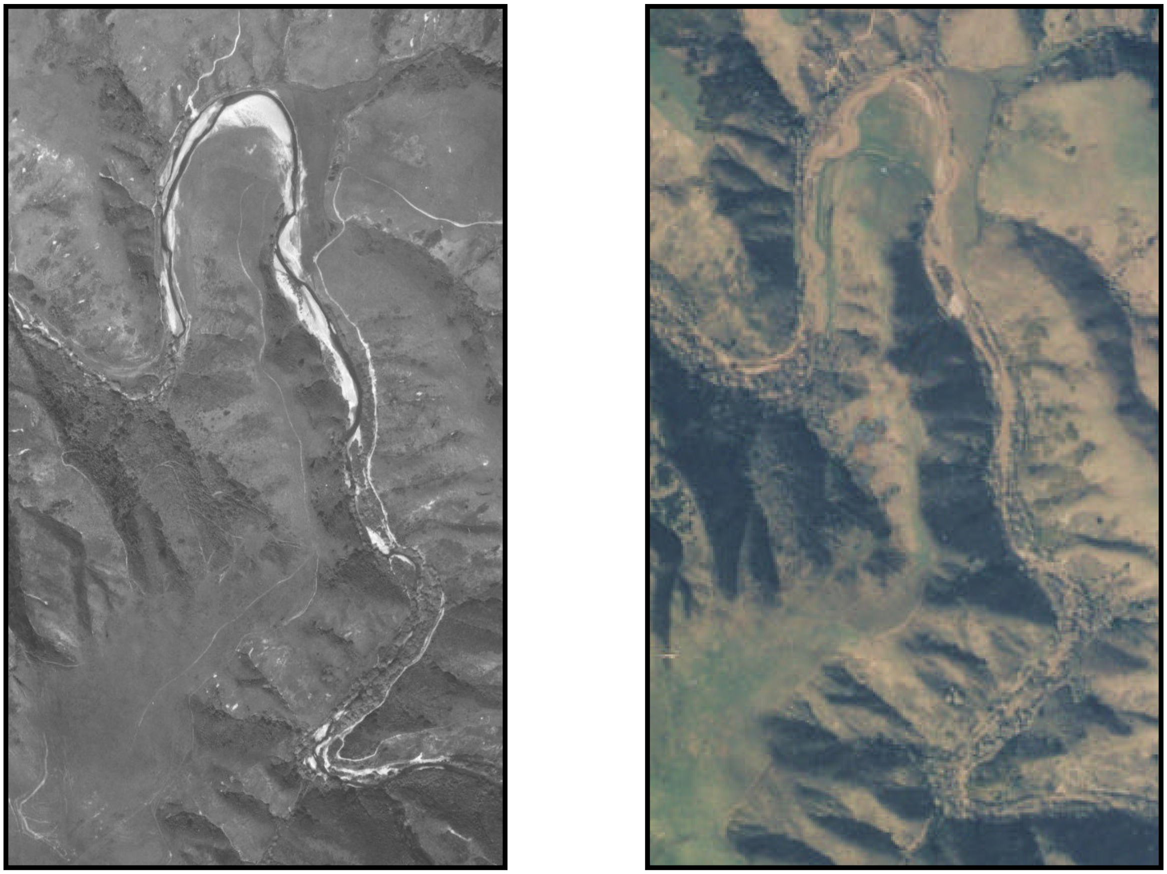

Figure 23. *Comparison of 1984 (left) and 1998 aerial photographs of the Valley Transfer Zone on mainstem Walker Creek.*

Reference Sites

No reference sites were measured in this Reach, as access was not available.

Classification

Table 5. *Classification of channel forms in the Valley Transfer Zone reach type.*

Reach Type 3
• Rosgen Classification o C4/C5 channel o Slightly entrenched, well-defined meandering • Downs Classification o R – recovering ,

m – lateral migration

- Channel Evolution Model
  - Stage 5-6 – aggradation and widening to quasi-equilibrium

Channel Dynamics, Sediment Distribution, and Habitat Features

It appears that sediment moving through the system is annually mobilized and redeposited in this reach, although not at the levels seen previously. The formation of a more sinuous channel pattern in this reach, and the consequent bank erosion are likely a result of decreased sediment loads. Reduction of overall sediment loads after the construction of Soulajule Dam and increased sediment storage in upstream reaches has altered the allocation of hydraulic forces. The available stream power was previously used to transport the abundant sediment load. With this reduced sediment load the hydraulic energy of the streamflow is now expended in planform shifts and bank erosion.

