Geomorphic Assessment of Butte Creek, Butte County, California

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Introduction

Butte Creek is one of three smaller tributaries to the Sacramento River with a significant run of naturally reproducing spring-run chinook salmon (*Oncorhynchus tshawytscha*), which is listed as threatened under both the California and federal endangered species acts . Butte Creek also supports a wild run of Central Valley steelhead (*O. mykiss*), also listed as threatened under the federal Endangered Species Act (ESA). Because of its ecological importance, over twenty million dollars in funds have been allocated or proposed for restoration projects in Butte Creek under state and federal programs to restore anadromous salmon. Channel migration and avulsion during a major flood on the first day of 1997 prompted bank stabilization measures costing additional millions that appear to compromise habitat restoration efforts unnecessarily. An understanding of the geomorphic and hydrologic processes driving the fluvial system on Butte Creek can help provide a basis for making good decisions about habitat restoration and stream management.

Beginning at an elevation of just over 7,000 feet, Butte Creek drains 147 square miles of the northern Sierra Nevada and southern Cascade mountains before reaching the Sacramento Valley near Chico, at an elevation of about 200 feet. Once in the valley, the stream descends south-southwesterly across a gently sloping alluvial fan to the Butte Basin, which also receives overflow from the Sacramento River and inflow from several smaller tributaries. Butte Creek reaches the Sacramento River either through the Sutter By-pass or through Butte Slough, the historical passage for the creek to the Sacramento River.

From the headwaters, the stream first flows through a portion of the Lassen National Forest, and then an extensive stretch of private timberland. Lower in the canyon, the stream travels through land managed by the Bureau of Land Management, land owned by PG&E, and residential parcels; finally, in the Valley, it flows through an extensive reach bounded by agricultural and wildlife habitat lands. This study focuses on the 36 miles of stream between the Centerville Head Dam in the upper canyon and the Highway 162 crossing in the Butte Basin. These 36 miles can be usefully divided into a canyon and a valley reach, with the transition occurring roughly between Highway 99 and the Durham-Dayton Highway, about 17 miles upstream from Highway 162.

As a part of this study, we visited most of the 36-mile study reach (except where we could not get permission from landowners), carried out geomorphic field surveys, and analyzed historic maps, land surveys, and historic and recent aerial photographs. Hydrologic statistics were computed for the drainage, and hydraulic computations were undertaken for specific areas of the creek. In this report we present a summary of our findings and discuss their implications for restoration strategies on Butte Creek.

Salmon and steelhead in Butte Creek:

Besides spring-run salmon and steelhead, Butte Creek also supports fall-run chinook and probably late fall-run chinook. Evidently Butte Creek has good potential as a salmon stream. Clark (1928) noted that "... the creek was formerly one of the best salmon steams, but because of the irrigation dams and low water the run has been almost destroyed.[1]" According to Hanson et al. (1940), Butte Creek was "...reported to have been a very fine salmon stream in the past, but mining and hydroelectric power developments in the upper and middle portions, and irrigation diversions in the lower sections have so altered the stream that it is no longer suitable for salmon."

Although returns of spring-run chinook dipped to very low levels in recent decades, the run has been larger in the late 1990's (Figure 1-1). Escapement has been estimated by various methods of varying accuracy since 1955. Snorkel surveys, which tend to underestimate numbers, began in 1994, and since then the run has averaged over 5,000 although it has been highly variable. The run in 1995 was estimated at 7,480. Progeny from these fish presumably returned in 1998 and 1999. The return in 1998 was very large, estimated at 20,200, and the return in 1999 was estimated at 3,680. This increase from the 1995 spawners shows that the creek can be very productive and deserves the attention that it has recently received.[2]

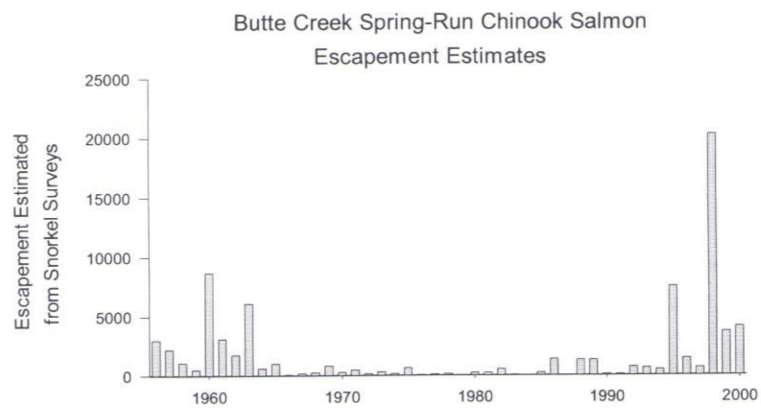

Figure 1-1: Estimates of the numbers of returning spring-run chinook salmon in Butte Creek. Data from the California Department of Fish and Game. Estimates were developed by various means before 1995, and by snorkel surveys thereafter.

Spring-run chinook salmon in Butte Creek enter the stream in the season suggested by their name, and hold over the summer in pools from about the Covered Bridge to the Quartz Bowl, a large plunge pool below an ~12 - 15 ft. vertical waterfall about a mile downstream from the Centerville Head Dam. Remarkably, a few fish were found above the fall in 1995, a year with unusually high spring flows. Many of the fish move back downstream to the alluvial reaches lower in the canyon before spawning, especially when runs are large (Figure 1-2). Biologists with long experience on Butte Creek report that spring-run now show many fewer facial

[1] Clark reported that "There is only a fall run in the creek as the water is very low and warm in the summer," but presumably he was mistaken; this was a broad-brush survey of entire Central Valley that probably depended on information provided by others for Butte Creek.

[2] The relation between the number of spawners and the number of resulting adults is called a "stock-recruitment" relationship in fisheries biology. Various equations or models have been developed to describe this relationship, and the Ricker model is most often used for chinook salmon (Williams 1999). With this model, the number of "recruits" declines at high spawner density. This makes the sharp increase from 1995 to 1998-99 even more impressive.

abrasions or other evidence of injury from barriers to migration (John Icanberry, USFWS, pers. comm. 2001), presumably because of recent removal or improvements of diversion dams.

Spawning habitat appeared to be limiting in 1998,[3] when many fish spawned in clearly unsuitable substrate (Kathy Hill, CDFG, personal. communication, 2000).

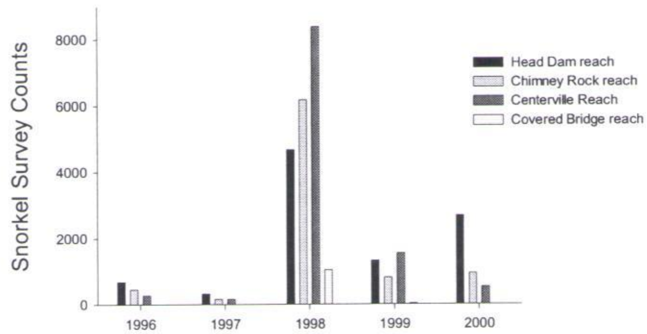

Figure 1-2. Spatial distribution of spring-run chinook salmon in Butte Creek during snorkel surveys, usually in August. Data from Kathy Hill and Tracy McReynolds, California Department of Fish and Game.

Spawning begins in late September, and emergence begins as early as late November. Most Butte Creek spring-run salmon emigrate as fry from mid-December through mid-February, as shown by catches in the fish screens and screw trap at the Parrott-Phelan Dam (Hill and Weber 1999), and only a small minority spend a year in their natal streams before emigrating. Apparently juvenile spring-run salmon in Butte Creek use low gradient reaches of the stream for rearing in the spring before migrating to the ocean. CDFG has collected preliminary evidence indicating that the Sutter By-Pass is important rearing habitat for these fish (Kathy Hill, CDFG, personal communication, 2000).

This life history pattern is unusual. Spring-run salmon typically exhibit the stream-type life-history pattern[4] and spend a year in their natal streams before migrating to the ocean. The Butte Creek pattern is probably a consequence of the relatively low elevation and high water temperatures in the reaches of stream used for spawning, which result in rapid embryonic development and emergence during the winter when days are short. Stream-type chinook that

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[3] The thought of 20,000 salmon in Butte Creek brings to mind a "Mr. Language-Person" column by Dave Berry that considered whether the proper usage is "up the wazoo" or "out the wazoo."

[4] Chinook salmon are generally divided between ocean-type and stream-type fish (Healey 1991); ocean-type chinook such as fall-run typically enter streams shortly before spawning and emigrate to the ocean in their first summer, while stream-type chinook typically enter streams months before spawning and do not emigrate to the ocean until their second spring.

experience a short-day photoperiod are stimulated to grow rapidly and to emigrate (Clarke et al. 1992), so environment rather than genetics probably accounts for the early emigration.[5]

Spring-run salmon in Butte Creek may to be more tolerant of high water temperature than other salmon. The California Department of Water Resources has been monitoring water temperature in Butte Creek for several years, and results from a pool about a half-mile above the Helltown Bridge show that mean daily temperatures often exceed 20°C (68°F) and can approach 22°C; daily maxima are about 2°C higher (Figure 1-3). Salmon in Butte Creek evidently survive these temperatures, although a recent review of the literature (McCullough 1999) strongly suggests that they should not. There are some deep pools that probably have cooler water at depth, but when runs are large fish hold all along the reach. Fortunately 1998 was unusually cool, and CDFG divers counted only 313 carcasses during the snorkel survey, despite the high density of fish. High mortality from high temperatures has been reported, however. Over 2,000 of 8,700 fish died in 1960 (BCWP 1999), so water temperature in summer holding habitat for spring run chinook is at the margin of the tolerable range. There is evidence that spring-run salmon in the San Juaquin River, now extinct, were also unusually tolerant of warm water; Clark (1943) reported spring-run salmon surviving in "good condition" in pools below Friant Dam in 1942, despite water temperatures that reached 22.7°C. Spring-run salmon in Butte Creek are genetically distinct from the spring-run in Mill and Deer creeks (Banks et al. 2000), but the functional significance of the genetic difference is unknown.

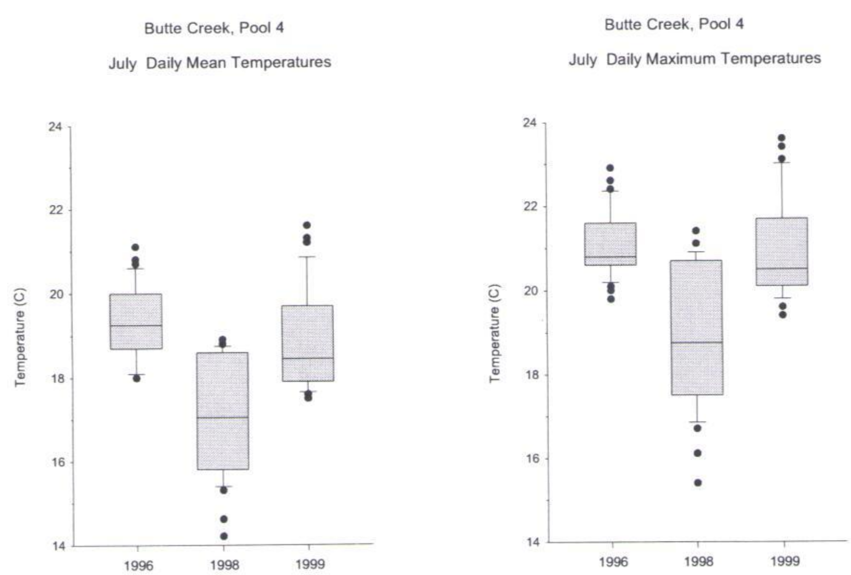

Figure 1-3. Water temperature in Butte Creek at Pool 4, a short distance above the Helltown Bridge, in the summer holding reach for spring-run chinook salmon. Data from the California Department of Water Resources..

[5] Spring-run fry in Mill and Deer creeks typically do not emerge until March (Frank Fisher, pers. comm. cited in Yoshiyama et al. 1996).

Fall-run Chinook salmon in Butte Creek have received much less attention than spring-run so there is only scattered information on their abundance (BCWC 1999), but apparently it has increased in recent years. Fall-run chinook in Butte Creek typically begin spawning in late October, overlapping the period of spring-run spawning. Fall-run spawn as far downstream as the Western Canal siphon, based on CDFG reports and our own observations. In the past fall-run spawned almost entirely below the Parrott-Phelan Dam, whereas spring-run spawned above the dam, so that the two runs were effectively isolated for reproduction. In recent years, however, perhaps because of recent improvements in conditions for migrating, significant numbers of fall-run have spawned above the dam. During our field work we saw fall-run as far upstream as the CSU Chico Ecological Preserve (to about Sta. 121,500 on the stationing in Appendix C).

The Department of Fish and Game has reported that there are also late-fall chinook in Butte Creek (CDFG 1993) but little is known about them.

Adult salmon carry nutrients as well as gametes to their natal steams, as has been emphasized by several recent studies (e.g., Bilby et al. 1996; Larkin and Slaney 1997; Bilby et al. 2001). Adult salmon are about 3% nitrogen and 0.34% phosphorus, and over 95% of their biomass comes from the ocean (Larkin and Slaney 1997), so 5,000 adult salmon with an average weight of 12 pounds would carry about 1,750 pounds of nitrogen and almost 200 pounds of phosphorous from the ocean. These nutrients fertilize not only the ecosystem of the stream (Bilby et al. 1996; Bilby et al. 1998), but also the riparian and nearby terrestrial ecosystems as well (Ben-David et al 1998; Cederholm et al. 1999). Channel features that tend to keep the carcasses from washing downstream therefore promote the productivity of adjacent ecosystems.

Figure 1-4: Salmon carry nutrients from the ocean to the stream in their bodies. Fungi have begun processing the carcass of this salmon in Butte Creek.

Steelhead occur in Butte Creek but have received little scientific attention. Steelhead rear for a year or more in Butte Creek, and have been seen in good numbers throughout the canyon reach. The CDFG memo reporting the 1999 snorkel survey for spring-run noted that "Rainbow trout (*Oncorhynchus mykiss*) were very abundant throughout the survey [from Parrott-Phelan Dam to the Quartz Bowl], especially in the second and third sections [Covered Bridge to Chimney Rock]. Several groups of large (14+ inch) trout were observed. We are unsure if they are anadromous. However, the numbers, size and distribution are encouraging." Because Central Valley steelhead have recently been listed as threatened under the federal ESA the steelhead in Butte Creek probably will receive more attention in the future.

Stream Channel Processes and Fish Habitat

Channel migration:

In recent years biologists have recognized that channel migration and other forms of disturbance create habitat as well as destroy it, and in the absence of disturbance habitats tend to degrade, so that disturbance is a necessary part of habitat maintenance (Pickett and White 1985; Reeves et al. 1998; Benda et al. 1998). When bank erosion causes riparian trees to fall into the stream, for example, the interaction of the flow and the tree tends to scour deep spots, and the tree itself provides cover for fish as well as substrate and food for various invertebrates and micro-organisms. The variation in bed topography tends to induce subsurface flow through permeable materials in the bed of the stream, with important ecological consequences that are described below. Erosion on one side of the channel typically leads to deposition of fine sediment on the other side, which creates a seedbed for the regeneration of riparian trees. Where channels are stabilized, either by armoring banks or by dams reducing high flows, channels and riparian plant communities tend to become less complex and less valuable as habitat.

This point of view, which has been adopted by CALFED, recognizes that habitat conditions at any particular place will change over time, depending on the severity of past disturbances and the time since the disturbances occurred, and that the objective of management should be to maintain the processes by which habitats are created rather than try to design, create, and maintain any particular set of conditions. As stated by Bisson et al. (1997):

> "Because streams are dynamic, establishing fixed habitat standards for parameters such as temperature, fine sediment concentration, woody debris abundance, or pool frequency (especially when applied to limited stream reaches) is not likely to protect the overall capacity of watersheds to produce fish or to recovery from natural or anthropogenic disturbances. Attempting to make streams conform to an idealized notion of optimum habitat through legal regulations or channel manipulations will not easily accommodate cycles of disturbance and recovery, and may lead to long-term loss of habitat and biological diversity."

Hyporheic flow:

Where streams flow over permeable materials such as sand and gravel, a portion of the flow moves through the bed material, where it may mingle with groundwater moving toward the stream. Over the last 10 or 15 years there has been increasing scientific understanding and awareness of the ecological importance of this "hyporheic flow," demonstrated by the recent publication of two books on the topic (Gilbert et al. 1994; Jones and Mulholland 2000). There is no "official" definition of hyporheic flow or of the hyporheic zone in which it occurs, but generally it involves water that has been part of the surface flow somewhere upstream, or the area occupied by organisms that are particularly adapted to live in the spaces between grains of sand or gravel. Hyporheic flow is particularly important for salmon and steelhead because they spend part of their life cycle (as eggs and alevins) living entirely in the hyporheic flow, and even as juveniles often burrow back down into the gravel, presumably to rest or for shelter. Accordingly, it is appropriate to think of salmon and steelhead habitat as including the upper layer of the hyporheic zone. Macroinvertebrates that provide food for juvenile salmon and steelhead also make extensive use of the hyporheic zone.

The zone is also important for basic ecological processes such as nutrient spiraling. Because the flow of a stream tends to carry nutrients downstream, ecologists speak of nutrients in streams as spiraling rather than cycling (Elwood et al. 1983). The average distance downstream that nutrients moves in the course of a cycle is called the spiraling length (Duff and Triska 1983), and in general streams with shorter spiraling lengths have higher biological productivity. Particles of gravel and sand or pieces of wood in the hyporheic zone are covered with a thin layer of organic material that contains bacteria. The bacteria take up dissolved organic matter from the water and process it in various ways, depending upon the amount of dissolved oxygen in the water. For example, much of the nitrogen in dissolved organic material is converted to nitrate or ammonium in the hyporheic zone, making it available to algae and other organisms when the hyporheic water returns to the surface stream. Since the total surface area of hyporheic particles is very large, this bacterial processing can substantially shorten the spiraling length for nitrogen. Although the details of hyporheic processing of nutrients in streams are complex and variable, it should be particularly important in salmon streams such as Butte Creek, which receive important fertilization from the carcasses of returning adults.

Figure 1-5. When the bed of the stream is permeable, as in this alluvial reach of Butte Creek, the stream flows through the bed as well as over it, especially where the bed of the steam is irregular. The subsurface or "hyporheic" flow is important for basic ecological processes such as nutrient

> spiraling, and provides habitat for salmon and steelhead eggs and larvae, or alvins. Juvenile salmonids also use the subsurface habitat for cover.

The extent of the hyporheic zone varies strongly with the geological setting of a stream. In bedrock streams it is limited to small patches of sand and gravel that occur in the lee of logs or boulders or in eddy zones downstream from bedrock constrictions. In confined alluvial reaches such as the lower canyon reach of Butte Creek, the hyporheic zone probably extends to the bedrock on either side, with clear boundaries. In larger alluvial basins there is no clear boundary, but rather a gradient that fades into groundwater that is not significantly affected, hydrologically or biologically, by water from the surface stream. Lower Butte Creek, which flows over relatively impermeable fine-grained soils, is effectively a "bed-mud" stream[6] in which the hyporheic zone is restricted to deposits of sand and gravel along the channel.

Hyporheic flow occurs over a large range of spatial scales. Hyporheic flow is often obvious at short spatial scales at gravel bars during low-flow periods, when water can often be seen seeping out of the gravel into areas that are lower in elevation than the adjacent surface stream. Similarly, hyporheic flow typically enters gravels at the downstream end of pools and resurfaces in the riffle downstream. Salmon and steelhead key in on this subsurface flow when they select sites for constructing their redds (Healey 1991; Vyerberg et al. 1997;Geist and Dauble 1998). At a larger scale, cool hyporheic flow upwelling into a channel where the subsurface channel is constricted can significantly moderate stream temperatures. This probably happens at the lower end of the canyon reach of Butte Creek.

Land-use activities that increase the amount of fine sediment entering streams commonly degrade the hyporheic habitat by reducing the permeability of the channel bed. Although fine sediments enter streams by various natural processes, this usually occurs during periods of high flows when the capacity of the streams to transport the fine sediments is high. Sediment production from land use disturbances frequently occurs during small or moderate storms when streams have little capacity to transport the sediment. Human activity can also deplete hyporheic habitat, as well as degrade it. Dams that induce incision by blocking sediment transport, and gravel mining that removes permeable sediments above a less permeable layer, simply reduce the volume of hyporheic habitat. Clear Creek in Shasta County, where incision following the construction of Whiskeytown Dam and gravel mining left the stream flowing over hard pan in a formerly alluvial reach, provides a clear example.

In summary, our view of streams needs to extend underground. The hyporheic zone is an important component of the stream system, much like the riparian zone. Like riparian zones, hyporheic zones can be highly variable along and among streams, and are affected by both geomorphic and biological processes, and by human disturbance.

Large woody debris:

Trees growing near streams may fall in, especially if the stream undercuts their roots, and debris flows or landslides also carry trees into streams. A few decades ago such trees were viewed as potential barriers to fish migration in smaller streams, and often were deliberately removed from streams. Since the 1970's, however, the role of large wood in streams in creating

[6] A duripan (Redbank Formation?) exposed in the bed of the stream resembles waterlogged adobe brick.

habitat for fishes and invertebrates has been recognized (Gregory and Bisson 1997; Bilby and Bisson 1998),[7] and the earlier practice of "cleaning" streams is now regarded as a very serious mistake (Hyatt and Naiman 2001). For salmon and steelhead, large wood is perhaps most important in steep bedrock streams where it can trap sediment to create patches of alluvium that serve as spawning habitat (Montgomery et al. 1996), but it is also important in alluvial reaches where it increases the complexity of habitat and provides cover from predators and high velocity flows for juveniles. Logs in alluvial streams also create fine-scale topographic variation that induces hyporheic flow and sometimes creates favorable conditions for establishment of riparian vegetation. Smaller woody debris also helps retain salmon carcasses in upstream reaches for ecological processing and provides substrate for various organisms.

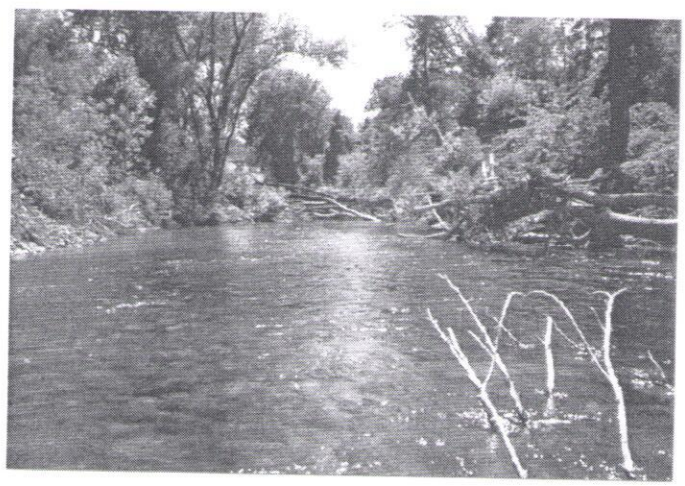

Figure 1-6: Fallen trees, like these on Butte Creek, are now regarded as important components of the stream ecosystems.

Geological Setting

The Butte Creek watershed lies in a transition zone between the Sierra Nevada and Cascade mountain ranges, which is reflected in the diverse lithology of gravel clasts in alluvial deposits along the creek. The upper watershed, including the topographically gentle Butte Meadows area, is composed predominantly of Pliocene volcanic rocks, mainly andesites and basalts. After leaving the meadows, at an elevation of about 4,000 feet, the stream cuts down into pre-Cretaceous igneous and metamorphic rocks of the Sierran basement complex. These resistant rocks form a deep canyon with a steep bedrock channel in which alluvial deposits occur only in isolated patches.

[7] Over 250 scientists from around the world attended the International Conference on Wood in World Rivers, October 23-27, Corvallis, Oregon; see http://riverwood.orst.edu/ for more information. A book comprising the invited talks will be published in 2001.

At lower elevations, the Sierran basement rocks are overlain by the Tuscan Formation, a massive late-Pliocene lahar (volcanic mudflow) deposit that forms the dramatic cliffs of the lower Butte Creek canyon, and by the Chico Formation, a Cretaceous marine sandstone. The upper canyon cuts through the Tuscan Formation, so the channel passes from the Basement Complex to the Chico Formation, in the upper portion of our study reach. The Chico Formation is less resistant to erosion, and the channel widens and alluvial deposits increase as the stream moves down through the formation. A short distance upstream from the confluence with Little Butte Creek the channel passes from the Chico Formation to the overlying Tuscan Formation, since the slope of the boundary between the two is steeper than the channel. Late-Pleistocene alluvial deposits forming the Modesto Formation first appear along the stream in the lower canyon, where the channel flows mainly over recent alluvium atop the Tuscan Formation.

After flowing over the Tuscan Formation, which dips more steeply as it nears the mouth of the canyon, the stream passes onto a fan of Pleistocene and recent alluvium. The Pleistocene deposits near the surface consist of older consolidated gravels called the Red Bluff Formation, and the more recent Modesto Formation. Over the upper portion of the fan, the channel is incised into the Red Bluff Formation, which is sufficiently resistant to hold the main channel of Butte Creek in place, although side channels apparently meandered over the fan until after Anglo settlement.

The Butte Creek fan grades down into the Butte Basin, where water backs up during high flows on the Sacramento River, although not so frequently since construction of Shasta and Oroville dams. Suspended clays settled out of this slowly moving water, creating fine-grained soils that are now used for rice farming. Somewhat coarser sediments were deposited on the fan, creating better draining soils that now support extensive orchards.

