State of California | The Resources Agency

Memorandum

Date : September 23, 1994

To : Ralph Scott
Linton Brown

Sacramento River Bank Erosion Memorandum Progress Report. September 23, 1994.

Department of Water Resources

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ento River Bank Erosion Investigation Memorandum Progress Report

The Department of Water Resources, Northern District, began the ***Sacramento River Bank Erosion Investigation*** to collect data on significant river geomorphic characteristics such as erosion, deposition, and meandering in the 100-mile reach between Red Bluff and Colusa. The study also considers long-range geomorphic changes caused by such human activities as dam construction, bank protection, and gravel mining.

These data are used by the Department of Water Resources and other agencies in addressing present and future significant issues, such as water projects, fish and wildlife, loss of wetlands and agricultural land. These data may be used to resolve land-use conflicts and develop a management plan.

The study consists of bank erosion, floodplain deposition, river channel changes, and Lake Red Bluff changes.

Our bank erosion study was divided into two phases. The Phase Aerial Photography Bank Erosion Study identified 67 eroding bank sites between Red Bluff and Ord Ferry. We measured the amount of erosion and sediment production at these sites over a 10-year period using aerial photography. In the Phase II-Bank Erosion Monitoring Sites Study, we surveyed 15 eroding bank sites between Red Bluff and Colusa. These have been resurveyed biannually since 1986.

Floodplain deposition was measured by resurveying cross-sections originally surveyed by the U. S. Corps of Engineers in the 1920s and the U. S. Geological Survey in the 1970s and 1980s. The cross-sections were compared and the amount of deposition or erosion measured.

We resurveyed U. S. Bureau of Reclamation cross-sections in Lake Red Bluff, U. S. Geological Survey cross-sections at stream gages, and measured river depths and widths to determine long-term changes.

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PART I: INTRODUCTION

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INTRODUCTION

One of the more interesting parts of the State is the Great Central Valley that occupies the central region. The southern end of this valley is called the San Joaquin Valley, and the northern part is called the Sacramento Valley, named after the rivers that run through them. The Sacramento River headwaters are on the east slope of Mt. Eddy in the vicinity of Mt. Shasta. The town of Mt. Shasta is known for being the city of pure water. From Mt. Shasta the river is cradled between the Cascade Range on the east and the Klamath Mountains on the west. The river then enters the Great Central Valley near Redding, flows through the Sacramento Valley and empties into the San Francisco Bay. The Sacramento Valley is approximately 150 miles long and from 30 to 60 miles wide. The elevation varies from 10 feet below sea level in the Sacramento-San Joaquin Delta region to about an elevation of 500 feet at the extremities. It is bordered on the east by the Sierra Nevada and Cascade Ranges, and on the west by the California Coast Ranges.

The Sacramento River is the largest and most important river system in California. It drains 17 percent of California's land area, yet yields 18.4 million acre-feet, or 35 percent of the water supply. The river is the State's most important salmon resource. The riparian corridor between Red Bluff and Colusa is one of the richest and most diverse wildlife habitats remaining in California.

About 150 years ago, the Sacramento River was bordered by up to 500,000 acres of riparian forest, with bands of vegetation spreading 4 to 5 miles. Less than five percent of the original acreage remains today (Resources Agency, 1989). In 1979 the U.S. Fish and Wildlife Service reported that 95 percent of the stream miles of salmon and steelhead habitat in the state was lost, as well as 91 percent of the natural wetlands used by migratory birds (Sudman, 1980). Today more than 65 major dams plug canyons and ravines on the Sacramento and its tributaries (Mayer, 1989).

Bank erosion is an active, natural process in the Red Bluff to Colusa study reach. It generally occurs on the outside of meander bends. Here, banks are susceptible to erosion because high-flow velocities impinge directly onto banks. The eroding banks typically consist of sand and silt underlain by sand and gravel. Over time, the river meanders across the floodplain by eroding one bank and depositing sediment on the other. The fish, wildlife, and riparian vegetation are adjusted to the cycle of erosion, deposition, and changing channel pattern in which the river swings slowly back and forth across the meander belt. The health and productivity of the system at any one point is dependent on the periodic rejuvenation associated with these changes.

The Sacramento River's geology, geomorphology, and hydrology have combined to produce a unique riparian habitat that supports a varied wildlife. In the past, the Sacramento River meandered freely across its floodplain, eroding high terrace lands and replacing them with low terrace gravels. Over time, sediment deposition would eventually convert these low terrace gravels back to high terrace land. This natural erosional-depositional cycle supported a unique riverine ecology adapted to these fluctuating processes.

Human-induced changes to the Sacramento River, including bank protection, gravel mining, pollution, riparian vegetation removal, flow regulation, and flood control, have resulted in a number of physical and ecological effects. This study focuses on changes in bank erosion, bank composition, river length, depth, width, sinuosity, and floodplain deposition.

DWR has been monitoring these changes using old survey maps, aerial photographs, and field surveys. Completed studies indicate that bank protection has significantly reduced a source of salmon spawning gravel from freshly eroded banks and will over time decrease the number of preferred spawning areas such as point bar riffles, chute cutoffs, multiple channel areas, and areas near islands. Bank protection also increases the tendency of the confined river to deepen and narrow, further reducing spawning habitat. Because of flood protection from dams and extensive bank protection along eroding banks, most of the rich high terrace soils and all but a small percentage of the original riparian forest has been converted to agriculture and other uses. In addition, only 45 percent of the original streambank vegetation remains.

Wildlife populations have declined markedly due to loss of riparian habitat and suppression of the natural successional processes that maintain the density and diversity of habitat within the riverine environment. Some species that are adapted to the dynamics of the erosional-depositional cycle are threatened with extinction or extirpation as key habitat elements are lost from the newly stabilized river system. Flood control has interrupted the natural equilibrium between erosion and deposition, resulting in reduction in bank erosion rates and in overbank sediment deposition.

Bank erosion has been a serious problem for farmers along the banks of the river. The river meander zone varies from about 500 feet to over 7000 feet depending on the location. Valuable cropland and orchards are routinely lost. Campgrounds, roads, levees and bridges are also at risk. The east bank at Woodson Bridge State Recreation area receeded over 45 feet in a single storm, resulting in the loss of a road and other park facilities.

Purpose and Scope

The purpose of the ***Sacramento River Bank Erosion Investigation*** is to collect data on significant river geomorphic characteristics such as erosion, deposition, and meandering. DWR and other agencies use these data in addressing present and future significant issues, such as water projects, fish and wildlife, wetlands, loss of agricultural land and others. These data will be used to resolve land-use conflicts and develop a management plan.

Shasta Dam was completed on the Sacramento River north of Redding in 1945. The dam eliminated access to a large portion of the traditional salmon spawning habitat. It has had major effects on the distribution of streamflow, resulting in geomorphic adjustments in bank erosion rates, river meander rates, and sediment deposition.

There are a number of concerns relating to the construction of Shasta Dam and proposals for future water storage and conveyance. Foremost amongst these is the effect of these projects on bank erosion along the Sacramento River. Erosion has caused the loss of prime agricultural land, but has also contributed up to 85 percent of the spawning gravel that salmon require (DWR, 1984). Also, there is a need to analyze baseline geomorphic data to quantify the complex relationships between bank erosion rates and flows, bank composition, channel geometry, and riparian vegetation. The long range use for these analyses includes:

- Providing the basic data required for development of an effective Sacramento River management plan.
- Studying the relations between bank erosion and other river processes such as riparian succession, wetlands formation, and spawning gravel recruitment.
- Reducing damage caused by present water management practices.
- Assessing the effects of human impacts, such as riprapping, gravel mining, agriculture, and diversions on the river system geomorphology. These changes in channel dynamics affect the unique riparian ecology that has evolved along the river. Some riverine species are listed as rare or endangered, or are pending listing.

The Department of Water Resources, Northern District, began this Sacramento River geomorphic study in 1986. The study consists of bank composition, bank erosion, floodplain changes, channel changes and Lake Red Bluff changes. The study also considers long-range geomorphic changes caused by such human activities as dams, bank protection, and gravel mining. Geomorphic changes include channel narrowing and deepening; changes in riparian vegetation, channel length, width, sinuosity, bank erosion and sediment transport rates.

In the Phase I "Composition of Eroding Banks" study, 67 eroding banks were identified between Red Bluff and Ord Ferry using aerial photography. We measured the amount of bank erosion and calculated the erosion rates and the amount and size of sediment introduced to the river at each site.

In the Phase II "Bank Erosion Monitoring Sites" study, ten bank erosion monitoring sites were surveyed in 1986 in the 58-mile study reach between Red Bluff and Colusa. An additional six sites were surveyed in 1988. The sites are resurveyed semi-annually. Each site was mapped and a plate prepared showing the geology, vegetation, hydrology and bank erosion for the period of record.

Floodplain deposition was also monitored. Deposition is the regenerative process which rebuilds the floodplain destroyed by erosion. Ten floodplain cross-sections were surveyed to monitor sediment deposition and long-term changes.

Cross-sections surveyed by the U.S. Bureau of Reclamation in Lake Red Bluff were resurveyed to determine historic changes. The purpose of this part of the study was to determine sediment transport in this part of the study area.

Cross-sections surveyed at various times by DWR at gaging stations were also compared. Changes in the cross-sectional areas were tabulated to determine long-range trends.

Previous Studies

Bank erosion was monitored as part of the ***Observations of Sacramento River Bank Erosion, 1977-1979*** (DWR, 1979). For two years, six active bank erosion sites were monitored periodically to document bank recession. A report was published in 1979 outlining the results.

The report concluded that erosion potential and appearance of any given site changed after each storm. During the life of an eroding bank, two identical flows will produce different amounts of bank erosion. The study also concluded that there is no fixed correlation between flow and erosion for a specific site.

Monitoring of four of the six sites was continued until 1983. The memorandum report, ***Effect of Enlarged Shasta Reservoir on Sacramento River Bank Erosion*** (DWR, 1985) presented the results of this study. The study correlated Sacramento River bank erosion with three parameters: the volume of flow between erosion measurements, the peak discharge, and the average daily discharge. In general, the correlation ranged from good to poor, depending on the erosion site and the correlation parameters.

The study concluded that a reduction in bank erosion would occur from the operation of Enlarged Shasta; an average annual reduction of as much as 20 percent would occur in certain river reaches; and winter erosion would be greatly reduced while summer erosion would be slightly increased. Other conclusions reached include:

- The reach of the river between Hamilton City and Colusa is the most erodible;
- Low flow erosion can occur from mechanisms unrelated to flow, such as rainfall, poor irrigation practices, or high water tables;
- High flow erosion typically occurs when high flows dislodges soil particles and undermine the banks;
- Of three correlation parameters, bank erosion correlated best with peak discharge;
- The erosion rates varied greatly between erosion sites, with the Princeton site the highest.

DWR has published a number of related reports on the Sacramento River. These include: ***Woodson Bridge State Recreation Area Erosion Study*** (1979), ***Upper Sacramento River Spawning Gravel Study*** (1980), ***Middle Sacramento River Spawning Gravel Study*** (1984), and the ***Sacramento River Spawning Gravel Studies - Executive Summary*** (1985). These three reports discuss Sacramento River morphology. The atlas appendices delineate the extent of the Sacramento River meander belt. The reports ***Land Use Changes in the Sacramento River Riparian Zone, Redding to Colusa, A Second Update - 1977 to 1982*** (1983), ***and Land Use Changes in the Sacramento River Riparian Zone, Redding to Colusa, A Third Update - 1982 to 1987*** (1987), provide details on changes in land use and riparian vegetation.

The two sources of regional information available for this area are the U.S. Geological Survey Red Bluff geologic map sheet (USGS, 1984) and the U.S. Soil Conservation Service county soils descriptions (SCS, 1967).

Site specific reports include the U.S. Bureau of Reclamation's investigation of the backwater effects of the Red Bluff Diversion Dam (USBR, 1970, 1985).

Location and Access

The focus of this investigation is on the 100-mile reach of the middle Sacramento River between Red Bluff and Colusa (Figure 1). This reach is identified as having the greatest amount of bank erosion along the entire river. The study area includes the tributary watersheds in this reach because of their influence on natural and human-induced processes.

Towns in the reach include Red Bluff, Hamilton City, Butte City, Princeton and Colusa. The reach is navigable with small craft such as canoes and rafts and jet boats. During the late fall low flows, some of the riffles are difficult to navigate.

Most of the reach between Red Bluff and Hamilton City is private and lacks public access except at the City of Tehama and at Woodson Bridge. From Hamilton City to Colusa, State Highway 45 roughly parallels the course of the river and provides access in a number of places. Public boatramps are located at Red Bluff, Tehama, Woodson Bridge, Hamilton City, Ord Ferry, Butte City and Colusa. Additional access is available at private resorts in a number of places.

Climate and Streamflow

The Sacramento Valley has a Mediterranean type climate with hot, dry summers and cool, wet winters. Topography significantly influences both temperature and precipitation. The average annual temperature ranges from about 60 degrees Fahrenheit in the valley to 40 degrees in the mountains.

Figure 2 shows the average annual precipitation pattern for the region (DWR computer analysis, 1993). Winter storms generated in the Gulf of Alaska usually cross this portion of California from northwest to southeast. The orographic effect of the Coast Range and Klamath Mountains causes the parallel pattern of isohyets along the northwest and west side of the valley. A similar set of parallel isohyets occur on the east side because of the Sierra Nevada mountains. On occasions when a strong high pressure ridge exists along the coast, these storms are forced to the south. The resulting storm track moves up the valley in a counterclockwise motion from the southwest and causes the same general pattern of rainfall.

The average annual precipitation varies from about 20 inches near Red Bluff to more than 70 inches in the surrounding mountains. Most of the precipitation occurs between November and April. Major winter storms often result in intense precipitation over a short duration. The precipitation pattern is one of large cyclonic storms in the winter and infrequent thunderstorms in the summer. The winter storms are caused when low pressure cells with moist unstable air are forced to rise over mountains. Some snow occurs in the upper parts of Mill, Deer, Thomes and Cottonwood Creeks. The lower edge of the normal semi-permanent snow pack is about 5,000 feet.

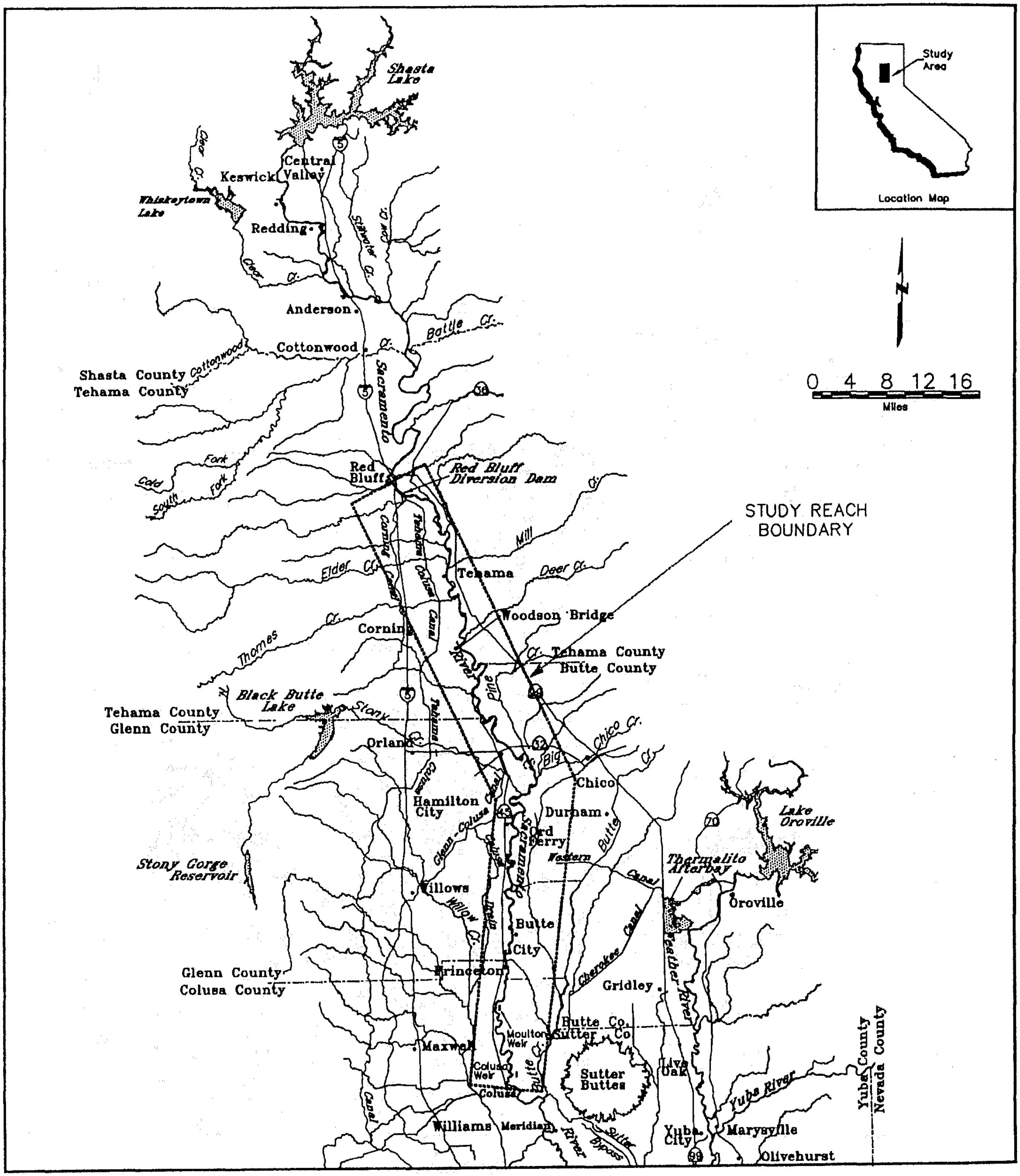
The westside tributaries generally flow from west to east, cross-cutting the regional geologic and soil trends. The major perennial streams, such as Cottonwood , Elder, Thomes and Stony Creeks, head near the crest of the Coast Ranges. The smaller, intermittent streams such as Reeds and Red Bank head in the valley foothills. These streams cease flowing in the late spring as base flow diminishes and seepage and evaporation exceeds available flow. All the westside streams cross the valley area from west to east in fairly straight and relatively narrow canyons confined by intervening low ridges.