Without riparian vegetation to stabilize the banks and dissipate excess hydraulic energy, the high rates of bank erosion and meander migration are likely to continue. Bioengineering techniques that include laying the vertical banks back and establishing willows may be used to stabilize the exposed banks and reduce the amount of annual erosion. The hydraulics of this reach are likely cause scour at the bend inflection points and repair failure, thus multiple plantings may be necessary in some locations. Rock bank repairs are not recommended as the erosion location will quickly migrate, requiring additional stabilization work. Once established, riparian vegetation combined with grazing control will also lead to enhanced channel structure, providing improved habitat for migrating salmonids. In general, this reach functions primarily as a through passage to upstream spawning, over-wintering, and rearing habitat.

#5 - Tidal Deposition Zone

From the mouth at Tomales Bay upstream to approximately 2 miles upstream of its confluence with Keys Creek the channel behavior and morphology is largely driven by tidal influences. This tidal zone also extends to the town of Tomales on Keys Creek, or did historically (Figure 8 and 24). Thus, this section of the watershed is typed the Tidal Deposition Zone. The bulk of the sediment delivered to this Reach is deposited in the channel or floodplain. Coarse sediment that enters this settles out in the upstream sections, with the location dependent upon hydraulic interactions of tide and streamflow. The grain-size distributions of the channel and floodplain deposits tend to decrease with proximity to the mouth. Sediment that makes it through the system is likely to be deposited on the delta at the mouth.

Figure 24. *The Tidal Deposition Zone extends from the mouth upstream to the town of Tomales on Keys Creek and approximately 2 miles upstream of the Highway 1 bridge on Walker Creek. Extensive aggradation of this reach occurred in the late 1800s. Fine sediment continues to accumulate and enlarge the delta at the mouth.*

The land use history and resultant changes in channel behavior in this Reach was previously outlined in the historical section. Channel aggradation occurred rapidly after the introduction of cultivated agriculture to the watershed. High sediment loads from Keys and Chileno Creeks initially filled in the deep tidal channels. Mainstem channel incision in the early 1900s contributed large amounts of sediment to this reach; building the delta into Tomales Bay, narrowing the channel, and depositing 4 feet or more of sediment on the floodplains.

No reference sites were surveyed in this reach as its habitat value and restoration potential is limited. Reduction of upstream sediment loads will promote entrainment and transport of sediment currently stored in this reach. Sites within this Reach may be used as summer rearing habitat by steelhead, though it is primarily considered to be a travel and resting zone on their way in and out of the watershed.

Upland Gully Source Areas

Extensive gullying is found in all portions of the watershed, and is the primary contributor of sediment to the tributaries and mainstem. The early European land-use practices and resultant changes to the hydrologic and sediment regimes that led to channel incision in the mainstem and principal tributaries concurrently impacted the upland drainage systems. Main channel incision combined with vegetation removal and increased runoff from grassland denudation instigated headcut development in the 1^{st} and 2^{nd} order, ephemeral tributaries. These headcuts quickly translated upstream. By the 1940s gully incision processes had developed an extensive, entrenched drainage network. The new upland channels were effective at transporting sediment and storm flows to the main channel system, contributing to further incision, habitat loss, and downstream aggradation.

The large-magnitude storm in the winter of 1982 destabilized many slopes, mobilizing large amounts of sediment and initiating new headcut and knickpoint activity. Many of the gully processes seen in the watershed today are ongoing landscape reactions to a combination of destabilizing historical landuse practices and the recent extreme hydrologic events of 1982 and 1998. Knickpoints are moving up the incised channels, channels are widening through slumping and lateral bank erosion, and headcuts are forming in grassland swales (Figure 25). Gullies are the primary sediment production and delivery features in the watershed. Their dynamics and potential for stabilization are discussed in more detail in the following sections.