Historical Human Impacts:

Human activities have strongly affected the channel of Butte Creek through most of our study reach, and continue to do so. Auriferus gravels from ancient stream channels occur at the boundary of the Basement Complex and the Tuscan Formation, and gold from these gravels has been redeposited in more recent alluvium. Gold mining, especially hydraulic mining, caused a massive increase in the sediment load of the creek. In the fall of 1862, the geologist William Brewer described Butte Creek near Chico as "turbid with miner's dirt" (Farquhar 1966). John Bidwell later testified that "The channel of Butte Creek has been filling up ever since that mining began and it has gradually increased, filling it up more and more until now ... the levees are such that I think nearly all the water now runs about what was originally the top of the banks" (Bidwell 1883). Subsequent dredging reworked much of the alluvium in the lower Canyon and on the upper fan, and probably also increased the sediment load, since early dredging often extended to and sometimes across streams. Most of the dredging probably occurred in the first two decades of the Twentieth Century, but some continued until mid-century (Ginney 2001.).

Concurrently with the mining, and probably partly in response to it, came channel clearance and levee construction. Soils on the Butte Creek fan are well suited for agriculture, which began before the mining but expanded rapidly to meet the demand created by the mining. As noted by Bidwell's testimony, some levees were in place by 1882, and leveeing of the stream across the fan and well into the basin was nearly complete by the time of the first USGS topographic survey in 1910.

Bidwell (1883) also described channel clearance: "(W)ell now, I can speak generally that our streams there are less liable to overflow than formerly from the fact that we cut out the drifts from them. Nearly all our streams are bordered by timber, sometimes by very large timber and sometimes oaks and other large trees will fall into the streams, and now the farmer everywhere within the valley will have cut away those drifts. They have for navigation purposes been removed to a very large extent in the Sacramento River." Logging in the upper watershed of the creek in the late 19th Century probably caused a temporary increase in the supply of large logs to the creek, as may a second round of logging in the 1920's or 30's, followed by a long-term decrease that probably still continues.

Most recently, bank stabilization measures in Butte Creek Canyon have increased along with construction of housing on recent alluvium that is subject to bank erosion, and with efforts to protect diversion structures. Logs along the river have been cut into short lengths to prevent damage to bridges and to reduce the probability of channel migration.

Reach Definitions:

Based on the geology, the study area can be usefully divided into four reaches. The *upper canyon reach* extends from the Centerville Head Dam to approximately the Centerville Power House, where significant alluvial deposits begin to occur. The *lower canyon reach* extends down to approximately Highway 99, where the stream moves out of the canyon and onto the alluvial fan. The *fan reach* extends from approximately Highway 99 to about the bend in the channel just above Adams Dam, where soils outside the levee change from coarser grained alluvial soils to basin clays. From the bend to Highway 162 is the *basin reach*. Sometimes we will refer to the upper and lower canyon reaches together as simply the *canyon reach*, and to the fan and basin reaches together as the *valley reach*. We hope that in context this will not be confusing.

Historical Channel Change

Methods:

Evidence of past channel change often provides the most useful information for understanding current conditions and for assessing future change. We used somewhat different approaches to documenting channel migration in the canyon and valley reaches because of differences in physical conditions and in the kinds of evidence available. In the lower canyon reach, channel migration is constrained within a relatively narrow alluvial strip, but the stream can migrate freely within much of it and relatively small shifts of the channel are of interest. We mapped recent channel migration from aerial photography taken from 1937 to 1998 in this reach. In the valley reach, Butte Creek is confined by levees from Highway 99 to about 3.5 miles upstream from Highway 162. The levees end where the stream joins the path of the Sacramento River overflow though the Butte Basin. Because these levees pre-date the earliest aerial photography we did not map recent channel changes beyond the Durham-Dayton Highway, but we did investigate earlier channel changes in the valley reach from historical maps and surveys. We also analyzed historical data on stream bed elevations to document incision or aggradation of the channel, and used information from soil surveys to make inferences about changes along the stream caused by the high sediment loads introduced into the creek by mining. In the field, we noted botanical and geomorphic evidence of channel change, and locations where resistant bed material limits incision.

Soils:

Soils can provide good evidence of past alluvial environments. Maps and detailed descriptions of the soils in the areas along Butte Creek are currently being developed by the Chico Soil Survey Office, as part of the Butte County Soil Survey being done by the Natural Resources Conservation Service (NRCS). Preliminary data and consultation were graciously provided by staff of that office and were of great assistance in understanding historical conditions in the Valley Reach of Butte Creek and the response of the fluvial system to hydraulic mining.

Lateral Channel Change:

Canyon Reach

The historical analysis in the canyon reach relied largely on aerial photographs taken since 1937 (Table 3-1), since early topographic mapping extended into the Butte Creek canyon only about a mile beyond the Parrott-Phelan diversion. We located aerial photography that provided good coverage of the area through the collections of the US Army Corps of Engineers, Sacramento Branch, and the collections and USDA, US Geological Survey, and NOAA photo indices at the map library of the University of California, Davis, which is the repository in the UC system for aerial photographs of the Central Valley[1]

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[1] Other sources such as the CalTrans index of state and federal photography were not searched, but if specific questions about events in certain historical time frames arise, they could potentially be answered through consulting additional photography through one of these other sources.

Year	Date	Agency	Scale	Flow (cfs)	Comments
1937	9-13-37	USDA	1:20,000	91	9" X 9" prints
	9-24-37			99	
	10-29-37			103	
1952	7-01-52	USDA	1:20,000	287	9" X 9" prints
	7-22-52			180	
1958	7-14-58	USDA	1:21,000	245	9" X 9" prints Not used in GIS analysis of channel position
1959	4-06-59	USDA	1:20,000	498	9" X 9" prints Not used in GIS analysis of channel position
1964	6-28-64	USDA	1:20,000	174	9" X 9" prints
1970	7-06-70	USDA	1:40,000	155	9" X 9" prints
	7-13-70			150	
1979	7-28-79	USDA	1:40,000	139	9" X 9" prints
1988	5-11-88	WAC	1:35,000	276	9" X 9" prints
1989	4-05-89	WAC	1:35,000	729	9" X 9" prints
1997	11-10-97	CalTrans	1:4,800	187	9" X 9" prints Not used in GIS analysis of channel position

Table 3-1. Aerial photography used in historical channel analysis. Flow values were taken from USGS gage #11390000 (Butte Creek near Chico) for the date of the photography.

As aerial photographs are subject to distortion, particularly near their edges, we rectified the images to US Geological Survey 7.5 minute quadrangles. First, we identified points recognizable on the photographs and on the Chico and Hamlin Canyon 7.5 minute quadrangles (corners of buildings, road intersections, etc.). Next, we configured a digitizing tablet by registering the corners of the quadrangles and adding monument points identified on the photos and on the map. We overlaid the photos with a mylar sheet, traced the channel thalweg and highlighted the monument points. On the digitizing tablet, we registered the mylar sheet to the monument points. The registration process occurred in groups of four points. Each group formed a "box" around the portion of the channel to be digitized. After digitizing the channel within the "box" of points, we registered the mylar to the next group of four points. This process reduced digitizing errors arising from photo distortion.

We then exported the digitized channel thalwegs to Arc/INFO, a suite of geographic information system (GIS) tools. In Arc/INFO, we "cleaned" the digital linework, "built" topological structure, and created "coverages" of each photo year so future spatial analysis could be performed. A TIFF image of the two quads, scanned from a conventional flatbed scanner, served as the base map for display purposes. We registered the digitized channel thalwegs to the TIFF image, using previously identified monuments points. To create the figures of historical channel change on Butte Creek, we exported the coverages and the base map to Arcview 3.1, another GIS program. The historical channels are displayed on the quads to provide a familiar reference for recognizing the extent of past channel change. It should be noted that the resulting maps do not reflect the full extent of past channels, but only those evident over the last six decades, during which encroachment of human infrastructure has controlled and influenced channel change.

Valley Reach:

Most of the major anthropogenic changes to Butte Creek in the Valley Reach had occurred by the time of the first available aerial photography. Nevertheless, photographs dating back to 1937 were obtained (Table 1) and were analyzed to for trends in riparian vegetation, extent of riprap along the channel, and channel behavior within the levees.

For evidence about the condition of Butte Creek before the construction of levees, we relied on historical maps and surveys. Ginney (2001) located maps and surveys at California State University at Chico, the Butte County Department of Public Works, the National Archives in San Bruno, and the University of California Water Resources Center, and we located additional materials at the University of California at Davis. Maps cited in our interpretation and discussion are list in Table 3-2, and other maps are described in Ginney (2001).

Date	Scale, size	Location	Notes
1859	1:31,680	Butte Co. Pub. Works	Survey of the Esquon Rancho, of which Butte Creek is the western boundary.
1873	1:760,320	UCD G4362 C4 V6 old maps	Published by the Board of Commissioners on Irrigation, compiled from maps of the Geological Survey of California
1880?	1:63,360, 94x168 cm	UCD G4363 B8, 1880, M2	Compiler and date unknown; emphasizes fluvial features and features associated with hydraulic mining.
1895	1:125,000	UCD	USGS topographic map with 100' contour intervals, surveyed "by reconnaissance methods" in 1886-8.
post-1910	1:24,000	Butte Co. Pub. Works	Drawn by E. C. Templeton for the Stanford Ranch, sometime after 1910; uses USGS topography.
1904-1910	1:31,680	UCD	USGS topographic maps with 5' contours in the valley. In downstream order, the quadrangles are: Clear Creek, Durham, Nelson, and Laidlaw. Corners of the Newhard and Butte City quadrangles are crossed by earlier channels.

Table 3-2: Maps considered in assessing historical channel change on Butte Creek.

Vertical Channel Change

USGS gage data:

The most detailed information available on changes in bed elevation comes from discharge measurements made at the USGS gaging station, Butte Creek near Chico, from 1938 to 2000. The USGS frequently makes such measurements, using current meters to measure water velocity at intervals across the stream, in order to calibrate the gage. Notes from the measurements include the water surface elevation, all referenced to the same elevation, as well as the depth as well as velocity for each interval.[2] We plotted channel cross sections from the data in the notes, by subtracting recorded depths at points across the channel from the water surface elevations. Since the measurements were made at the same location, the cross-sections can be overlaid with good accuracy. We used these to evaluate long-term trends in incision and aggradation, also plotted water surface elevation or stage at discharge to show the effect of the 1997 high water on the channel.

Bridge Transect Data:

We obtained and plotted information on streambed elevation at bridges from the CalTrans bridge books and from Butte County records (Table 3-3). CalTrans or county personnel typically measure the vertical distance from the bridge to the stream bed during bridge inspections, and channel cross-sections can be approximated from these data. Unfortunately, the measurements are often made only at the piers, to check for scour at the piers. This is less than ideal for our purposes, since the measurements may reflect local scour around the piers or debris collected on the piers. Profiles are also drawn on "as built" plans, but these too are of uncertain accuracy. Some of the profiles include measurements between the piers, however, and the bridge reports often include information about channel conditions that can assist interpretation of the profiles. We found useful data in the Cal-Trans bridge books or in Butte County files on changes in bed elevation at the following bridges: We re-measured the profiles in July and August 2000, except for the Skyway.

Bridge	Data (other than Aug. 2000)
Honey Run Road	1992 profile
Skyway	1978 as-built plan, 1992 profile
Highway 99	1955 and 1963 profile
Oro-Chico Highway	1985, 1992 profile
Durham-Dayton Highway	1970, 1972, 1986, and 1992 profiles
Midway	1932, 1972, 1997 profiles
Durnell Road	1975 profile
Nelson Road	1960 as-built plan, 1992 profile
Aguas Frias	1972 profile

Table 3-3. Bridge profile data from CalTrans or Butte County Records.

[2] Numerous boxes had to be retrieved from the federal archives in San Bruno and searched in order to obtain these data. We are indebted to Pat Shiffer of the USGS California District Office and her staff for this effort.

Stumps:
We found stumps standing in growth position in the channel near the Covered Bridge. We also noted locations where resistant materials limit channel incision.

Results:

Soils:

Preliminary soils mapping by the NRCS for the area including the transition between the fan and the basin shows a strong influence of sediment from mine waste "overwash" (Figure 3-1). A large lobe of anthropogenic soils extends along the right bank of the creek past the Oro-Chico Highway, and a smaller lobe extends from the left bank upstream to just past the highway. Between the levees, the overwash soils continue beyond the area of the figure to the bottom of the study area.

The natural sequence of soils is preserved away from the creek. Along the western edge of the figure, for example, the soil grades from Conejo Loam (NRCS # 418) of the fan through the Conejo Clay Loam (420), the Busacca Clay Loam (105) and the Edjobe Silty Clay Loam (519) into the Esquon-Neerdobe Clay (520) of the basin.. Along the eastern edge of the figure, the transition is from the Conejo Clay Loam to the Busacca Clay Loam to the Esquon-Neerdobe Clay, which extends somewhat farther north on this side of the creek.

Closer to the creek, this transition is obscured by anthropogenic soils, particularly the Conejo Fine Sandy Loam (419), which is described as "overwash topping clay loam," and Govstanford Loam (525 & 526) that is "overwash topping clay/silty clay." The 526 soil continues downstream between the levees. The 419 soils along the channel upstream from the Durham-Dayton Highway indicate substantial overbank flow along the part of the creek that is now deeply incised into the Red Bluff Formation. This suggests that the coarser fraction of the mining debris caused considerable aggradation in this reach, as suggested by testimony from John Bidwell described below at p. 48, or that the channel has by now incised below its historical level because the levees contain high flows and increase their power to scour the bed. Both may be true.

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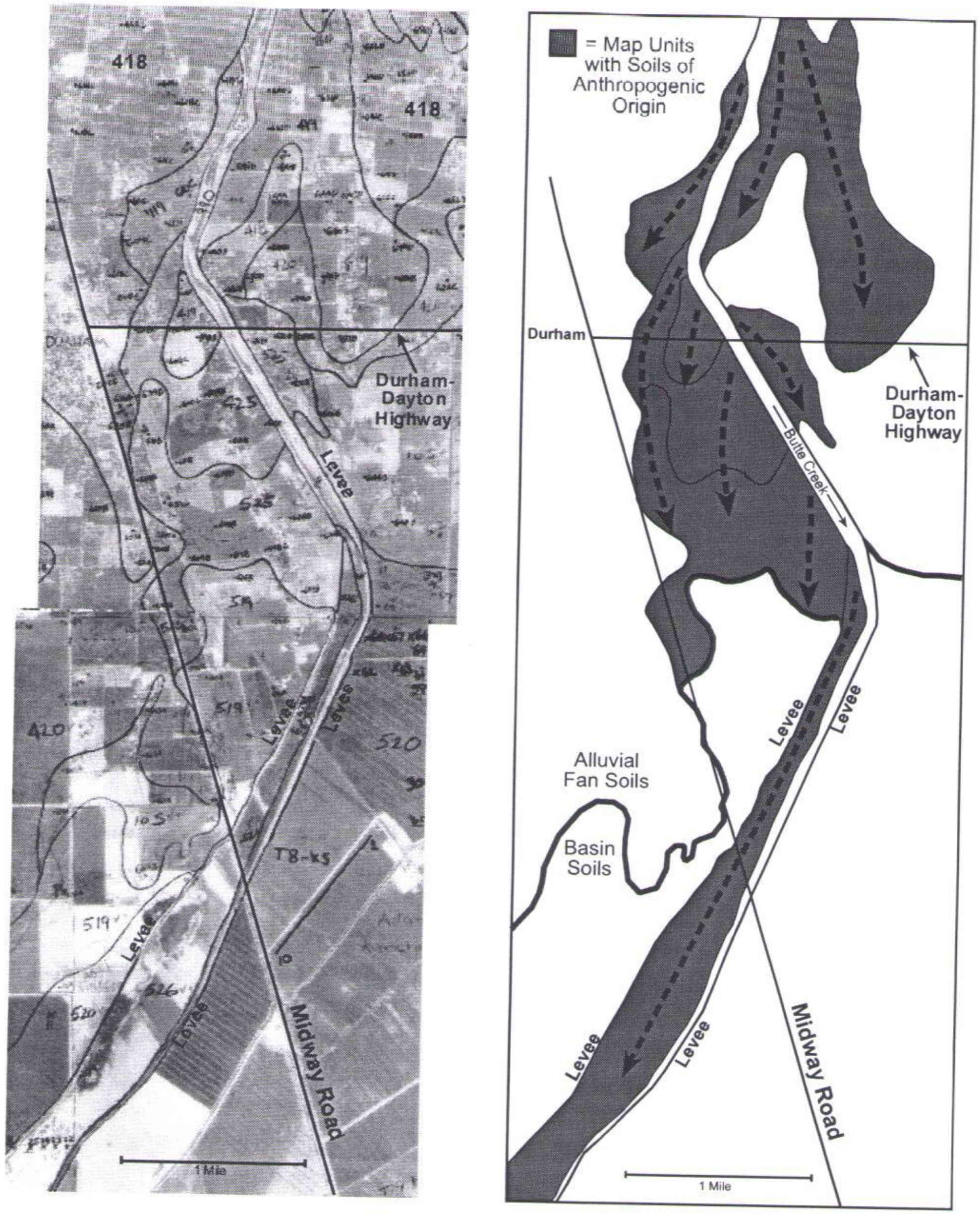

Figure 3-1: A portion of the NRCS preliminary soils map, showing the transitional area between the Butte fan and basin, together with a schematic showing anthropogenic soils and the transition between the fan and basin soils. The transition is actually more gradual than suggested by the lines.

Lateral Channel Change:

Canyon Reach:

Maps were prepared from aerial photography showing channel locations in 1937, 1952, 1964, 1970, 1979, 1988-89, and 1998, for the reach from the CSU Chico Ecological Preserve downstream to the Durham-Dayton Highway. Although the mapping is reasonably accurate some distortion remains from the rectification process, especially with the 1937 photography, and from the process of creating and combining the different maps. As a result the 1937 channel is mapped on top of Humbug Road in several places, rather than close to it.

Lateral channel change in the lower Canyon Reach during the period of photographic record was significant but not remarkable (Figure 3-2). The width of the band occupied by the mapped channels varies from about 300 to 900 feet. The channel has not occupied all of the area within this band, however, since the channel moved by jumps, or avulsions, as well as by migration resulting from erosion on one bank and deposition on the other. A well publicized avulsion occurred in January 1997 when Butte Creek cut a new channel that by-passed the Parrott-Phelan Dam. Other significant avulsions occurred downstream from the dam, where the channel shifted to the southeast, and in the Ecological Preserve, where the channel shifted to the northwest. Avulsions and gradual migration are not unrelated, however. The avulsion around the Parrot-Phelan Dam was preceded by the gradual development of a bend upstream from the dam, and the avulsion occurred at the bend (Figure 3-2)

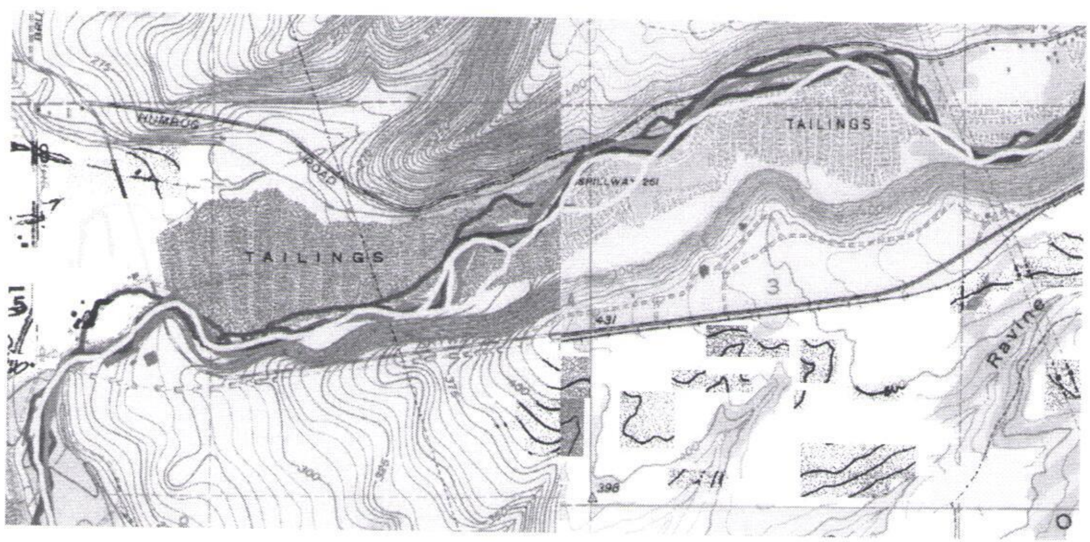

Figure 3-2. Black and white reproduction of a portion of a map of channel change from 1937 to 1998, based on aerial photography; compete maps with color coded channels are provided in Appendix A. The avulsion away from the Parrot-Phelan Dam is shown by the split in the 1998 channel (light-colored) where it turns away from Humbug Road. Note the development of the bend just upstream from the dam, where the avulsion occurred. In the avulsion marked by the split channel farther downstream, the creek has now shifted almost entirely to the SE channel, away from the historical location.

Unvegetated dredger tailings are prominent in the 1937 and 1952 photography, so the photography provides little information about the natural floodplain or earlier channel alignments. Topographic maps based on 1910 surveying (Durham and Clear Creek quadrangles) show the channel generally within the band mapped from the photography, but there are hints of an older channel lying closer to the south side of the canyon in the area now accessed by Spanish Gardens Drive.

Valley Reach:

We found four maps or sets of maps that provided particularly useful information (Table 3-2):

1859 Esquon Rancho:

This plat map of the Esquon Rancho, surveyed in 1859 by James Trask, is in the files of the Butte County Dept. of Public Works, and depicts the creek from the mouth of the canyon to about 2,000 feet downstream from the current location of the Durnell Road bridge. Since Butte Creek makes up the western boundary of the Rancho, the map gives courses and distances for most of the channel as it then existed, as well as geomorphic detail (Figure 3-3). Courses are given to degrees or half-degrees, which suggests the limits of the accuracy of the survey.

At the top of the fan, the map shows the creek wrapping more tightly around the hill at the mouth of the canyon than it does now. The distributary Little Butte Creek is shown leaving the right bank of the stream at that point. From about the location of Durham, the streams is shown running more directly south than at present. About 1,000 feet downstream from the location of the Durham-Dayton Highway, the channel splits to create a basin vegetated with tules. It appears that the surveyor decided that the basin was part of the channel, for boundary purposes, as the Rancho boundary bisects the basin. Geomorphically, the basin marks the transition from the Butte Creek fan to the Butte Basin. Farther downstream the channel splits again, but in this case the surveyor selected one channel as the boundary.

1873. Board of Commissioners on Irrigation map:

The map, with a scale of 1:760,320 (1 inch = 12 miles), was compiled primarily form maps of the Geological Survey of California, and is notable for our purposes largely because the distributary Little Butte Creek is labeled by that name, as well as shown. Evidently it was regarded as a significant feature. Given the scale, the map adds little information to what is shown on the plat of the Esquon Rancho or the untitled 1880 map described below.

Please continue to the Figure 3-3, a portion of the plat of the Esquon Rancho, on the next page.

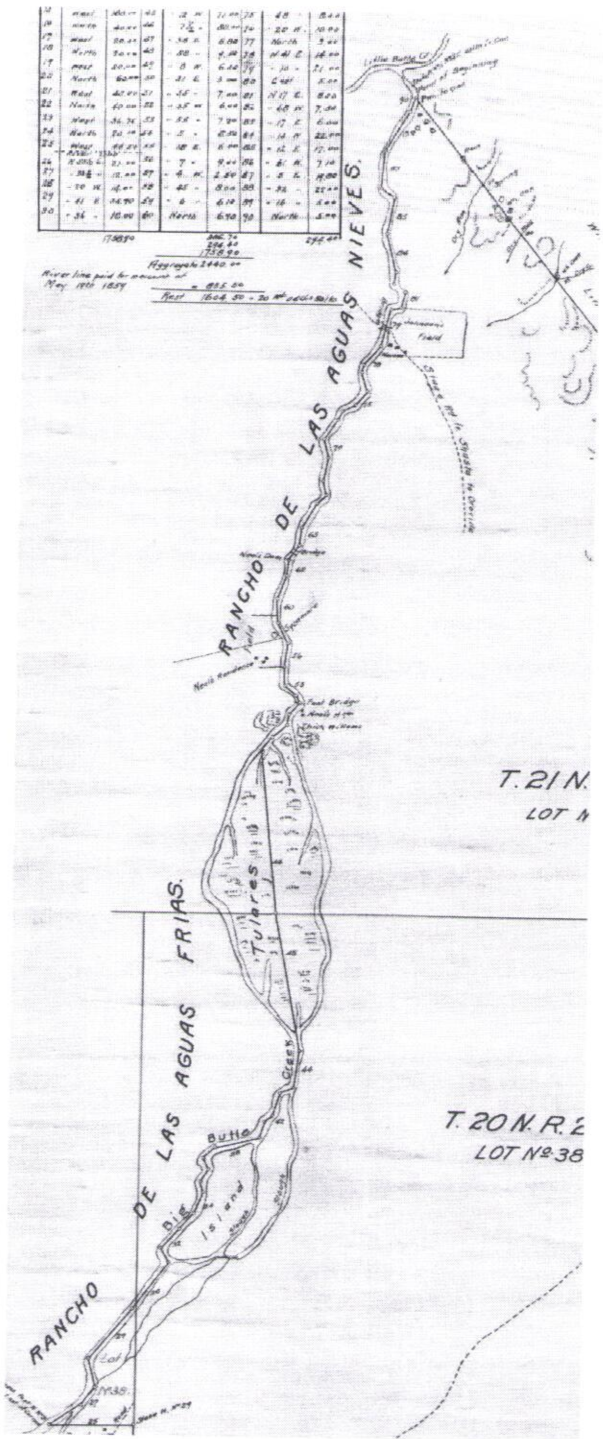

Figure 3-3: A portion of the plat map of the Esquon Rancho, surveyed in 1859 by James Trask. The basin filled with tules marks the boundary between the Butte fan and basin. The Durham-Dayton Highway now crosses the stream about 1,000 ft above the site of this basin..