The eastside tributaries flow from the Cascade Range and Sierra Nevada westward into the valley and the Sacramento River. These include Antelope, Mill, Toomes, Deer, Pine, Big Chico, and Butte Creeks. These are perennial streams by nature but most of their spring and summer streamflows are diverted for agriculture.

Before settlement of the Sacramento Valley, the Sacramento River was free flowing. Late summer flows were low, averaging 3,000 cubic feet per second, and in dry years dropping as low as 1,000 cfs. The river, however, would fluctuate widely in response to winter rains and spring snowmelt. Periodically, it would overflow its banks and flood large areas of the valley floor. These areas were covered by dense forests of riparian vegetation adapted to the periodic flooding.

In 1944, Shasta Dam was completed for flood control, recreation and water storage purposes. Regulation of the discharge has dampened low and high extreme events below the dam, resulting in a regulated flow in the summer averaging 7,000 cfs to 13,000 cfs and a regulated peak flow in the winter of 80,000 cfs. Since December 1963, water has been diverted from the Trinity River basin into the Sacramento River basin.

Figure 1



STATE OF CALIFORNIA
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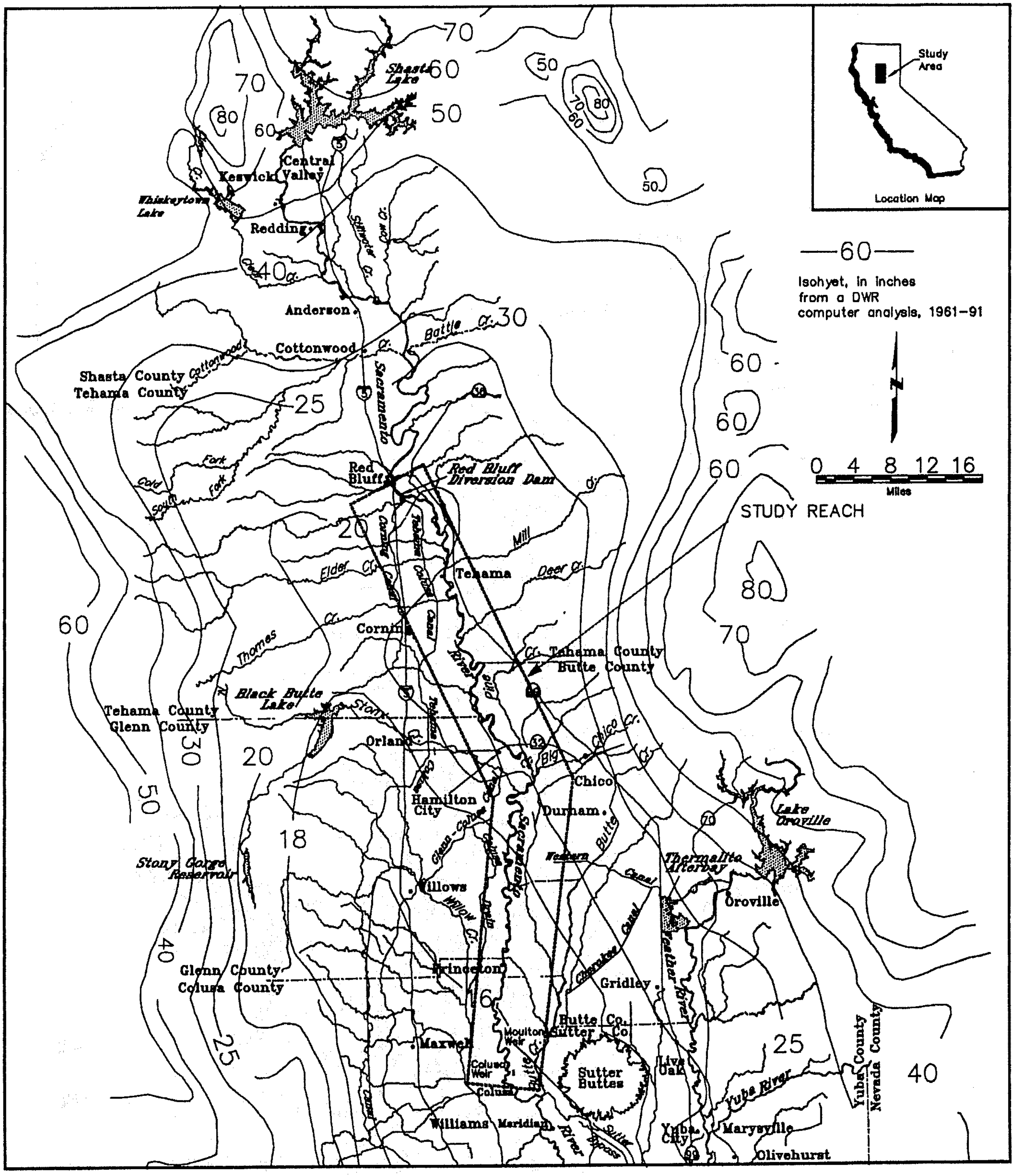
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

Sacramento River Bank Erosion Investigation
Location Map
Sacramento River from Red Bluff to Colusa

Figure 2



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Sacramento River Bank Erosion Investigation
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Sacramento River from Red Bluff to Colusa

The Sacramento River discharge has been further modified by diversions on the river and tributaries. Three major diversions exist between Red Bluff and Colusa, diverting water for agricultural irrigation. These are the Red Bluff Diversion Dam, the Glenn-Colusa irrigation canal, and the River Branch canal at Sidd's Landing near Princeton. Numerous minor diversions and pumps also exist along the river.

A number of tributaries enter the Sacramento River along the study reach. Some of these tributaries also have diversions that divert water for agricultural irrigation. These diversions reduce discharge to the river, reduce downstream spawning gravel recruitment, and may impede fall runs of spawning salmon.

Vegetation

The northern Sacramento Valley was first settled by Americans in 1844 with grants obtained from the Mexican government. The area was heavily forested at the time, with evergreen conifers in the mountains to the east and west, and oak woodlands in the rolling foothills, and a mixture of valley oak, sycamore, cottonwood, black walnut and other riparian vegetation along streams. Most of the valley riparian woodland has been converted to row crops, orchards or urban development. The blue oak woodland of the foothills has been used primarily for livestock grazing and firewood harvesting.

Vegetative types in the study reach between Red Bluff and Colusa include floodplain riparian forests, blue oak woodland, live oak riparian woodland, grassland and savannah.

Floodplain Riparian Woodland

Floodplain riparian woodland occurs on the rich soils of the Sacramento Valley floodplain. Most of the river in the study reach lies within this vegetative unit. Valley oak (Quercus lobata) is the predominant oak, with sycamore (Platanus racemosa), cottonwood (Populus fremontii), black walnut (Juglans nigra), box elder (Acer negundo) and willow (Salix spp.) being the other common tree species. Brush species include poison oak (Toxidendron diversilobum), wild blackberry and grape.

Establishment of riparian vegetation occurs sequentially over time as one plant community replaces another. This plant succession is driven by the processes of erosion and deposition. The sequence begins when cottonwood and willow seeds germinate at the waters edge of a newly formed gravel bar. As the river meanders, successive bands of younger trees form, resulting in a gallery forest with many ages and stages of riparian growth. Sand and silt deposit over time, reducing the availability of subsurface moisture. Within the first ten years, sycamore, bow elder, and other species tolerant of dry and shady conditions are established. Black walnut and Oregon ash begin to appear as the cottonwood forests mature. As the cottonwoods age and begin to die out, a climax forest of valley oaks may become established (Resources Agency, 1989)

The floodplain riparian woodland is naturally a mosaic of habitat types of different ages, species compositions, and vegetative structures that are continually renewed. For this to occur, however, the natural erosion-deposition-regrowth cycle must be allowed sufficient width and time.

Blue Oak Woodland

The blue oak community forms a nearly continuous ring around the Central Valley of California, generally between 300 and 1000 feet elevation. It is essentially a two-layered community. This community occurs in a few places along the Sacramento River where the river impinges directly on older geologic units such as terrace deposits or the Tehama and Red Bluff Formations.

The major vegetative type is the blue oak woodland (Quercus douglasii). Some individual live oak (Quercus wislizenii) and valley oak (Quercus lobata) may be interspersed. Poison oak is the predominant shrub. Under natural conditions, the blue oak woodland grades gradually into grassland where the soils, slope, and aspect limit tree growth. Blue oak can occupy sites receiving as little as 10 inches of precipitation annually (DeLasaux and Pillsbury, 1987).

Oak woodland occurs on moderately rich, loamy, well-drained soils with neutral or slightly basic pH. Topography is often gently rolling to steep. Oak woodland often occurs in a mosaic with grassland, savannah and chaparral-- a mosaic that reflects differences in slope, aspect, elevation, soil depth, oak harvesting and frequency of fire more than differences in climate (Barbour, 1987).

The present distribution and density of blue oak woodland reflect the effects of land conversion. Major areas that have been converted to grassland and upland agriculture are readily discernible by differences in canopy density and distribution, abrupt straight-line boundaries along section and property lines, and other obvious anomalies. It is estimated that more than 50 percent of the original blue oak woodland has been converted to grazing land or farmland.

Live Oak Riparian Woodland

The live oak riparian woodland is rare. Major plants include live oak, sycamore, California buckeye (Aesculas californica), cottonwood, and willow. The predominant shrubs are poison oak and wild blackberry. This forest type is most commonly found near the major tributary drainage channels since most of these species have a high water requirement.

Open Grassland and Savannah

Open grassland and savannah generally has five percent or less blue oak canopy cover but may range to as high as 10 percent. A large part of the western Sacramento Valley area is now open grassland consisting of annual and perennial grasses and forbs. Most of the grasslands outside of the Sacramento River flood zone were probably originally blue oak woodland converted to grassland by oak harvesting. Wildfires may have created patches of open grassland and mixed-age stands of blue oak, live oak and brush. The current major land use in these areas is seasonal grazing with some dryland farming.

Chaparral

Brushland does not occur in the valley but in foothill areas with shallow soils too low and dry to support timber. Species common to the area include manzanita (Arotostaphylus sp.), deerbrush (Ceanothus integerrimus), mountain whitethorn (Ceanothus cordulatus), buckeye, poison oak and digger pine (Pinus sabiniana). A broad chaparral belt extends along the foothills from Thomes, northwest through the upper Red Bank Creek and South Fork

Cottonwood Creek basins. A similar but less continuous belt extends along the valley's east side.

Fir-Pine Forest

Evergreen forests occur in the upper elevations. Principal commercial conifers are ponderosa pine (Pinus ponderosa), sugar pine (Pinus Lambertiana), Jeffrey pine (Pinus Jeffreyi), Douglas-fir (Pseudotsuga menziesii), white fir (Abies concolor), red fir (Abies magnifica) and incense cedar (Librocedrus decurrens). Much of the forests have been selectively cut and some have been clearcut.

Cultivated

Large areas have been cultivated both periodically and permanently during the last 100 years. Alfalfa, winter wheat, oat, hay, and other forage types are the major crops grown. Most of the dryland farming occurs along the flat-bottomed valleys of Sacramento River tributaries. Most of the irrigated acreage occurs along the Sacramento River, in the lower part of the Sacramento Valley, and on terraces along the lower part of the major tributaries.

SUMMARY AND CONCLUSIONS

The Department of Water Resources, Northern District, began this Sacramento River geomorphic study in 1986. The focus of this investigation is on the 100-mile reach of the middle Sacramento River between Red Bluff and Colusa. This reach is identified as having the greatest amount of bank erosion along the entire river. This study includes discussion of the tributary watersheds in this reach because of their influence on natural and human induced processes. Nine bank erosion monitoring sites were surveyed in the 58-mile study reach. An additional six sites were surveyed in 1988. The scope was also expanded to include overbank deposition and bank composition. Ten floodplain cross-sections were surveyed to monitor sediment deposition and long-term changes. All the eroding bank sites between Red Bluff and Ord Ferry were identified, erosion measured, and sediment volumes estimated. Data from gaging stations in the reach were compiled, including hydrologic data and cross-sections. Lake Red Bluff cross-sections originally surveyed by the U.S. Bureau of Reclamation were resurveyed for this study.

The Sacramento River is the largest and most important river system in California. It drains 17 percent of California's land area, yet yields 35 percent of the water supply. The river is the State's most important salmon resource. The riparian corridor between Red Bluff and Colusa is one of the richest and most diverse wildlife habitats remaining in California.

The average annual precipitation varies from about 20 inches near Red Bluff to more than 70 inches in the surrounding mountains. Most of the precipitation occurs between November and April. Major winter storms often result in intense precipitation over a short duration. The precipitation pattern is one of large cyclonic storms in the winter and infrequent thunderstorms in the summer. The winter storms are caused when low pressure cells with moist unstable air are forced to rise over mountains. Some snow occurs in the upper parts of Mill, Deer, Thomes and Cottonwood Creeks. The lower edge of the normal semi-permanent snow pack is about 5,000 feet.

Human-Induced Changes

Human-induced changes to the Sacramento River, including bank protection, gravel mining, pollution, riparian vegetation removal, flow regulation, and flood control, have resulted in a number of physical and ecological effects. This study focuses on changes in bank erosion, bank composition, river length, depth, width, sinuosity, and floodplain deposition.

Before the current modification of the valley during the last 150 years, the Sacramento Valley was quite a different place than it is today. The Native Californians of ancient times would hardly recognize the present California. In fact when Anza, an early Spanish explorer, trekked up the great Sacramento, Father Font, who was traveling with him on the expedition, wrote that, for the most part, the valley was a great lake studded with islands. (Dana, 1939). This might seem like a very strange observation to anyone who has grown up living in the Great Valley today and is used to the relatively tame modern rivers which rarely flood. Before modern flood control and other water projects were constructed, the valley often would remain flooded for several months out of the year. The area of flooding, although irregular in pattern, varied in width from about two to thirty miles and extended from the mouth of the Sacramento River to the present site of Red Bluff, a distance of 150 miles, and comprised an area in excess of one million acres (Jones, 1967).

As a result of the flooding, great forests of tule reeds appeared along the sides of rivers and the surrounding swampy areas. Surrounding the tule lands lay belts of higher and more fertile lands near the stream channels called rim-lands.

Since about 1850, the study reach has undergone a number of hydrologic, geomorphic, and environmental changes, most of which have been detrimental to locally adapted species. These changes are caused by dams and diversions, bank protection, urbanization, stream gravel removal, hydraulic mining, agriculture, and logging. Many of these changes have had long-reaching effects, including alteration of river characteristics, such as depth, width, gradient, sinuosity, and bank erosion. This in turn has reduced riparian vegetation, water quality, hydrologic diversity, and fish and wildlife resources.

Because of the extensive wetlands, the Central Valley of California was the most important waterfowl wintering area in the Pacific flyway, supporting about 60 percent of the total population. Four million acres of wetlands, mostly surrounded by grasslands and riparian areas, provided ideal wintering and breeding habitat for waterfowl and other wildlife that flourished throughout the region. These wetlands provided a wide variety of benefits including wildlife habitat, fish rearing, groundwater recharge, and sediment control.

Since the mid-1950s, duck populations have shown sporadic fluctuations related to weather and land use changes. However, in the late 1970s, populations started to decline, and by the mid-1980s, fall flights were approximately 30 percent below long term averages. A wide array of other wetland species including shorebirds, wading birds, amphibians, reptiles, fish, mammals, invertebrates and plants depend on wetlands. Fifty-five percent of the threatened and endangered species in California are associated with wetlands.

Urbanization, primarily in Redding, Anderson, Cottonwood, and Red Bluff, has caused additional problems in the study reach. Gravel extraction for highways, housing, and other projects averages more than 1.3 million cubic yards per year in Shasta County and 0.5 million in Tehama County, mostly from tributary streams (DWR, 1980; 1984). This, in conjunction with Shasta, Keswick, Whiskeytown, and other dams that prevent gravel recruitment from upstream reaches, has eliminated the spawning gravel available in downstream reaches.

California agriculture has had the largest impact on Central Valley wetlands and riparian lands. First to be converted to agriculture were the fertile rimlands. Rimlands are next to the river, higher than the surrounding tule lands, and are less often flooded. Flood control had its inception in the low levees constructed on the rimlands by farmers protecting their crops.

Next to be developed were the tule, swamp and overflow lands. Through a series of legislative acts passed between 1855 and 1868, the State sold these lands to farmers who were obliged to reclaim them individually or through the formation of reclamation districts. Within a period of three years following the last act, practically all of such lands had passed into private ownership (Jones, 1967). To date, as a consequence of just these two kinds of agricultural development, about 95 percent of the original Sacramento River riparian forest has been removed.

A large number of chinook salmon (Oncorhynchus tshawytscha) migrated up the Sacramento River each year to spawn. Although there were probably four runs then, as there are today, the two largest runs were thought to have occurred in the fall and spring. The other two runs, winter and late fall, are not as well documented historically, especially their numbers. Most of the spring-run and winter-run salmon, as well as part of the fall and late fall salmon, were thought to have spawned upstream from the present location of Shasta Dam. However, large numbers of spring-run and fall-run salmon also spawned in many Sacramento tributaries. A large part of fall run spawned in the study reach.