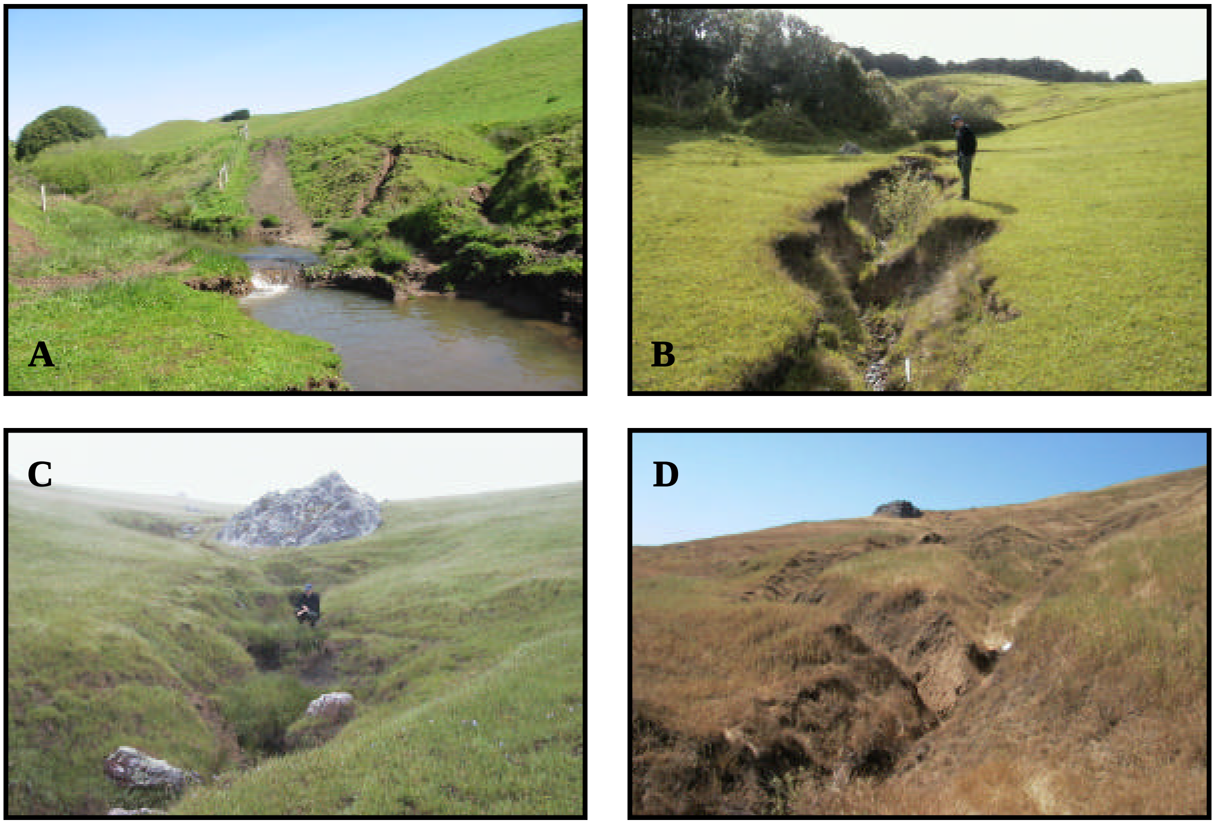

Figure 25. *A selection of active gully sites in the Walker Creek watershed. Images A and B are examples of locations that are appropriate for more aggressive gully repair methods that control widening and extension processes and promote channel aggradation. Sites such as C and D are examples of low repair priority sites due to the potential sediment yield and erosion processes—these sites would benefit from exclusionary fencing and revegetation.*

SEDIMENT DYNAMICS

In-channel sediment distribution, features, and dynamics were observed and sampled during site visits to the geomorphic reference reaches throughout the watershed. These on-site observations were supplemented with 1998 air photos and oblique landscape photographs and channel descriptions taken during the Walker Creek Erosion Assessment (PCI, 2001). Information developed from this analysis provides a snapshot of localized conditions and features, as well as a general picture of reach-wide transport and deposition dynamics. The assessment of current, overall channel form and sediment distribution was then compared to the historic conditions, as observed in 1942, 1953, and 1984 air photos.

Accounts of landuse changes over time, sedimentation issues, and channel-form change in the sub-watersheds, combined with air photo analysis, allows inference of historic sediment sources and relative yields. Recently active sediment sources were inventoried in 2000 and 2001 by PCI. Fifty-eight percent of the watershed (below Soulajule Dam and Laguna Lake) was assessed for erosion sites. This database was reviewed to assess sediment sources and the ranking of each erosion type in relation to total relative sediment yield. Historic air photos were studied for indications of active erosion sites in 1942 and 1984. Only large-scale erosion features can be observed in the photos, thus many of the common sediment sources (gully headcuts, small bank failures) could not be historically inventoried.

Sediment Sources and Activity

Active sediment in the system (material with potential for entrainment and redistribution) is derived from both upland and channel sources. The relative percentage of sediment from each of these sources has changed with landuse practices and channel form alterations. Primary sediment sources in the watershed include sheetwash, gully extension and widening, channel incision through headcut migration, and bank erosion. Additional sources include, but are not limited to, landslides, rotational slumps, subsurface tunneling, animal burrowing, trampling, and rainsplash.

Hillslope sources contribute sediment primarily to colluvial storage. Sheetwash and landsliding may contribute directly to channel sediment, depending on landuse and proximity of the source to the channel. Disconnected gullies and tunneling (collapse pits) in upland swales temporarily store their sediment in colluvial hollows until they become incorporated into the 1st order tributary gully system through headcutting and bank erosion.

Production of in-channel sediment in Walker Creek is from three primary sources. The first is enlargement of the drainage network through downcutting and bank erosion in the 1st order tributaries and new gully development. Sediment produced from these processes originates from both colluvium and stored alluvium. Sediment from these sources ranges in size from fine silt and sand to cobble. The second source is 2nd and 3rd order channel bank erosion and bed mobilization. This sediment is generally Holocene alluvium, though some may be of Pleistocene origin deposited during a very different climate and channel regime. Channel bank materials are generally fine gravels, sand, and silt. The third source, contributing primarily fine sand and silt to the system, is near-channel sheetwash. Exposed surfaces from grazing pressure and livestock trails deliver fine sediment directly to perennial channels and indirectly across pastureland to gully and shallow drainage networks.