1880: Untitled.

This is a beautiful map, by an unknown cartographer, drawn at a scale of one inch to a mile in four large sheets, of which the northern two are preserved at the UC Davis map library. The map show the Feather and Sacramento River as well as Butte Creek, and emphasizes fluvial features, showing for example the 1879 high water and "slickens" deposits along Table Mountain Creek. As could be expected from the broad coverage, however, the map was compiled from a variety of sources, as shown by various features end that end at section lines, and the accuracy of the mapping must vary from place to place in consequence. Unfortunately, comparison of artificial features such as rancho boundaries with recent maps shows that the map is not accurate enough for quantitative assessment of channel change along Butte Creek. Also, the map sections at UC Davis do not include the legend, so it is not entirely clear why some tributaries and secondary channels are inked in brown instead of in blue. Nevertheless the map seems carefully prepared and probably provides a qualitatively correct depiction of the creek in the decades before 1880.

Cultural features of interest along Butte Creek include the locations of three hydraulic mines in the canyon, the Spring Valley Mine and Irrigation Co. (Cherokee) Canal, the California-Oregon (Southern Pacific) Railroad, towns, roads, rancho boundaries and section lines.

As in the plat map of the Esquon Rancho, the streams is shown running more directly south from Durham than it does now. The stream is shown forking a short distance above the railroad, with two channels about a half-mile apart crossing under the track. The northerly channel is shown as the main channel, and it forks again just downstream of the rail line. The channels re-converge about 1.3 miles below the fork, but minor channels inked in brown extend farther downstream on the south-east side. Durham Slough is also shown inked in brown, as is Little Butte Creek, which extends down to about the Butte County line. The map also shows other channels or channel alignments pencilled in, but not inked. In some cases these seem to reflect adjustments of the position of mapped features, but in other cases they may reflect different configurations of the channel shown on different source maps. The tule basin shown in the plat map of the Esquon Rancho is not shown, but the triple channel just downstream is.

1895 USGS Chico Quad

This map, surveyed between 1886 and 1888 with 100 foot contours by H.M. Wilson and R.H. McKee, shows Butte Creek from the almost to the Butte Meadows downstream into Colusa County. Cultural features include Helltown, Centerville, Durham, the Southern Pacific Railroad, and various roads. The map should not be taken too literally. A note at the bottom of the map cautions that "This area surveyed by reconnaissance methods. Maps of adjacent areas surveyed by modern methods may not join this sheet exactly." In particular, the depiction of the creek in the lower canyon is suspiciously straight, and it seems likely that the surveyors regarded it as a changeable feature that did not deserve close attention for the purposes of the map. Similarly, there is no indication of levees, although there is good evidence (described below) that levees existed by that time. Nevertheless, the general picture presented by the map should be reliable. The distributary Little Butte Creek is shown leaving the stream just downstream from the site of the Parrot-Phelan Dam and flowing along the course of what was later called Edgar Slough and then Comanche Creek, to meet the Sacramento River just south of the Colusa County line. The channel mapped as Little Butte Creek in the 1873 Board of Irrigation Commissioners map appears as a separate drainage that does not connect to the creek at the upstream end, but instead heads at about the Oro-Chico Highway. In the mouth of the canyon, the map shows Butte Creek running close to Humbug Road somewhat farther north than do later maps. This is plausible, based on more detailed topography surveyed in 1910, but it is also plausible that this merely reflects the limited accuracy of the ~1887 survey. The tule basin shown in the plat of the Esquon Rancho does not appear in the USGS map, presumably because it had been covered with mining debris, although the triple channel just downstream does.

Stanford map

This map, titled "Topography and Geology if the Stanford-Durham Ranch. A property of Leland Stanford Junior University in Butte County, California," was prepared by E. C. Templeton under the direction of J. C. Branner. The date is unknown, but must be after 1910 since the map used USGS topography surveyed in that year. The map shows Butte Creek from above the Durham-Dayton Road to below Durnell Road, as well as a large area east of the creek. Topography is given with contours at five foot intervals, and clearly shows many meandering channels in the basin deposits east of the creek. The western boundary of the area mapped in detail is the Esquon Rancho boundary, so the straight portion of that boundary in Figure 3-4 shows as the line running through the "tulares" in Figure 3-3. Elongated gravel bars are shown in the creek down to the "Big Bend," with "islands" below the bend; presumably these were capped with significant deposits of fine sediments.

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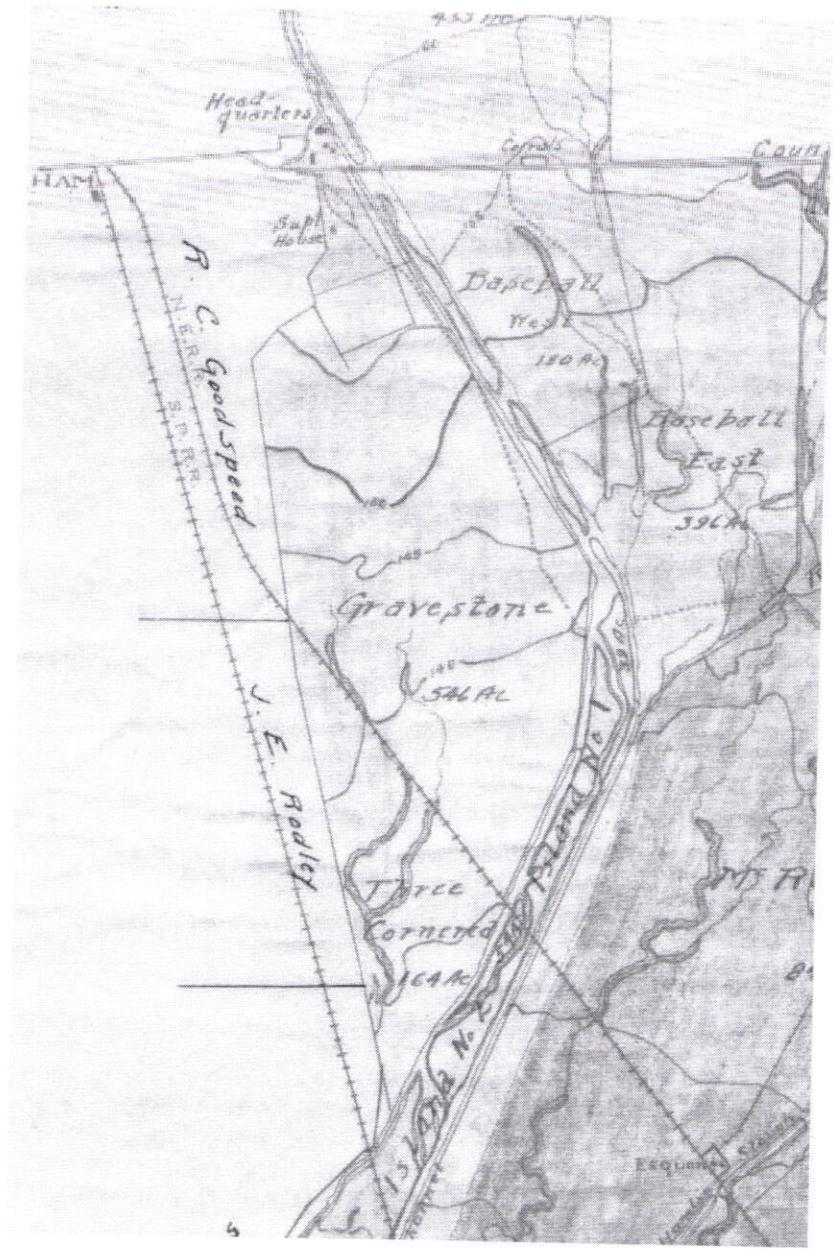

Figure 3-4: Portion of the map of the Stanford Ranch, showing the re-aligned channel of the creek from the location of the Durham-Dayton Highway to the Midway. Note the gravel bars in the channel at the "Big Bend" and upstream, and the "islands" downstream. The straight left edge of the area mapped in detail is the line bisecting the area of "tulares" in the Rancho Esquon survey (Figure 3-3)..The date of the mapping is unknown, but is probably shortly after 1910.

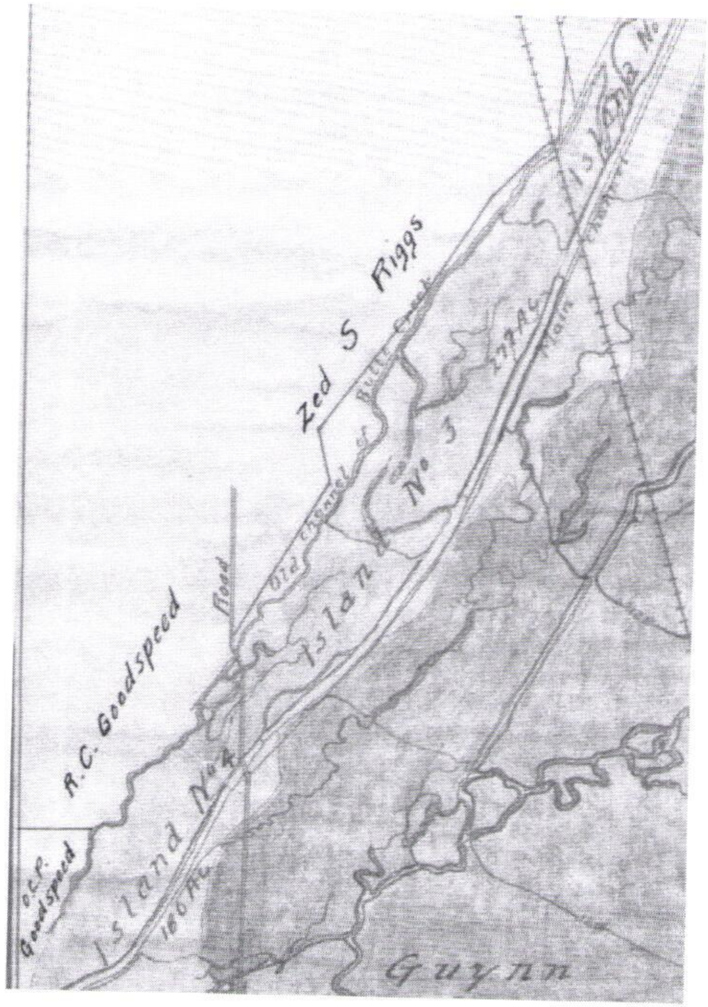

Figure 3-5: Portion of the map of the Stanford Ranch, showing the old channel and the re-aligned channel of the creek downstream from the Midway and railroad crossing. A portion of the straightened channel of Sanborn Slough appears in the lower right section of the figure. The "old channel" shown is the main channel in the 1859 Esquon Rancho survey, and is still marked on the landscape by the position of the right bank levees.

1904-1910 USGS Topographic Maps:

The first detailed USGS maps of the region were completed early in the 20th Century. The mapping is complete for the Valley Reach of Butte Creek, but extended only a few miles up the canyon, to about two miles past the Parrott-Phelan Dam. The date of the survey upon which the mapping is based is given on each sheet. The contour interval is five feet for most of the area. These are highly detailed maps, and although the accuracy is not up to modern standards it is amazingly good given the equipment that was available at the time.

By 1910, Butte Creek was already in approximately its current position. Across the fan and basin, the channel had been straightened and leveed, as had Hamlin Slough (then called Roberts Creek). The levees extended as far as they do now on the left bank, although they stopped at Aquas Frias Road on the right bank, and generally appear to be in their current location. By 1910, the topographic expression of some channels, such as the old Butte Creek channel just east of Durham and the upper end of the distributary Little Butte Creek, was already modified or even obliterated, although other relict channels were still strongly expressed on the landscape. Relict channels, either of distributaries or of the main channel, were prominent to the east of the current channel where it leaves the canyon, and were mapped as about five feet deep in the area now crossed by Highway 99 (Figure 3-6). One of these channels, perhaps the one shown as the main channel on the Esquon Rancho plat map, cut through a training levee that extended southwestward from the hills to flow through the area now occupied by the Butte Creek Country Club. Relict channels are common farther downstream, on both sides of the creek.

Continue to the Figure on the next page.

Figure 3-6. A portion of the USGS Durham Quadrangle, based on surveys in 1910. The contour interval is five feet. Highway 99 now crosses the creek just downstream from the island (about a third of the way down the figure, just north-east of a symbol marking a structure at the end of an east-west trending road), approximately parallel to the dash-dotted line which is the boundary of the Esquon Rancho. Note the break in the levee on the left bank just upstream from the island, and the relict leading from it. Only a trace remains of the distributary Little Butte Creek, leaving the channel from the right bank.

Vertical Channel Change:

USGS channel geometry data

Channel cross-sections plotted from the USGS discharge measurements show variation throughout the period. The largest change occurred at the beginning of 1997, presumably during and after the 1 January 1997 peak flow, estimated at 35,600 cfs. when the channel widened by about 20 feet and also incised (Figure 3-6). Data on the stage at various levels of discharge during the last decade show a step change at the beginning of 1997, as would be expected from the cross-sections (Figure 3-8).

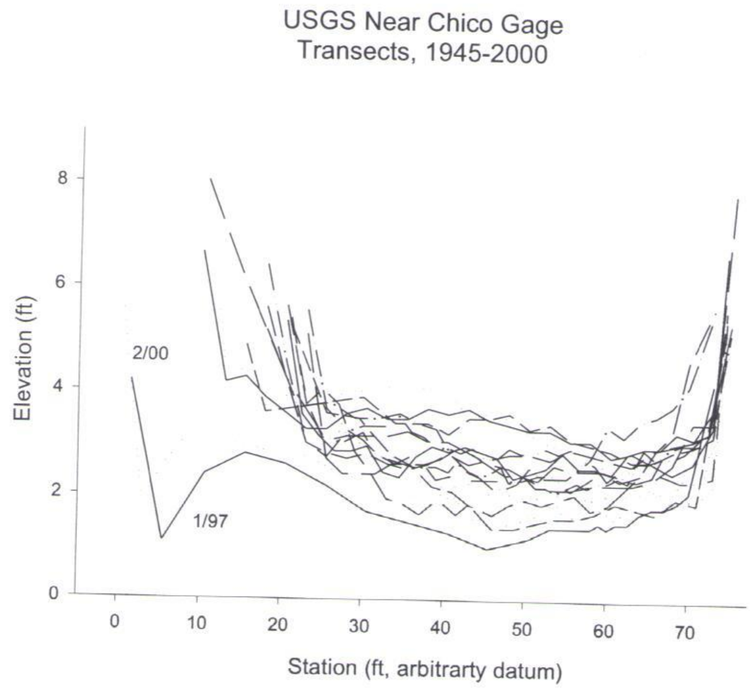

Figure 3-7: Measured transects for the USGS Near Chico gage, for 1945-2000. Note the widening and incision following the January 1997 high water.

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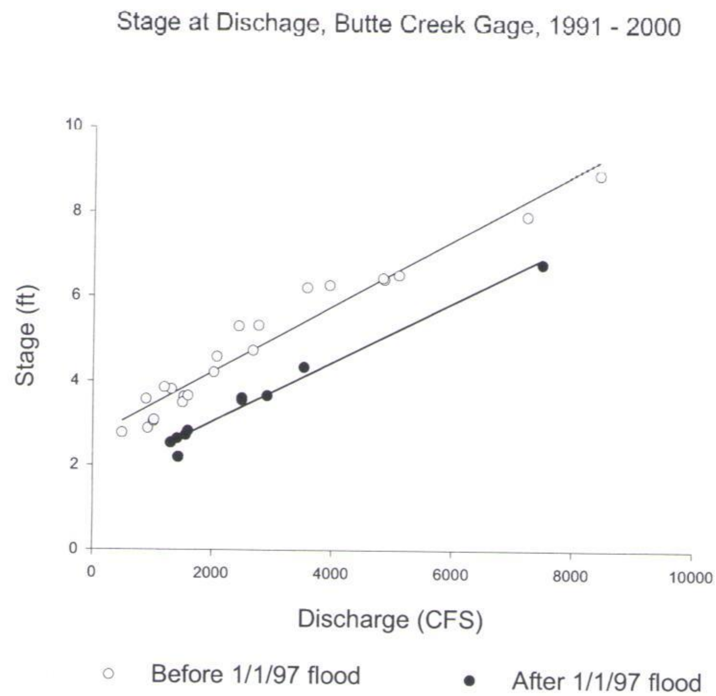

Figure 3-8: Plot of stage at discharge at the USGS Near Chico gage, showing a step change after the January 1997 high water. Although the stage-discharge relation is nearly linear for this range of flows, a non-linear relation as in Figure 3-9 would provide a better fit.

Analysis of the cross-section data for the period before 1997 also shows a general tendency toward incision, although there is considerable variation around this trend and the incision apparently reversed between the mid-1970's and 1997. To illustrate the trend and the variation, we fit a line to the stage-discharge data from 1938 through 1996 using non-linear regression, and then plotted the residuals from the fit line (Figure 3-9). The plot of residuals shows the data in temporal order, but since the measurements were not made at regular intervals the distribution of the data in time is shown only approximately. The residuals show a clear declining trend through approximately measurement 100, or the mid-1970's, demonstrating the trend toward incision. From the mid-1970's to 1997, however, the residuals show a trend back toward zero, or deceased incision, as shown by the line fit by the Lowess (locally weighted regression) method (Cleveland 19895; Efron and Tibishirani 1991).[1] However, the scatter in the residuals also increased beginning with measurement 136, made shortly after the February 1986 high water, indicating increased variability in channel geometry.

[1] The smoothing parameter in lowess was selected by inspecting residuals from the fit lowess line, and selecting the largest value of the parameter (0.5) that resulted in evenly distributed residuals.

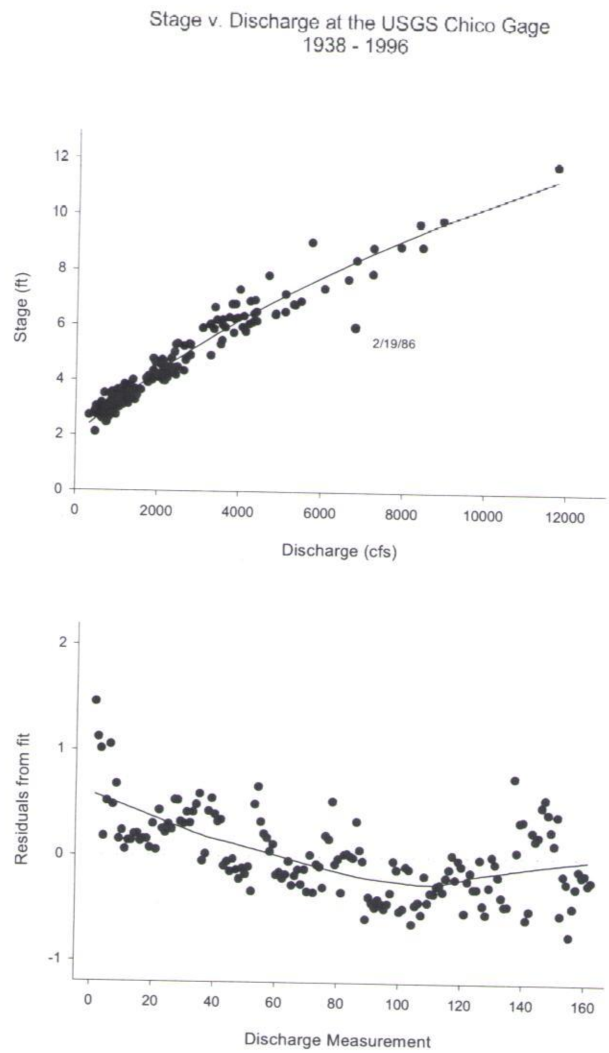

Figure 3-9: Upper panel: stage at discharge at the Butte Creek near Chico gage for 1938 - 1996, fitted with a line by non-linear regression. Lower panel: residuals from the fit line, in temporal order, with a line fit by the lowess method using a smoothing parameter of 0.5. A data point for 2/19/86 shows up as a clear outlier, probably reflecting temporary incision following the February 1986 high water, and was not used in the analysis. The residuals show a trend toward increasingly negative residuals until about measurement 100, or the mid-1970's, indicating incision. From the mid-1970's to 1996 the residuals on average increased toward zero, although the scatter in the residuals increased after the February 1986 high water (measurement 135), indicating a higher rate of change in channel geometry.

There are too few post-January 1997 data to draw conclusions about trends. Upstream erosion in that year introduced large amounts of sediment into the stream, which may be reflected in the aggradation indicated by the February 2000 transect shown in Figure 3-7. A geologic control on incision downstream from the gage probably limits incision at the gage site.

Bridge Cross Sections:

Historical bridge data and our re-surveys generally indicate channel incision under bridges on Butte Creek.

Honey Run Road

The Honey Run Road Bridge (12C-322) was built 1965 and has three 65 ft spans. A report from 1986 notes erosion on right abutment, but notes accompanying measurements in 1992 indicate no scour. Significant scour was reported in an April 1997 report, which is consistent with the scour reported at the gaging station a short distance downstream. Our measurements in 2000 show up to seven feet of incision since 1992.

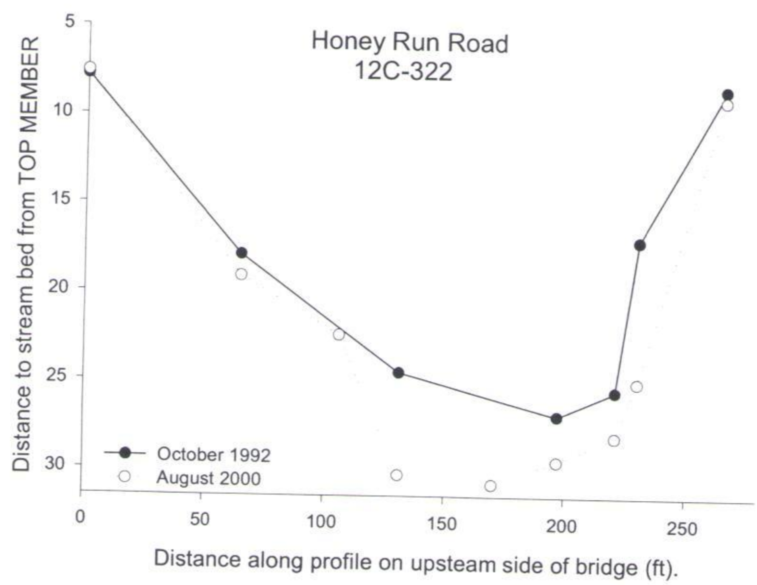

Figure 3-10: Channel cross section at the Honey Run Road Bridge from measurements in 1992 and 2000.

Skyway

There are two bridges for the Skyway, of different ages. The upstream bridge (12C-09L) was built in 1949, and has five spans of 31.5, 34, 34, 34, and 31.5 feet. We found data on the stream bed elevation on the general plan for the bridge, and from a 1972 bridge report. It did not seem safe to attempt measurements in 2000 on either bridge because of the traffic. Comparison of the bed elevation from the 1949 plan and from the 1972 report indicates aggradation during this period. The profile from the plan agrees reasonably well (within 0.6 ft) with the 1972 measurements where a haul road passed under the bridge on the left bank of the stream, and the 1972 report makes no mention of scour, so we think the aggradation was real. A 1988 report did describe incision and scour, however, particularly at Pier 4, which had collected drifting debris. The report attributed the incision to a downstream gravel mine, but a shift in the active channel toward the right bank may also have been involved. A 1992 report noted "no significant change to this structure since the previous investigation."

The downstream bridge (12C-09R) was built in 1978 and has spans of 70, 80, and 80 feet. Borings done as part of planning the bridge show more than 20 feet of alluvium under the center of the channel, with a buried channel incised at least 10 feet into the underlying Tuscan Formation. Comparison of the profile from the 1978 plans and measurements in 1992 indicates scour, as reported for the upstream bridge for the same period.

Highway 99.

We found profiles for 1955 and 1963 for this bridge, but more recent profiles were not in the Caltrans files.

Oro-Chico Highway

The existing bridge for the Oro-Chico Highway was constructed in 1986, and data on the previous bridge have been lost. Profiles are available from the "as built" plans and from measurements in 1992 and 2000, and indicate several feet of incision on the right side of the channel, mostly occurring between 1992 and 2000. The bridge has two piers, each 85 feet from the abutments, and 108 feet apart, so the bridge is well designed in terms of passing woody debris. The Butte Creek channel is confined within resistant banks of the Redbluff Formation in this area.