Dams and unscreened, or poorly screened, diversions have severely depleted the river fishery. Early dams and diversions built by miners and farmers obstructed miles of habitat without allowance for fish passage or mitigation measures. By the 1920s, at least 80 percent of the Central Valley spawning grounds had been cut off by obstructions, according to the U. S. Bureau of Reclamation. Dams affect riparian areas mostly by the reduced incidence of flooding, bank erosion, and silt deposition required for the regeneration of riparian habitat. Flood control also encourages the development on riparian lands along the river.

The Sacramento River Flood Control Project was a project that built upon existing levees that had already been built in some areas, but in some cases created whole new sections of levee. The project was envisioned to make the inhabitants of several key cities safe from the seasonal flood waters. The project was funded by local residents, the State government and the Federal Government, who passed the resolution starting the project in 1917.

In 1967, the Sacramento River Flood Control Project covered over 440 miles of river, canal, and stream channels; three major drainage pumping plants; 95 miles of bypasses comprising areas aggregating 100,000 acres; five low-water check dams; 50 miles of drainage canals and seepage ditches; and numerous appurtenant structures including minor weirs and control structures, bridges and gaging stations (Jones, 1967).

Traditional bank protection is the placement of rock riprap on banks and levees to stop erosion. Bank protection, when effective, stops bank erosion and lateral migration. It prevents loss of valuable agricultural lands, transportation facilities, and structures.

Because of flood protection from dams and extensive bank protection along eroding banks, most of the rich high terrace soils and all but a small percentage of the original riparian forest has been converted to agriculture and other uses. In addition, only 45 percent of the original streambank vegetation remains.

Bank protection, particularly if it is along all the eroding banks of the river, will cause some long-range geomorphic changes. First, it will have a stabilizing effect on length and sinuosity. Second, it will prevent the re-entrainment through bank erosion of gravel deposited on point bars. This will have some long-range effects on the amount of available spawning gravel, and will over time decrease the number of preferred spawning areas such as point bar riffles, chute cutoffs, multiple channel areas, and areas near islands. Third, over a period of time, it will tend to narrow the channel, increase the depth of flow, and reduce the hydrologic diversity. Sloughs, tributary channels, and oxbow lakes will fill with sediment over time and no new ones will be created. This will result in loss of valuable wetland habitat along the river corridor.

More recently, major water development projects, such as Shasta and Keswick Dams and the Trinity River Diversion, have affected Sacramento River hydraulics. In the fall of 1945, Shasta Dam was first used to control flood waters that threatened the Sacramento Valley below. The reservoir was constructed by the U. S. Bureau of Reclamation on the upper Sacramento River above Redding. Shasta Dam stores 4.5 million acre-feet and, to a large extent, regulates flows from the Pit, McCloud, and upper Sacramento Rivers. Keswick Dam, 9 miles downstream from Shasta, provides power, water regulation, stops salmon migration, and acts as a fish-trapping facility.

The effect of Shasta Dam on the natural flow (DWR, 1984) has been to:

1. Decrease the minimum discharge and increase the number of very low discharges. This occurred in the past when the powerhouse at Keswick Dam was closed for repairs. This no longer occurs because present minimum fish flow releases are above pre-Shasta Dam historic lows.

2. Increase the number of moderate discharges, particularly during the summer and fall irrigation season.

3. Reduce the number, peak, and volume of high and very high flows.

Since December 1963, water has been diverted from the Trinity River Basin through the Clear Creek Tunnel and Judge Francis Carr Powerhouse to Whiskeytown Lake. The Spring Creek Tunnel then diverts Trinity water and most of Clear Creek water through another power plant into Keswick Lake. An average of about 1 to 1.25 million acre-feet of Trinity River water was diverted into the Sacramento River Basin. Since the late 1980s the diversion amount has been reduced to about 900,000 acre-feet to improve water flows in the Trinity River. The effect of the Trinity River diversion on post-Shasta flows has been to increase average Sacramento River discharge by about 1,000 to 1,500 cubic feet per second throughout most of the year.

The effect of Shasta Dam on floodflows are also dramatic. The 100-year natural flood flow of 300,000 cubic feet per second (cfs) is reduced to 79,000, or 26 percent at Keswick Dam. The uncontrolled 100-year flood at Red Bluff would be 420,000 cfs. This flow would be reduced to 66 percent, or 277,000 cfs by the Shasta Dam.

The peak of the flood flows in the Sacramento River increase downstream between Red Bluff and Vina. Between Vina and Hamilton City, the peak discharge remains about the same, but between Hamilton City and Butte City the peaks decrease. This is caused by overflow into the Butte and Colusa basins, which is not gaged. Between Butte City and Colusa there is a major decrease because of overflow into the Colusa bypass.

The Red Bluff to Colusa river reach contains the best remaining remnants of the original Sacramento River riparian corridor. This habitat supports several rare species that have evolved within this unique riverine environment. Some of these species that are listed or pending listing on the California threatened, rare, and endangered species list include the chinook salmon, bank swallow, yellow-billed cuckoo, and the Sacramento Valley longhorn elderberry beetle.

These species and their associated habitat have been and are being impacted by various human activities along the river. Some of the activities that significantly affect or have affected the study reach include flood control, bank protection, agriculture, logging, hydraulic mining, stream gravel removal, and urbanization. These activities impact stream bank erosion rates, riparian vegetation, water quality, hydrologic diversity, and fish and wildlife resources.

About 150 years ago the Sacramento River was bordered by 500,000 acres of riparian forest, with bands of vegetation spreading 4 to 5 miles. Less than five percent of the original acreage remains today (Resources Agency, 1989). In 1979 the U.S. Fish and Wildlife Service reported that 95 percent of the stream miles of salmon and steelhead habitat in the state was lost, as well as 91 percent of the natural wetlands use by migratory birds (Sudman, 1980). Today more than 65 major dams plug canyons and ravines on the Sacramento and its tributaries (Mayer, 1989).

Geology

In the study reach, the river is primarily an alluvial stream, in that it flows across its own sedimentary deposits of sand, silt and gravel. However, the geomorphic characteristics such as meander rates, sinuosity and gradient is also influenced by the underlying structure and geologic units.

The oldest geologic unit exposed is the Pliocene Tehama Formation. It is exposed in a number of places such as near Red Bluff, Tehama, Woodson Bridge, Hamilton City, and Ord Ferry. The Tehama is semi-consolidated and erosion resistant. Bank recession is slow on banks with exposed Tehama Formation. Deposited on top of the Tehama are the Red Bluff Formation and four terrace levels. The four levels are the Lower and Upper Riverbank Formation and the Lower and Upper Modesto Formation. These terrace deposits occur in places but are typically too thin to compose both the banks and bed of the river. Where terrace deposits occur on the banks of the river, the Tehama is typically exposed in the lower banks and the channel. The terraces and the Tehama are typically more erosion resistant than the more recent alluvial deposits. Recent alluvial deposits within the Sacramento River floodplain and meander belt consist of sand, silt, clay and gravel. These deposits are typically the most erodible.

Pleistocene folding and faulting have affected the Sacramento River by exposing the erosion resistant Tehama Formation in the banks and the bed. This has constrained and stabilized the river in short, straight geomorphic reaches alternating with longer, meandering, more unstable reaches.

Geologic evidence indicates that the northern part of the Sacramento River is actively being uplifted at the present time.

Geomorphology

The study reach from Red Bluff to Colusa is divided into three parts, called Reaches 6, 7 and 8, with each reach divided into a number of sub-reaches. Reach 6 extends from Red Bluff to Chico Landing and has 8 sub-reaches. Reach 7 extends from Chico Landing to Princeton and has 3 sub-reaches. Reach 8 is from Princeton to Colusa and has 3 subreaches. Each reach and subreach has different geomorphic characteristics from the reach directly above and below.

Bank erosion is an active, natural process in the Red Bluff to Colusa reach. It generally occurs on the outside of meander bends. Here, banks are susceptible to erosion beacuse high-flow velocities impinge directly onto banks. The eroding banks typically consist of sand and silt underlain by sand and gravel. Over time, the river meanders across the floodplain by eroding one bank and depositing sediment on the other. The fish, wildlife, and riparian vegetation are adjusted to the cycle of erosion, deposition, and changing channel pattern in which the river swings slowly back and forth across the meander belt. The health and productivity of the system at any one point is dependent on the periodic rejuvenation associated with these changes.

Meandering rates are highly variable. A river may change little in many years, yet experience rapid movement in one flood season. Different stream reaches have widely varying meander rates depending on such factors as bed and bank composition, sediment transport, flow and riparian vegetation.

DWR has been monitoring these changes using old survey maps, aerial photographs, and field surveys.

Analyses of channel length and sinuosity were done on eleven sets of maps and photographs dated between 1896 and 1987. No trends were apparent, except that some reaches are increasing in length and sinuosity and others are decreasing.

Bank erosion generally occurs on the outside of meander bends. Here, banks are susceptible to erosion because high-flow velocities impinge directly into banks and turbulent motion along the channel thalweg undercuts the banks. Eroding banks may be either high-terrace or low terrace. High terrace banks normally have a deep soil profile containing mostly loamy sand and silt. Below the soil is a thicker deposit of sand and gravel. A low-terrace bank consists mostly of a sand and gravel with a thin silt profile on top. Generally, banks with the smaller radii of curvature are the more erosive. Most of the bank erosion occurs during the winter. Summer erosion is significant in a few places along the river.

Bank erosion has been a serious problem for farmers along the banks of the river. The river's meander zone varies from about 500 feet to over 7000 feet depending on the location. Valuable cropland and orchards are routinely lost.

Structures such as campgrounds, roads, levees and bridges are also at risk. The east bank at Woodson Bridge State Recreation area receded over 45 feet in a single storm, resulting in the loss of a road and other park facilities. The bank was subsequently protected using the Palisades bank protection method. This method consists of piles and netting designed to slow flow velocities and encourage silt deposition.

Between River Mile 243 and 193, approximately between Red Bluff and Chico Landing, 103,500 feet of riverbank have been riprapped and an additional 81,000 feet of riprap have been proposed. If this is developed, the total riprap in this reach would comprise 35 percent of the riverbank. Between River Mile 193 and 165, 48,000 feet or 16 percent of the banks are protected and an additional 10 percent are planned. Between River Mile 165 and 143.5 26,400 feet of bank, or about 12 percent of the banks have been protected.

Bank Erosion Studies

Our bank erosion study was divided into two phases. The Phase I - Aerial Photography Bank Erosion Study identified 67 eroding bank sites between Red Bluff and Ord Ferry. The amount of erosion at these sites over a 10-year period were measured using aerial photography. In the Phase II-Bank Erosion Monitoring Sites Study, we surveyed 16 eroding bank sites between Red Bluff and Colusa. These are resurveyed semi-annually.

In our Phase I aerial photography bank erosion study, sixty-seven sites with observable erosion were identified between Red Bluff and Ord Ferry. The purpose of this phase of the study was to determine total bank erosion, bank composition, gravel and silt produced from bank erosion, and bank recession rates. A total of 67 bank erosion sites were identified and evaluated by comparing 1976 and 1987 aerial photographs. All visibly eroded areas from Red Bluff to Ord Ferry were measured using a planimeter.

Eroding alluvial banks in this reach average about 25 feet tall from crest to thalweg. The banks are composite, consisting on the average of about16 feet of gravel and 9 feet of silt. The volume of material eroded during an 11 year period between 1976 and 1987 was 48.5 million cubic yards (4.4 million cubic yards per year), including 19.7 million cubic yards (1.8 million cubic yards per year) of silt and 28.8 million cubic yards (2.6 million cubic yards per year) of gravel.

Erosion sites vary considerably in erosion rates, ranging from about 2.7 to 75 feet per year between 1976 and 1987. The average eroding bank length is 2940 feet and the average bank recession is 235 feet (21.4 feet per year). There were 196,000 feet of eroding bank in this reach. This represents about 32 percent of the total banks. The remainder is riprapped or aggrading. The average bank recession for the entire river reach for this 11 year period was 6.8 feet per year. This is considerably higher than the long-term average of about 3 feet per year, mostly because of the 1983 and 1986 storms that occurred during this period.

In our Phase II "Sacramento River Bank Erosion Sites" study, sixteen bank erosion sites were surveyed and monitored in the period between 1986 and 1993. The banks were surveyed twice yearly to monitor bank erosion. Unfortunately, one of California's longest recorded droughts occurred in the same period. Only during the 1993 water year did high flows and moderate flows occur. Two erosion sites were riprapped during the study period.

No detailed mathematical correlations were done because of the lack of high flow data. Significant factors contributing to Sacramento River bank erosion will be investigated further when additional high flow data are available.

Floodplain Profiles

Ten floodplain cross-sections were surveyed between 1986 and 1988. These extend from one side of the floodplain or centerline of a project levee, across the floodplain, across the Sacramento River to the opposing side of the floodplain or project levee. These surveys re-established historic profiles done by the U. S. Geological Survey between 1976 and 1980 and the U.S. Corps of Engineers between 1917 and 1923.

Floodplain deposition regenerates high-terrace soils lost by bank erosion. Bank erosion occurs year-round. The floodplain deposition occurs during large floods on an episodic basis. An average of 3 to 6 inches to, in places, several feet of silt may be deposited during a single flood. The deposition process can rebuild high-terrace soils at a fairly rapid rate. Areas that were river bottom in the 1940s are presently being farmed. The rate of formation of high terrace soils has been reduced by flood control.

It was generally believed that through bank erosion, high-terrace lands were being replaced by low-terrace point bars because Shasta Dam reduced deposition of soils on the floodplain. Observations made during this study indicate that this may not be the case. Although the incidence of floodplain deposition has decreased, so has the rate of bank erosion. In a study of land use changes in the Sacramento River riparian zone, DWR (1983) came to a similar conclusion that there has been no overall loss of high terrace prime soils since Shasta Dam went into operation, suggesting an overall balance between erosion and deposition.

Five of the cross-sections show that channel fill in excess of 25 feet is common over a fifty year period. On the floodplain far away from the river, deposition of two to five feet is not uncommon.

The other five cross-sections show that the same amount of deposition is not uncommon within a 10-year interval. Two major storm events occurred during this time interval, one in March 1983 and the other in February 1986. After these floods, floodplain deposition was observed in a number of places. Deposition varied from zero inches to over 2 feet, with an average of several (3-6) inches within the flooded area.

Lake Red Bluff Cross-Sections

The Red Bluff Diversion Dam is on the Sacramento River immediately below the mouth of Red Bank Creek. The dam is operated by the U.S. Bureau of Reclamation. It was completed in 1966.

DWR has performed sonar surveys of Lake Red Bluff in 1982, 1986, and 1988 to quantify the backwater effects on sediment deposition during high flow. Aggradation and degradation in the lake are indicators of the amount of sediment transport in the Sacramento River.

The goals of this program are to examine the backwater effects on in-channel sedimentation and determine the amount of bedload moving down the Sacramento River. Thirty-two monuments were set in the fall of 1986. These monuments are composed of galvanized pipe set in concrete. The distance between monuments was measured using an electronic distance measuring device. The profiles were established by using a depth sounder mounted on a boat. The collected data are plotted to calculate changes in cross-sectional area of the channel at each profile location.

About 4 feet of aggradation is evident between the completion of the dam in 1966 and 1986, for a total of about 56,000 cubic yards of sediment. Major stormflows in March 1983 and February 1986 contributed the majority of this sediment. The U.S. Bureau of Reclamation dredged the mouth of Reeds Creek several times to remove accumulated sediment. Since the fall of 1986, the dam has been opened during the winter months and the accumulated sediments are beginning to scour out of the reach.

The small change in the surveyed cross-sections and calculations by the Bureau suggest low bedload sediment transport and low rates of deposition in the reservoir area. In general, there was aggradation between 1968 and 1986. Between 1986 and 1987, there was degradation. This was the first year that the gates were left open during the winter months. Clearly a new survey should be done to see how effective this is in keeping the reservoir from accumulating sediment.

Gaging Station Cross Sections

Cross-sections from four gaging stations were compared using data from available years for each station. The data were collected by DWR as part of streamflow measurements. The cross-sections show that the bottom profiles change from year to year, but no distinct trends were evident. More recent cross-sections should be surveyed at these sites.

River Depths and Widths Next to Eroding and Riprapped Banks

Thalweg depths were measured opposite 30 eroding banks between Red Bluff and Ord Ferry. Depths were obtained by using a sonar depth-finding instrument mounted on the back of a jet boat. Individual surveys were started at the downstream end of the site and continuous soundings recorded as the boat followed a sinusoidal path across the thalweg adjacent to each bank. The resultant strip chart recordings were analyzed and an average thalweg depth for each site was obtained. The same procedure was used for measuring thalweg depths opposite 37 riprapped sites between Red Bluff and Ord Ferry. Data analysis shows that the mean thalweg along riprapped banks average 6 feet deeper than comparable eroding banks. The average thalweg depth for riprap has a mean of 15.8 feet, ranging from a minimum of 8 feet to a maximum of 23 feet. The average thalweg depth for eroding banks has a mean of 10.0 feet, ranging from a minimum of 5 feet to a maximum of 18 feet.

A similar analysis was completed for low-flow river widths. Widths opposite erosion sites are generally greater than at riprap sites by an average of 65 to 90 feet, depending on how the average is calculated. Eroding banks have a mean width of 480 feet, ranging from a minimum of 325 feet to a maximum of 600 feet. Riprap widths were narrower, with a mean of 410 feet, ranging from a minimum of 290 feet to a maximum of 600 feet. The difference in widths appears to remain fairly constant from Ord Ferry (RM 184.3) to RM 223; upriver from there, the difference decreases until from RM 235 to Red Bluff, it is essentially nonexistent. This is a consequence of the naturally more stable banks near Red Bluff.