Erosion processes and relative sediment source activity is affected by landuse practices and changes in channel conditions. Most erosion processes occur naturally, as bedrock weathers and material is transported downslope through gravitational and hydraulic forces. Channels are dynamic, constantly adjusting systems that go through cycles of erosion and deposition, both temporally and spatially. Landuse practices can amplify erosion processes, causing increased rates of erosion and sediment yields. Table 6 lists the sediment sources in Walker Creek watershed and the landuses that affect sediment production levels. The erosion processes are also distinguished in Table 6 by their behavior—chronic or episodic sediment production activity.

Table 6. *Types of sediment sources in Walker Creek watershed and landuses that affect erosion activity. (Modified from Reid and Dunne, 1996)*

Sediment Source	Activity Type	Forces driving occurrence and severity				
		Natural	**Land Clearing**	**Grazing**	**Cultivation**	**Roads**
Landslides	Episodic	X	X	X		X
Gullies	Episodic Chronic		X	X	X	X
Sheetwash	Chronic	X	X	X	X	X
Bank Erosion	Chronic	X	X	X	X	
Channel Incision	Episodic		X	X		

The majority of new sediment production in the Walker Creek watershed is from gully development and expansion (Table 7). Headcuts are moving up most 1st order tributaries, reactivating gullies that appear to have been stable for a number of years and initiating gully development in upland swales. As headcuts move up gully systems, bank destabilization and widening occurs. Sediment derived from upland gullies ranges in size from cobble to silt. Episodic landsliding and gully development in the steep, shallow colluvium areas of the watershed appear to be the primary source of coarse material in the Walker Creek watershed.

Table 7. *Percentage of occurrence of erosion types in the subwatersheds of Walker Creek based on erosion inventories. Inventory spatial coverage was not complete, thus these numbers can only be considered representative. These numbers do not reflect the relative yields produced by each sediment source. Gullies, headcuts, and road-related erosion typically have a higher yield potential than bank erosion. Sediment delivery from landslides and slumping is episodic, yet can produce large amounts of sediment. (Modified from PCI, 2001: Table 1)*

Sediment Source	**Subwatersheds**						**Total Percentage by Source Type**
	Salmon Creek	**Lower Arroyo Sausal**	**Mainstem Walker Creek**	**Chileno Creek**	**Keys Creek**	**Lower Walker Creek**	
Headcut/ Gully	50	67	53	62	76	72	**61**
Bank Erosion	44		28	36	24	14	**29**
Road Erosion	6	33	8			7	**5**
Landslide/ Slump			11	2		7	**5**

Bank erosion and bed mobilization is occurring at levels that reflect a complex response to landuse impacts and their resultant channel evolutionary stage. Channels throughout the watershed have incised over the past 200 years. Minimal bank erosion is occurring in the reaches where appropriate widening has already occurred and riparian vegetation is present (Reach Type 3 and portions of Reach Type 1 and 2). Many of the channel reaches have not completed their post-incision widening cycle (Reach Type 2, Reach Type 6, and portions of Reach Type 1). During the widening phase of channel evolution bank erosion will be common and extensive, especially where stabilizing riparian vegetation is limited.

The remaining primary sources of sediment delivered to channels are roads and alluvial, rotational slumps. Ranch roads contribute to sheetwash, gully development, and landsliding. Undersized or poorly designed culvert crossings appear to be the main cause of road erosion. Many hillslope slumps that formed during large rainfall events over the last 20 years are still producing sediment through surface rilling and small scale sliding.

The total sediment yield and relative significance of each source has varied over time depending on landuse activities. Table 8 illustrates these temporal trends in the different sediment sources. It is likely that sediment yields in the watershed are at the lowest point seen since European settlement in the early 1800s. The construction of Soulajule dam in 1979 has further reduced the channel sediment load by impounding all sediment from the Arroyo Sausal subwatershed. Channel adjustments to this reduced load can be seen in the establishment of riparian vegetation on once-active gravel bars and transition to a sinuous channel planform within the incised banks. Reduced sediment loads are contributing to the natural recovery processes observed throughout many of the channels in the Walker Creek watershed.