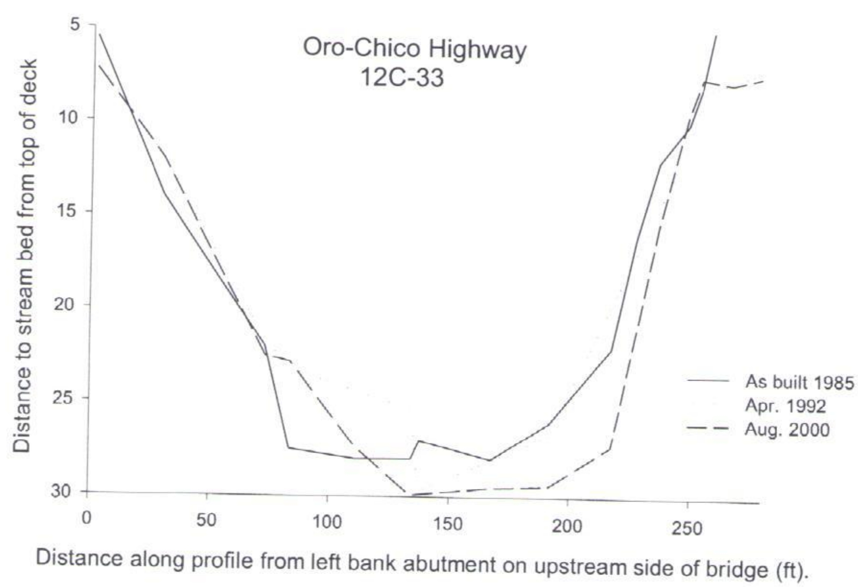

Figure 3-11: Channel cross section at the Oro-Chico Highway Bridge from measurements in 19985, 1992 and 2000.

Durham-Dayton Highway

The earliest available profile for the Durham-Dayton Highway Bridge is drawn on the "as built" plans for the bridge, dated January 26, 1970. A profile was measured on November 28, 1972, and shows substantial aggradation on the left side of the channel. A report in 1974 noted that one to three feet of the pile shells were exposed on bents 5 through 11. A flow of 12,600 cfs at the USGS gage occurred in 1974. There was a higher flow (22,000 cfs at the gage) before the next profile was measured in June 1986, and the thalweg moved about 80 feet to the left and incised over two feet. Some aggradation of the thalweg occurred by April 24, 1992, when the next profile was measured, presumably because a check dam was installed just downstream of the bridge after 1986. This profile did not extend over the full width of the channel, so it seems likely that the there was not evidence of additional incision or aggradation along the western side of the profile at the time. Our measurements show that the thalweg had moved back toward the center of the channel by 2000, but with little change in bed elevation.

This bridge was damaged in 1986, when one of the columns along the upstream edge was broken off by floating debris, and was further compromised by channel incision. The problem was not undermining the support of the piers, but rather increasing their slenderness ratio (exposed length divided by radius) up to 30%. A report in the CalTrans file by Carlton Brown attributed the incision to removal of a gravel bar downstream from the bridge, and recommended installation a check dam, which was completed in 1988. Another report in 1998 noted that some of the boulders in the check dam were displaced in the 1997 high water, and also noted incision at some piers and aggradation at others.

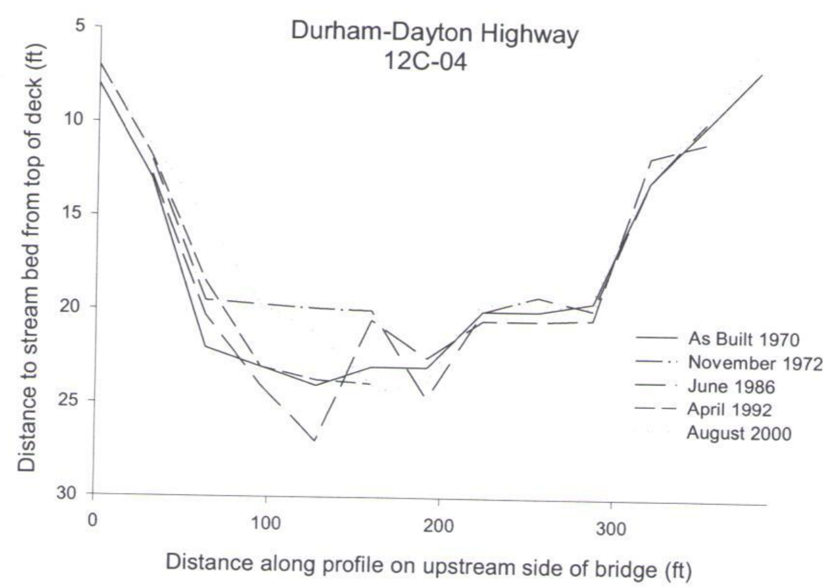

Figure 3-12: Channel cross section at the Durham-Dayton Highway Bridge from measurements between 1970 and 2000.

Midway

The Midway Bridge was built in 1915. We found measured profiles for August 1932, October 12, 1972, and April 1, 1997, and measured a profile in August 2000. The 1972, 1997, and 2000 profiles were measured along the upstream edge of the bridge, but the 1932 profile was along the bridge centerline and so is not strictly comparable, but is nevertheless revealing given the magnitude of subsequent incision and aggradation.

The general condition of the bridge was described as poor in a 1936 bridge inspection report. A supplemental bent was installed in 1937, but the bridge was nevertheless described as "weak and overstressed throughout." Additional bents were installed in 1940, and load restrictions previously in effect were relaxed. The bridge was transferred to Butte County in 1955, but evidently it was necessary to install temporary bents in the 1970's, presumably in response to the approximately five feet of incision indicated by measurements in 1972. The additional bents must have contributed to the tendency of the bridge to catch floating debris during high flows, as it did in 1986; according to a 1986 report "Recent stream debris has accumulated beneath span 1 and spans 4 through 10, with much scour and erosion present." There was also erosion along the left abutment. More erosion occurred subsequently, on the right side of the channel, probably much of it during the 1997 flood. Concrete blocks or boulders were placed around the piers at various times to protect them from scour, particularly after the high water in 1986 and 1997. According to a 1998 report, "Scour mitigation of Piers 2, 3, and 4 has been completed with the placement of large boulders around the piers and throughout the channel on the upstream side of the bridge." Our measurements in August 2000 show about five feet of aggradation since 1997, presumably because of the boulders. However, these data give only a generalized depiction of the current channel. Murky water was backed up from Gorrill Dam in August, so the channel bottom was not visible. We visited the bridge in January 2001, and could see that there are scattered boulders all across the channel (Figure 3-14), as well as boulders piled around the piers (at ~ 60, 120, and 180 ft on the profile). Our data point at ~ 90 feet probably fell between boulders. Accordingly, the true profile is much more jagged than that shown in the figure, but the loss of channel cross-section and flood conveyance capacity indicated by the figure for the 1997-2000 period probably is reasonably accurate. Under the railroad bridge, which is just upstream from the highway bridge, the thalweg appeared to be about four feet deeper.

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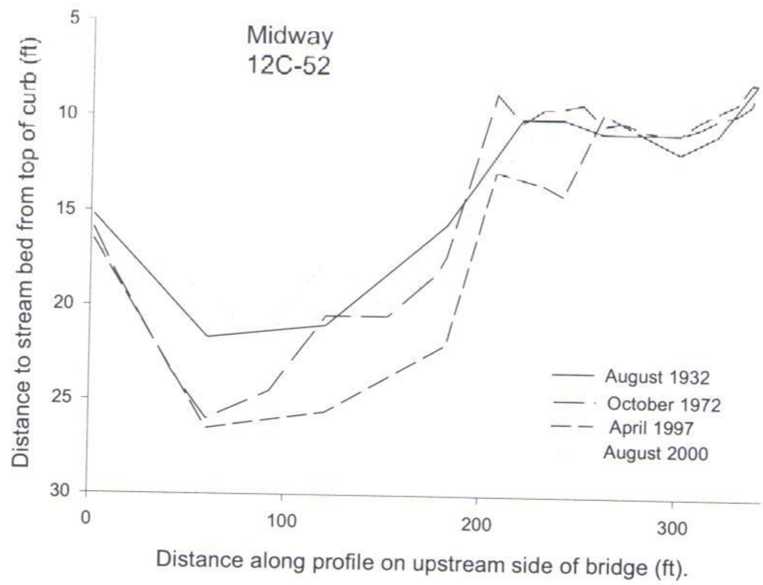

Figure 3-13: Channel cross sections at the Midway Bridge from measurements between 1932 and 2000.

Figure 3-14: Large rip-rap placed around piers under the Midway Bridge after the January 1997 high flow to control scour. (The light surface in the lower right corner is the reflection of the sky.)

Durnell Road

We found one useful profile, dated January 3, 1975, for the Durnell Road Bridge. Our resurvey in 2000 showed over 2.5 feet of incision since 1975..

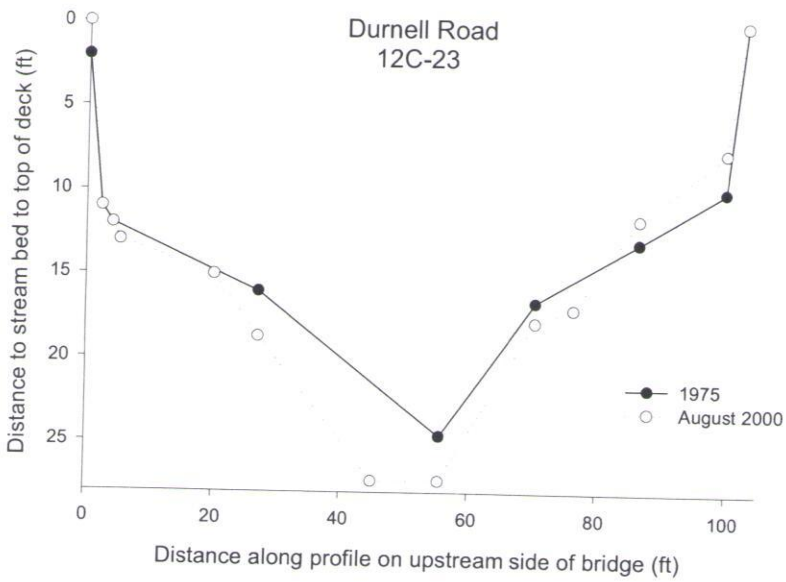

Figure 3-15: Channel cross section at the Durnell Road Bridge from measurements in 1975 and 2000.

Nelson Road

The Nelson Road Bridge was constructed in 1960. The as-built plan shows an "original ground" profile, as well the finished profile, showing that the channel was significantly enlarged and deepened during bridge construction. The 1992 profile shows about two feet of aggradation of the thalweg and considerable narrowing of the channel Our resurvey in 2000 showed additional narrowing and about two additional feet of aggradation across most of the bed, although the thalweg aggraded only 0.6 feet. The dominant change appears to be adjustment back toward the 1960 channel, especially along the right bank.

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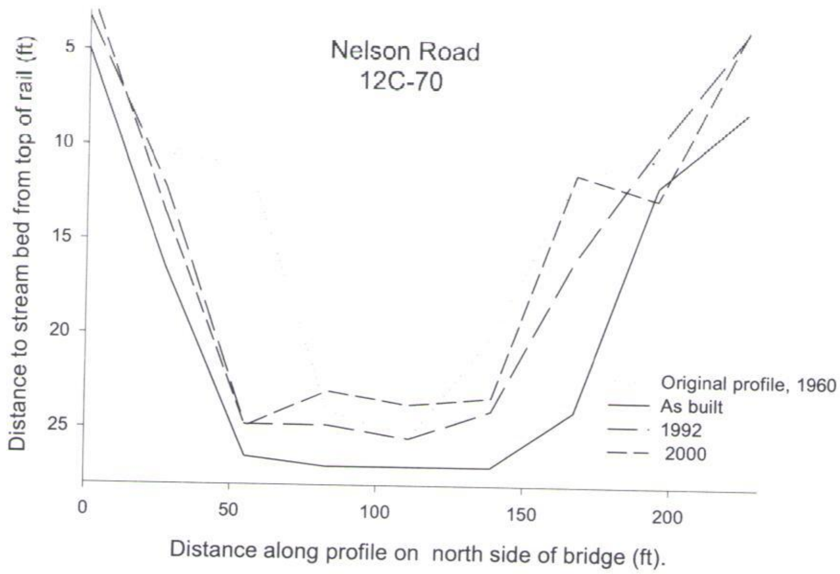

Figure 3-16: Channel cross section at the Nelson Road Bridge from measurements between 1960 and 2000.

Aguas Frias

A profile of the creek under the Aguas Frias was measured on July 26, 1972, but there are no accompanying notes in the file. The bridge was inspected again in 1986, after the high water, and again in 1992, but on both occasions the stream was high and profiles were not made. Our resurvey showed over two feet of incision at the thalweg since 1972, but aggradation along the right bank.

Stumps in the channel:

There are stumps in growth position exposed in the channel upstream and downstream from the Covered Bridge (Figure 3-16), which probably reflect past aggradation in this area. The stream must have been below the elevation of the root crown when the trees were growing. Probably the stumps were covered by sediment from hydraulic mining, and are now being exposed by gradual incision, but we have no direct stratographic evidence on this point. Dating the stumps by dendrochronology or carbon 14 could shed light on it.

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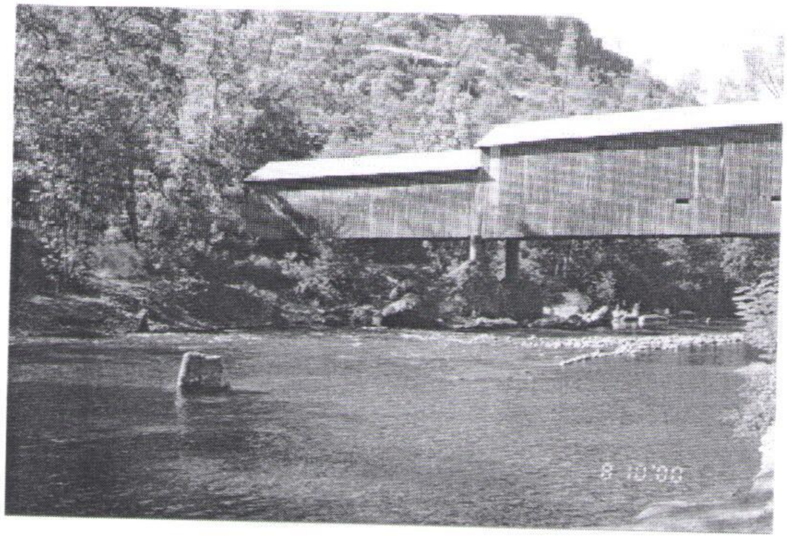

Figure 3-17: Stumps in growth position in the channel of Butte Creek downstream from the Covered Bridge show that the channel has aggraded in this reach. The stream must have been below the elevation of the stumps when the trees were growing.

Discussion:

Canyon reach:

Upper canyon reach

From a geomorphic perspective, the main effect of human activity on the upper canyon reach probably has been a change in the supply of large softwood tree trunks to the channel, from logging. Large logs that jam across the channel create sites for sediment deposition in steep streams that increase the biological productivity of the streams as well as provide spawning habitat (Montgomery et al. 1996). Based on experience elsewhere, logging probably caused a transient increase in the supply of logs to the stream, followed by a larger decrease. Large trees take a long time to grow, so even in the absence of further human disturbance the effects of logging will persist for a long time.

The effects of mining in the upper canyon reach seem smaller and more transient. Although evidence of mining still exists along the stream, effects within the channel itself in this reach probably have been erased by the stream, which has a large capacity for sediment transport in this steep reach.

Hydropower operations have a significant effect on summer flows that are important biologically, but not on the large winter flows that are effective geomorphically. The effects of hydropower facilities on sediment transport were significant for a short time, but not since sediment filled the Butte and Centerville Head dams. Spawning habitat in the upper canyon reach probably is limited more by a shortage of sites for sediment deposition than by a shortage of sediment supply.

Lower canyon reach:

The massive disruption of the floodplain by mining has had major effects on the channel in the lower canyon reach. The stumps in the channel near the Covered Bridge suggest that the channel is still adjusting to aggradation resulting from the hydraulic mining for gold. In the areas affected by dredging for gold the topography of the floodplain has been extensively altered, and since early dredging operations went right into streams during periods of low flow it seems reasonable to assume that the planform of the channel has been more or less affected by the dredging, as well. The dredging has also most destroyed topographic evidence of earlier channel locations.

Channel change since 1937 is well documented by aerial photography. The channel has moved by jumps or avulsions as well as by more gradual erosion on one side of the channel and deposition on the other. There is nothing unusual about such channel migration. The average gradient between the Skyway Bridge and the Honey Run Bridge is about 0.005, rather steep for an alluvial stream with high flows as large as those in Butte Creek, so substantial channel migration and avulsions should be expected.

Pits in the lower canyon that were dug below the water table (and so filled with water to create ponds) are a legacy of sand and gravel mining for construction aggregate which followed dredging for gold. Some of the pits are close to the current channel and it seems inevitable that eventually they will be "captured" by the channel as it migrates across the floodplain, as has occurred elsewhere (Kondolf 1997). Pit capture will cause a temporary interruption in the sediment supply to the channel downstream and may initiate local instability in the channel, but the ponds are not large and given the flows and natural sediment supply in Butte Creek the pits are likely to fill within a relatively few years[2]. Accordingly, the pits present less of a problem than do pits on streams below dams that trap sediment. Nevertheless, it would be prudent to fill the pits if economical ways to do so with suitable materials present themselves.

Valley reach:

Under natural conditions, sediments were sorted by size as the stream flowed out of the mountains and into the valley. Coarser-grained sediments were deposited on the fan, but smaller particles were carried farther downstream to create the clay soils of the Butte Basin. Distributary channels helped spread coarse sediments over the fan. Hydraulic mining in the Butte Creek canyon caused a massive increase in the sediment load in the stream which continued through the low flow season when the stream had little energy to transport sediment. The anthropogenic soils on the fan and margin of the basin reflect the resulting channel aggradation and extensive deposition of "overwash," which probably helped motivate the construction of levees that confined Butte Creek to a single channel. The levees increased the hydraulic efficiency of the channel, leading to incision and the transport of coarse sediment far down into the basin, along with the development of coarser-grained soils within the levees.

There has been little historical channel migration from Highway 99 to just upstream from the Durham-Dayton Highway, where the channel is incised into the resistant Red Bluff Formation in this reach. There have been significant modifications of the channel just upstream from Highway 99, however. Early maps shows Little Butte Creek as a prominent distributary,

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[2] We have not been able to find usefully accurate estimates of sediment transport in Butte Creek.

which left the main channel at about the location of the Durham Mutual Dam and crossed the fan to pass under the Midway where it makes a slight bend to the south about a half-mile southeast from Entler Avenue. The old channel of Little Butte Creek has been mostly obliterated, and is blocked by a levee that runs north from the right bank of Butte Creek,[3] but traces of its course still show in current topography. Before the area was modified, therefore, part of high flows and sediment from Butte Creek could leave the main channel and spread out over the alluvial fan. The gravel deposits left by this or similar, earlier channels were mined using dredges, as evidenced by the tailings between the forks of the creek shown on the 1978 topographic map (a small area of tailings still remains undeveloped). There were also important distributaries to the east of the main channel that motivated construction of a levee southwestward from the hills, which was breached sometime before the USGS surveyed the area in 1910. The trace of one of these channels is still apparent on current USGS Chico Quadrangle, running down through the area now occupied by the Butte Creek County Club

Butte Creek leaves the Red Bluff Formation a short distance upstream from the Durham-Dayton Highway, and historical channel migration is evident from this point downstream. The 1859 survey of Rancho Esquon and an untitled map dated at 1880 show the channel striking roughly south past Durham, west of its current location. By the time of first USGS topographic mapping 1910 the stream had been moved to its present course and been leveed. Probably the leveeing was at least partly a response to destabilization of the creek by hydraulic mining debris, although we have not found historical documentation to confirm it. John Bidwell testified in trial of *People v. Gold Run Ditch and Mining Co.* that "tolerable extensive" mining along Butte Creek began in 1850, and that "(T)he channel of Butte Creek has been filling in since that mining began and it has gradually increased, filling it up more and more until now the levees where the Public Road crosses -- that is the only place that I have examined lately -- the levees are such that I think nearly all the water now runs about what was originally the top of the banks." Hence, at least some of the levees already existed when Bidwell testified, probably in 1882.

Farther downstream in the basin, the early maps show multiple channels that diverge and reconverge, with indications of older channels particularly on the untitled 1880 map. The general picture that emerges for this reach is of an actively migrating and anastomosing (forking and re-joining) channel occupying a belt about half a mile wide, but with evidence of greater channel changes in the more distant past.

Vertical channel change:

Evidence regarding aggradation and incision in the Valley Reach is somewhat unsatisfactory. We have not found clear evidence of the age of the incised section of channel downstream from Highway 99. The channel was in its present location at the time of the earliest surveys, and the bed seems resistant to erosion, but the occurrence of riprap on the bank and the two feet of incision at the Oro-Chico Highway since 1975 indicate that some erosion does occur. Moreover, the early mappings of Little Butte Creek channel show that at least part of the stream flowed out over the fan in the distributary Little Butte Creek at the time of Anglo settlement, and there is clear topographic evidence of other past channels to the east of the current channel. These were mapped as about five feet deep in 1910, which suggests that they also were incised

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[3] The levee extends far enough to guide water (up to 4,500 cfs) from Little Chico Creek into Butte Creek during very high flows.

into the Red Bluff Formation. It is also possible that other relict channels incised into the Red Bluff Formation may be buried under alluvial deposits on the fan; as suggested by reports of upwelling water on the fan during periods of sustained high flow. It seems plausible that the current channel has enlarged and incised significantly since levees forced the entire flow of the creek into it. Unfortunately, older data on bed elevations at the Oro-Chico Highway bridge that might have shed more light on post-levee rates of incision were lost after a new bridge was built in 1986.

During the historical period, evidence of incision on the lower fan and in the basin is much more clear, although it was preceded by aggradation from mine debris. The channel in the basin is now cut down into a clay hardpan, indicating net incision. Incision is a logical consequence of the levee construction, which has increased the depth and velocity of flow at a given discharge and so increased the erosive capacity of the stream. As described elsewhere in this report, coarse sand and gravel are now transported through the lower part of the study area, which presumably increases the rate of erosion of the hardpan that makes up the bed in most this reach.

On a shorter time-scale, there is evidence of both incision and aggradation at different bridges. Clearly there have been episodes of incision, demonstrated by scour problems at the bridges, and some of the aggradation indicated by the bridge data results from works intended to protect the bridges. There have been other episodes of aggradation as well, however, presumably reflecting pulses of sediment carried into the reach by high winter flows. Generally, however, the main tendency seems to be toward incision, as could be expected from the hydraulic effects of the levees, although incision is limited by exposures of resistant material in the bed at many locations.

Current Channel Conditions

Methods:

We investigated current conditions in the study reach of Butte Creek by a combination of field reconnaissance by foot and by boat, by surveying, by consulting other knowledgeable people, and by studying documents and aerial photographs.

Aerial Photography:

Aerial photography of the Canyon Reach, from the Skyway to about 1.0 mile above the Helltown Road Bridge, was flown for CSU, Chico in February and November 1997, in black and white with a negative scale of approximately 1:4800, or one inch = 400 feet. The 1997 photos document the condition of the creek just after the high-magnitude event of January 1, 1997. Additional photography was flown for the California Department of Fish and Game on June 22, 1999, at a negative scale of 1:2000, also in black and white. Aerial photography for the Valley Reach, from Highway 162 to the Skyway, was flown for CSU Chico on December 9, 1998, at a negative scale of 1:4800, or one inch = 400 feet, with stereo (overlapping) coverage in natural color. Considerable detail, such as people standing on the levees, can be seen in the photographs.

The photographs were assembled into a mosaic. Since the purposes of the project did not justify the expense of rectifying the images, the central (least distorted) portion of each scanned aerial photograph was extracted and placed in a mosaic using Adobe PhotoShop, producing an adequately accurate map for qualitative and approximate quantitative analyses. Once the photographs were in the mosaic, the images were imported into AutoCAD engineering software. Using selected features from USGS 7.5 minute topographic maps, the scale of the image was estimated, and set using AutoCAD. In addition, a line was placed down the center of the creek in the estimated location of the centerline of the channel during bankfull discharge. This line was stationed every 100 ft. to add an approximate scale to the images for field interpretation, and to provide an unambiguous method for specifying the location of transects, pebble counts and physical features along the channel. Maps constituting an atlas of the Valley Reach (Appendix B) were printed from the mosaic. A similar atlas of the Canyon Reach was created from the black and white DFG photography (Appendix C). Considerable time was also spent simply studying the photography for the whole area.

Field Surveys:

We surveyed 29 transects at selected locations along the stream, and also surveyed the longitudinal profile of the stream over 38,647 ft or 7.3 miles of the creek. Survey data is presented in as Appendix E. (A less-accurate long profile for the entire reach was plotted from USGS topographic maps.) In the survey, we tabulated station and elevation data for the thalweg and for the water surface. We noted breaks in water surface slope during the low-water conditions existing during the surveying. We also noted any recent channel changes (beyond what was seen in the recent aerial photographs), large woody debris accumulations, rip-rap, locations of spawning and holding salmon, and factors related to incision or deposition of sediment. We re-surveyed selected transects in 2000 to assess channel adjustments following the 1997 event, and surveyed a transect upstream from the Parrott-Phelan Dam four times. Following the 1997 avulsion of the channel away from the dam, the flow was returned to the old channel to allow continued diversions at the dam, and the new channel was converted into a rock-armored, high flow by-pass with a sill on the left bank of the stream. The transect was located just downstream from the sill, to monitor the effects of the flow-split into the high-flow by-pass around the dam.