The effects of Shasta Dam on river geomorphology are complex. In principle, Shasta Dam would tend to reduce width because of less frequent floodflows. However, this effect may be offset by factors that tend to increase channel width, such as riparian loss. Further study is necessary to adequately assess this complex issue.

RECOMMENDATIONS

The Sacramento River Bank Erosion Study has developed and compiled a large amount of data. Unfortunately most of the bank erosion data were collected during California's extended six-year drought. Funding for the study has been reduced to support data collection only.

We recommend the following:

- Monitoring be continued. High flow data needs to be developed to complement the large volume of low-flow erosion data. Since the Sacramento River system is in a state of natural flux, these monitoring programs are vital for providing baseline data for understanding and evaluating this dynamic system. Since there is the possibility that our survey control benchmarks may be removed during a period of high river discharge, it is recommended that all controls be resurveyed, using satellite survey techniques. This will enable us to relocate the essential control needed to continue our monitoring programs. At some later date, funding should be increased to include data analysis.

- Lake Red Bluff be resurveyed. The operation of Lake Red Bluff was changed in 1986 so that the diversion dam gates are raised and the reservoir empty between September and March. The survey would measure the amount of sediment washed out of the lake. This would help determine the amount of sediment transport in the Sacramento River.

- A program to study the loss of wetlands be implemented. In a natural system, the river is constantly creating new wetlands by meandering across the floodplain. At the same time, flood deposition is filling in these wetlands. Bank protection has severely constrained the river; however, sediment deposition is still filling in the wetlands. The rate of wetland loss needs to be assessed and mitigated.

- A comprehensive management plan be developed. Human-induced changes in the river system have been extensive. Some of these changes are known but many of these long-term changes are unknown or only partly known. The management plan must be flexible enough to change as our knowledge of changing river dynamics increase. The management plan should:

  - Protect, enhance, and maintain the natural fish, wildlife, and riparian habitat along the Sacramento River. This includes regulation to protect erosion-dependent features such as salmon spawning areas, bank swallow nesting sites, oxbow lakes and offstream wet areas, riparian vegetation, and the attendant wildlife habitats;

  - Identify and prioritize essential areas in the existing study reach that are most susceptible to human impact, and

- Continue to explore alternatives to bank protection. It appears that bank protection is deleterious to river resources. Therefore, alternatives that do not impact the natural equilibrium of the Sacramento River system should be seriously considered. We feel that the meander belt concept, or some variation thereof, holds the most promise for balancing agricultural interests with the need for maintaining unique and irreplaceable natural resources.

PART II: NATURAL SURROUNDINGS

HISTORY
GEOLOGY AND GEOMORPHOLOGY
HYDROLOGY

HISTORY

Although one would assume that there is a great deal of recorded history regarding the early days of California, in actuality there is very little. The native Indian population had not developed a writing system other than pictographs and those are rare. The largest find of pictographs was discovered in the mountains above the Feather river. These pictographs were carved onto the mirror smooth granite slopes at the head of Rock Creek (Dana, 1939). These pictographs relate the earliest recorded history of California. The Indians who made them had long since vanished before the first explorer made his way into the country, and unfortunately none of the more recent tribes had followed in the custom of their ancient ancestors.

The Native Californians lived well in a valley that was teeming with life. The populations that thrived in the Sacramento valley were isolated into small pockets of culture, and rarely traveled beyond the next village to trade items. One of the reasons for this localization, and indeed a probable cause was the amazing variety of different languages. There are more native languages credited to California than to any other equal area in the world: fifty Indian dialects were spoken in the Sacramento Valley. Many of these Indians spoke different dialects of the same tongue, or had loose alliances with other neighboring tribes and so took on the same name. Of these were the Maidus, Miwoks, Wintuns, Yokuts and the Costanoans (Dana, 1939).

The main preoccupation for most of these Native Californians, besides trading with other villages or contests of skill, was food. Throughout the Sacramento and San Joaquin valleys the climate was mild, and plant and animal life was abundant (Rawls, 1984). The Native Californians had a wide and varied diet quite different from that of the plains Indians. The Wintuns often had large hunting parties venturing out for elk or deer using javelins or bows and arrows. Those Wintuns living near Mt. Shasta built wooden scaffolds over the swift stream and speared the uprushing salmon or used dip nets for the smaller trout. Many tribes would use poison on river fish, making them float to the surface. Traps were also set to snare small animals such as rabbits. Rabbit skins and puma skins were often worn as clothing. Wintuns of the river even used duck decoys of bound rush stems with stuffed duck heads to lure wildfowl to their nets (Dana, 1939).

The Maidu also used the Sacramento River in their small boats netting lamprey eel and salmon. Their boats were made of plentiful materials in the area, tule reeds, log rafts, and flat square ended dugout canoes (Dana, 1939). Individuals who lived near the river had fish, elk and venison steaks nearly the year round as well as having grapes in the harvest season. Fresh water clams were also often on the menu as well as a variety of insects and grubs.

The Maidu, like many other tribes, practiced a simple form of slash and burn agriculture. They would start small quick burning brush fires in order to clear the land for planting. Occasionally tule would be burned to make navigation easier, and ambush harder (Dana, 1939). California receives an average yearly precipitation of about 23 inches; however, throughout the late spring, the entire summer, and early autumn there is very seldom any precipitation at all. As a result of this lack of rain during the growing season, and the fact that Californians never developed a system of irrigation, their harvests, if any, were very limited.

Some of the first Europeans to arrive in the territory of the Native Californians were those men who came in search of furs and gold, or priests who started a series of missions along the south coast. Many years passed while the missions developed and expanded. With time, the government began hearing tales of other white explorers entering into the valley. Previously the great mountains on the east side of the valley, the Cascade and the Sierra Nevada ranges, had slowed immigration.

Ensign Gabriel Morga led an expedition up through the Bay of San Francisco searching for the great flow of water which fed the bay. Luckily for history, he kept a diary of events of this momentous trip. In time he came to a deep, clear, strongly moving river, many hundreds of feet across, which in honor of his church's holiest sacrament, the eucharist, he named the Sacramento. On his trip he encountered an environment rich in wild game. Thousands of antelope, tule elk, and deer grazed the valley floor in drifting bands; grizzly bears hunted the thickets near the rivers; and the many small and larger watercourses were full of fish. Morga also encountered many different native cultures on his visit.

An early Russian visitor (looked upon as an intruder by the Spanish), Kirill Khlebnikov, also made note of the Indians eating habits near Fort Ross, "The oak produces acorns, which comprise the chief provision; in many places wild rye grows, the grain of which is gathered by the Indians. In the ground they find many hamsters, Siberian marmots, mice, frogs... geese, ducks, mountain sheep, goats and deer" (Rawls, 1984).

As Khlebnikov noted that the Indians ate food from the ground, another explorer, this time a European named Jedediah Smith, taking a land route and trapping furs as he went, noted that "Their principal diet during the fall season consists of roots and weeds... all of which they eat raw" (Rawls, 1984). It was from this "digging" habit that the derogatory term "'Digger Indian" began being applied to the Native Californian.

George Yount, a member of Smith's party, reported California to be the finest country in the world - "having a charming Italian climate and a soil remarkably productive...that the Sacramento and San Joaquin abounded with salmon and that beavers were abundant in all the creeks and rivers" (Rawls, 1984).

Other explorers were occasionally allowed to land and explore California while it was under Spanish rule for "scientific purposes" which were usually just expeditions that wrote reports to their homelands telling of the inept Spaniards and how they were unfit to utilize such a rich and bountiful land. Jean Francois Galup de La Perouse when he put down anchor in Monterey Bay in 1786 noted the abundant wildlife in his journal. He noted that the ships were surrounded by a herd of spouting whales and that the surface of the bay was covered with cavorting pelicans. He also made a list of animals as he journeyed into the valley area including seals, hares, rabbits, stags, bears, foxes, wolves, wildcats, partridges, woodpeckers, sparrows and titmice. La Perouse also noted that "There is not any country in the world, which more abounds in fish and game of every description." (Rawls, 1984).

Another early Frenchman visitor made note of the Indians eating habits and made a brief mention to the content of the soil in the process, "Tho' heaven has been so bountiful to the (California Indians), and tho' their soil spontaneously produces what does not grow elsewhere without a great deal of trouble and pains, yet they have no regard to the riches and abundance of their life, they are little solicitous about everything else" (Rawls, 1984).

In 1839 John Sutter, originally from Switzerland, landed a chartered boat and unloaded his supplies to start a new colony. The location of his landing spot is approximated to be about where 29th and B street cross in downtown Sacramento. He had the blessings of the Mexican government and would be granted Mexican citizenship if his colony continued more than one year (McGowan, 1983). There were eighteen men, two women, and one bulldog who started the colony of New Helvetia (New Switzerland). Heavy rains hampered life the first year, which turned his encampment into an island in the middle of an inland ocean but by 1840 Sutter was busy building his fort and received Mexican citizenship and a sizable land grant. In 1841 he was receiving visitors into his fort from different countries. By 1843 the fort was completed and served for many years as an outpost of civilization. After some disastrous financial and military adventures, Sutter's Fort and the nearby town of New Helvetia celebrated their first independence day under the United States flag on July 4, 1847. At this point John Sutter conducted a census report for the town. Including indians, blacks, and whites there were a total of 22,657. However whites (including Mexicans) were in the minority, accounting for only 289 people (McGowan, 1983).

Along with the early settlers came their impure seed crops that not only contained the plants that they intended to grow, but also the typical weeds of European descent, including wild oats, alfilaria, mustard and bur clover. This makes it very hard to go anywhere in California today and see vegetation as it was before the settlers arrived.

In May of 1948, the discovery of gold would lead the a dramatic population increase that would alter California forever. Shortly thereafter, the skeptical editor of a San Francisco newspaper, decided to come and look at the so called gold strike at Sutter's Mill. He thoughtfully included a description of the riverfront district of Sacramento. "...A forest of noble sycamores, dense and deep, guarding a mighty solitude like a vast army of giants in array, their bright green banners mirrored in the clear stream. Not a human habitation in sight save the Indian ferryman's hut, near J street, and an Indian sweathouse about a hundred yards above. Moored to the bank was an Indian canoe. A broad, well-beaten road led back from the river's bank, the only clearing visible in all this waste and solitary place."

Upon returning to San Francisco, he wrote that rumors of gold were groundless (McGowan, 1983). The gold rush was, according to some sources, started by Sam Brannan, a man who had set up a store with everything that gold seekers would need and who subsequently traveled to San Francisco and aroused some 800 inhabitants into a state of delirium. Easterners, however paid little attention to the gold finds until President Polk mentioned the gold rush in his annual message to Congress on December 5, 1848. The 49'ers, as they were to be called, started appearing in California soon after.

In the winter of 1849, a portion of New Helvetia was subdivided to make the new town of Sacramento. Sutter had been no fool when he placed his community of New Helvetia back from the river on high ground, but this new town went right to the banks of the river thus inviting danger, and at the same time encouraging trade and commerce. Transportation along the river became of supreme importance. Several steam powered ships, run by enterprising men, started to ferry people from San Francisco and Sacramento on a regular basis. This rapid influx of inhabitants as well as its newfound wealth were strong arguments for statehood. In 1850 the inhabitants heard the news that their land of California had indeed become a state of the union.

A series of disasters befell Sacramento during the 1850s starting with famine and plagues and ending with fires and floods. Each time the inhabitants cleaned up or rebuilt their city. In 1851 crude levees were built to protect the town from another flood as unusual rainfall in March had caused most of the snowpack to melt early. Surprisingly these crude reinforcements made of dirt and small rocks held, and the following year plans were set in motion to build permanent levees to protect the city. These plans were put on hold in 1852 when a fire, blown by a strong north wind, engulfed the business district (McGowan, 1983). Many of the new buildings were built from stone and brick, some materials were brought halfway around the world compliments of California's newfound wealth.

Soon after the beginning of the gold rush, inventive minds started making and selling devices to obtain gold in a variety of innovative ways. Most did not function as their inventors claimed. One of the most interesting, and unusual, of the inventions that did work was the mechanical 'gold boat'. It was developed to recover gold from the center of rivers where miners could not wade. The first few gold boats were failures, however in 1875 an Englishman in Australia perfected a bucket dredge that operated with buckets hooked in an endless chain. In 1877 the Risdon Iron Works in San Francisco built a similar craft which worked. Unfortunately the buckets would not dredge deep enough to collect any substantial amount of gold (Dana, 1939). In the early 1900s gold dredging came to the Oroville area, but it was an expensive proposition, with some of the gold dredgers having steel hulls costing over a half a million, and deposits being covered by an average of twenty feet of sediment thrown down the streams by the hydraulic miners.

Around 1873, the first commercial supplier of water started bailing water out of the river and into his cart. It was not long before suction pumps were used to lift the water out of the river. In 1854 the city completed a three-story water works building at the foot of I Street. The main part of the building was city hall. On the roof were two six-foot deep tanks which held 240,000 gallons of water, pumped up from the river and distributed to the city by gravity flow (McGowan, 1983). Water pollution started to be a problem within the growing city. One lake, Sutter's lake, also known as China Lake for it was near a densely populated Chinese area, became so clogged with oily debris that it actually caught fire and burned!

Gold miners soon noticed that gold seemed to be deposited over great length of the river in patchy areas. It was soon deduced that the gold found in present canyons came from the gravel deposits of ancient stream channels which had been destroyed, possibly by volcanic action, and which had been cross-cut by the newer system of streams to the extent that the remnants of the ancient gravel deposits occupied the ridges and hilltops between the present canyons (Jones, 1967). This soon led to a new mining technique.

The first hydraulic activities in 1852 were relatively small individual operations consisting of pointing streams of water on the ancient gravel deposits. Rubber or canvas hose with one inch nozzles dislodged the gravel and washed it through sluice boxes where gold was caught by riffles (Jones, 1967). However, within a year or two, operations had increased to the point of using nozzles up to nine inches in diameter spraying water up to five hundred feet and with a nozzle velocity of one hundred feet per second. Often blasting with as much as 20 tons of powder would precede the mining process.

The practice of hydraulic mining assumed tremendous proportions during the period 1852 to 1895 and was until about 1940 responsible for the largest unnatural increment of sediment load in the river channels (Jones, 1967). Hydraulic mining washed tons of sediment down tributaries each year making the water in the Sacramento dirty and unpleasant to drink. A shot glass of whiskey often resembled a glass of drinking water. Thus Sacramentans jokingly referred to their water as "Sacramento Straight" (McGowan, 1983).

As early as 1860, a bar formed in the Sacramento River across the mouth of the American River, and by 1866 the larger river steamers could no longer reach their landing point at Sacramento. By 1876, the channels of Bear and Yuba rivers had been completely filled and the adjacent agricultural lands were being so rapidly covered with sand and gravel that a suit was filed by agricultural interests against the mining companies. This case, although it dragged on for years, was the beginning of the end for hydraulic mining in California. Even though hydraulic mining was stopped, the great mass of debris still continued to flow, or rather slump, down the tributaries and rivers. Other miners had deposited the used soil on banks in piles which slowly eroded away, thus continuing the flow of sediment into the rivers long after hydraulic mining had stopped. This rising layer of sediment raised the beds of rivers significantly, causing widespread flooding. Although hydraulic mining left a legacy of scars across the face of the Sierra Nevadas, some good did come of it. Irrigation on a small scale became possible using the old hydraulic mining equipment and ditches.

Even more important to the northern valley than the discovery of gold at Sutter's Mill was the discovery of gold at Redding's Bar (near present-day Redding) on the Sacramento River (Grimes, 1983). Overland travel to the area was hampered by periodic flooding and muddy roads so river travel was the mode of choice. Water travel was dependent on the depth of the river and was only possible a few months out of the year.

As the gold rush drew miners to the north end of the valley, transportation became the key issue in a town's survival. The key to being successful was to become the head of navigation (Grimes, 1983). Many towns and villages grew up and vanished along the Sacramento, while others became permanent and are still thriving today. Red Bluff, for example, was a town dependent on the river for its survival. In 1853 a new line of shallow draft river boats were put into operation on a route that ran to Red Bluff. This increased trade to the north prompted many businesses to move their forwarding companies there.

Irrigation became important to Californians around 1910. At this point in history dry grain prices fell to all-time lows. Many of the larger farms subdivided their land and put it under irrigation. In 1916 an even more rapid increase in water use occurred with the rise of the rice industry, which was stimulated by the abnormal demands for food during the first World War (Jones, 1967).

The Native Californians of ancient times would hardly recognize the California of today. In fact when Anza, an early Spanish explorer, trekked up the great Sacramento River, Father Font, who was traveling with him on the expedition, wrote that, for the most part, the valley was a great lake studded with islands. This might seem like a very strange observation to anyone who had grown up living in the valley today and is used to a relatively tame river which rarely floods, but before the modern flood control and other water projects were constructed the valley would often remain flooded for several months out of the year. The flooded area, although irregular in pattern, varied in width from about two to thirty miles and extended from the mouth of the Sacramento River to the present site of Red Bluff, a distance of 150 miles, and comprised an area in excess of 1,000,000 acres.

As a result of the flooding, which went on for months at a time, great forests of tule reeds occurred along the sides of the river and the surrounding swampy areas. Surrounding the tule lands lay belts of higher and more fertile rim-lands near the stream channels. With the advent of agriculture these rim-lands were the first to come under cultivation and, being less often flooded and more accessible to water transportation, were the first to be settled (Jones, 1967).

The Sacramento River Flood Control Project was a project that improved upon existing levees, but in some cases created whole new sections of levee. The project was envisioned to make the inhabitants of several key cities safe from the seasonal flood waters. It was funded, at least at the onset, by local residents and later by the State government and the Federal Government, who passed the resolution starting the project in 1917.