Table 8. *Relative activity and yields for each of the major sediment sources for sequential time periods in Walker Creek. The periods correspond to significant changes in land use in the watershed (i.e. 1850-1900 primarily potato farming and land clearing; 1900-1950s some cultivated crops and high density dairies; 1950s-1980s transition to cattle ranching and rotational grazing; 1980-present Soulajule dam construction and channel enhancement projects, such as exclusionary fencing).*

Sediment Source	1850-1900s	1900-1950s	1950s-1980s	1980s-present
Landsliding	X	X	X	X
Gullies	XX	XX	XX	X
Headcuts	XX	X?	X?	XX
Channel Erosion	XXX	XXX	XX	X
Slopewash	XXX	XX	XX	XX
Road-related	X	X	X	X
Livestock-related	X	XX	X	X

Sediment Transport and Deposition

Sediment delivered to the channels via the processes and pathways described above is either transported out of the watershed or temporarily stored in the channel or floodplain. The capacity and mechanisms for sediment storage within each Reach Type are dependent upon channel planform and morphology. The dominant sediment process is indicated in the Reach Type name; however both processes occur to some degree and vary between channel forms within a Reach.

Most of the perennial channel reaches appear to have the competence to transport their available sediment loads. They may be transport-limited at some flows, as is evidenced by fine grained, in-channel deposits and poorly sorted gravel bars. A few reaches are clearly transport-limited with no equilibrium between their sediment and flow regimes; appearing to be inundated with high annual sediment delivery. Lower Chileno Creek is a reach where significant in-channel accumulations of unconsolidated sand and fine gravels are present and available for delivery downstream (Figure 27). Portions of Reach Type #3—Inset Floodplain Exchange Zone—have both the hydraulic competency and complex morphologic structure of channels in dynamic equilibrium (Figure 27). These reaches exhibit defined pool and riffle structure and the bed and bank material is well sorted by morphologic location, providing functional habitat.

Figure 27. *Comparison of channel features in transport limited (left) versus equilibrium (right) channels in Walker Creek.*

Prior to the last 10-15 years, sediment deposition and long-term storage in the watershed has been limited to the tidally influenced sections of Walker and Keyes Creek. Temporary in-channel and active gravel-bar storage took place in Reaches 1, 3, and 4 (Figure 8). Today significant storage occurs throughout Reach 3 and in sections of Reaches 1 and 2 that have widened and contain near-channel riparian vegetation. Density and maturity of riparian vegetation dictates the location, potential volume, and size distribution of stored sediment. Typically as tree and shrub species increase within the active flood zone, depositional features develop, including point bars, high lateral gravel bars, levees, side channels, eddy deposits, and marginal terraces. Woody riparian vegetation then further acts to stabilize the depositional features. Increased active floodplain widths also provide greater sediment storage area and complex depositional environments.

Fine sediment (silt, sand, fine gravel) is the size fraction considered to be most detrimental to ecosystem health in Walker Creek, as it smothers spawning gravels, fills in pools, and binds with mercury and biologic contaminants. Fines are found throughout the watershed in channel deposits—intermixed with gravels in the bed and bars, as overbank flood deposits, in discrete near-bank eddy deposits, and as thick accumulations in pools and glides after floods. Long-term storage opportunities for fine sediment require broad floodplain areas and complex vegetation structure to trap and stabilize deposits.

DISCUSSION – CHANNEL BEHAVIOR, FISHERIES HABITAT, AND RESTORATION POTENTIAL

The nature of channel adjustments to specific landuse practices, or more specifically the alteration of sediment and hydrologic regimes, has been well documented (Downs and Gregory, 2004; Thorne et. al., 1997). However, predicting the precise magnitude, spatial extent of the impact, and temporal adjustment period is difficult. This is especially true when multiple system perturbations have occurred over an extended period of time, as is the case in Walker Creek. Table 9 outlines the changes that typically occur with historic and present-day landuses. The number of system-disrupting factors combined with a highly sensitive stream network starts the development of a complex channel-response pattern. This complex response pattern makes a detailed assessment of potential channel change impractical.

Table 9. *Landuse and natural events impacting the hydraulic and morphologic characteristics of the Walker Creek watershed. Direction of change in each attribute is indicated as increasing (+), decreasing (-), or varied (+-). The occurrence time each of landuse disruption was outlined in the historical background and is generally listed from earliest to most recent. The length of time for the attribute to react to the landuse change is dependent upon system sensitivity, as well as magnitude and location of impact.*

	Sediment Discharge	Water Discharge	Roughness	Slope
Riparian Clearing	+		-	
Cultivation	+	+	-	
Channel Straightening		+		+
Grassland Composition Changes	+	+		
Grazing Pressures	+	+	-	
Channel Incision	+			+
Mining	+			
Soulajule Dam	-	+-		
Improved Land Management	-		+	
Large Floods (1982, 1998)	+	+		

General trends in response patterns to system perturbations can be determined by understanding the balance between four variables required to maintain a stable channel. Dynamic equilibrium can only be maintained by balancing sediment load, sediment size, stream discharge, and slope. The relationship is graphically illustrated in Figure 28. In Walker Creek, riparian vegetation density plays a greater role than sediment size in controlling aggradational and depositional processes, thus vegetation (or roughness) can be substituted for sediment size in Figure 28. Inserting the attribute response direction for various landuses or time periods (Table 8), one can track the common channel behavior. For example, in the 1800s through early 1900s sediment and water discharge was increasing while channel roughness had decreased substantially. The concurrent increases in sediment and water may have balanced themselves out, but the added factor of decreased roughness tipped the scale towards channel degradation. In the last 20 years, improved land management, sediment reduction projects, and increased riparian vegetation in many channel reaches has tipped the scale back towards dynamic equilibrium.