We performed the surveys with an auto-level, and when possible, referenced the surveys to permanent benchmarks from CalTrans or the Department of Water Resources. In areas too remote to "carry" an elevation from an existing benchmark, we set arbitrary benchmark elevations using a semi-permanent monument such as a large nail or lag bolt in a mature tree. All surveys were closed to within 0.1 ft, and under most circumstances, surveys closed to less than 0.03 ft. Endpoints of surveys were noted on aerial photographs, and subsequently mapped on the photo-mosaic atlases produced for the study (Appendices B and C). Data from the 29 surveyed transects are provided in Appendix D, and selected transects are presented below as part of a reach-by-reach description of the creek.

We conducted pebble counts at 45 locations along the creek to document trends in sediment size distributions and provide data for assessing channel conditions for salmon spawning (Table 4-2). Nine of the counts were on fall-run chinook redds. We plotted size distributions and calculated parameters of the distributions for hydraulic analyses. The locations of pebble counts were recorded on the photo atlas to facilitate future assessment of trends in future studies. The method used for the counts followed Kondolf (1997).

We observed high water at Durnell Road on 14 February 2000, when discharge at the gage peaked at 7,357 cfs about 1.5 hours before our observation, and subsequently confirmed our observation of the stage from high water marks. We surveyed a transect through the high water marks the following summer, but could estimate slope only from the topographic map, because we did not have permission to go up or downstream from the county right of way. We assumed that accretions between the gage and Durnell Road balanced any damping of the peak by channel storage, and used the recorded discharge to calculate the average velocity and Manning's n, a measure of flow resistance, at the transect.

Field Reconnaissance:

Originally, we planned to reconnoiter the valley reach of Butte Creek on foot and map field observations onto enlarged aerial photographs, but we were forced to abandon this plan because we could not get permission to enter many parcels along the creek. Instead, we floated the stream from Highway 99 to the Midway, and from Aguas Frias Road to Highway 162. Two landowners in the intervening reach denied us access. We floated the reach from Highway 99 almost to the Midway on October 27, during the spawning season for fall-run chinook salmon, and from Aguas Frias Road to Highway 162 on January 18, 2001. This gave us a good view of the channel, although it was not possible to see much of the overbank area in most places. However, these areas are visible in aerial photography such as the 9 December 1998 images. We also surveyed along the stream, by wading, and surveyed cross-sections from levee to levee on property where we had permission to go up on the banks. We did not map channel change beyond the Durham-Dayton Highway because the stream is confined by levees that predate aerial photography.

Before the project began, we rafted the stream from the Centerville Powerhouse to the Parrot-Phelan Diversion Dam with personnel from the CSU Chico Watershed Projects Office. Subsequently, we walked the flume to the Centerville Head Dam to reconnoiter the upper canyon reach and inspected selected sites such as the Quartz Bowl. We also inspected the stream in the vicinity of Helltown.

Results:

Surveys:

Transects:

We surveyed 29 transects over the study reach (Table 4-1). Selected transects are presented in the reach-by reach discussion below. All transects are presented in Appendix E.

Location name:	Cross Section #	Station
Hostetler/landslide	XS # 1	159250
Marylin Cannon's Residence	XS # 2	158400
DS of DFG Weir @ Ctrvlee PH	XS # 3	155750
Carmen's 1	XS # 4	155200
Carmen's 2	XS # 5	155400
Sorenson XS	XS # 6	141600
Merliss XS	XS # 7	130700
Mike Smith XS	XS # 8	129950
DS of USGS Gauge	XS # 9	123680
Honey Run C	XS # 10	121500
Honey Run B--NOT COMPLETED	XS # 11	120700
Honey Run A	XS # 12	119950
NRCS Site B-Big Bar	XS # 13	113250
NRCS Site B-Riffle	XS # 14	112600
NRCS Site B-Pool/Ponds	XS # 15	112180
Okie Dam-US across Main Chl	XS # 16	110300
Okie Dam-Across Chl Split	XS # 17	110200
Okie Dam-Across Dam Chl	XS # 18	109950
Drake XS	XS # 19	108400
Sitton XS	XS # 20	107300
Kato XS	XS # 21	105550
DS of Hwy 99	XS # 22	95000
US of Oro Chico	XS # 23	90725
DS of Oro Chico	XS # 24	87050
US side of DD Hwy Br	XS # 25	76880
DS of DD Hwy	XS # 26	74625
US side of Durnell Rd Br	XS # 27	51425
US of WCWD siphon crossing	XS # 28	42550
DS side of Aguas Frias Rd Br	XS # 29	27650

Table 4-1. Transects surveyed along Butte Creek. Stationing is in feet from Highway 162. XS 11 was not completed because the surveying crew left the area when it came upon a marijuana patch.

Long Profile:

The long profile of study reach as estimated from USGS topographic maps has a typical concave-upwards shape (Figure 4-1), with a slight hump upstream from Highway 99, in the mouth of the canyon.. This is more apparent when the profile is plotted from Highway 99 upstream (Figure 4-2) and reflects the influence of the warping of the Tuscan Formation by the Chico Monocline in this part of the creek.

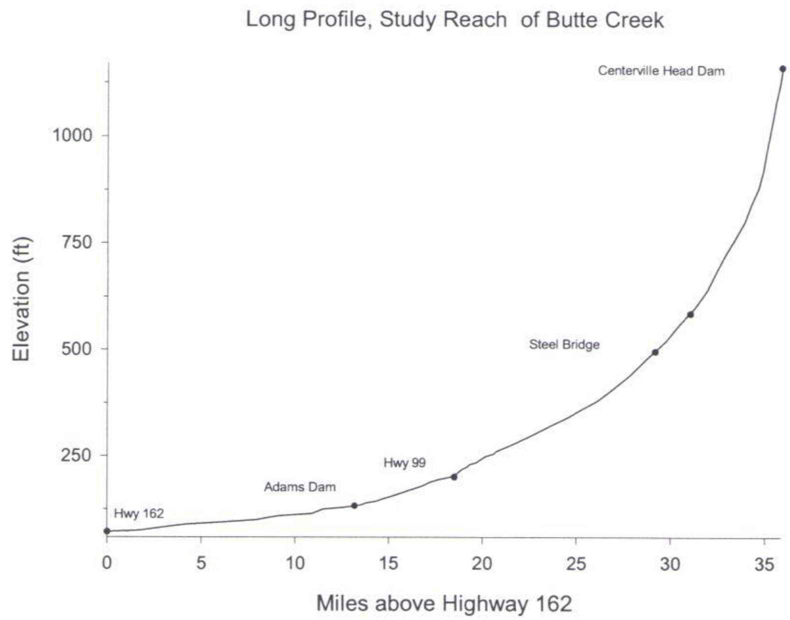

Figure 4-1: Long profile of the entire study reach on Butte Creek, from Highway 162 to the Centerville Head Dam, estimated from USGS topographic maps.

In the Valley Reach, with a lower gradient, the profile developed by measuring along the channel on USGS topographic maps and noting the distance at which the contour lines cross the channel is less satisfactory, and results in considerable uncertainty in the depiction of local changes in slope. Nevertheless, the data are good enough to be useful. The channel slope decreases from about 0.001 near Highway 99 to about 0.0004 Highway 162, and is generally steeper on the fan (~ to Adams Dam) than in the basin. Absent the levees, the channel would meander more than it does downstream from the Durham-Dayton Highway to the end of the levees (about four miles upstream from Highway 162), so the natural long profile probably was less concave. The relatively steep reach just upstream from Highway 162 seems anomalous, but it is consistent with the topography of the Butte Basin, which is steeper between elevations of 80 and 90 feet than between 90 and 100 feet (see Butte City and Llano Seco Quadrangles), and may reflect the tectonic warping that has produced the Llano Seco rise. The actual complexity of the long profile of the channel across the fan is suggested by the surveyed profile (Figure 4-4), but this is still only a two-dimensional slice through a complex three-dimensional form.

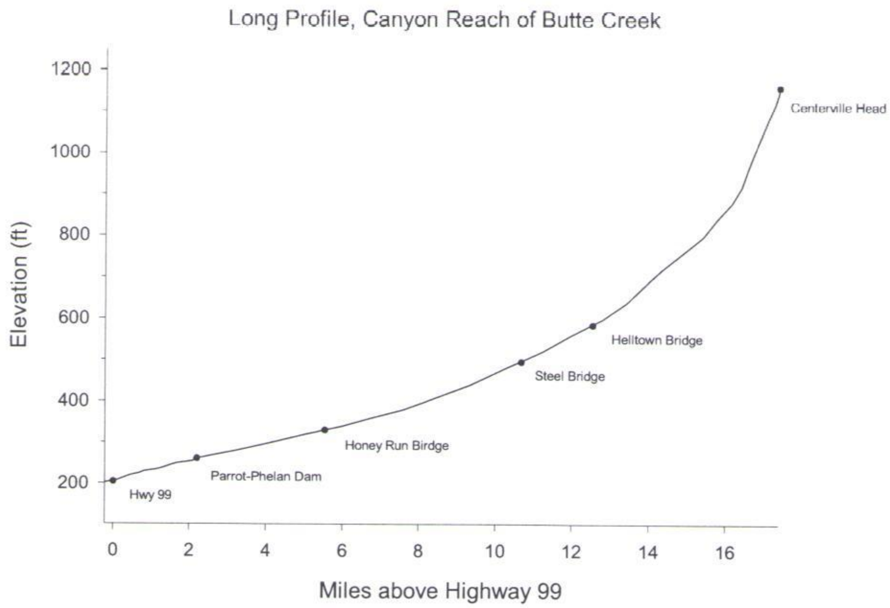

Figure 4-2. Long profile of Butte Creek from Highway 99 to the Centerville Head Dam. The linear or slightly humped part of the profile near Highway 99 shows the influence of the Tuscan Formation on the creek profile.

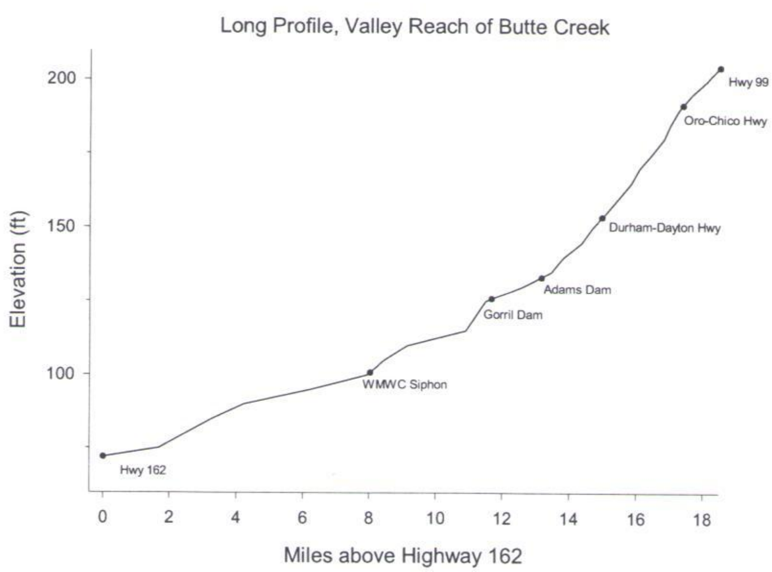

Figure 4-3: Long profile of the Valley Reach of Butte Creek, estimated from USGS topographic maps.

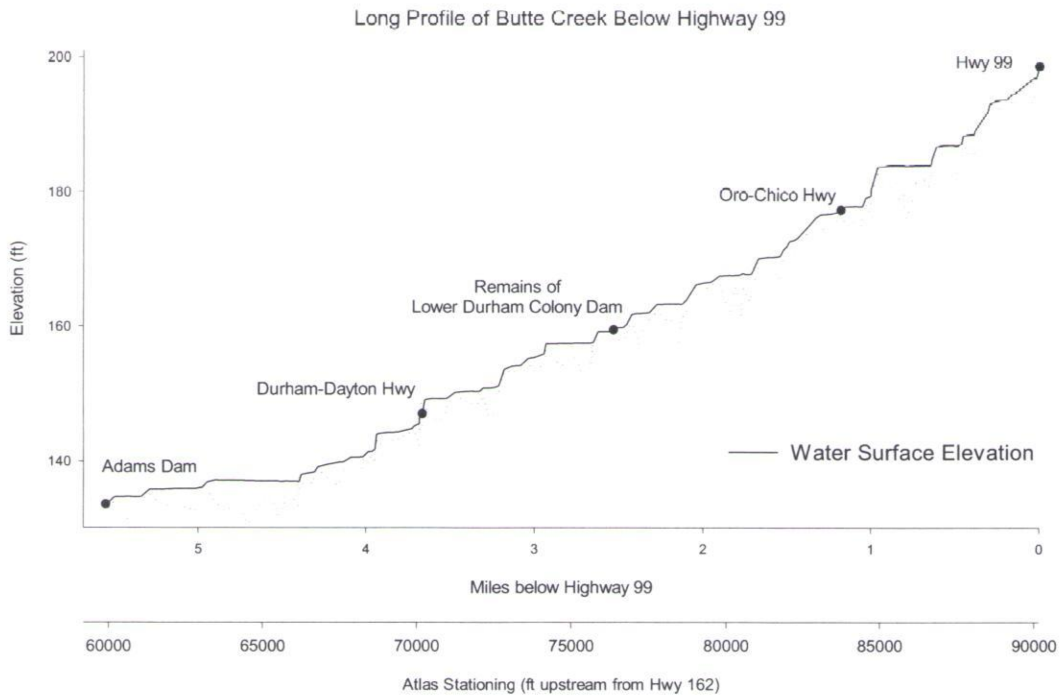

Figure 4-4: Surveyed long profile of Butte Creek from Adams Dam to Highway 99, showing both the channel bed (dotted line) and the water surface profile (solid line).

Pebble Counts:

Median grain sizes[1] for all 45 pebble counts ranged from 12 to 149 mm (0.5 to 5.7 inches), while those for the nine counts on redds were 32.5 to 55 mm (Table 4-1, Figure 4-5) . There is a general increase in gravel size and variation in size going upstream, as expected, although sizes do not increase upstream from about SM (sta. 100,000). There is a suggestion of a decrease upstream from Station 100,000, but this is probably because we made counts in selected sites in that area on bar surfaces that had particularly large clasts. The sample sites were not located randomly, so no real statistical inferences can be made from the data. Generally, however, there was no apparent size difference between the counts made on exposed bars and those made on submerged bars. Data on all size categories for the pebble counts are provided in Appendix E.

[1] Grain sizes are given in terms of the length of intermediate axis. The longest and shortest straight lines through a piece of gravel define the long and sort axes, and the intermediate axis is perpendicular to both. This is easy to identify and measure in the field. Over 100 pebbles were measured for each count.

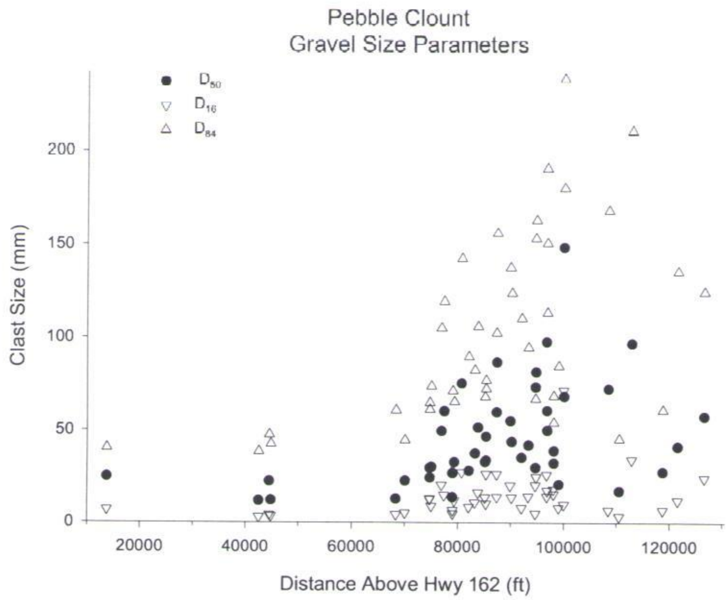

Figure 4-5. Grain size parameters for 44 pebble counts, showing the expected downstream decrease in substrate size. D_{50} = median size; D_{16} and D_{84} = 16th and 84th percentile sizes.

Butte Creek Pebble Counts

Station	D_{50}	D_{16}	D_{84}	Notes
13700	25.1	7.1	40.5	instream
42500	12.0	3.1	38.7	exposed bar
44500	22.6	4.4	47.8	"
44800	12.2	3.7	42.7	"
68300	13.0	4.5	61.0	instream
70000	22.8	5.2	44.8	"
74680	29.8	13.2	61.3	exposed bar
74700	24.6	12.9	65.1	"
75020	30.3	9.1	74.1	instream
76890	49.8	20.7	105.4	redd
77400	60.4	15.0	119.7	exposed bar
79000a	27.0	5.0	71.5	"
79000b	14.0	6.8	28.2	"
79325	32.9	12.1	65.7	instream
80700	75.6	27.5	142.7	"
83250	37.6	11.1	82.8	"
83800	51.7	16.4	106.3	exposed bar

continue to the next page

Station	D_{50}	D_{16}	D_{84}	Notes
85150	33.1	13.9	68.2	"
85300a	46.8	26.5	77.3	redd
85300b	34.0	10.5	72.7	"
857300	60.0	26.5	102.8	exposed bar
87350	87.0	14.1	156.5	instream
89880	55.3	20.4	137.9	exposed bar
90130	44.0	13.8	124.2	redd
92000	35.4	8.1	110.7	exposed bar
93280	42.2	14.4	95.0	redd
94600a	73.6	20.5	153.7	exposed bar
94600b	30.1	5.2	67.2	"
94700	81.8	24.9	163.7	instream
96700	98.0	26.2	191.5	exposed bar
96740	60.8	14.4	151.2	instream
96815	50.0	17.7	113.8	redd
98045	39.1	15.7	68.8	"
98050	32.5	18.4	54.4	"
99000	21.0	8.3	85.1	instream
99900	148.8	71.9	239.2	"
99990	68.6	10.0	181.0	instream
108400	72.7	7.0	168.9	"
110475	17.3	3.6	45.5	"
112820	97.1	34.5	211.5	exposed bar
118700	27.8	7.1	61.1	"
121500	41.3	12.2	135.8	"
1265500	57.8	24.5	125.0	"

Table 4-2. Size parameters for pebble counts along Butte Creek. The stationing is in feet from Highway 162, the lower limit of the study area.

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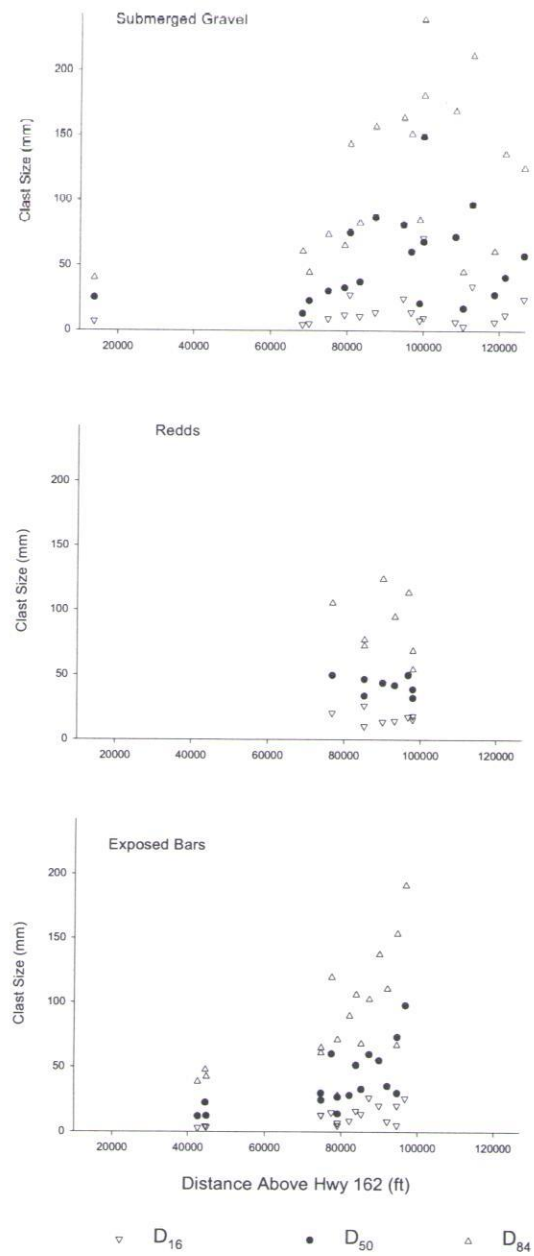

Figure 4-6: Pebble count data plotted by category. Note the relatively narrow size range of gravels selected by salmon for redds, with median sizes from 32 to 50 mm.

The most surprising data are those from farthest downstream, where the channel bed is mainly duripan but gravel appears in patches. One count, with a median size of 25 mm, was made about 2.6 miles upstream from Highway 162, and three counts were made just upstream from the Western Canal siphon. The stream is well into the Butte Basin in this area, and the soils outside the levee are heavy clays. We observed salmon spawning in gravels near the Western Canal siphon.

Reach by Reach Results and Discussion:

We have tried to integrate many of our findings about Butte Creek in the reach-by-reach descriptions that follow. Stationing is in feet upstream from Highway 162, and matches stationing in the maps in appendices B and C. We also prepared a summary table that makes up Appendix D.

Lower Centerville Diversion Dam (Centerville Head Dam) to the Helltown Bridge (Sta. 190,080-160,250)

The character of the stream in this steep 5.65 mile reach is dominated by the geology and by the gradient, which averages about 0.023. The creek cuts through very old geologic formations that comprise the Basement Series of the Sierra Nevada. These formations are ancient sea floors associated with plate-tectonic spreading centers that have been transported great distances from their place of origin in the Pacific Ocean. The original orientation of the rocks has been lost during transport, with some layers now rotated 90 degrees so that originally horizontal strata are now vertical.[2] These resistant formations create a steep landscape, through which the stream passes with many narrow chutes, steep drops, at least one significant (~ 12-15 feet) waterfall about a mile below the dam. The channel widens somewhat when the stream enters the more erodable sandstone of the Chico Formation in the end of the reach, but the channel is still steep and controlled by bedrock.

Figure 4-7 Aerial view of a portion of the Butte Creek Canyon, showing the steep terrain and the Centerville flume on the left bank above the stream. Flow is from left to right.

This reach is primarily a sediment transport zone in which fluvial processes are dominated by the bedrock channel and the gradient. Pools in this reach provide holding good habitat for spring-run chinook, but the waterfall blocks salmon except in years with high spring flows, when a few fish are able to ascend it (Kathy Hill, CDFG, pers. comm.). Presumably, the reach also

[2] Chimney Rock, a prominent rock formation easily seen from the Centerville Canal in this reach is a good example of such an up-turned bed. The relatively resistant metamorphosed limestone has outlasted the other, less-resistant metamorphosed sedimentary rocks around it, resulting in a striking spire jutting several hundred feet from the left bank of the creek.

provides habitat for juvenile steelhead. In the upper 3.6 miles of this reach, where the resistant rocks of the Sierra Basement Complex form the channel, gravel deposits suitable for spawning occur only at the tail of pools or in the lee of large boulders or other obstructions. Small pockets of alluvium behind bedrock projections into the channel support most of the sparse riparian vegetation. In the lower 1.25 miles the channel enters the more erodable sandstone of the Chico Formation and gravel bars begin to appear on the inside of bends, but spawning habitat remains limited compared to the alluvial reach downstream. Many of the fish that hold over the summer in this reach move downstream to spawn.

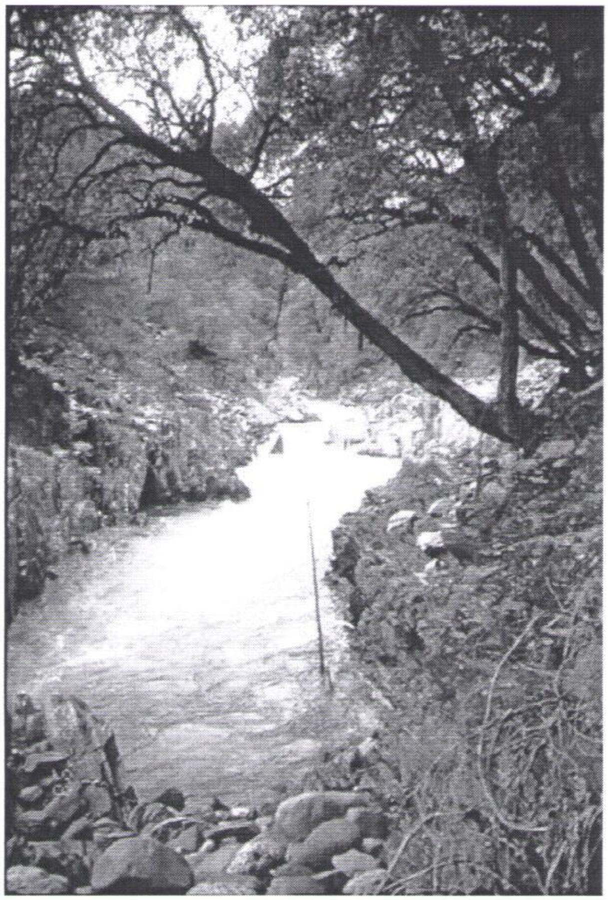

Figure 4-8: Pool in the upper canyon reach of Butte Creek.