By 1967, the Sacramento River Flood Control Project covered over 440 miles of river, canal, and stream channels; three major drainage pumping plants; 95 miles of bypasses comprising 100,000 acres; five low-water check dams; 50 miles of drainage canals and seepage ditches; and numerous appurtenant structures including minor weirs and control structures, bridges and gaging stations. At that date the project was 90 percent completed (Jones, 1967).

In the fall of 1945, Shasta Dam was first used to control flood waters that threatened the Sacramento valley below. The reservoir was constructed by the U. S. Bureau of Reclamation on the upper Sacramento River above Redding. Flood control releases through Shasta Dam during and immediately following floods are coordinated with downstream tributary inflows in such a manner that flow will not exceed 80,000 cubic feet per second at Redding, 100,000 cfs at Red Bluff or 130,000 cfs at Chico Landing, insofar as possible. Folsom Dam and Reservoir serves a similar purpose on the American River. It was completed in 1954 and first used for flood control in December of 1955.

GEOLOGY AND GEOMORPHOLOGY

The study area lies in one of the more interesting parts of the State, the Great Valley geomorphic province that occupies the State's central region. The southern end of this valley is called the San Joaquin, after the river that flows through it. Likewise the northern part of the valley is called the Sacramento valley. The Sacramento River headwaters in the vicinity of Mt. Shasta on the eastern slope of Mt. Eddy. From Mt. Shasta the river flows along the boundary of the Klamath Mountains and the Cascade Range, then down the Sacramento Valley and into San Francisco Bay. The valley is approximately 400 miles long and from 30 to 60 miles wide. The elevation varies from more than 10 feet below sea level in the Sacramento-San Joaquin Delta region to about 500 feet in the north. It is bordered on the east by the Sierra Nevada and Cascade Ranges, on the north by the Klamath Mountains and on the west by the California Coast Ranges (Figure 3).

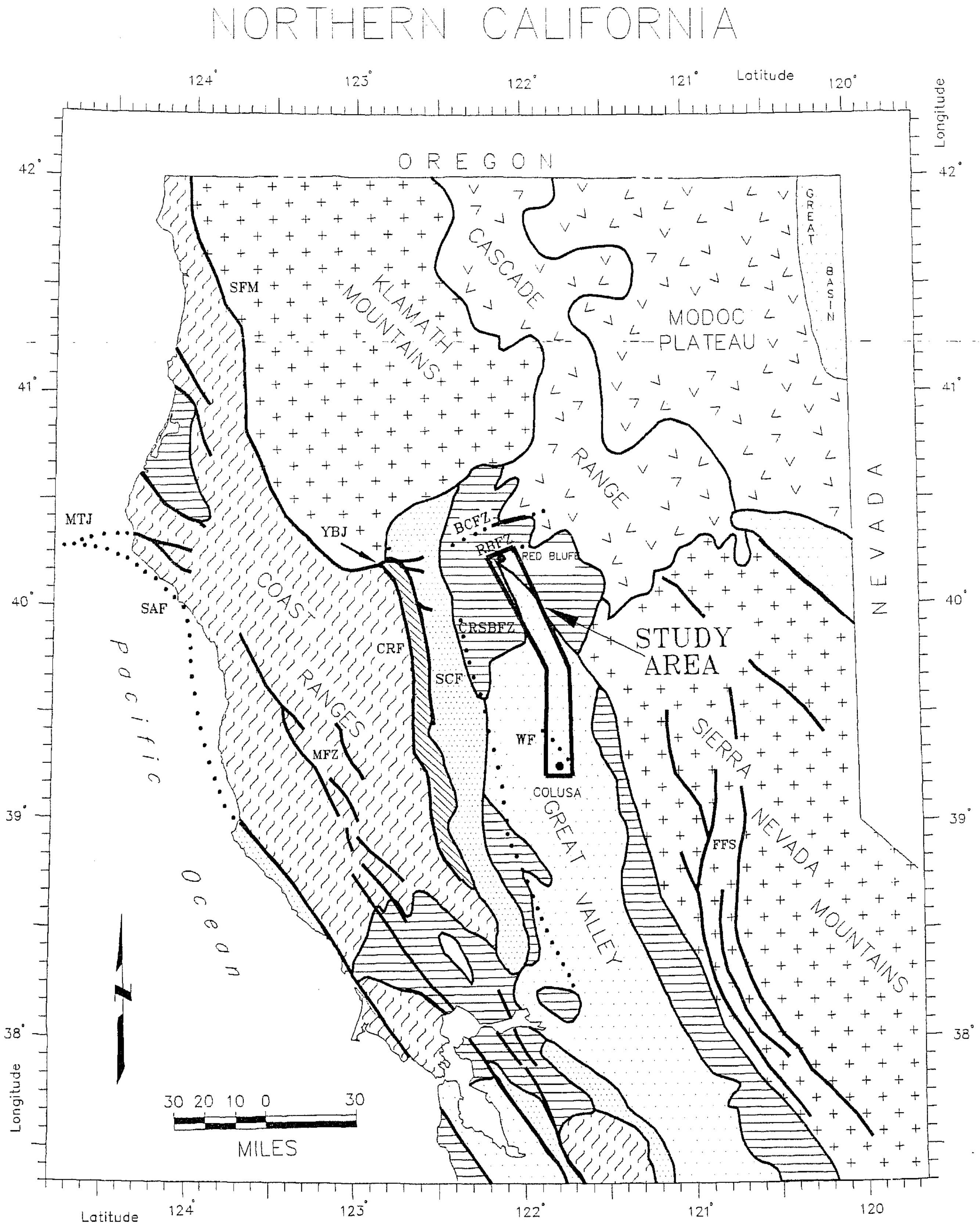
The Klamath Mountains province is the oldest province, ranging in age from early Paleozoic to Jurassic. The Klamath Mountains province covers an area about 70 miles wide, extending from north of the study area into Oregon. In general, the province consists of several well-defined mountain ranges, including the Trinity, Marble, Scott, and Salmon mountains. These mountains comprise a series of northwest-trending metamorphic terranes separated by major faults. Each terrane differs in age, stratigraphy, and tectonic deformation. Large bodies of intrusive rocks, such as the Shasta Bally batholith, occur throughout the province.

The Sierra Nevada is about 400 miles long, and terminates to the north near Mount Lassen. The rocks of the province are of diverse composition and age, but consist mostly of igneous and metamorphic units. Structurally and tectonically, the Sierra Nevada region is very complex. Some structural deformation dates back 300 million years or more, and is attributed to Paleozoic and Mesozoic subduction.

The Cascade Range is a 500-mile long sequence of volcanoes extending from Mount Lassen to Mount Garibaldi in British Columbia. Rocks of the California Cascade Range are predominately volcanic rocks of great variety and form. In northern California, Upper Cretaceous and Eocene sedimentary rocks are at the base of the sequence. These are overlapped by Upper Eocene volcanic rocks of the Western Cascade series and Quaternary-Tertiary pyroclastic rocks and flows. Near Mount Lassen, the Upper Pliocene Tuscan Formation rests directly on Cretaceous and Eocene sedimentary rocks.

Tectonically, the Cascade volcanoes are the product of the active subduction of the Gorda plate (California), and the Juan de Fuca or Cascadia plate (Oregon) beneath the North American plate. Since the deposition of the Nomlaki Tuff member of the Tehama Formation (3.4 million years ago), volcanic activity has occurred intermittently along the southern Cascade Range.

Figure 3



LEGEND

FAULTS

⁓	Geologic Contact
━┅	Fault, dotted where concealed
SAF	San Andreas Fault
CRF	Coast Range Fault
SFM	South Fork Mountain Fault
SCF	Stony Creek Fault
BCFZ	Battle Creek Fault Zone
MFZ	Maacama Fault Zone
FFS	Foothills Fault System
YBJ	Yolla Bolly Junction
MTJ	Mendocino Triple Junction
ECFS	Elder Creek Fault Zone
OFF	Oak Flat Fault
SSF	Sulphur Spring Fault
CFFZ	Cold Fork Fault Zone
RBFS	Red Bluff Fault Zone
CRSBFZ	Coast Range-Sierran Block Boundary Fault Zone
WF	Willows Fault

GEOLOGIC UNITS

☐	Quaternary Sedimentary Deposits
∠ V	Quaternary and Tertiary Volcanic Rocks of the Cascade Range and Modoc Plateau.
☰	Tertiary Sedimentary Deposits
░	Upper Jurassic/Cretaceous sedimentary rocks of the Great Valley
▨	Upper Jurassic/Cretaceous Sedimentary Rocks of the Coast Ranges
▧	Upper Jurassic to Cretaceous Mafic to Ultramafic rocks
⁙	Mesozoic - Paleozoic Metamorphic and Granitic Rocks of the Klamath and Sierra Nevada Mountains.

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

Sacramento River
Bank Erosion Investigation

Regional Geologic Map

The Coast Ranges province consists of a mixture of rock types and structures ranging in age from Jurassic to Tertiary. Together, the varied assemblage of graywacke, metagraywacke, shale, chert, limestone, mafic and ultramafic rocks make up the Franciscan complex. Pervasively deformed by folds and faults, the Franciscan complex is commonly characterized by zones of extensive shearing and the presence of ophiolite-serpentinite melanges.

The Great Valley province is a 400-mile-long by 30-to 60-mile-wide sedimentary basin. At the base of the Great Valley is a fragmental assemblage of ultramafic rocks called the Coast Range ophiolite, consisting of middle to late Jurassic oceanic crust and upper mantle. One of the more complete ophiolite sequences occurs west of Red Bluff along South Fork Elder Creek (Suchecki, 1984). North from Elder Creek, the Coast Range ophiolite narrows and then terminates. Above the ophiolite are late Jurassic to late Cretaceous marine sandstone, shale and conglomerate of the Elder Creek terrane and the Great Valley Sequence. These were deposited in the western continental forearc basin during the middle to late Mesozoic.

The Elder Creek terrane is comprised mostly of mudstone, with minor sandstone and conglomerate. The ophiolite is considered to be part of this terrane. The Great Valley Sequence unconformably overlies the Elder Creek terrane. The Sequence crops out in a wide belt along the valley's western foothills. The Sequence consists of interbedded middle to late Cretaceous sandstone, conglomerate and mudstone. The bedding dips east and strikes northwest, forming long linear ridges and valleys.

Geologic Units in the Study Reach

Younger deposits consist of sedimentary and volcanic deposits of Tertiary and Quaternary age, such as the Tehama Formation, the Nomlaki Tuff member and the Red Bluff Formation. Quaternary alluvium, basin, marsh and terrace deposits cap the sequence. The study reach is underlain by these younger units. The distribution of geologic units are shown on Plates 1, 2, and 3.

Tehama and Tuscan Formations

The Pliocene Tehama Formation underlies much of the valley and lower foothills region on the west side. The clast lithologies indicate that these Tertiary semiconsolidated fluvial deposits were derived from the Coast Ranges and Klamath Mountains to the west and northwest (Russell, 1931). The Tuscan Formation is similar in depositional mode and form but is derived from the volcanic Cascade Range on the east side.

It is exposed along near vertical Sacramento River banks in a number of places such as Red Bluff, Woodson Bridge and Hamilton City. The Tehama Formation is composed of fluvial sedimentary deposits of semi-consolidated pale-green, gray and tan sand, tuffaceous sand, silt, and clay. The Formation has scattered, discontinuous lenses of gravel. The Tehama grades finer away from the source areas. The Formation has a low regional dip towards the east and the

Sacramento River. The Nomlaki Tuff member is a Pliocene, white to light-gray dacite pumice tuff and lapilli tuff that occurs near the base of the Tehama Formation. The bedding probably conforms with the shallow eastward dip of the Tehama Formation. The member is a massive, non-layered volcanic ash that forms resistant vertical banks along tributary streams and gullies. Maximum thickness is approximately 30 feet.

In general, the Tehama Formation forms rounded hills with moderate relief and has a thin soil cover. Along tributary streams, exposures form 20-to 60-foot high vertical bluffs. Cut-banks with 1:1 and steeper slopes are normally stable.

Exposures of the Tertiary Tuscan Formation in the valley typically consist of volcanic-derived siltstone, sandstone and conglomerate. The Tuscan is exposed in the stream channels of eastside tributaries in areas too small to show on the geologic map. In other areas, it is typically overlain by more recent deposits.

Red Bluff Formation

The Pleistocene Red Bluff Formation is a coarse gravel deposit with a brick-red clayey matrix. This Formation originally formed on a regional, gently inclined erosional surface, or pediment, on the Tehama Formation. Erosional remnants of the Red Bluff crop out as far north as Lake Shasta, along the western base of the Coast Ranges, along ridges between watersheds and on both sides of the valley floor as far south as Princeton. The Red Bluff is fairly thin, ranging from 6 to 15 feet thick.

Terrace Deposits

The Sacramento River and major tributaries have developed a set of flanking terrace levels. These terraces stair-step in elevation away from the active channel, with the upper terraces the oldest. A typical terrace consists of several to 10 feet deep dark gray, fine sand and silt overlying four to six feet of poorly sorted cobbly gravel. The older terrace deposits are typically more elevated and have more developed soils.

Terrace deposits are typically complexely intertwined, and each terrace may have several minor deposits of different age and elevation associated with it. These are typically not differentiated. Seven to nine terrace levels have been identified along tributaries. Four of these have been given formational names and occur near the Sacramento River.

These four Pleistocene terraces are the Upper Riverbank, Lower Riverbank, Upper Modesto and Lower Modesto. These terraces have been correlated by their absolute age, soil stratigraphy, geomorphic expression to the Riverbank and Modesto Formations of the San Joaquin Valley (USGS, 1984).

Riverbank Formation. The Pleistocene Riverbank Formation has been divided into an upper and lower member. These are combined into one unit on the geologic map. The lower member is lithologically similar to the Red Bluff Formation and has nearly the same red color, and consists of gravel, sand, silt and clay. It occurs on the higher of two flat terraces that have been cut and filled into the surface of the Red Bluff or Tehama Formations.

The upper member is younger, and formed during a long period of stable climatic conditions. This member occurs as extensive flat stream terraces along the major creeks.
A typical outcrop consists of 8-10 feet of tan to light brown sandy silt underlain by 1-3 feet of gravel and a few rocks up to eight inches in diameter. Soils of the member display medial development with strong textures. The soil contains a B-horizon and local hardpan but profile development is not as great as on the lower member.

Modesto Formation. The Modesto Formation has also been divided into an upper and lower member that were combined on the geologic map. The lower member is the youngest terrace that has a pedogenic B-horizon. Terraces display fresh depositional morphology with few erosional features. The Upper Modesto does not have a soil horizon. This unit borders existing channels and is generally less than 10 feet thick. It is composed of gravel, sand, silt, and clay.

Paleochannel Deposits

Paleochannels were identified (Robertson, 1987) along the eastern margin of the Sacramento River from the latitude of Thomes Creek to near the town of Colusa. These braided paleochannels, with multiple branches and islands, are a striking departure from the meandering channel of today. The braided morphology of these channels suggest a higher bedload, a higher width to depth ratio, and higher discharges than the present Sacramento River. The age of these channels is believed to be between 150,000 and 450,000 years based on buried soils (Robertson, 1987). This is equivalent to the Riverbank Formation in age. In most areas the paleochannels have a thin cover of silt and clay mapped in various areas as lower Modesto or basin deposits (Helley and Harwood, 1985). The paleochannel deposits are mapped as older channel deposits on the geologic map.

The bedload was considerably coarser than that in the present Sacramento River and consisted mostly of volcanic rocks, suggesting a Cascade Range source area. The deposit may date back to a period of high volcanic activity near the Lassen area. These deposits are fairly well indurated and erosion resistant. The western edge of the paleochannel is the eastern edge of the historic meander belt.

Alluvial Fan Deposits

Alluvial fans occur near the edge of the valley on some of the tributaries. Most notable are the Antelope, Mill, Deer, Big Chico and Stony Creek fans. Most of these fans have several or more abandoned channels visible on aerial photographs and topographic maps. Fan deposits on the east side tend to be well indurated, with cobbles and boulders in a matrix of gravel, sand, silt and clay. A considerable amount of volcanic ash is evident in the matrix.

Westside fans tend to be gravelly. The Stony Creek fan is the largest and has numerous abandoned channels, some of which flowed south into the Colusa Basin.

Historic Meander Belt

This belt is older than the 100-year meander belt and is delineated using aerial photographs. Oxbow lakes, meander scrolls, sloughs and curved lines of riparian vegetation are indicators of old river channels. Agriculture, particularly through land leveling and riparian vegetation removal has erased much of the evidence. Delineation of this belt is also dependent on the time necessary for river processes to remove evidence naturally.

Two features are differentiated. These are oxbow lakes and meander point bar scrolls. Oxbow lakes are remnant river channels separated from the active channel by meander avulsion. Point bar scrolls are distinctive curvilinear depositional features left by the river as it meanders across the flood plain. The more distinct scrolls are shown as dashed lines on the geologic map.

The historic meander belt includes an unspecified amount of time, probably in the range of 100-to-1000 years.

100-Year Meander Belt

This belt is smaller than the historic meander belt. The belt is delineated using old survey maps, topographic maps and photographs showing actual river channels at specified times. This belt was mapped by DWR (1984) and shown on the *"Middle Sacramento River Spawning Gravel Study: River Atlas."* It was updated using 1991 aerial photographs and plotted at a scale of 1 inch equals 4,000 feet.

Undifferentiated Stream Alluvium

This unit is deposited by the river but does not show the distinctive fluvial geomorphic features of the 100-year or historic meander belts, either because of changes with time or extensive agricultural development.