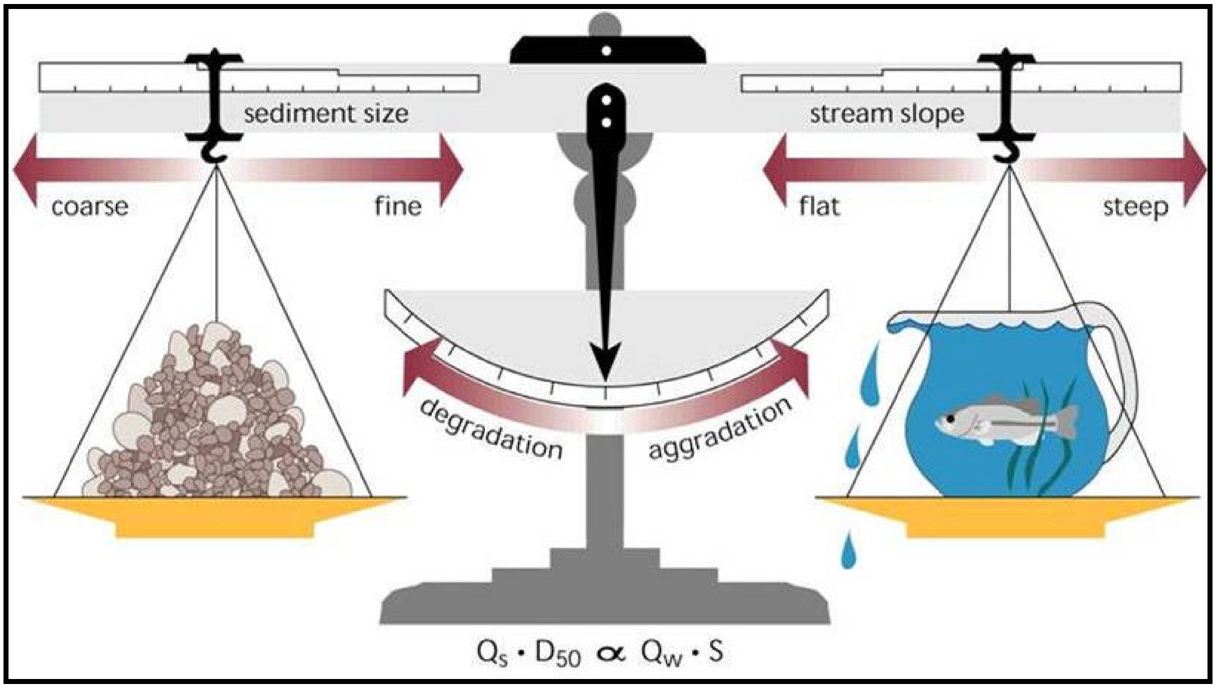

Figure 28. *Illustration of the general response pattern to changes in sediment size, sediment volume, stream discharge, and slope. In the Walker Creek watershed, vegetation density (roughness) can be substituted for sediment size in the above diagram. For example, if sediment load or riparian vegetation increases, channel aggradation will occur. However, high streamflows are likely to counteract that response and may cause channel degradation, depending on the magnitude of the flood. (Source: NOAA Sediment Removal Guidelines 2004, citing Lane 1955).*

Although a balance in the four variables that lead to channel stability and dynamic equilibrium may be occurring in some reaches of the Walker Creek watershed, the channels are still responding to the previous disruptions. This response can be seen in the form of multiple knickpoints and knickzones moving up the system, planform changes, and gully expansion processes. It is not possible to predict when, or if, these adjustments will taper off. As erosion control and riparian restoration projects are implemented additional complex channel responses are likely. Reducing sediment loads may initiate additional bed incision, but riparian revegetation offsets this effect and will potentially lead to channel aggradation. Because of the continued watershed unpredictability and sensitivity to system perturbations, enhancement projects that work with natural channels processes to move the system towards stability are favored.