Based on observations by CDFG personnel doing snorkel surveys, there was a substantial infusion of coarse sediment into this reach in the January 1997 high water. A memorandum reporting the August 1997 survey noted that:

> Salmon holding habitat was degraded by the New Year's Day storm - many holding pools were significantly filled in, through the Barrier and Chimney Rock Pools still have adequate depth for summer holding temperature. The entire Butte Creek canyon is

significantly changed - many side channels and main stem riffle habitats were created and a tremendous amount of spawning gravel was added to the waterway, though at the expense of holding habitat. Between Chimney Rock and the Powerhouse, most of the riparian vegetation was lost, but alders are resprouting in some places.

The memo for the 1998 survey notes that "(M)any of the pools that had partially filled in during the winter of 96/97 were scoured out by last winter's storms, so holding habitat has increased somewhat."

This reach has been modified primarily by water diversions for hydropower, and the current operations typically increase flows during the summer because imports of Feather River water through the Toadtown Canal usually exceed diversions at the Centerville Head Dam. Mining occurred along this reach but was not extensive and probably had no lasting effects on the stream. Diversion dams upstream no longer trap sediment. The effects of early logging are more difficult to evaluate, but may be significant. The upper Butte Creek basin, especially the Butte Meadows area, supported a forest of large coniferous trees that must have contributed large and relatively rot-resistant tree trunks to the stream. Such large wood debris can substantially increase the habitat value of bedrock channels by creating sites for alluvial deposits (Montgomery et al. 1996), and so hyporheic habitat. These deposits provide habitat for invertebrates upon which juvenile salmonids feed, as well as habitat for salmonid spawning, incubation, and rearing. Since alluvial deposits are scarce in this reach, a decrease in the supply of large logs would adversely affect the value of the reach for salmonids.

Helltown Bridge to Centerville Powerhouse (Sta. 160,250 -155,750)

A large Quaternary-age landslide dominates this 0.85 mile reach of the stream. Geologic mapping (Helley and Harwood 1985) and site reconnaissance indicate that the left side of the canyon gave way, blocking the creek with material from both the Chico Formation and the overlying Tuscan Formation. The stream has since incised along the right side of the canyon, eroding both the landslide debris on the left and the sandstone of the Chico Formation on the right bank, and any alluvial deposits that may have formed above the slide have been eroded away. Along the stream, the toe of the slide is now armored by large resistant boulders from the Tuscan Formation, and the softer Chico Formation sandstones have been carved into a series of tall (up to 120 ft) cliffs along the right bank (Figure 4-3). The landslide ends about 2,500 feet upstream from the powerhouse, and for this distance the Chico Formation makes up both banks.

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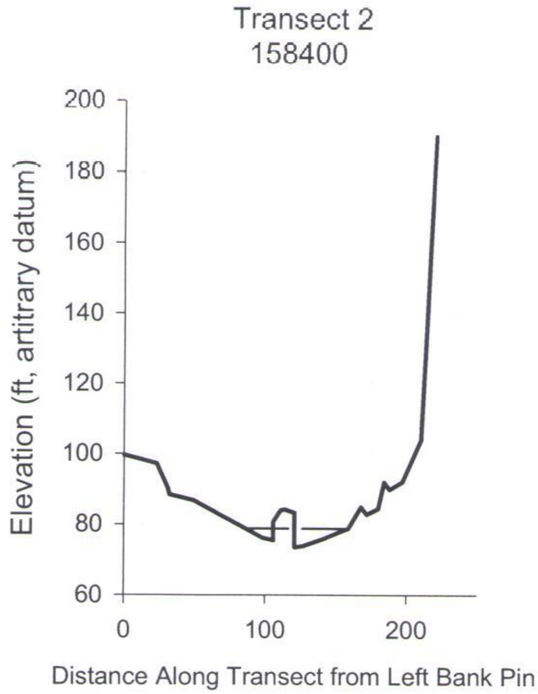

Figure 4-9: Transect across Butte Creek at Sta. 158400; the view is downstream. There is a cliff of Chico Formation sandstone on the right bank. The dashed line shows the water surface at the time of the survey, 7/30/99.

The channel tends to be wider in this reach than it is farther upstream, and the increased width provides room for lateral bars and small point bars, with a corresponding increase in riparian vegetation (Figure 4-10). Spawning gravels are also more plentiful here, and spring-run salmon also hold in pools in this reach. The bed of the stream is still highly irregular, as shown by a surveyed long profile in the lower part of the reach.(Figure 4-11).

Large woody debris inputs in this reach appear to be modest; although the trees in the area are currently undisturbed, many were cut for lumber and firewood during the Gold Rush and again during the Great Depression, so old trees are scarce. The Helltown Bridge is a privately maintained structure, and though rather undersized, it appears to be able to pass most large wood.

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Figure 4-10: Sandstone cliff appear on the right bank of Butte Creek where it cuts through the Chico Formation. The view is upstream.

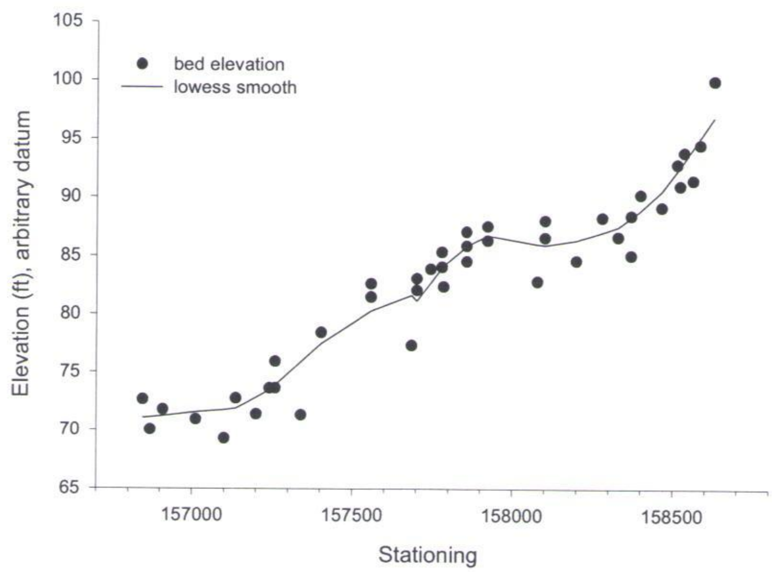

Figure 4-11 Surveyed long profile of a portion of Butte Creek. Spot elevations are smoothed using "locally weighted regression" (lowess) to emphasize local variation in slope; variation around the smoothed line reflects the roughness of the channel. The average slope is 0.0162

Miners worked all along this reach, as evidenced by old reservoirs and canals on the left bank, and the shafts of several drift mines into the Chico Formation along the left bank both up and downstream of the landslide, but effects of the mining are no longer evident in the channel itself. A cluster of houses known as Helltown has been built on the landslide, although the historical mining town by the same name was on the right bank across the Helltown Bridge. Except for a mobile home at the historical location of Helltown, the homes of contemporary Helltown are now the farthest upstream along the creek. Although two creekside homes are built on landslide debris, the Tuscan boulders provide enough bank protection that no revetment has been installed.

Centerville Powerhouse to Honey Run Covered Bridge (Sta. 155,750 - 127,000)

The stream in this 5.45 mile reach cuts through the Chico Formation, as it does just upstream, but the channel tends to be a bit wider and the gradient lower, about 0.007 More sediment is stored in the channel and in the banks along the stream, where large areas were dredged. For most of the reach, however, at least one bank is of sandstone, and there are a number of deep scour pools that create good holding habitat for spring-run chinook. Gravel bars, particularly at the downstream end of pools, provide good spawning habitat, and the reach provides what appears to us as high quality rearing habitat. Discharge increases in this reach from return flow at the Centerville Powerhouse and, near the lower end of the reach, flow from Little Butte Creek. Alluvium on the banks supports substantial riparian vegetation, and provides more hyporheic habitat than occurs further upstream.

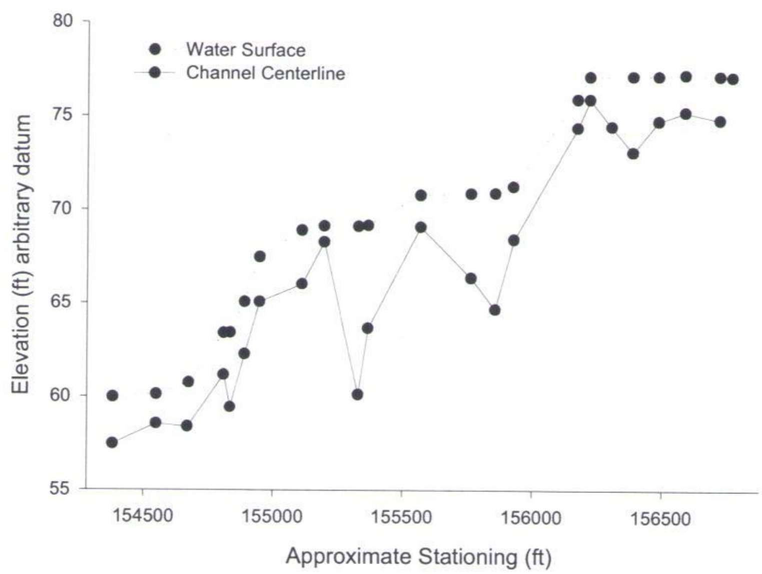

Figure 4-12: Surveyed channel profile from the Steelbridge upstream, showing pools used by spring-run salmon for holding over the summer.

Homes are common along this reach of the stream. The majority are in high, safe locations, typically on outcrops of Chico Sandstone, but a number are on low-elevation alluvial surfaces along the creek that are hydrologically well-connected to the stream. These surfaces, which are covered by riparian forest where undisturbed, may be inundated during high flows and are at risk from channel migration. Unfortunately, between storms they seem attractive for residential development, and considerable development has occurred. The Castle Rock Court development is an example. The site was first dredged for gold, then leveled and developed. After significant bank erosion in 1997, 1,248 linear feet of streambank were riprapped through the NRCS Emergency Watershed Protection Program. One landowner (who had the space to do it) moved his home a considerable distance from the stream, but others had no alternative to trying to stabilize the banks. Unfortunately, others have not learned from this experience; one home further upstream was constructed on a point bar after the 1997 high water, close to a house that was damaged in 1997 and received EWP monies for bank stabilization.

Honey Run Covered Bridge to 1,400 ft. above Skyway Bridge (Sta. 127,300 - 103,300)

Butte Creek becomes a predominately alluvial stream in this reach and the gradient drops to about 0.004. The floodplain of the creek expands below the Covered Bridge and the USGS gauging station. This is an important reach for salmon and steelhead. Research in the Pacific Northwest shows that alluvial streams support higher production of salmon than confined, bedrock streams (Reeves et al. 1995). This is not surprising, in view of the connections between aquatic and riparian ecosystems; alluvial valleys are generally more biologically productive than canyons. This is one of the reasons that humans also favor alluvial valleys. Although the details remain to be worked out, it seems that the productivity of alluvial streams is linked to the extent of the hyporheic and riparian zones and to the dynamics of channel migration and habitat renewal. Unfortunately, human occupancy of alluvial valleys tends either to exaggerate or dampen those dynamics, through activities such as mining, clearing riparian vegetation, flow regulation, bank stabilization, and removal of logs from streams and floodplains.

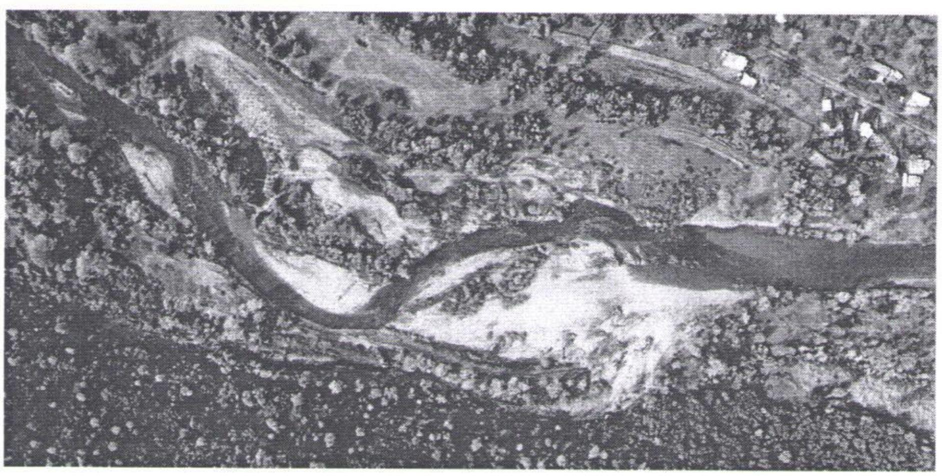

Figure 4-13. The alluvial channel of Butte Creek in the lower canyon reach can be highly dynamic, as shown by this 1997 aerial view of the CSU Chico Ecological Preserve. Flow is from right to left.

This reach of stream has been the most influenced by gold dredging and gravel mining, as shown by the extensive areas of dredger tailings shown in historical Aerial photography and on the USGS topographic maps (Chico and Hamlin Canyon quadrangles). Dredges move across the landscape on a pond of their own creation. As the head of the dredge chews into the floodplain, the tail end of the dredge disgorges the larger cobbles and gravel into piles of "tailings" at the other end of the pond. In this way, the dredge works the pond across the floodplain, leaving the characteristic series of elongated piles seen in Figure 4-14. The finer sediments are sluiced for gold within the dredge and discharged into the pond, where they settle to the bottom, to be covered later by the tailing piles as the dredge moves along. As a result, the alluvium is inverted; the soil and fine-grained sediments normally at the surface and interspersed through the alluvial sediments are buried, leaving barren piles of relatively uniform cobble across the landscape.

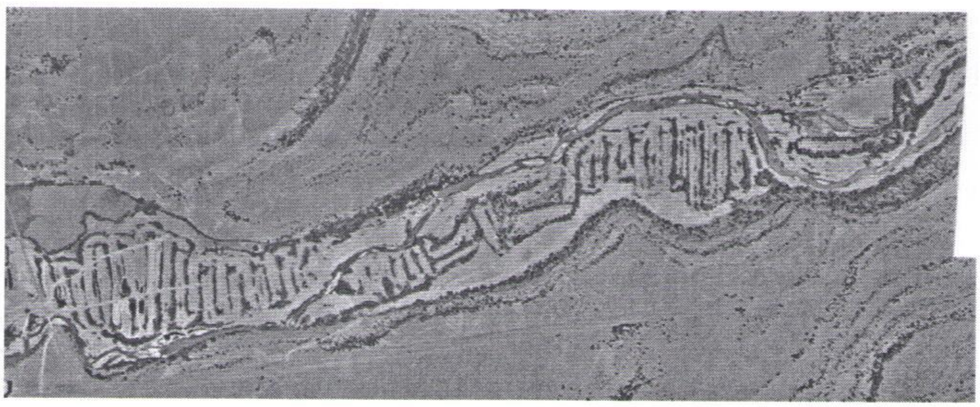

Figure 4-14: The floodplain of the Lower Canyon Reach was extensively mined by dredges, as shown by this 1952 aerial photograph. Flow is from right to left.

Gravel mining followed the dredging. The demand for aggregate expanded with the population of California, and the dredge tailings were an obvious source of supply. Notable features left by the gravel mining activities include mining ponds, remnants of an old haul road, a bridge footing, and compacted, raised road prisms that now function in some places much like levees.

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Figure 4-15: View upstream in the lower Butte Creek Canyon. Much of the canyon floor has been dredged for gold and mined for gravel, obliterating any natural terraces or remnant channels. Note the mining pond in the lower left, separated from the creek by the eroding remains of a gravel haul-road (look for the patch of reflected sky just above the road at the edge of the figure).

The channel in this reach tends to move by jumps or avulsions during high flows, as well as by gradual erosion at bends. A dramatic example of an avulsion occurred in 1997 when the stream abandoned the section of channel containing the Parrot-Phelan Dam. The stream was returned to its previous channel by the Natural Resources Conservation Service under its Emergency Watershed Protection Program. This was a two-phase project, with moving the

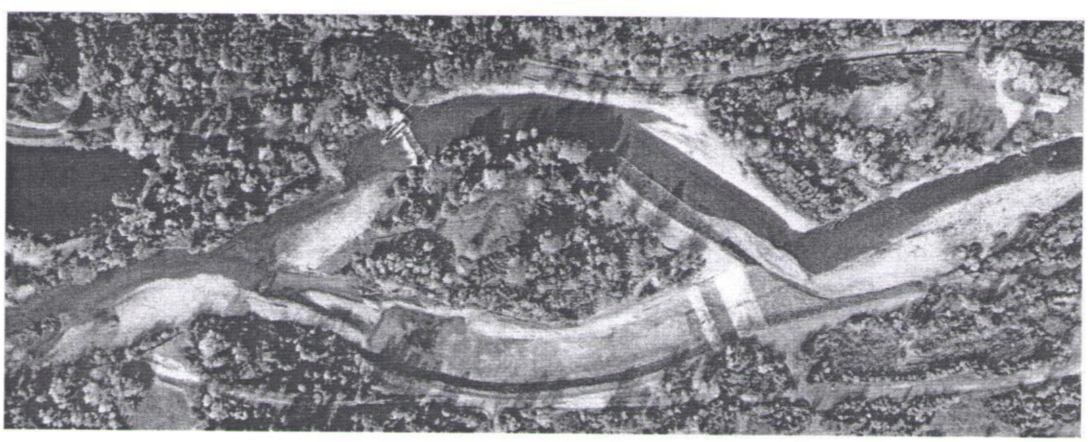

Figure 4-16: Aerial view of the Parrot-Phelan Dam and high-flow by-pass channel. Flow is from right to left. A sill keeps low flows from entering the by-pass. Note the mining pond on the right bank near the left edge of the figure.

creek back to abandoned channel as the first phase. This allowed diversions at the dam to resume. The second phase, still under emergency status and with no environmental review, was intended to keep the stream flowing past the diversion through a massive application of rip-rap along the left bank of the stream and on both sides of the newly created channel, which was turned into a high-flow by-pass channel (Figure 4-16).

Rip-rap now extends along more than 3,000 feet of the left bank of the creek from this project alone, and based on experience elsewhere there will be a tendency to extend the rip-rap if channel migration upstream seems to put the existing rip-rap at risk from erosion. This loss of active alluvial channel constitutes a significant degradation of habitat for listed salmon and steelhead, as well as for other aquatic and riparian species.

The 1997 channel avulsion around the Parrot-Phelan Dam resulted at least in part from changes in the channel planform over the preceding decades.[3] A bend developed upstream from the dam, so that the channel now makes a hard turn to the right before approaching the dam, and the avulsion occurred at the left bank of this bend (Figure 3-2). The new high-flow by-pass leaves the left bank of the channel at the same point. Flow dynamics at this bend tend to create a bar along the right side of the channel. During flow events that move significant amounts of gravel, part of the flow passes over the sill on the left bank into the by-pass channel. This reduces the discharge in the main channel, and so reduces the competence of the stream to transport coarse sediment. In consequence, the bar along the right side of the channel grows, increasing the proportion of the flow going into the high-flow channel at a given discharge, and reducing the discharge at which water begins to flow into the by-pass (we have observed flow going into the high-flow channel at flows about 1,500 cfs). As the frequency of flow into the by-

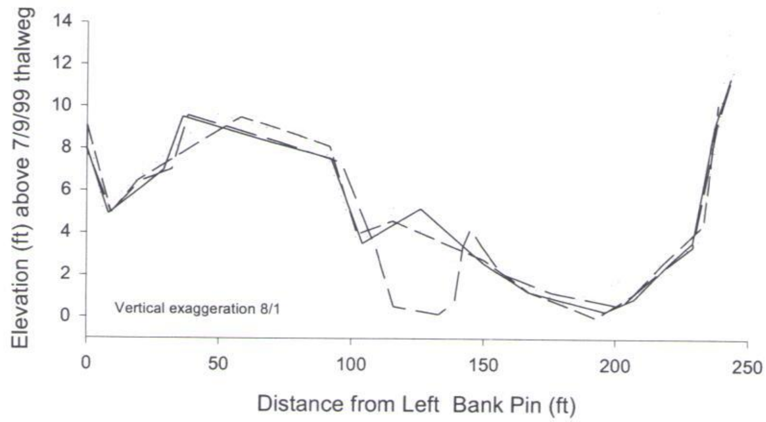

Figure 4-17: Repeated surveys of a transect upstream from the Parrott-Phelan Dam showing rapid re-growth of a gravel bar after material was removed to increase channel capacity: the view is downstream. The lines are: solid 11/98, dotted 7/99, dashed 7/99, dash-dotted 7/00.

[3] This has been described previously in a seminar paper and a conference presentation by Eric Ginney; development of the bend is documented in Appendix A, Figures 2-7.

pass channel increases, so too does the problem of fish being stranded in the by-pass. Repeated surveys of a transect just downstream from the high-flow bypass for the Parrott-Phelan Dam (Sta. 109,950) document the problem: the gravel bar along the right bank recovered rapidly after material was removed from the bar, in an attempt to maintain the capacity of the channel. (Figure 4-17).

The 1997 New Years Day storm recruited large numbers of trees and logs to Butte Creek, many of which were left along the channel in this reach. Because of concerns that these logs would clog bridges or cause other damage in future storms, Butte County funded a program to cut the logs into pieces about four feet long. Recruitment of large wood to streams is episodic, and these logs probably represent a large percentage of the total that will enter the stream for decades. Current research on the importance of large wood in streams for salmonid habitat indicates that cutting up the logs in this reach will have a negative effect of the habitat of listed species for some time, but as far as we know this was not considered in planning the project.

1,400 ft. above Skyway Bridge to Highway 99 Bridge (Sta. 103,300 - 96,900)

A transition from the canyon to the Butte Creek fan occurs in this reach, in which the nature of the stream is affected by outcroppings of the Tuscan Formation in the bed. The Tuscan Formation dips more steeply in this reach and dives under the Sacramento Valley as part of the Chico Monocline. The gradient of the stream is also steeper, at 0.006, and is controlled by outcrops of the Tuscan Formation in the bed of the stream upstream from the Skyway Bridge and from the Highway 99 Bridge (at about Stations 97,700, 99,600, and 103,300 in the Atlas). The channel is also less sinuous in this reach than in the more fully alluvial reach upstream.

The channel is also more highly modified than it is upstream. There has been extensive dredging, gravel mining, and industrial development, and levees constructed by the Corps of Engineers begin about 2000 feet upstream from Highway 99 on the right bank. An extension of this levee into the Little Chico-Butte Creek Diversion Channel introduces water from Little Chico Creek during floods. A major distributary channel (also called Little Butte Creek) that once carried water and sediment onto the fan has been obliterated. Based on aerial photographs, the industrial yard on the right bank downstream from the Skyway has expanded toward the channel, presumably on rip-rap like the concrete rubble that is currently exposed in the bank. The remains of an old railroad crossing and the dam and headworks of the Durham Mutual Water Company further constrain the stream just downstream from the yard, and the right bank levee begins just below the dam. Nevertheless, there is significant riparian habitat between the levee and the creek, in an area where early maps show an island in the stream (e.g., Figure 3-6), and we observed many fall-run chinook spawning around Station 98,500, between two exposures of the Tuscan Formation.

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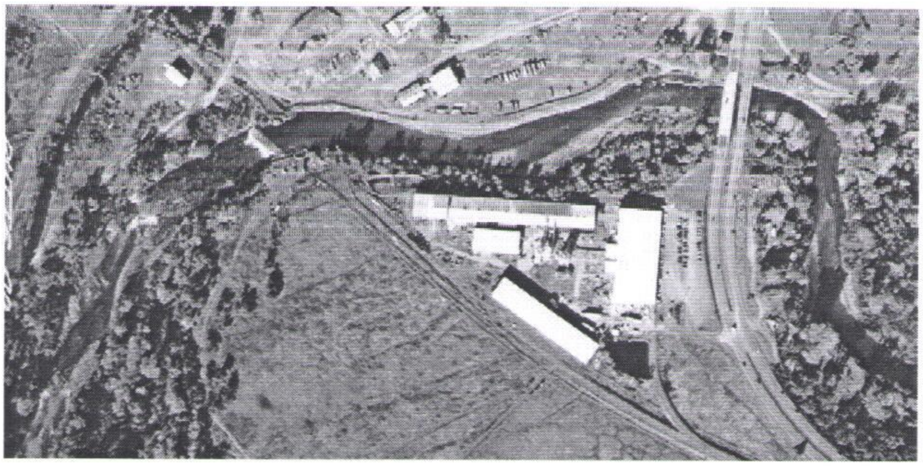

Figure 4-18. Butte Creek downstream from the Skyway (flow is toward the left). Industrial development is encroaching on the stream on the right bank, but there is good riparian habitat just downstream. The Durham Mutual headworks are just downstream from an old railroad alignment that is shown on early maps. The Tuscan Formation outcrops in the streambed downstream from the headworks.

Historically, the distributary Little Butte Creek left the channel on the right bank just below the area shown in the figure, as did a smaller distributary on the left bank (Figure 3-6).