Basin Deposits

Basin deposits are fine-grained silt and clay derived from the Sacramento River and tributaries that deposited in local basins, the Butte Basin on the east or the Colusa Basin on the west. The clay-rich deposits are especially suitable for rice production. Thickness varies from several to almost 200 feet.

Marsh Deposits

Marsh deposits are fine-grained, very organic rich sand, silt and clay associated with the basin deposits. They are differentiated from the basin deposits by generally being under water.

Stream Channel Deposits

Tributary stream channel deposits occurs as loose, unconsolidated sand and gravel in the active stream channel. Sacramento River stream channel deposits occur within the 100-year Meander Belt and are not differentiated.

Floodplain Deposits

These deposits occur as sand, silt and clay with minor lenses of gravel on the flood plain adjacent to the active channel. The floodplain deposits form an approximately flat terrain broken by oxbow lakes and meander scrolls. The floodplain receives a thin cover of sand and silt during floods, thereby replendishing that lost through bank erosion. These deposits are not differentiated on the geologic map because they are contiguous with the historic and 100-year meander belts.

Geologic Structure

The main geologic structures in the study area include faults, folds, and bedding. The southeast to northwest trending isoclinal folding of the Great Valley Sequence is the most prevalent structural feature on the valley's west side. It strongly influences the regional topography, which consists of a series of northwest trending ridges and valleys. The Chico Monocline is the most significant structure on the east side. A number of fold axes and buried faults cross the Sacramento River.

Folds

The Sacramento Valley is a northwest-trending, asymmetric synclinal trough filled with a thick accumulation of sediments in excess of 60,000 feet thick. Upper Jurassic to Cretaceous east-dipping sediments of the Great Valley Sequence are isoclinally folded along the west side of the valley.

The Chico monocline is the most distinctive feature on the east side. A series of parallel folds and associated tension faults trend north-norwest through the west-dipping monoclinally folded beds of the Tuscan Formation. The age is believed to be between 2.4 and 1.1 million years (Harwood and Helley, 1982).

The Inks Creek fold system crosses the Sacramento River a few miles north of the study reach. Here the Sacramento River is obviously structurally controlled. It flows southwest around the nose of a plunging anticline near Jellys Ferry, northwest around a syncline at Table Mountain and around another fold at Bend, before entering the Sacramento Valley proper at Red Bluff.

The Tehama Formation unconformably overlies the Great Valley Sequence. The Tehama dips slightly eastward. The surface of the Red Bluff Formation also appears to have been somewhat folded, particularly toward the center of the valley. This is shown on a structural contour map by Harwood and Helley (1982) and indicates that Quaternary to Recent structural deformation is ongoing in the Sacramento Valley.

Near Corning the Red Bluff Formation is folded to form the Corning domes. The age of this period of deformation is estimated to be between 1.1 and 0.45 million years (Harwood and Helley, 1982).

Harwood and Helley (1987) identified two minor folds that parallels the course of the Sacramento River. These are the Los Molinos syncline, located between Red Bluff and Los Molinos, and the Glenn syncline, located between Woodson Bridge and Glenn. These narrow synclines coupled with the Corning domes to the west and the Chico monocline to the east have tightly controlled the course of the Sacramento River and influenced alluvial deposition during the late Quaternary. South of this area, late Quaternary alluvial deposits spread laterally across much of the valley and over the Glenn syncline, the actual trace of which controls the present course of the river as far south as the town of Glenn.

Faults

The Stony Creek and Coast Range faults extend southward through the Red Bank, Elder and Thomes creek watersheds on the Sacramento Valley westside. The Elder Creek fault, believed to be late Cretaceous (ESA, 1980), is found in the upper reaches of Elder Creek. The Coast Ranges-Sierran Block Boundary has also been postulated to be an active tectonic zone that lies hidden beneath the entire length of the western Sacramento Valley (Wong, et al. 1988).

The Battle Creek fault system includes a series of northeast trending faults and the associated Inks Creek fold belt that crosses the valley north of Red Bluff. Tuscan and Tehama Formation beds have been uplifted from 150 feet on the west to 1,450 feet on the east. The age is estimated at about 0.45 milllion years.

The Red Bluff fault is a subsurface feature that extends northeast and southwest from Red Bluff. The location is shown on a map from Harwood and Helley (1987) and is based upon proprietary subsurface data. They report that there are no surface features that can be associated unequivocally with the fault even though there may be as much as 450 feet of subsurface vertical offset, south side down.

The Willows fault is a major northwest-trending subsurface fault that crosses the Sacramento River north of Colusa, follows the river for 15 miles, diverges from the river below Princeton and leaves the river corridor near Butte City. Uplift is on the east side of this fault. It intersects the Corning Fault, which trends northward to Red Bluff. Field investigations and sub surface data indicates that the youngest deposits deformed by the Corning fault are gravels of the Red Bluff Formation, dated at between 0.45 and 1.1 million years old.

Tectonic setting

Plate tectonics have played a major role in the tectonic development of California. From late Jurassic to mid-Tertiary, the eastern Pacific oceanic lithosphere (Farallon plate) was subducted beneath the western margin of the North American continental plate. This subduction resulted in the formation of an arc-trench system that included an accretionary prism, a forearc basin, and a magmatic arc. Today these terranes are represented by the Franciscan complex, the Great Valley Sequence, and the Klamath and Sierran plutonic/metamorphic belt, respectively. Figure 4 is a pictorial cross-section from west to east across Northern California showing these features.

Throughout Cretaceous time, rocks eroding from the surrounding plutonic and metamorphic belts were deposited by submarine turbidity currents into the deep forearc basin. These sediments, the Great Valley Sequence, continued to accumulate, filling the forearc basin to near sea level by Paleogene time. During this same period, ocean floor and trench deposits of the Franciscan complex were being dragged down by the Pacific plate, and underthrust in a wedge against the continental margin and beneath the Great Valley sediments (Ingersoll, 1983). Subsequent underthrusting resulted in the sediments of the forearc basin to be uplifted and tilted to the south and east (Harwood and Helley, 1987).

Marine deposition and subduction continued through Oligocene time. As subduction ceased during mid-Tertiary, uplift became more rapid and the transition to a strike-slip regime began offshore in southern California. This transition led to the formation of the San Andreas fault.

As the San Andreas fault evolved, a triple junction between the Pacific-Farallon, North American, and Gorda lithospheric plates began to develop and migrate slowly northward. During this period, the Great Valley experienced several episodes of uplift and subsidence. By early Miocene, most of the northern valley had emerged from the inland seas and was subjected to fluvial erosion and deposition (Harwood and Helley, 1987). Concurrently, volcanic eruptions were occurring along the northern Sierra Nevada, damming streams and filling narrow valleys. At about the same time, extensional forces from behind-the-arc spreading east of the Sierra Nevada reached their peak. These forces are responsible for the rapid uplift of the Sierra Nevada.

By early Pliocene, the Mendocino Triple junction had migrated north to the same latitude as the study area. Evidence suggests that as the triple junction continued to move northward offshore, structures in the valley began to simultaneously exhibit compressive deformation along a similar northward-progressive pattern (Harwood and Helley, 1987).

By the Pliocene, the Great Valley Sequence had been regionally tilted and had gone through several cycles of uplift and erosion. During the Pliocene, continental sediments of the Tehama and Tuscan Formations were deposited as large coalescing alluvial fans over the sedimentary rocks at the foot of the emerging Coast Ranges and Cascade Range. The Nomlaki Tuff Member, which occurs locally at or near the base of both formations, is an ash fall from volcanic eruptions that blanketed much of the northern valley about 3.4 m.y. ago.

Eventually, the Tehama and Tuscan Formations covered the Great Valley Sequence with sediments to a depth of 0-2,500 feet on the eroded surface of the tilted sequence (Earth Sciences Associates, 1980). Subsequent erosion and redeposition have formed the present outcrop patterns of geologic units. Fluvial processes have formed the terrace and alluvial deposits as they appear today.

Presently, the Gorda plate is subducting beneath the North American plate. Activity associated with this movement includes the surface folding, faulting and uplift of the northern Coast Ranges, and in a 152-mile long zone of eastward dipping intermediate-focus earthquakes. Beneath the basin, several intermediate and deep-focus Magnitude 4 earthquakes correlate with the Gorda plate subduction (Cockerham, 1984; Walter, 1986).

Presently, the northern Sacramento Valley lies between the large-scale right-lateral transform tectonism of the San Andreas fault to the west, and the major east-west crustal extension of

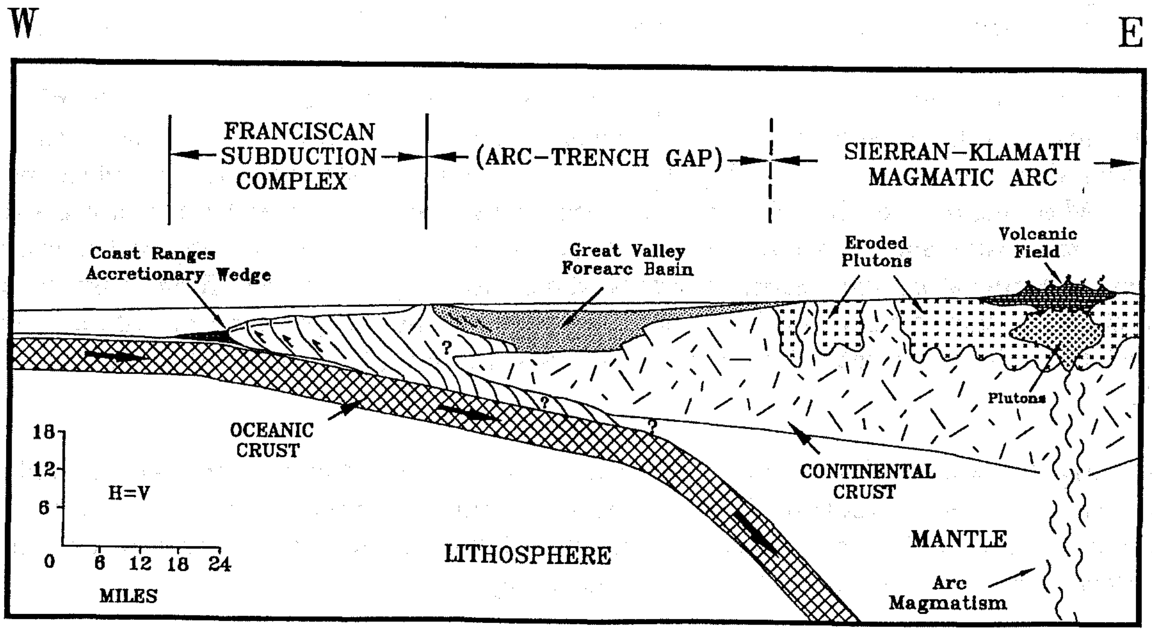


Figure 4 Schematic Profile of Subduction System Across Northern California During the Late Mesozoic.

the northern Basin and Range province to the east. The direction of stress may vary locally, but in general, the direction of maximum compressive stress is approximately northeast-southwest.

Evidence of this stress regime manifest itself as a series of northwest trending folds and faults along the western Sacramento Valley. The faults dip steeply east, with reverse and minor left-lateral movement. In the northern valley to the north of Red Bluff, the structural trend shifts and folds and faults become oriented in a more east-to-northeasterly direction. These faults typically dip steeply to the south, with normal offset and minor right-lateral movement.

Recent studies suggest that uplift along folds paralleling the western valley is active, and may represent the shallow expression of deeper thrusting. Interpretation of seismic reflection data (Unruh, 1991) indicates that these folds are caused by active thrusting along a very large triangular wedge of rocks. This imbricate zone of detachment faults may represent the boundary between the rocks of the Coast Ranges, Great Valley, and Sierra Nevada. Additional evidence presented by Wong (1988), Stein (1989), and Wentworth and Zoback (1990), suggests that this zone of faulting (commonly referred to as the Coast Ranges-Sierran Block boundary zone) extends the full length of the western valley and is most likely responsible for the two 1892 Winters/Vacaville earthquakes (Magnitude 6-7) and the 1983 Coalinga earthquake (Magnitude 6.7).

Geomorphology of the Study Reach

Below Red Bluff, bank erosion and lateral migration across the floodplain were natural processes. Large floods would uproot streamside vegetation, causing banks to recede and the river to meander. Sediment derived from tributaries and from bank erosion deposited in overbank areas where vegetation reduced water velocities.
Over a period of years, erosion and deposition were roughly in balance, so that the valley floor neither aggraded nor degraded. The riparian forests played two important roles by reducing bank erosion and by inducing deposition on the floodplain.

The geomorphic characteristics of the study reach are an intrinsic function not only of the geology underlying and surrounding the river, but also of the regional climate and river hydrology. Human induced changes, such as dams, levees and diversions have also had a profound effect.

Above the study reach, the upper Sacramento River between Red Bluff and Redding is bounded and underlain by the Tertiary-Quaternary Tehama Formation, consisting of semi-consolidated fluvial deposits, and the Tertiary Tuscan Formation, consisting of interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone and pumiceous tuff. These resistant deposits confine the river, resulting in a relatively stable river course.

Below the study reach, the river is relatively stable, with a decrease in stream gradient, bypass overflow, increased clay in the banks, and confinement of the river by man-made levees.

DWR (1984) divided the study reach into two geomorphic reaches, each divided into distinct sub-reaches. For this investigation, we divided the study reach into three distinct reaches based on channel characteristics, meander pattern, and bank erosion rates. These are called Reaches 6, 7 and 8. Reach 6 extends from Red Bluff Diversion Dam (River Mile 243) to Chico Landing (RM 193) and has 8 sub-reaches. Reach 7 extends from Chico Landing to Princeton (RM 165) and has 3 sub-reaches. Reach 8 is from Princeton to Colusa (RM 143.5) and has 3 sub-reaches.

Some characteristics, such as the downstream lowering of the river gradient and development of natural levees, are predictable. Other characteristics are unique and the result of many variables. Table 1 shows the three reaches and describes the geomorphic characteristics.

These divisions are based on channel characteristics such as gradient, geometry, underlying rock types, degree of bank erosion, sinuosity, meader belt width, and natural levee development. Typically, short, narrow, straight sub-reaches with low sinuosity, gradient, and minor bank erosion alternate with longer, sinuous, unstable reaches. This is caused by structural control as described in a previous section, and geologic control by the erosion resistant paleochannel deposits, Modesto, Riverbank and Tehama Formations. The Tehama outcrops in a number of places along the Sacramento River, such as Red Bluff, Tehama, Woodson Bridge, near Snaden Island, Hamilton City and Ord Ferry. In most places, the Tehama is overlain by terrace deposits at these sites. These areas are probably areas where differential uplift, followed by incision, have occurred.

Using such channel characteristics as gradient, geometry, underlying rock types, and gravel distribution, it is possible to divide the Sacramento River between Redding and Colusa into seven distinct reaches. These reaches were described in detail by the Department of Water Resources (1980; 1984) and are only briefly described here.

Typically, the river between Redding and Red Bluff (reaches 1 to 5 in DWR, 1980) is underlain by bedrock. The river is entrenched in many places, with some vertical banks more than 100 feet high.

Below Red Bluff, the Sacramento River is mostly an alluvial stream. Alluvial streams flow across their own alluvial deposits. Reach 6 (DWR, 1984) is between Red Bluff and Chico Landing. It is sinuous and anabranching. Reach 6 has been divided into eight subreaches (6A to 6H) based on bank erosion, sinuosity, and meander belt width. Reaches 6A, 6C, 6E, and 6G are short, narrow, straight reaches with low sinuosity, low gradient, and only minor bank erosion. Between the short, stable reaches are the longer, more sinuous, unstable reaches 6B, 6D, 6F, and 6H.

TABLE 1 GEOMORPHIC CHARACTERISTICS OF THE SACRAMENTO RIVER

River Reach	River Miles	Length (Mi)	Slope	Bank Erosion	Meander Width (feet)	Sinuosity	Channel Shape
6	243-193	48.1	.00054			1.33	
6A	243-238.5	4.5	.00050	Low	1200	1.0	Straight with gravel bars
6B	238.5-231	7.4	.00076	High	1400-5400	1.4	Sinuous, anabranching
6C	231-228.5	2.5	.00056	Low	700	1.05	Straight
6D	228.5-218.5	9.8	.00054	High	700-5000	1.3	Sinuous with gravel bars
6E	218.5-216	2.5	.00030	Low	900	1.05	Straight
6F	216-201	13.4	.00054	High	900-5100	1.5	Meandering, anabranching
6G	201-198.5	2.5	.00033	Low	800	1.05	Straight
6H	198.5-193	5.5	.00052	High	1300-6600	1.5	Meandering
7	193-165	30.2	.00033			1.37	Development of natural levees
7A	193-178	17.2	.00037	High	1200-4600	1.5	Meandering, numerous oxbows
7B	178-176	2	.00025	Low	600	1.0	Straight, channelized
7C	176-165	11	.00027	High	400-6800	1.23	Sinuous
8	165-143.5	20.3	.00022			1.34	
8A	165-155	10	.00029	Moderate	500-2500	1.15	Sinuous, oxbows in the floodplain
8B	155-151.5	3.5	.00019	Low	600	1.2	Oxbows in floodplain
8C	151.5-143.5	6.8	.00021	Moderate	400-2200	1.7	Meandering

Reach 6 exhibits a marked tendency for anabranching, channel meandering, and bank erosion. This meandering is constrained to a relatively narrow belt by tectonic deformation and older terrace deposits from the west and fanglomerates from the east. These geologically older alluvial deposits are elevated above the present river channel and act as geologic control in such places as Tehama and Woodson Bridge. The floodplain has an average width of about 2-1/2 miles.

Reach 7 is between Chico Landing and Butte City. Here the gradient is less; the river tends to be more sinuous with fewer islands. The most distinctive feature of this reach is the gradual downstream development of natural levees. This reach has been divided into three subreaches (7A to 7C), based on the criteria used for Reach 6.