Fine sediment intrusion and lack of channel structure appear to be limiting factors for steelhead and Coho salmon habitat health. Riparian cover, and its dependent variable water temperature, may also be a limiting factor. The restoration guidelines outlined in the following section provide suggestions for improving riparian and instream habitat quality. The dramatic channel incision observed throughout the watershed is a universal occurrence in the regional stream systems. Incised channels go through a well-defined sequence of adjustments on their way to ecosystem-function recovery. A large percentage of the Walker creek system is in the final two stages of this evolutionary sequence, exhibiting wide, inset floodplains and accretion of sediment in complex assemblages. Much of the stream network has the potential to re-establish a new quasi-equilibrium state that will provide enhanced functionality and habitat structure.

RESTORATION GUIDELINES

A sustainable ecological restoration of the Walker Creek watershed's waterways will use multiple approaches to enhance riparian function and habitat values. Fundamental changes in the channel network, drainage density, and hydrology will likely preclude complete recovery to pre-agricultural channel form and function. However, a level of channel stability and ecological function can be attained that reflects a dynamic equilibrium under the altered hydrologic and sediment regimes. The proposed enhancement actions (Table 10) are designed to assist the channel along its natural trajectory to a dynamic equilibrium condition. These actions include: 1) reducing fine sediment loads; 2) promoting sediment deposition; and 3) providing in-channel structure, such as complex riparian vegetation, that encourages adjustment toward morphologic function.

Table 10. *Listing of priority enhancement actions by channel Reach Type. Priorities are ranked from 1 to 3, with level 1 indicating the actions that will most effectively reduce fine sediment inputs and increase channel function and habitat. Action items ranked at level 2 or 3 are important enhancement actions that will either have a less marked effect on channel characteristics or are natural adjustments that happen over longer time frames.*

Channel Reach Type (#)	Function and Habitat Enhancement Actions	Relative Priority
Alluvial Valley (1)	Promote riparian vegetation establishment and maturation.	**1**
	Provide dense grassland-filter buffer zone along channel banks. Install riparian fencing.	**1**
	Reduce sediment delivery from gullies, 1st order tributaries, and sheetwash. See Upland Source description.	**1**
	Promote channel width increases. Allow natural erosion or actively widen and develop floodplain.	**3**
Incised (2)	Allow channel width to increase, manually widen where appropriate and form inset floodplain area.	**2**
	Promote riparian vegetation establishment and maturation.	**1**
	Provide dense grassland-filter buffer zone along channel banks. Install riparian fencing.	**1**
Inset Floodplain (3)	Reduce fine sediment delivery from upstream reaches and tributaries.	**1**
	Promote continued riparian vegetation establishment and succession. Plant willow along low flow banks.	**2**
Valley Transfer (4)	Promote riparian vegetation establishment and maturation. Use bioengineering along banks (no rock).	**2**
	Provide dense grassland-filter buffer zone along channel banks. Install riparian fencing.	**2**
Tidal	Reduce fine sediment delivery from upstream	**1**

Influence (5)	reaches and tributaries.	
Upland Sources	Promote sediment deposition and storage in tributaries. Install grade control structures to trap sediment where feasible and revegetate.	**1**
	Repair headcuts to halt extension.	**2**
	Install riparian fencing around gully heads and lengths.	**2**

Reducing the volume of fine sediment entering the system and promoting deposition and storage in the channel is the highest priority enhancement goal. Prior to European-settlement landuse changes, the stream systems in the alluvial valley areas and upland swales functioned as sediment and nutrient traps. Today they produce large quantities of fine sediment and transport it downstream to the mainstem, where it degrades habitat by filling in pools, embedding riffle gravels, and contributing to sedimentation of the estuary and Tomales Bay. Sediment is derived primarily from gully sources, surface sheetwash and rilling, and bank erosion.

Gullies go through natural cycles of incision and filling that are dependent on climate and environmental conditions. Although it is unlikely that the extensive drainage network that developed in the 1800s can be restored to its pre-agricultural swale morphology, there are techniques available to trap this upland sediment close to its source. Grade control structures, sediment traps, and regrading can effectively store sediment, provide material for vegetation establishment, and reduce the propagation of headcuts through the system. An added benefit of this approach, if combined with revegetation, is increased infiltration and storage of winter precipitation. Sediment capture through grade control and revegetation will be most effective in the valley flats, upland swales, and other gently sloping areas. Figure 26 provides a general picture of locations within the Walker Creek watershed, as indicated by slopes less than 25%, where these techniques may be appropriate.