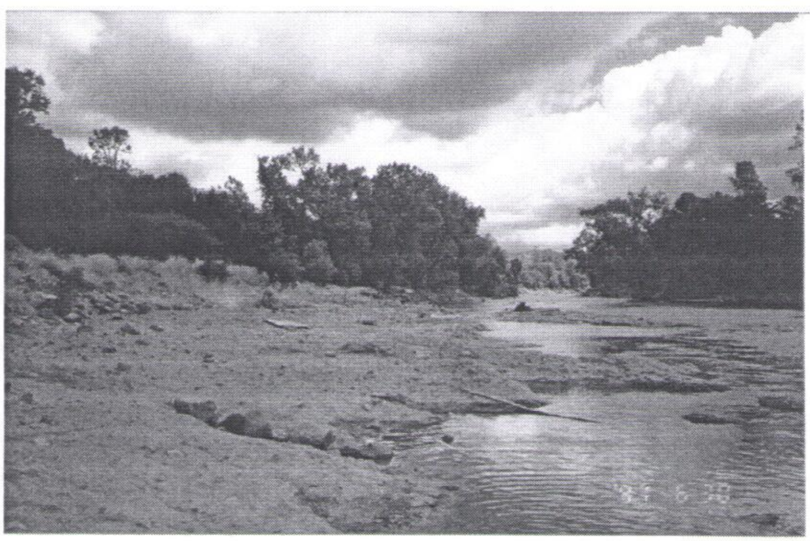

Figure 4-19: Resistant material in the bed limits channel incision in a number of places along Butte Creek, exemplified by this exposure of the Tuscan Formation at Sta. 9,600, about 2,300 feet downstream from the Skyway Bridge. The outcrop is visible near the left edge of Figure 4-18 above.

Highway 99 Bridge to Oro-Chico Highway Bridge (Sta. 96,900 - 90,200)

In this reach Butte Creek is incised into the Red Bluff Formation, a reddish Pleistocene conglomerate consisting largely of stream-transported gravels that overlies the Tuscan Formation in this area (Figure 4-20). This resistant formation is widely distributed along the eastern and northern edges of the Sacramento Valley, and strongly influences stream channels that cross it. The Red Bluff Formation first appears in the bed of the stream about 800 feet upstream from Highway 99, and extends for about 5000 feet along the creek past the Oro-Chico Highway Bridge. The average slope of the stream decreases to about 0.0033, reflecting the transition from the canyon mouth to the fan.

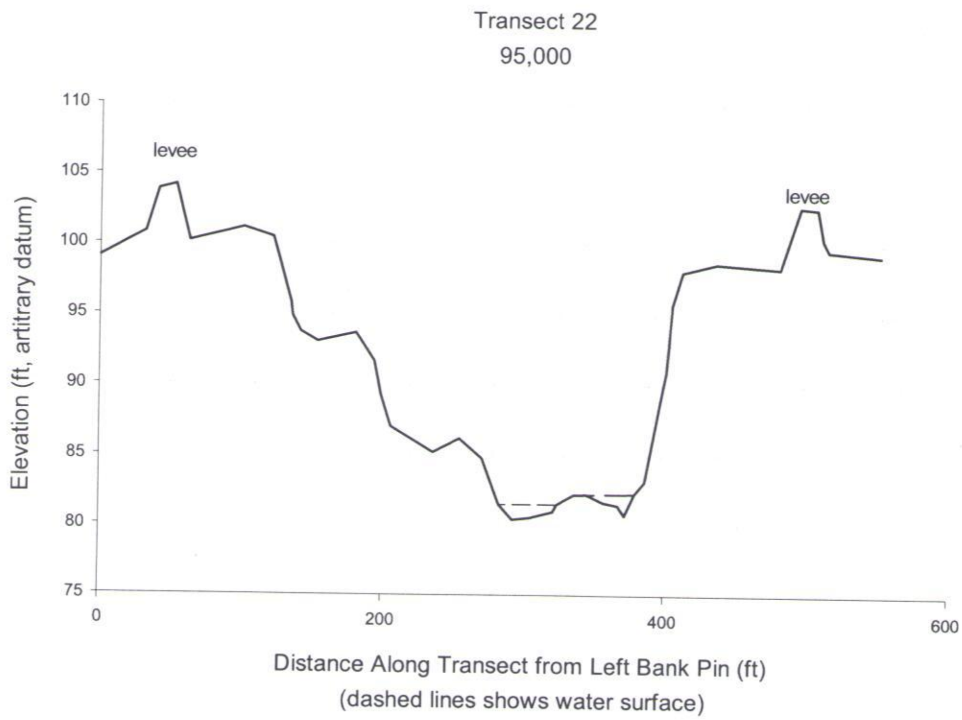

Figure 4-20. Transect across Butte Creek at Sta. 95,000, 1,900 feet downstream from Highway 99; view is downstream. Butte Creek is incised over 15 feet into the Red Bluff Formation at this location, where the low flow at the time of the survey (10/2/99) was spilling across a mid-channel bar.

This reach is leveed on both sides with no agriculture or infrastructure within the levees. Although the banks are relatively resistant to erosion, riprap has been placed along the channel in several locations, presumably in response to bank erosion. Increased rates of erosion are a logical consequence of the levees which increase the depth and velocity, and so the erosive force, of the flow. Boulders scattered on bars in this reach (Figure 4-21) are also indicative of the high shear stresses in this reach. It seems likely that channel incision has accelerated since the levees were constructed, but firm data on this point are lacking.

Figure 4-21. Boulders on this bar downstream from Highway 99 indicate the high shear stresses that occur during high flows in this incised and leveed reach.

There is little riparian vegetation in this reach, presumably because of the high shear stresses, the unsuitable substrate, and levee maintenance practices. Spawning gravels occur mainly in small pockets that occur in the lee of obstructions, or in short riffles at the ends of pools. Although the scarcity of data allows only speculation, it seems likely that there was more alluvium in this reach, and so better habitat, before the levees cut off flows into distributary channels and onto the floodplain. In any event, there is little opportunity for restoration in this reach because of the high shear stresses in the channel and extensive development just outside the levee on the left bank.

Oro-Chico Highway Bridge to Durham-Dayton Highway Bridge (Sta. 90,200-76,800): The stream continues across the Butte Fan in this reach, but the levees are farther apart and the channel is somewhat wider than above the Oro-Chico Highway (Figure 4-22). There is more alluvium in this reach, because of the greater width and decreased slope (0.0023), and a pattern of alternate bars is evident along the channel. These bars provide spawning habitat for fall-run chinook salmon. The Red Bluff Formation underlies the channel to about Sta. 85,000, but is much less prominent in the banks than it is upstream. Instead, the banks are primarily of the late-Pleistocene alluvium of the Modesto Formation, or recent alluvium. Below Sta. 85,000, the underlying material grades into a duripan that resembles saturated adobe, and may be part of the Riverbank Formation. This duripan underlies the channel for the rest of the study reach, with important consequences for sediment transport. Gravel transport is mainly in the "partial bed mobility" mode, in which clasts move individually rather than in mass.[4] At the lower end of the gravel reach, clasts typically move one by one onto the duripan. Once gravel clasts are on the bare duripan, they lose any protection from adjacent clasts, so that the entire upstream surface of the clast is exposed to the force of the flow. Clasts that are so exposed can be moved by flow at much lower velocity than clasts that form part of a gravel deposit, where they are partly shielded from the flow by adjacent clasts. In consequence, clasts tend to be swept through reaches with a duripan bottom, especially where the channel is narrow. This point is discussed in more detail below, in the paragraphs on the reach ending at Durnell Road.

[4] Andrews (1994) gives a good discussion of partial bed mobility.

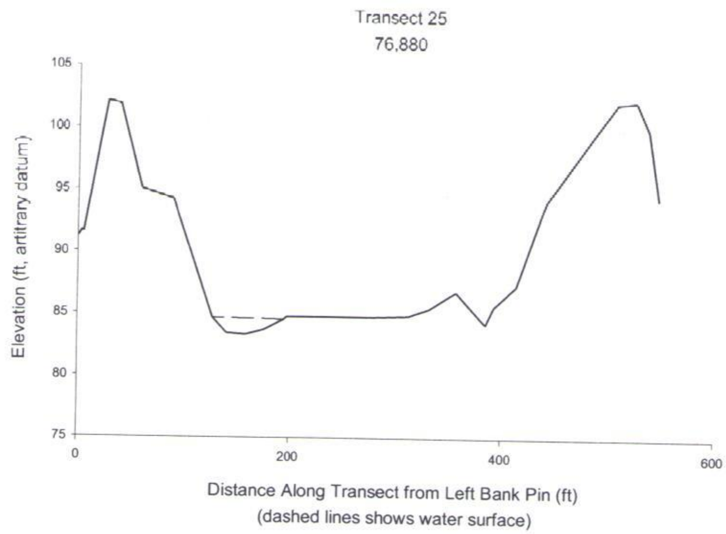

Figure 4-22: Transect across Butte Creek just upstream from the Durham-Dayton Highway bridge, at Sta. 76,880, showing a longitudinal bar within the channel near the right bank. Surveyed 10/99.

There are orchards outside the levees on both sides of the stream, and a small orchard and relict riparian trees on a terrace inside the levee on the right bank. Otherwise riparian vegetation is mostly limited to a narrow shrubby fringe.

Durham-Dayton Highway to the "Big Bend" (Sta. 76,000 - 69,750)

The channel was straightened in the reach before it was leveed, and a strongly developed pattern of alternate bars dominates the appearance of the stream at low and moderate flows. The stream flows along one levee, then cross the channel and flows along the other. The bed is mainly gravel near the upper end of this reach, but downstream the duripan is increasingly exposed in the low-flow channel, despite the gravel bars to either side. The slope flattens in this reach, with a break in slope evident on the long profile of the channel (Figure 4-4) at about Sta. 73,100. There is also a sharp drop at the top of the reach, resulting from the grade control structure just downstream from the Durham-Dayton Highway Bridge.

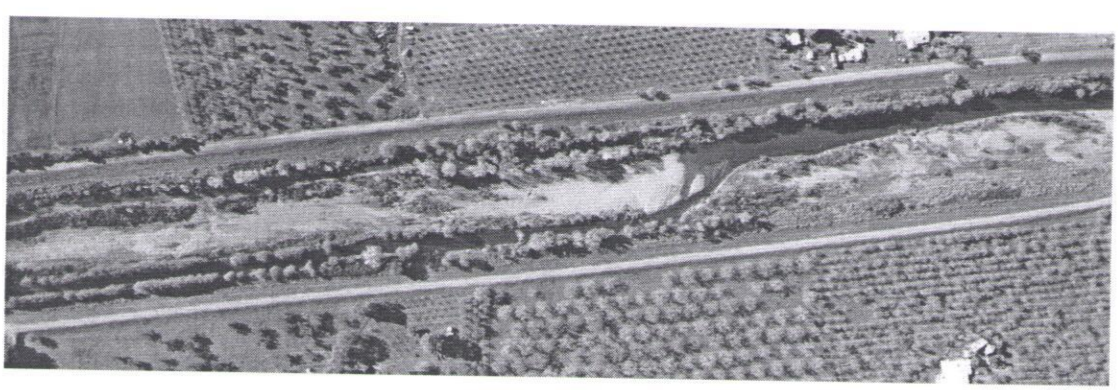

Figure 4-23: Large alternate bars in the channel downstream from Durham-Dayton Highway

Historically, the transition from the fan to the Butte Basin occurred in the area crossed by this reach, where the channel divided around a basin vegetated with tules. The location of this transition is still evident on the soils map (Figure 3-1), from the occurrence of clay soils. By confining the flows, the levees have increased the transport capacity of the stream, and substantial quantities of gravel, sand and silt have been transported into and through this reach.

The potential for restoration in this reach is low, as there is little room between the levees and there are houses and other buildings close to the levees on either side of the channel. However, there is enough gravel in the reach that the existing habitat has considerable value for salmon, and there is enough vegetation to provide some riparian habitat as well.

"Big Bend" to Midway Bridge (Sta. 69,750 - 59,800):

The stream continues along the edge of the fan in this reach, but the soils on the floodplain, and those to the west of the levee, are strongly influenced by fine-grained mining debris. The Adams Dam is near the top of the reach, at Sta. 66,800. The right-bank levee moves back from the channel in this reach, making room for an orchard and the Keeney Restoration Project on the floodplain along the right-bank, but there are rice fields outside the left bank levee. The channel stays close to the left bank levee, and the gradient continues to decline (Fig. 3-3). The channel is incised into the duripan through most of the reach, as shown by channel profiles at the Midway bridge (Figure 3-13). In consequence, a flow greater than the five-year event is need to inundate the floodplain; one of us (E. G.) witnessed a flow of over 9,000 cfs contained entirely within the channel. There are now alternate gravel bars forming upstream from the Midway and railroad bridges (Figure 4-24). The gravel bars may result from the backwater effect of the bridges and the riprap that was been placed around the piers of the Midway bridge after 1997 to control scour (Figure 4-18), from increased transport of gravel into the reach during and after January 1997, or, most likely, from a combination of the two.

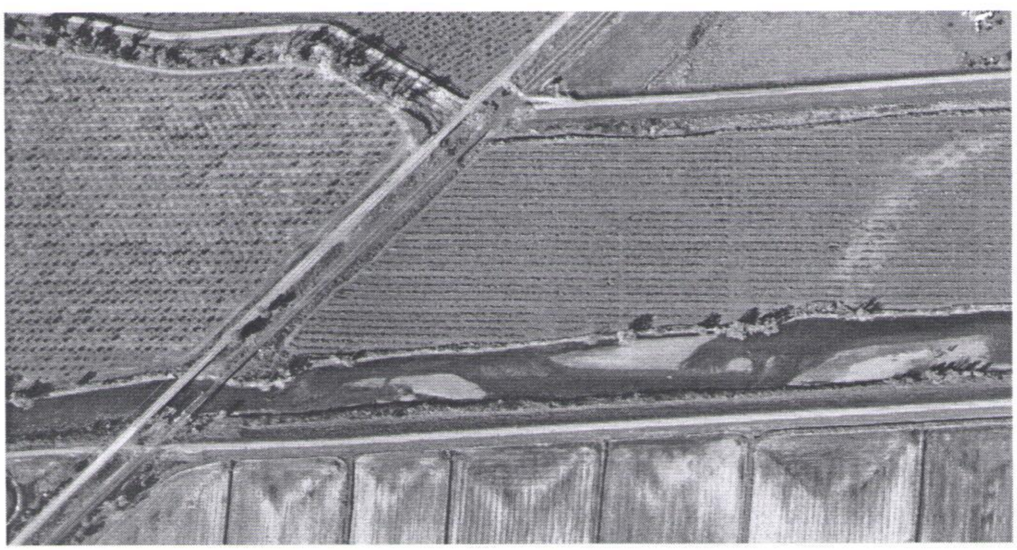

Figure 4-24: Alternate bars in the channel upstream from the Midway Bridge. The light colored arc on the right overbank near the right of the picture is the remnant of a channel meander that shows clearly in 1952 aerial photography.

Midway Bridge to Durnell Road Bridge (Sta. 59,800 - 51,400):

The channel continues straight along the left bank levee through this reach, with the right bank levee set back and meandering along the historical channel. There are orchards on the right bank inside the levees. The Gorrill Dam is located near the top of the reach, at Sta. 59,080, and the summer backwater from the dam extends upstream past the bridges. We were denied access to this part of the stream, but from the aerial photographs it is apparent that the stream flows directly over the duripan, and the channel is narrower than it is upstream or downstream. There is a narrow fringe of riparian trees along the right bank, particularly just above the Durnell Road Bridge, where a narrow slot has been eroded into the duripan (Figure 2-3). The channel here seems to transport sediment very efficiently; only a few gravel clasts can be seen in holes in the duripan near the bridge, although there are gravel bars farther downstream. Summer flows in the lower part of this reach can be very low because of diversions upstream (Figure 2-3).

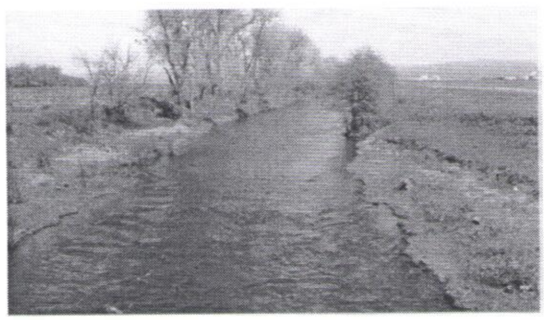

Figure 4-25: Butte Creek flowing through the Butte Basin; view upstream from the Durnell Road Bridge. The levee is well back from the stream on the western side in this area.

Channel roughness at Durnell Road is very low. Stage at Durnell Road peaked at 18.3 ft above the thalweg on 14 February 2000, when discharge at the USGS gage reached 7,300 cfs. We estimated that the average velocity at the peak flow was 7.9 feet per second, using a transect surveyed in the county right-of-way just upstream from the bridge, and assuming that upstream accretions balanced the tendency of channel storage to damp peak flows. Substituting this value into the Manning equation gives an estimate of Manning's n of ~0.018.[5] This is a very low value for n, so it may be that our assumption about the discharge or our estimate of slope is incorrect. For any reasonable values of slope and discharge, however, the data show that the channel in this reach is hydraulically very efficient. This probably results from the smooth duripan that makes up the channel bed here and in most of the basin reach.

[5]The precise value depends upon the extent to which the transect is smoothed in calculating the channel perimeter. Our calculations used 930 ft^2 for area, 140 ft for the wetted perimeter (substantially smoothed) , and 0.0007 for the slope.

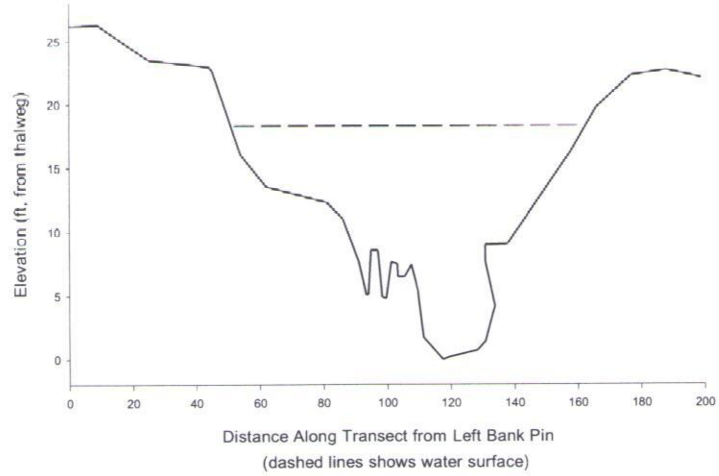

Figure 4-26: Transect across Butte Creek upstream from the Durnell Road Bridge, showing the high water observed on 14 February 2000. The left bank pin is on the levee. Vertical exaggeration is 4/1.

The low hydraulic resistance and the nature of the bed in the hardpan channel in the basin reach of Butte Creek make the channel efficient for moving gravel, despite the low gradient. The effect of the hardpan bed on sediment transport in the bed can considered in terms of the figure below, copied from Middleton and Southard (1984), which shows the relation of forces that determine whether a grain of gravel in a bed of similarly size gravel will rotate out of the pocket in which it sits to begin movement. If the size of the surrounding grains is reduced, the pivot angle α will also be reduced, making it easier for the particle to move. On a firm, smooth bed, α will depend on the shape of the grain, but in general will be small. As intuition suggests, the force F_g that resists motion will decrease as α decreases, so the piece of gravel will roll much more easily on a smooth bed than on a gravel bed. Besides rolling, a grain can also move by sliding. This also is much easier on a smooth bed, because the entire upstream projection of the particle is exposed to the flow, and a grain resting with a flat side (and therefore a relatively large α) might well move by sliding rather than rolling. The net result is that particles will move over a smooth bed at substantially lower velocities than would be required to move the particle over a bed of other particles, such as a gravel bar.[6]

[6] For an analytical consideration of some of the issues involved here see Wiberg and Smith (1987), Calculation of the critical shear stress for motion of uniform and heterogeneous sediments. Water Resources Research 23:1471-1480.

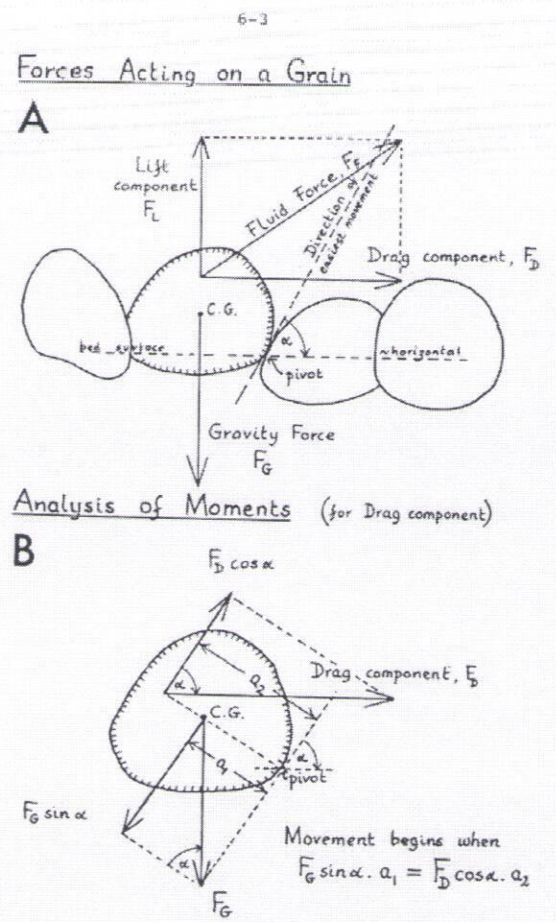

Figure 6.1 (A) Forces acting on a grain resting on a bed of similar grains. (B) Analysis of moments acting on a grain at the beginning of grain movement.

Figure 4-27: Schematic of forces acting on a gravel particle on the bed of a stream, taken from Middleton and Southard (1984)

Durnell Road Bridge to Western Canal Siphon (Sta. 51,400 - 40,000)

The upper 3,000 feet of this reach is much like the reach upstream, but the gradient increases to about 0.0016 in the lower half of this reach, the channel widens, and gravel bars begin to occur at about Sta. 45,500. The stream flows along the left bank levee to about Sta. 43,500, and then crosses a prominent gravel riffle to the right bank. The levees move closer together, to approximately 700 feet apart, and remain at about that spacing to the end of the levees. (Transect 29 crosses the riffle at about Sta. 43,550.) Hamlin Slough enters from the left bank at Sta. 47,500, and the 1048 Slough, which carries return flow from lands irrigated with Feather River water, enters from the right bank at Sta. 42,900.

We observed salmon spawning in this reach in 1999, including one pair with a redd directly over the Western Canal siphon. We suspect that these were strays from the Feather River, since the spawning was concentrated near the mouth of the 1048 Slough, through which irrigation return flows of Feather River water enter Butte Creek, and other fish were holding below the check dam on the slough.

There is some good riparian habitat along a relict channel near the right bank levee in the upper part of this reach, extending down to the 1048 Slough, although it is separated from the creek by cultivated fields.

Western Canal Siphon to End of ACE Levees (40,000 - 19,700)

Except for a kink at Aguas Frias Road where the channel moves from next to right bank levee to next to the left bank levee, the channel is nearly straight through this long, low gradient (0.0005) reach. The duripan is exposed in most of the bed, but there are some small gravel deposits. The levees are 600 or more feet apart through this reach, and rice is grown on the overbank except for the lower 3,000 feet which belongs to DFG and has been left fallow. There is a thin fringe of riparian vegetation along the channel, perhaps a bit more than farther upstream.

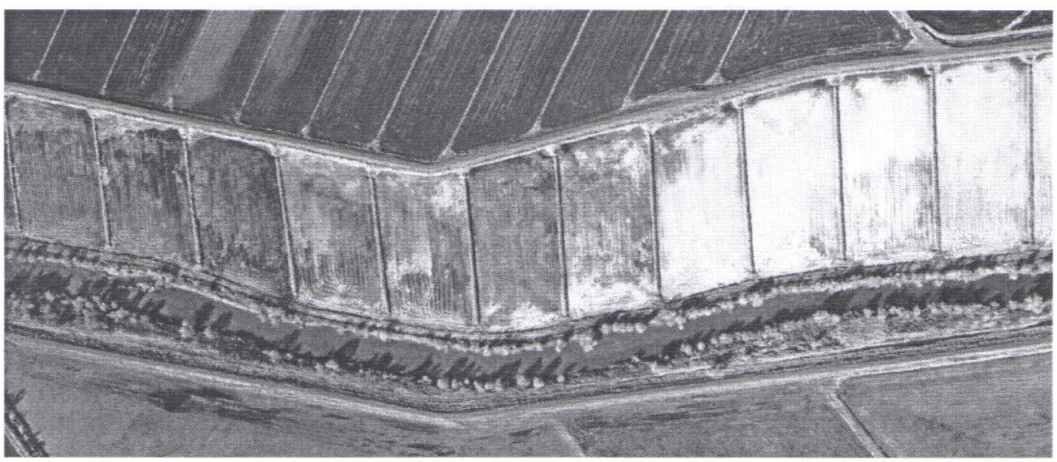

Figure 4-28: Butte Creek near the end of the Corps of Engineers levees. Rice is grown on the right overbank between the levees. Flow is from right to left.

End of ACE Levees to Highway 162 (19,700 - 0)

The Corps of Engineers levees end where Butte Creek joins the Sacramento River overflow and turns to run due south. The slope of the land increases in this area, perhaps as a result of the tectonic uplift that created the Llano Seco, and the channel gradient in the upper part of this reach also increases. There is a sharp drop at the top of the reach where the stream passes over a particularly resistant outcrop of duripan (Figure 4-29), and several other smaller drops over outcrops in the next few thousand feet downstream.

Figure 4-29: Outcropping of particularly resistant duripan in the channel about 19,700 feet upstream from Highway 162.