Reach 7 is similar to Reach 6 in that it has an alluvial channel and is meandering. However, it is distinguished by a lesser gradient, a decrease in variability of the river width, fewer islands, more pronounced sinuosity, and the gradual downstream development of natural levees (USGS, 1977).

Reach 8 is between Butte City and Colusa. This reach is also divided into three subreaches (8A to 8C). It differs from Reach 7 by its distinctive meander wavelength.

In Reach 8, the width and width variability of the river decreases further as the natural levees increase in height and width, and the river gradually loses any tendency toward anabranching or braiding. Abandoned cutoff loops on the floodplain are infrequent and tend to be narrow and elongated, a characteristic of a naturally leveed stream. Reach 8 is constrained on the east by the paleochannel deposits and on the west by fan deposits, terrace deposits, and in places, the Tehama Formation.

Meandering

Meandering is defined as a characteristic habit of a mature river where it winds freely on a broad flood plain. The curves are formed by the bank erosion-point bar deposition process. Erosion is greatest across the channel from the point bar. As the point bars build out from the downstream sides of the bar, the bend gradually migrates down the valley. As the meander moves laterally and longitudinally, the loops move at unequal rates, resulting in meander cutoffs, oxbow lakes, and irregularities in the channel. On the Sacramento, however, most loops are bypassed by chute cutoffs.

Meandering rates are highly variable. A river may change little in many years, yet experience rapid movement in one flood season. Different stream reaches have widely varying meander rates depending on such factors as bed and bank composition, sediment transport, flow, bank protection, and riparian vegetation.

One of the earliest surveys was made by the U.S. Army Corps of Engineers in 1896, when detailed studies were conducted on the Feather and Sacramento Rivers. Additional Corps surveys were made in 1908, 1923, and 1935.

From the middle and late 1930s to 1991, the channel location was determined using U.S. Soil Conservation Service aerial photographs, U.S. Geological Survey topographic maps and Corps and DWR river atlases.

Meander lines between Colusa and Keswick Dam have been published in the *Middle Sacramento River Spawning Gravel Study Atlas* (DWR, 1984) and the *Upper Sacramento River Spawning Gravel Study Atlas* (DWR, 1980). These reports show meander lines up to 1981 and 1976 respectively.

Plates 4, 5, and 6 show the meander belt at a scale of 1 inch equal to 4000 feet. The meander lines represent the location of the river at various times, as delineated on aerial photographs, surveys and topographic maps. The meander lines were plotted in Autocad and have been added to the DWR Northern District's Geographic Information System.

Figure 5 shows the variation in meander belt width from Red Bluff to Colusa. The width is determined from the greatest extent of all the meander lines from 1896 to 1991, as measured perpendicular to the general trend of the meander belt. The width, and hence bank erosion, is highly variable, ranging from less than 500 feet to 7000 feet. Certain short reaches of river appear to be stable.

The Figure shows three distinct patterns. The first extends between River Mile 243 (Red Bluff Diversion Dam) and River Mile 198 (a few miles above Chico Landing). The second extends between River Miles 198 and 165 (Princeton) and the third between River Miles 165 and 143 (Colusa). There appears to be a certain periodicity in the spacing of the unstable areas. Between Red Bluff and Chico Landing, the spacing is about eight miles. Between Chico Landing and Princeton, it is about 4 miles. Between Princeton and Colusa, the spacing is about 10 miles.

Sinuosity

Analyses of channel length and sinuosity were done on eleven sets of maps and photographs dated between 1896 and 1987. No trends were apparent, except that some reaches are increasing in length and sinuosity and others are decreasing.

The 14 geomorphic reaches in the study area from Red Bluff to Colusa were evaluated for centerline distances and sinusoidal ratios, then compared with similar historical values (see Table 2). Centerline lengths were measured from the June 1987 aerial photos. Sinuosity ratios were calculated using the ratio:

$$\text{Sinuosity Ratio} = \frac{\text{measured centerline length of reach}}{\text{down valley length of reach}}$$

River meanders were delineated by tracing the maximum left and right bank extent of the current river channel.

Centerline Length

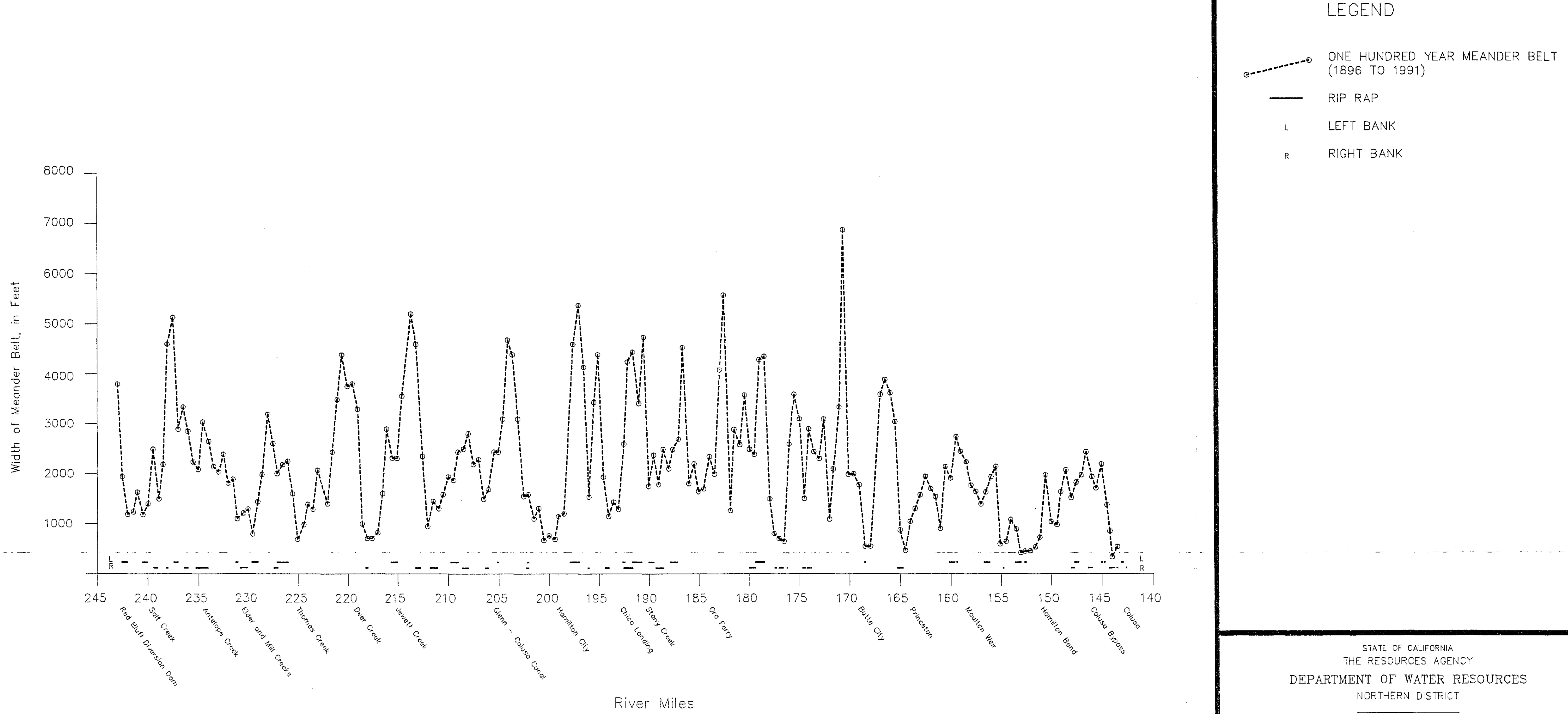
Centerline lengths of the Sacramento River were measured on maps and aerial photos ranging from 1896 to 1987. Table 3 shows the centerline lengths by reaches.

Bank Protection

In Reach 6, approximately between Red Bluff and Chico Landing, 103,500 feet of riverbank have been riprapped and an additional 81,000 feet of riprap have been proposed. If this is developed, the total riprap in this reach would comprise 35 percent of the riverbank. In Reach 7, River Mile 193 to 165, 48,000 feet or 16 percent of the banks are protected and an additional 10 percent are planned (USCE, 1988). Reach 8 has 26,400 feet of bank protection, or about 12 percent of the banks. Table 4 shows Federal and private bank protection projects between Colusa and Red Bluff.

Bank protection, when effective, stops bank erosion and lateral migration. It prevents loss of valuable agricultural lands, transportation facilities, and structures.

Bank protection, particularly if it is along all the eroding banks of the river, will cause some long-range geomorphic changes. First, it will have a stabilizing effect on length and sinuosity. Second, it will prevent the re-entrainment through bank erosion of gravel deposited on point bars. This will have some long-range effects on the amount of available spawning gravel. Third, over a period of time, it will tend to narrow the channel, increase the depth of flow, and reduce the hydrologic diversity. Sloughs, tributary channels, and oxbow lakes will fill with sediment over time and no new ones will be created. This will result in loss of valuable wetland habitat along the river corridor.



STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

Sacramento River
Bank Erosion Investigation

Variation in Meander Belt Width
Red Bluff to Colusa

TABLE 2 CENTERLINE SINUOSITY
SACRAMENTO RIVER FROM RED BLUFF TO COLUSA

	Date of Survey									
Reach	1896	1908	1923	1937	1946	1956	1960	1964	1969	1981	1991
6A	1.15	1.15	1.15	1.15	1.50	1.50	1.50	1.50	1.28	1.28	1.10
6B	1.20	1.20	1.33	1.33	1.18	1.15	1.15	1.15	1.40	1.40	1.20
6C	1.16	1.16	1.16	1.16	1.15	1.10	1.10	1.10	1.17	1.17	1.04
6D	1.28	1.27	1.32	1.32	1.25	1.24	1.24	1.24	1.35	1.37	1.42
6E	1.24	1.24	1.26	1.26	1.28	1.32	1.32	1.32	1.32	1.33	1.08
6F	1.41	1.41	1.35	1.35	1.41	1.36	1.36	1.36	1.57	1.26	1.28
6G	1.27	1.27	1.27	1.27	1.30	1.44	1.44	1.44	1.34	1.37	1.00
6H	1.71	1.71	1.90	1.90	1.22	1.27	1.21	1.21	1.31	1.10	1.30
7A	1.61	1.48	1.48	1.51	1.49	1.37	1.37	1.50	1.57	1.73	1.73
7B	1.14	1.14	1.14	1.18	1.11	1.11	1.11	1.07	1.08	1.08	1.00
7C	1.43	1.15	1.15	1.40	1.05	1.05	1.05	1.13		1.28	1.34
8A	1.33	1.41	1.41	1.27	1.13	1.13	1.16	1.16	1.16	1.21	1.30
8B	1.17	1.17	1.17	1.20	1.20	1.20	1.20	1.21	1.21	1.21	1.27
8C	1.86	1.71	1.71	1.52	1.76	1.76	1.76	1.69	1.69	1.64	1.85

TABLE 3 CENTERLINE LENGTH OF THE SACRAMENTO RIVER RED BLUFF TO COLUSA (1896-1991) IN FEET

Reach	1896	1908	1923	1935	1937	1946	1955	1960	1964	1969	1981	1991
6A	17,500	17,500	17,600	17,600	17,600	22,400	22,900	22,900	22,900	19,500	19,500	22,700
6B	33,500	33,500	37,300	37,300	37,300	33,000	32,100	32,100	32,100	39,000	39,000	35,600
6C	13,300	13,300	13,300	13,300	13,300	13,200	12,600	12,600	12,600	13,400	13,500	12,500
6D	48,800	48,300	50,300	50,300	50,300	47,500	47,100	47,100	47,100	57,400	52,100	51,400
6E	11,800	11,800	12,000	12,000	12,000	12,000	12,500	12,500	12,500	12,500	12,600	13,600
6F	68,400	68,400	65,400	65,400	65,400	68,400	66,000	66,000	66,000	76,000	61,000	61,900
6G	17,200	17,200	17,200	17,200	17,200	17,600	19,500	19,500	19,500	18,100	18,500	13,000
6H	30,000	30,000	33,000	33,000	33,000	21,400	21,200	21,200	21,200	22,900	19,300	24,900
7A	86,800	79,400	79,400	74,200	81,200	79,900	73,700	73,700	80,400	84,600	83,200	90,600
7B	10,500	10,600	10,600	10,500	10,900	10,300	10,300	10,300	9,000	10,000	10,000	8,600
7C	57,200	48,000	46,000	49,000	56,500	48,200	47,000	47,000	51,500	51,500	51,800	57,000
8A	60,500	58,400	58,400	53,200	55,000	49,000	52,000	52,000	50,500	50,500	52,200	51,200
8B	20,500	21,500	21,500	22,100	22,800	21,900	21,800	21,800	22,400	22,400	22,500	18,200
8C	31,600	32,900	32,900	33,400	33,000	32,400	33,000	33,000	28,200	28,200	29,200	35,400

TABLE 4 BANK PROTECTION PROJECTS
COLUSA TO RED BLUFF

River Mile	Bank	Length (feet)	Year Constructed
143.5	right	450	*
143.8	right	2900	*
144.7	left	1930	*
145.0	left	730	*
146.0	right	2150	*
147.3	left	830	*
147.6	left	1100	*
147.7	right	1930	*
148.0	right	450	*
152.5	left	710	*
152.6	left	300	*
153.0	left	3300	*
154.7	right	600	*
156.1	left	3170	*
159.3	left	900	*
159.6	left	1200	*
159.8	left	2000	*
164.7	right	1700	*
165.1	right	1050	*
168.4	left	750	*
173.8	right	450	*
174.0	right	1360	*
174.4	right	1565	*
176.2	right	440	*
176.6	right	2500	*

TABLE 4 BANK PROTECTION PROJECTS COLUSA TO RED BLUFF (Continued)

River Mile	Bank	Length (feet)	Year Constructed
176.8	right	475	*
177.3	right	650	*
177.4	right	470	*
178.5	left	4900	*
179.4	right	2460	*
179.5	right	2972	*
187.1	left	645	*
187.1	left	2805	*
187.2	left	670	*
187.4	left	2600	*
188.5	right	4600	*
188.8	right	1800	*
189.5	left	3000	*
190.7	left	5537	*
191.6	right	5100	*
192.4	left	1200	*
194.0	left	2800	1973
196.3	left	2100	1973
197.0	right	6400	1975
199.5	left	4000	(private)
202.0	right	600	1975
204.4	left	1300	1976
204.9	right	1240	1978
206.5	right	700	(private)
207.0	right	1900	1976
208.4	left	4470	1974

TABLE 4 BANK PROTECTION PROJECTS COLUSA TO RED BLUFF (Continued)

River Mile	Bank	Length (feet)	Year Constructed
209.0	right	4000	1983
211.1	left	4000	1976
213.1	left	2080	1974
215.0	right	2300	1982
216.5	left	11000	(private)
218.3	left	587	1970
219.4	left	2580	1963
220.3	right	4800	1963
226.3	right	7300	1978
227.0	right	6500	1983
227	left	1300	(private)
229.0	right	3200	1975
229.2	right	500	1968
230.5	left	3500	1975
231.2	right	1000	1978
233.9	left	1400	1978
234.2	left	2040	1963
234.7	left	2140	1963
235.8	left	2600	1971
237.2	right	3700	1963
239.1	left	2650	1963
240.0	left	2700	1963
241	right	3500	1983
242.6	left	2600	1978

* Date not available

HYDROLOGY

The study reach lies in the Sacramento Valley between the Red Bluff Diversion Dam and Colusa, a river distance of about 96 miles. The contributing drainage area between the Sacramento River above Bend Bridge gaging station and the Sacramento River at Colusa gaging station comprises 3,190 square miles.

Within the study area are a number of tributary streams, some of which are gaged. Gaged tributaries entering from the west side include Red Bank, Elder, and Thomes Creeks. Entering from the east side are Antelope, Mill, and Deer Creeks.

Precipitation in the study area is seasonal, with more than 80 percent in December, January, and February. Precipitation varies with elevation and from west to east because of the rain shadow effect on the east slope of the coast range. The average annual rainfall is 22 inches in the valley and flanking hills, increasing to 70 inches in the headwaters of Thomes Creek, and to 90 inches in the upper Mill Creek drainage.

The drainage above Red Bluff, including the Pit and McCloud Rivers and headwaters of the Sacramento River, comprises an area of 8,900 square miles. The northernmost area lies in the high, wet regions of the Cascades and the Klamath Mountains. The runoff from this area reflects the precipitation pattern -- high flows occur from direct precipitation between November and April; April and May are months of large sustained flows from snowmelt. Low flows occur during July, August, September, and October. Prior to dams and diversions, the combined flows from the Cascade and Klamath Mountains during winter and spring months caused severe flooding and damage in the Redding basin and Sacramento Valley, while hot, dry summer months provided little water to irrigable lands.

Hydrologic changes in the watershed that affect conditions in the study reach are caused mostly by dams and diversions. These include changes in mean monthly discharge, peak monthly discharge, flow duration, flood peaks, and flood frequency.

Dams and Diversions

Numerous small dams and diversion structures were built in the watershed above Red Bluff and the study area, but until the completion of Shasta Dam in 1943, they had little effect on the hydrology. Today, Shasta Dam, Keswick Dam, Red Bluff Diversion Dam, and the Trinity Project control, divert, and regulate flows in the Upper and Middle Sacramento River.

Shasta Dam

Shasta Dam stores 4.5 million acre-feet and regulates flows of the Pit, McCloud, and upper Sacramento Rivers. The project, which began water storage and regulation in December 1943, was built for a number of uses: river flow regulation, flood control, irrigation, domestic water supply, power generation, recreation, and salinity control in the Sacramento- San Joaquin Delta.