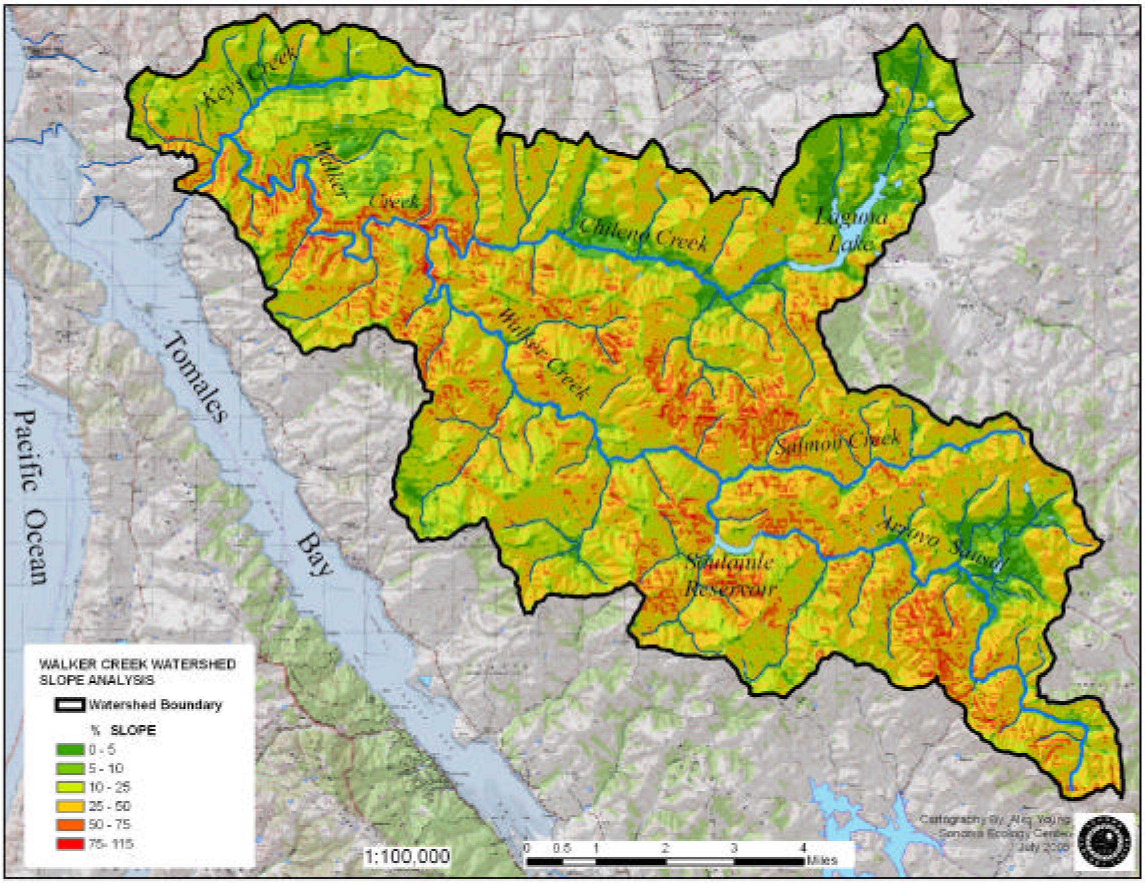

Figure 26. *Valley and hill slopes in the Walker Creek watershed. Gully erosion sites located in areas of lower slopes, shown in green, are likely to respond favorably to restoration techniques involving grade control and sediment storage.*

A wide riparian buffer zone with complex vegetation structure promotes sediment and nutrient deposition by slowing floodwaters down and allowing sediment to drop out of suspension. A wide, continuous, densely thatched grass strip along the banks and on the valley floor parallel to the channel will capture fine sediment derived from pasture land and valley slopes. The grass buffer zone will also promote infiltration of storm water runoff, reducing flood peaks and extending the base flow season. Low shrubs and berries protect steep banks and provide songbird foraging and nesting habitat. Willows and alders within the channel further slow down storm flows, promote sediment deposition, and produce areas of concentrated flow for pool and riffle development. Development of a riparian buffer zone will move these channels towards ecosystem function recovery. Long-term effects of sediment trapping and riparian vegetation establishment include raised water tables in the alluvial valleys and prolonged stream base flows.

Channel incision throughout the watershed has led to the entrenchment of the channels into valley fill. Historically the valley floor was the active floodplain for these channels. Now flood flows are contained within the entrenched banks. A more complete recovery towards historic function and habitat requires widening of the channel banks for development of inset floodplains. Bank erosion may occur at discrete locations, such as the outside of meander bends or flow diversions around vegetation. This is a natural process and should be allowed to occur where no infrastructure is threatened. Bank erosion is typically discrete and self-limiting in systems that have minimal disturbance and sufficient riparian structure. In locations where bank erosion has become chronic and extensive, such as in portions of Reach Type #2, enhancement projects that pull the bank back, create a wide inset floodplain, and establish woody riparian vegetation with bioengineering techniques may be appropriate.

The enhancement priorities and techniques outlined here are based on an ecological, design-with-nature approach to channel and watershed restoration. They are designed to enhance natural channel processes and support the channel network in transition to a new dynamic equilibrium. This approach is appropriate for an agricultural watershed like Walker Creek that is already on a trajectory towards ecosystem recovery.

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