Surprisingly, there is a small gravel deposit with a median grain size of 25 mm at Sta. 13,700. This occurs where the gradient of the channel seems to flatten out again, although we are not certain of this since we did not survey a long profile in this part of the stream. We also found scattered gravel clasts on the duripan banks of the stream in the upper part of this reach (Figure 4-30), one of which had an intermediate axis measuring about 180 mm. There are also scattered deposits of sand on the bank, and the soil in the banks seems more silty than the clay soils outside the levees.

Figure 4-30: Gravel clasts next to the channel about 15,100 feet upstream from Highway 162; the intermediate diameter of the largest clast is over 180 mm (there is a pen on top of the clast for scale).

Recommendations

In this section we provide general recommendations regarding potential restoration projects on Butte Creek between the Centerville Head Dam and Highway 162.

UPPER CANYON REACH (Centerville Head Dam to the Centerville Power House):
Restoration efforts in this bedrock-dominated reach should focus on protecting the existing habitat, particularly in the accessible lower end of the reach. However, the reach could also be affected by activities that increase the delivery of fine sediment to the stream in the upper watershed, for example in the Butte Meadows, so these areas should not be ignored.

Spawning habitat in this reach probably is limited by sites for deposition of gravel rather than by gravel supply. Addition of large logs to the reach to provide such sites may be warranted on an experimental basis, although it seems sensible to try this first on other bedrock streams such as Clear Creek below Whiskeytown Dam, where logs could be delivered to the stream by truck. Helicopters would be needed to deliver logs to the parts of this reach Butte Creek where they would do the most good, so the work would be very expensive. Experience in the Pacific Northwest indicates that cabling logs in place generally is not advisable (Bisson et al. 2000), but may be necessary on Butte Creek because of concerns about poorly designed bridges and other infrastructure downstream.

We are not recommending either for or against proposals to provide passage for salmon and steelhead beyond the study reach, since that was not within the scope of our study. Holding habitat for spring-run salmon in Butte Creek is marginal because of high water temperature, however, as indicated by the data presented in the Introduction and the high mortality in years such as 1960. Given global warming, long-term prospects for spring-run chinook salmon in Butte Creek seem bleak unless they get access to habitat at high enough altitude that temperatures will remain tolerable. This would be a major project, however, that should not be undertaken lightly and may not even be feasible; in any event, care should be taken that existing habitat such as the plunge pool at the Quartz Bowl not be adversely affected by any such effort.

LOWER CANYON REACH (Centerville Power House to Highway 99):
General Recommendations:
Substantial alluvial deposits occur along this reach of Butte Creek and make up the bed and banks of the stream in most places. The alluvial areas of this reach provide most of the spawning habitat for spring-run salmon and steelhead, and much rearing habitat as well. They also provide most of the hyporheic habitat along the creek, and support valuable riparian habitat. This reach of the stream was severely affected by hydraulic mining and dredging, although substantial recovery has occurred. More recently, the channel has been affected by bank stabilization projects and by the loss of intact tree trunks that were sawed into pieces to reduce the risk of flood damage downstream.

We recommend that the restoration objective for the channel in this reach be to allow natural processes to proceed as much as possible. This includes the disturbances that accompany natural processes of channel migration; such disturbances are now recognized as critical for the long-term maintenance of habitat for native fishes (Naiman et al. 1992; Reeves et al. 1995; Schlosser and Angermeier 1995; Power et al. 1995; 1996; Wiley et al. 1997), even though they may involve short-term loss of habitat.

Appropriate measures to achieve this objective include purchase of land or "erosion easements" from willing sellers. Because parcel lines typically do not coincide with geomorphic boundaries there may be opportunities to purchase and re-sell parcels with appropriate deed restrictions that would limit development to geomorphically sensible areas without removing the parcels from the tax rolls. Houses and other infrastructure that are at risk from bank erosion should be moved back away from the stream, if this is feasible. This would be a more appropriate use of public money than bank stabilization with rip-rap or similar structures that degrade public trust resources. Artificial channel "enhancements" are not an effective substitute for naturally created habitat, and are unlikely to mitigate the effects of bank stabilization measures.

We have not tried to identify specific areas along the stream that might be better suited for restoration than other areas because of high rates of channel migration or similar factors. Trying to identify such areas usually is dubious. Although it is possible to make useful predictions of long-term rates of channel migration on low gradient, meandering streams such as the Mississippi and parts of the Sacramento (Larsen 1995; Larsen et al. 1998), this is not yet possible on higher gradient, higher energy streams such as this reach of Butte Creek (Pizzuto in press)[1] The historical record and recent experience shows that the channel in this reach tends to migrate in jumps, or avulsions, with which existing models of channel migration do not deal. Avulsions also complicate intuitive assessments of erosion hazards. For example, a homeowner downstream from the Parrott-Phelan Dam spent many thousands of dollars to stabilize the bank of a channel that was abandoned by the stream a year later. It is more sensible to recognize that the channel probably has occupied any part of the valley where recent coarse-grained alluvial deposits occur, and to assume that the channel may do so again.

It is easier to identify areas where bank erosion will not occur, or will occur only slowly, because of highly resistant materials in the banks. Doing this comprehensively would have required better access to sites than we had, and in some cases subsurface sampling, so we have not tried to map such areas, although an obvious example is shown in Figure 5-1. Areas with resistant banks are better suited for homes and other infrastructure than alluvial sites, even if they are closer to the creek. Therefore, we recommend against using some arbitrary distance from the stream as a criterion for judging proposed developments.

As should be evident from our comments about large wood in the upper canyon reach, the practice of cutting up logs in the channel and on the floodplain tends to reduce the habitat value of the stream for juvenile salmonids and other organisms, and should be discouraged. Large wood has important ecological functions in alluvial channels, as described in the Introduction.

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[1] Pizzuto (in press) concludes his excellent review of numerical modeling of fluvial processes with this paragraph. "The models reviewed above have several features in common. Few of the models have been routinely used in practical applications (although the 1-dimension bed material wave model of Cui et al. (in review) is currently being used in several projects). Few of the models are commercially available, and few have been thoroughly tested in a wide variety of field settings. Finally, it is important to recognize that the conceptual basis for many of the models discussed above is still being actively debated. Scientists still do not agree on the essential controlling mechanisms for many of the processes simulated by these models."

Figure 5-1: Resistant banks protect these homes in the Canyon from channel migration.

Infrastructure along the stream should be designed to let floating trees pass, if it is to be consistent with maintaining and rehabilitating environmental values in the stream.

Where re-vegetation projects are contemplated, it seems appropriate to design plantings for the existing conditions, rather than undertake expensive earthmoving projects in order to recreate some idealized riparian topography. In areas of dredger tailings with highly irregular topography it may be worthwhile to do some smoothing of the land surface if there are botanical reasons for doing so, but in terms of fluvial geomorphology *per se* such work is unnecessary. In other words, areas that are now effectively terraces should be planted with species appropriate for terraces, for example on the right bank within the Honey Run Ecological Reserve. If channel migration eventually makes floodplains of these areas the plantings will contribute useful wood to the channel, and floodplain species will recruit naturally, as is occurring in area such as the channel abandoned by the avulsion in the reserve.

Parrot-Phelan Diversion By-Pass Channel:

The sill at the entrance to the Parrot-Phelan Diversion By-Pass Channel should be raised. During flow events that move a significant amount of gravel, part of the flow passes over the sill on the left bank upstream from the Parrot-Phelan Diversion and passes the diversion in an armored artificial channel. This reduces the discharge in the main channel, and so reduces the competence of the stream to transport coarse sediment. In consequence, a bar forms opposite and downstream from the sill that increases the proportion of the flow going into the high-flow channel at a given discharge, and reducing the discharge at which water begins to flow into the by-pass (we have observed flow going into the high-flow channel at a discharge of about 1,500 cfs).[2] As the frequency of flow into the by-pass channel increases, so too does the problem of fish being stranded in the by-pass.

[2] We inspected design documents for a design discharge for overtopping the sill, or for calculations reflecting a design discharge, but found none, so the bias of the design is unknown.

Figure 5-2: Equipment removing gravel from the channel upstream from the Parott-Phelan Dam to maintain channel capacity.

At the least, the current situation creates a need to remove material from the bar periodically, using heavy equipment. This occurred in August, 1999, and again in August, 2000. Material excavated in 2000 was trucked to the right bank of the creek downstream of the Parrott-Phelan Diversion Dam, where it was placed at an elevation such that a very high flow will be required to mobilize it. Although we recognize the need to minimize releases of fine sediment during these summer low-flow operations, some method should be developed for returning the sediment to the stream. Pushing the sediment into the stream during periods of high flow seems one alternative, but it seems better to raise the sill at the entrance to the Parrot-Phelan Diversion By-Pass Channel to minimize the need for mechanically moving the sediment around the dam[3]

A potential problem occurs near the lower end of the by-pass channel, where a beaver dam has created a pond that becomes quite warm in the summer and probably creates good habitat for larval bullfrogs and other introduced species. Biological evaluation of this pond seems warranted.

Mining Ponds:

There are mining ponds in the floodplain along the right bank of Butte Creek at about Sta. 116,000 (RM 22), in an area that lies between two properties that are managed for habitat (Figure 5-3). Although these ponds do not present as severe a problem as mining ponds along streams below dams where the sediment supply has been severely reduced, the ponds would disrupt the transport of coarse sediment to the stream if the stream were to "capture" them by channel migration. This would promote further channel instability and migration in the vicinity of the ponds, and create a short-term tendency for channel incision farther downstream. Like the beaver pond mentioned above, these ponds may provide habitat for bullfrog larvae and other

[3] We inspected design documents for a design discharge for overtopping the sill, or for calculations reflecting a design discharge, but found none, so the basis of the design is unknown. We have been told that a design discharge of 10,000 cfs for the stream channel was given verbally at a 25 March 1997 meeting of the Butte County Board of Supervisors.

exotic species, and deserve biological evaluation. The ponds may provide a logical place to put clean fill that may become available at little or no cost from landslides on the road or similar sources. However, if the ponds are filled with sediments much finer than the gravels that existed before, hyporheic flow through the alluvium any be negatively affected, and when the channel eventually erodes in the former pit the fill may become a source of excess fine sediment.

Figure 5-3: The mining pond along the right bank of Butte Creek in the Canyon Reach, in the right-center of the photograph, is now separated from the creek only by a narrow berm that shows clear signs of erosion.

Valley Reach

Opportunities for habitat restoration vary along the valley reach of Butte Creek, but generally increase with distance downstream. In some areas, such as the Virgin Valley Ecological Reserve upstream from Highway 99, there are opportunities to re-establish native vegetation on terraces. Where the creek is incised into the Red Bluff Formation, from about Highway 99 to the Oro-Chico Highway, opportunities for restoration are very limited by the high sheer stresses that occur within the incised channel. Over the lower part of the fan, opportunities for restoration are greater than in the confined reach but remain constrained by the typically close spacing of the levees and the value of property outside the levees. Farther downstream, where the levees typically are farther apart and basin clays do not support orchards, opportunities are greater still. These range from limited actions along the creek to bold development of a meanderbelt within set-back levees. The costs and benefits of such actions would also span a very wide range.

Localized riparian restoration projects within existing levees:

The opportunities for localized restoration projects within the existing levees depend on the local hydraulic conditions, as demonstrated by the experience of the Keeney Ranch Restoration Project. This project, just upstream from the Midway, provided for some restoration of riparian habitat. However, the Reclamation Board required the Keeney Project to be designed and managed so that it will have little effect on hydraulic conditions in the channel, in order to avoid increased risk of levee failure. To the extent that such projects have to be designed to leave hydraulic conditions in the channel unchanged, the benefits to the stream ecosystem will be minor, because the existing incised channel is not well connected hydrologically to the overbank.

The available evidence indicates that the road and highway bridges at the downstream end of the Keeney Project create backwater conditions that control flood elevations in the project area, but the practical consequence of the Reclamation Board's position is that detailed (and therefore expensive) hydraulic studies will be needed for restoration projects within the existing levees. This constraint is probably weakest along the lower part of the study reach, where there is little development, so the potential losses to flooding are much less and any increased risk could be mitigated by ring levees around such infrastructure as exists. There is a good deal of land between the levees that potentially could be converted from rice field to riparian vegetation.

Ecosystem restoration projects within set-back levees:

If levees along the lower part of the valley reach of Butte Creek could be set back to meet concerns about flood conveyance, then there would be great potential for restoration of a naturally functioning ecosystem comprising both stream and riparian habitat. We cannot think of another situation in the Central Valley that offers the possibility of such a long corridor of riparian vegetation of substantial width, along a stream in which the flow regime during winter and spring is substantially natural. Such a project would benefit a wide range of riparian species, and so reduce the likelihood of future listings under the ESA. Evidence from the Sutter and Yolo by-passes (Sommer et al. 2001; Tracy McReynolds, CDFG, personal communication 2000; CDWR 1999) also suggests that such restoration could provide significant benefits to spring-run and fall-run chinook salmon, by creating good rearing habitat for emigrating fry. Unlike the by-passes, the existing straightened and incised channel offers few places for these fish to find slowly moving water in which to rest or feed.

If such a project were implemented, it should include measures to reverse the existing incision of the channel, and so to promote better connectivity between the stream and the floodplain. There has been little experience with such endeavors, so an experimental program with expert guidance would be in order. Strategically placed "plugs" made of gravel and trees seem a possible approach.

Proper evaluation of the benefits of a restored channel in the valley reach of Butte Creek for spring-run salmon would depend on development of better understanding of valley habitat use by the juvenile spring-run. A 10-year study funded by the Anadromous Fish Restoration Program is underway.[4]

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[4] We suggest that the study might usefully include examination of the microstructure of otoliths from spawning adults could provide information on the early growth rates of fish that successfully complete the life cycle. Such information should be combined with development of data on measures of growth and condition from samples of fry collected at different locations along the creek. Such data would provide evidence about the relative value of the habitat at the locations. For example, the ratio of RNA to DNA in sample tissue provides an index of the rate of the short-term growth, since the amount of DNA in cells is relatively constant but the amount of RNA varies with growth rate. Such data could be used to test the hypothesis that the hydraulically simplified channel of Butte Creek provides lower habitat value than areas of the channel farther downstream or in the Sutter By-pass. This would require destructive sampling, so any such study would have to be carefully designed to take the minimum number of fish required to obtain meaningful results. Initial efforts should target fall-run fry that migrate down the channel somewhat later than the spring-run. Results from sampling fall-run fry could be used to develop a good study design for work on spring-run, and would be valuable in themselves as well.

Social and economic considerations:

There would be social and economic costs to restoration within set-back levees, including loss of agricultural land, that would need to be taken into account along with the benefits. We need to leave assessment of these costs to others (e.g., Adams et al. 2001), since it is beyond our area of expertise, but we recognize that the costs would be substantial, and would need to be weighed carefully against the benefits. We also recognize that the costs and benefits of such a project would accrue to different geographical areas; the costs would be focused in Butte County, but the long-term benefits would be more widely distributed. This raises equity issues that also would need to be addressed.

The term restoration is used here in a loose sense, because modifications to the stream over the last 150 years preclude a return to pre-existing conditions. From a geomorphic perspective, the increase in the sediment supply from mining activity, and the increase in sediment-transport capacity of the stream resulting from the leveeing and steepening of the stream and from the consequent incision, is particularly important. In conjunction with the reduction of backwater conditions in the Butte Basin by dams on the Sacramento and Feather rivers, this has resulted in the transport of silt, sand and even gravel well down into the Butte Basin. Accordingly, a restoration project in this area would develop on coarser-grained soils than occurred naturally, and the stream channel would have a somewhat different character than the anastomosing channels with steep, clay-rich banks that probably existed previously. We think the area has great potential value as aquatic and riparian habitat nevertheless.

Bridges:

Bridges along Butte Creek vary in their ability to pass large pieces of wood. The older bridges especially tend to have short spans between the piers and to become hydraulic constrictions during floods. Evidently this occurred at the railroad and Midway bridges in 1997, for example, when a drop of several feet in the water level was reported at the bridges. Replacements for these bridges should be designed with longer spans. This would be an important long-term step toward restoration of Butte Creek.

Gravel aggradation within the levees:

Concern has been expressed regarding localized areas of aggradation in the channel, for example in the reach upstream from the "Big Bend." We recommend caution regarding removal of such deposits, which provide hyporheic habitat that is very limited in this reach. We suspect that the aggradation may be episodic, alternating with periods of incision. We suggest that a period of monitoring precede any removal of gravel, unless hydraulic modeling demonstrates a significant decrease in the flood conveyance capacity of the channel.

APPENDIX D, Geomorphic Assessment of Butte Creek, Butte County, California

Reach #	Reach Name	Stationing Begin	Stationing End	Length of Reach (miles)	Average Bed Slope	Reach #
1	Lower Centerville Diversion Dam (a.k.a. Centerville Head Dam) to Helltown Bridge	190080	160250	5.65	0.01928	1
2	Helltown Bridge to Centerville Powerhouse	160250	155750	0.85	0.01444	2
3	Centerville Powerhouse to Honey Run Covered Bridge	155750	127000	5.45	0.00591	3
4	Honey Run Covered Bridge to 1,400' US of Skyway Bridge	127000	103300	4.49	0.00494	4
5	1,400' US of Skyway Bridge to Highway 99 Bridge	103300	96900	1.21	0.00563	5

6	Highway 99 Bridge to Oro-Chico Highway Bridge	96900	90200	1.27	0.00328	6
7	Oro-Chico Highway Bridge to Durham-Dayton Highway Bridge	90200	77300	2.44	0.00194	7
8	Durham-Dayton Highway Bridge to "Big Bend"	77300	70100	1.36	0.00069	8
9	"Big Bend" to Midway Bridge	70100	60000	1.91	0.00149	9
10	Midway Bridge to Durnell Road Bridge	60000	51400	1.63	0.00116	10
11	Durnell Road Bridge to Western Canal Siphon crossing	51400	40000	2.16	0.00175	11

12	Western Canal Siphon crossing to End of ACOE Levees	40000	19700	3.84	0.00049	12
13	End of ACOE Levees to Highway 162	19700	0	3.73	0.00091	13
			total	36.00		

Bed Material	Channel Morphology	Channel Conditon
mainly bedrock (meta-sedimentary/metavolcanic) and boulders; some pool-tail and pocket gravels	Step pool, confined by bedrock; deep, bedrock holding pools	Natural; bedrock confined; no bank revetment or channelization. Good channel complexity
large boulders, cobble, gravel, sand	Pools and steep riffles/rapids, one good holding pool	Natural; some homes, yet no revetment; creek is flanked by Quaternary landslide (Qls) debris on LB causing erosion of RB sandstone cliff. Good channel complexity
boulders, cobble, gravel, sand; (large boulders [>2.5' dia] still present through first 3 miles) with %-age of larger caliber sediment decreasing with distance DS)	Series of pool-riffle-run complexes with isolated steep riffles/rapids; deep holding pools typical where creek flow parrallels of focuses directed against Chico or Tuscan Fmtn.	Natural, but with homes and bank revetment; channel bounded by either bedrock (sandstone) banks/cliffs (comon in upper end of reach) or alluvium (lower end). Good channel complexity
cobble, gravel, sand, with %-age of larger caliber sediment decreasing with distance DS	Meandering channel, with pools, riffles and runs; migration zone confined by Tuscan canyon walls	Recovering from gold and gravel mining operations; heavily reveted (grouted and ungrouted riprap) in several reaches, including a constructed secondary "flood channel" and weir. Channel complexity fair
same as above, but with outcrops of Tuscan Fmtn. Forming riffles relatively resistant to incision	Pools, riffles, and runs; leaves canyon and goes from meandering to confined by riprap and levees	Confined by riprap from highway bridges, dams, and equipment yard; ACOE levees begin in middle of reach. Channel complexity fair to poor

cobble, gravel, sand, with %-age of larger caliber sediment decreasing with distance DS; outcrops of Red Bluff Fmtn.	Pools and riffles; no opportunity to meander as channel is leveed, riprapped, and incised in Red Bluff Fmtn.; limited spawning areas	Deeply incised. Channel is bounded by levees and rip-rapped on all major curves and at the Oro-Chico bridge. Channel complexity poor
same as above, including silts, except last Red Bluff Fmtn. exposure dives below channel bottom 5,000' into reach. A solidified silt/clay "hardpan" (perhaps the Riverbank Fmtn.) begins to appear in this reach	Long pools interspersed with riffles; little meander; numerous fall-run spawning areas.	Creek is leveed; incised, but much less than the extreme case just upstream. Riprap at Oro-Chico Bridge and a few other isolated locations. Channel complexity poor, but better than Reaches 6 & 9
gravel, sand, silt, and clay; major exposures of Riverbank/hardpan in channel	Long, straight pools and runs; channel is incised to "hardpan" for entire reach, all alluvium in between levees is a veneer moving over the "hardpan"	Creek is leveed. Channel runs straight along first the RB levee, then the LB, then back to the RB. Channel complexity poor
gravel, sand, silt, and clay; major exposures of Riverbank/hardpan in channel	Long, straight pools; better floodplain access/less incised	Creek is leveed, though the width increases here at the large bend of the creek to the south-west. Relatively extensive floodplain area between levees. Channel complexity poor.
scoured clean to hardpan; all alluvium appears to be shot through during high flows	Straight. Channel has incised into the hardpan and at low water is one, long, slow moving pool entrenched completely in the "pan." No bars or lateral migration.	Creek is leveed and incised; though RB levee is set back. Floodplain (RB) is in orchard agriculture. Channel complexity extremely poor. Prior to changes in late 1800s/early 1900s, channel flowed to the north of present channel.
scoured to hardpan for 2/3 of reach, then fine gravel, sand, silt, and clay begin to emerge in low bars	Straight. Channel is mostly a pool, with some riffles emerging ~3,500' US of the siphon crossing.	Creek is leveed. Though RB levee is set-back, channel is incised. Floodplain (RB) is in field crop agriculture. Channel complexity poor.

scoured to hardpan for the entire reach, with accumulations of fine gravel, sand, silt, and clay on the surface	No bars or lateral migration. One significant nick-point (drop of >5') may be the result of tectonics or base-level changes in the Sacramento River.	Creek is leveed to the end of this reach. For a significant distance, the channel has been channelized and forced to either side of the floodplain to make room for rice cultivation
Scoured to hardpan in upper portion of reach, grading to silt/clay mud at Hwy 162. Gravel (size XXX mm) is still present in the channel however.	Reverts to a relatively natural channel, though still incised. Two isolated (& small) gravel deposits occur in protected pockets and eddy locations	Relative to the reach US, fairly good; isolated riprap to protect wetland/waterfowl projects. The channel begins to meander, though it has not migrated in some time.

Riparian Zone	Hyporheic Zone
Narrow, along water's edge	Minor. Restricted to patches of alluvium; confined by bedrock
Narrow, along water's edge; yet more extensive due to softer Qls debris & sandstone (Chico Fmtn.) as bank material	Minor, though more extensive than US due to orientation of Qls deposits & more extensive alluvial pockets
Extensive in areas with alluvium; minimal removal due to homes and revetment; areas with Chico Fmtn. as bank material have either "single-stem" width or are overhung by upland species	Intermediate. Restricted in some areas by banks of Chico Fmtn., at times in the form of small cliffs; extensive in several areas with wide alluvial floodplain
Extensive where tailings piles (cobble) are not present; largely eliminated from banks that are riprapped or grouted	Extensive. Alluvium from one canyon wall to the other for most of the reach; identified as the beginning of a major groundwater recharge zone on the creek (DWR, cite)
Extensive in 1,400' US of Skyway; DS of Skyway, limited to water's edge and one patch inside the levees on the bar DS of the Little Chico Creek Diversion Channel	Still partially intact. Levees and removal of distributary channels have likely reduced extent, particularly for "return flow" in reaches DS

Limited. Incision has disconnected floodplain, and deepened flow from levees appears to limit recruitment of bars and other lower surfaces	Limited/restricted to patches of alluvium; actions US have disconnected returns to this reach from distributary channels; impeded by shallow Red Bluff Fmtn.
Limited. Extent ranges from discontinuous bands one to several stems wide along water's edge, to several larger patches in areas where levees are wider; orchards inside levees have maintained several decadant sycamores and valley oaks	Limited. Restricted to narrow band of alluvium between levees
Poor. Though much of reach has vegetation from water's edge up-slope until point where cleared for levee maintenance, this amounts to quite a narrow band	Limited to mid-channel bar that runs the length of the reach.
Poor. Limited to a few stems' width at water's edge. Floodplain in upper reach is a orchard; lower is a riparian preserve, but was recently destroyed by a stand replacing fire.	Likely non-existant. Limited vertically by depth to hardpan and by banks of "Basin Clay."
Poor. Limited to a discontinuous, one-stem-width band, mostly on RB.	Likely non-existant. Limited vertically by depth to hardpan and by banks of "Basin Clay."
Poor. Limited to a discontinuous, one-stem-width band, mostly on RB. Some additional riparian located along the 1048 Slough to the west.	Likely non-existant. Limited vertically by depth to hardpan and by banks of "Basin Clay."

Limited to a short distance from the channel. Rice cultivation comes w/in one canopy-width of the channel for most of the reach.	Likely non-existant. Limited vertically by depth to hardpan and by banks of "Basin Clay."
1.5 miles in middle in the middle of the reach are the best in the basin portion of the creek; zone in last 9,000' of reach to Hwy 162 is thin; LB in last 5,000' shows signs of heavy cattle grazing (in the channel at points)	Likely non-existant. Limited vertically by depth to hardpan and by banks of "Basin Clay."