The maximum allowable discharge from Keswick Dam is coordinated with downstream tributaries so as not to exceed 79,000 cubic feet per second at Redding, 100,000 cfs at Red Bluff, or 130,000 cfs at Hamilton City during high water periods. An attempt is made to attain a mean flow of 12,000 cfs during summer months and 6,000 cfs during winter months.

Keswick Dam, 9 miles downstream from Shasta, has a storage capacity of 23,800 acre-feet. Besides water regulation and power generation, Keswick Dam acts as a fish trapping facility. Salmon and steelhead are trapped at the dam and transported to a fish hatchery on Battle Creek.

Flow regulations at Shasta and Keswick have noticeably lowered discharge maximum and increased discharge minimums along the Sacramento River. Although mean yearly discharge was not appreciably altered, changes in seasonal discharges are considerable.

A formal agreement exists between DFG and the U. S. Bureau of Reclamation concerning minimum releases during critical spawning times. This agreement states minimum releases shall not be lower than 2,300 cfs from March 1 to August 31, 2,600 cfs from December 1 to February 28, 3,900 cfs from September 1 to November 30, except in emergency situations. Flow commonly exceeds these minimums due to power and irrigation requirements. There is no formal agreement to date concerning maximum releases during the fall spawning season.

Trinity River Diversion

Since December 1963, water has been diverted from the Trinity River basin through the Clear Creek tunnel and Judge Francis Carr Powerhouse to Whiskeytown Lake. The Spring Creek tunnel then diverts Trinity water and most of Clear Creek water through another power plant into Keswick Lake. From 1963 to 1991, an average of a million acre-feet of Trinity River water has thus been diverted into the Sacramento River basin each year. The average between 1981 and 1991 is 905,000 acre-feet although only about 700,000 have been diverted in the last 3 years.

Since 1981, 68 percent of the releases from Clair Engle Lake (Trinity Reservoir) are diverted into the Sacramento River system. This affects the flows of both the Sacramento and Trinity Rivers. The Trinity River near Burnt Ranch has had about a 40 percent decrease, and the Sacramento River above Bend Bridge a 15 percent increase in mean annual discharge.

Diversions Between Keswick Dam and Red Bluff

One of the first water development efforts in the Redding area resulted in the formation of the Anderson-Cottonwood Irrigation District. The District contains 33,100 acres with over 17,000 acres irrigated. The ACID Diversion Dam, the first on the Upper Sacramento River, was completed in 1918. The dam is 440 feet long, about 15 feet high, and its sole purpose is to divert water into an irrigation system.

In June 1967, the District contracted with the U. S. Government for a water supplement to their natural flow rights of 165,000 acre-feet. This contract allows for an additional diversion of 10,000 acre-feet, making a total of 175,000 acre-feet of water available to the District each year.

Water use by ACID between the months of April and October comprises about 80 to 85 percent of the approximate 190,000 acre-feet diverted yearly between Redding and Red Bluff. The remaining percentage is diverted by the City of Redding, industry, private farms, and small towns.

Many tributary streams in the study area have intricate systems of canals and dams for power generation or diversions for irrigation. Power diversions often leave long stretches of creeks dry, or at very low flows. Irrigation diversions create more drastic changes as water removed for irrigation is consumed and generally not returned to the stream.

Diversions Between Red Bluff and Colusa

At the upper end of the study reach, the Red Bluff Diversion Dam diverts water from the Sacramento River to the Tehama-Colusa and Corning Canals. During an average water year 700,000 acre-feet are diverted to the Tehama-Colusa Canal and an additional 50,000 acre-feet are diverted to the Corning Canal.

The Glenn-Colusa Irrigation District diverts water into its main canal about 11.5 miles upriver from Chico Landing. The earliest diversion into the GCID was in 1905 when the flow capacity was 700 cfs. In the ensuing years improvements have increased canal capacity to about 3,000 cfs. The GCID now diverts an annual average of 767,300 acre-feet from the Sacramento River. Numerous smaller diversions are in the study reach.

By 1960, the average yearly diversions from the Sacramento River were about 40 percent greater than the pre-Shasta period, when diversions depended on natural runoff.

Streamflow

Hydrologic data were developed from DWR project and water supply data, U.S. Geological Survey (USGS) gaging stations, and U.S. Army Corps of Engineers (USCE) and U.S. Bureau of Reclamation (USBR) hydrologic and dam operations data. Some of the USGS gaging stations were abandoned in 1980 and subsequently operated by DWR. The DWR data on these stations were not used or discussed because of incompatible computer data files. Figure 6 shows stream gaging station locations and Table 5 vital statistics of Sacramento River gaging stations.

Yearly changes in hydrology were determined by comparing streamflow data for the period of record. The streamflow data may conveniently be divided into the following three hydrologic periods based on major human alterations of the river regime: (1) pre-Shasta Dam (to December 1943); (2) post Shasta, but pre-Trinity River diversion (December 1943 to December 1963); and (3) post Trinity River diversion (December 1963 to present). The Trinity River diversion is also referred to as post Shasta and pre-Whiskeytown Dam.

Hydrologic changes were analyzed for the Middle Sacramento River above Bend Bridge near Red Bluff (USGS 11377100), at Vina Bridge (USGS 11383730, DWR A02700), near Hamilton City (USGS 11383800), at Butte City (USGS 11389000), and at Colusa (USGS 11389500). Streamflow was not analysed at the Ord Ferry gaging station.

The Red Bluff gage, (at Jellys Ferry, 1892-1902; near Red Bluff 1902-1967; above Bend Bridge, 1967- present) about 17 miles upstream from the Red Bluff diversion dam, has a natural watershed of 8,900 square miles. Before the Trinity diversion, average annual discharge for the period of record was 11,400 cubic feet per second. The average post Whiskeytown Dam discharge at this station is 13,360 cfs. Approximately 190,000 acre-feet are diverted between Keswick and Bend.

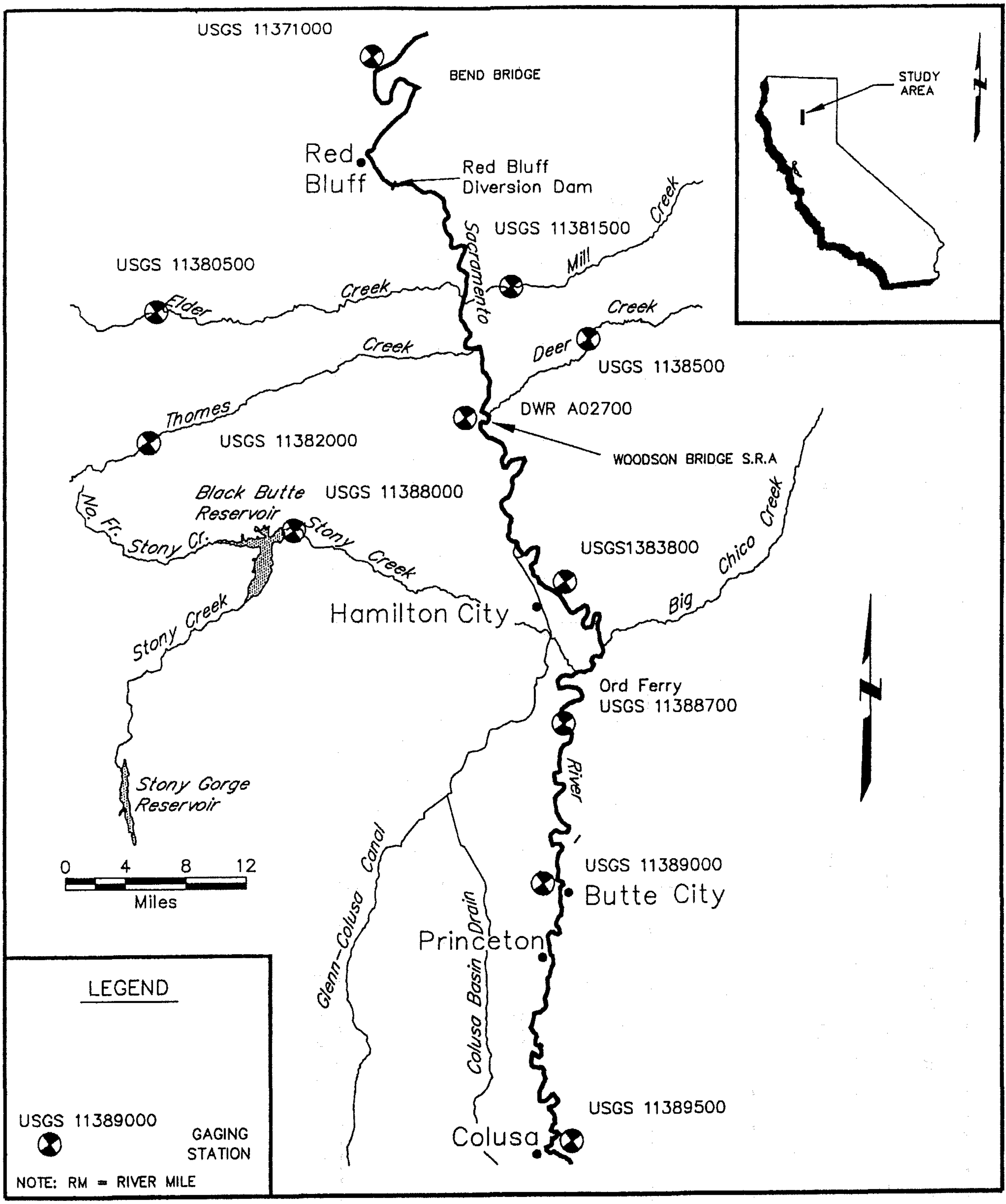
The Vina gage, about midway in the study reach, has a watershed of 10,930 square miles. The average post Whiskeytown Dam annual discharge at this station is 13,590 cfs. Approximately 950,000 acre-feet are diverted between Keswick and Vina.

The Hamilton City gage, about 4.5 miles upriver from Chico Landing, has a watershed of 11,060 square miles. The average post Whiskeytown Dam annual discharge is 13,550 cfs. An additional 760,000 acre-feet is diverted from the river between Vina and Hamilton City, for a total of 1.71 million acre-feet between Keswick and Hamilton City.

The Butte City gage is directly south of Butte City. It has a watershed area of 12,075 square miles. The average annual post Whiskeytown Dam discharge is 14,040 cfs.

The Colusa gage is at the town of Colusa. It has a watershed area of 12,090 square miles. The average annual post Whiskeytown Dam discharge is 12,130 cfs. This is less than the Vina, Hamilton City, and Butte City gages because of overflow during floods into flood control weirs.

Figure 6



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Sacramento River Bank Erosion Investigation
Stream Gaging Stations
Sacramento River from Red Bluff to Colusa

TABLE 5 SACRAMENTO RIVER GAGING STATIONS

Stream Gaging Station	River Mile	Period of Record	Drainage Area (Mi^2)	Mean Annual Flow (cfs)
Sacramento River at above Bend Bridge (USGS 11371000)	260.5	1892 to current year	8,900	11,830
Sacramento River at Vina Bridge (DWR A02700)	218.3	1945 to current year	10,930	13,770
Sacramento River at Hamilton City (USGS 11383800)	199.3	1945 to current year	11,060	12,460
Sacramento River at Butte City (USGS 11389000)	169.0	1965 to current year	12,075	13,130
Sacramento River at Colusa (USGS 11389500)	143.0	1921 to current year	12,090	11,380

DWR maintains a gage at Ord Ferry not used in this analysis.

It is important to note that for the Vina, Hamilton City, Butte City and Colusa gages, overbank flow is either not gaged or not precisely gaged. Also note that the Butte City and Colusa gages have major overflow weirs such as the Moulton and Colusa weirs that divert major floodflows out of the main channel.

Mean Monthly Flow

Figure 7 shows the average mean monthly discharge for the three hydrologic periods at the "Above Bend Bridge" gaging station. At this gage, the effect of Shasta was to reduce mean winter discharge to 80 percent of the pre-Shasta flows. However, since the Trinity diversion, the average December discharge has increased to 130 percent of the pre- Shasta normal, January flows are near normal, and February flows are about 75 percent of normal. The most striking changes, however, have been in summer and fall flows. Post Shasta, pre-Trinity diversion mean flows are about 200 percent of pre-Shasta, and post Trinity diversion flows are more than 250 percent of pre-Shasta flows. Present summer flows at Red Bluff average 10,860 cfs. Figures 8 to 11 show the hydrologic changes at Vina, Hamilton City, Butte City and Colusa gages only for the post Shasta and post Whiskeytown hydrologic periods because these gages were not in operation prior to Shasta Dam. The summer flows at these gages are lower than at Bend Bridge because of diversions.

Flow Duration

Flow duration curves show the percent of time a specified discharge is equalled or exceeded. A computer program, provided by the USGS, separates all mean daily flows during the study period into 34 classes. The computer then determines the percent of time each flow class was equalled or exceeded. These data are then plotted on log-percent paper.

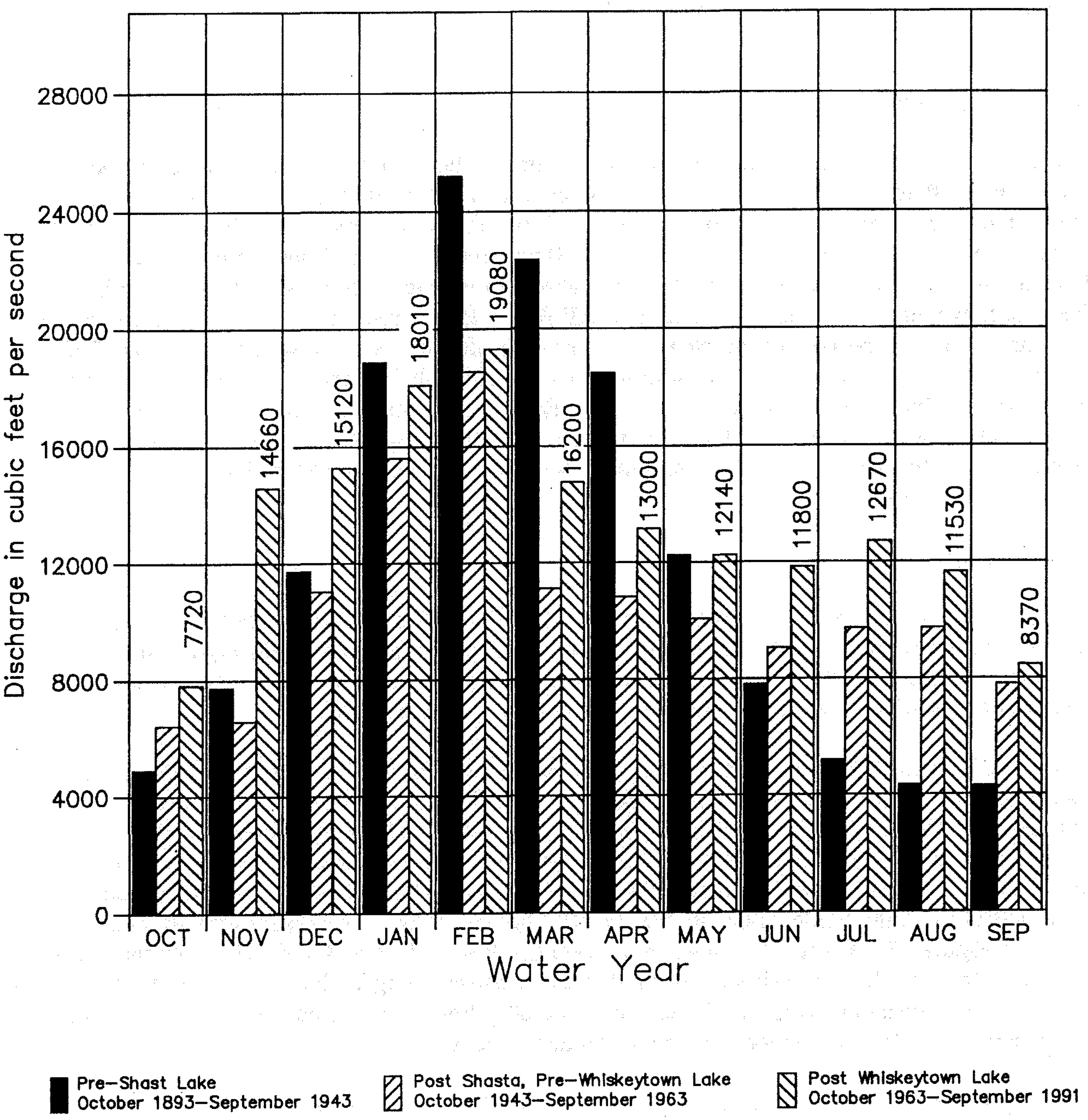
Figure 12 shows the flow duration curve for the Sacramento River above Bend Bridge and at Vina Bridge for the post Whiskeytown hydrologic period. The graph shows that post Whiskeytown flows exceed 70,000 cfs 1 percent of the time (1 of every 100 days), 6000 cfs 50 percent of the time, and 2,800 cfs 99 percent of the time. These discharges are lower than one would expect because of the five years of drought between 1986 and 1991. The comparative discharges at the Vina Bridge gage are 90,000, 10,000 and 4,000. The Hamilton City gage, shown on Figure 13, exceedence flows are 80,000 cfs, 9,000 cfs, and 4,200 cfs. Note that on this figure, the low flows are similar for the three downstream gages. Note also that the high flows for the Colusa gage (Figure 13) have considerably lower peaks than the other two gages. This is caused by flood diversions into Moulton and Colusa weirs.

The effect of Shasta and Keswick Dams on the natural flow duration curve has been to:

1. Decrease the minimum discharge and increase the number of very low discharges. This occurred in the past when the powerhouse was closed for repairs and before minimum flow releases for fish were mandated.

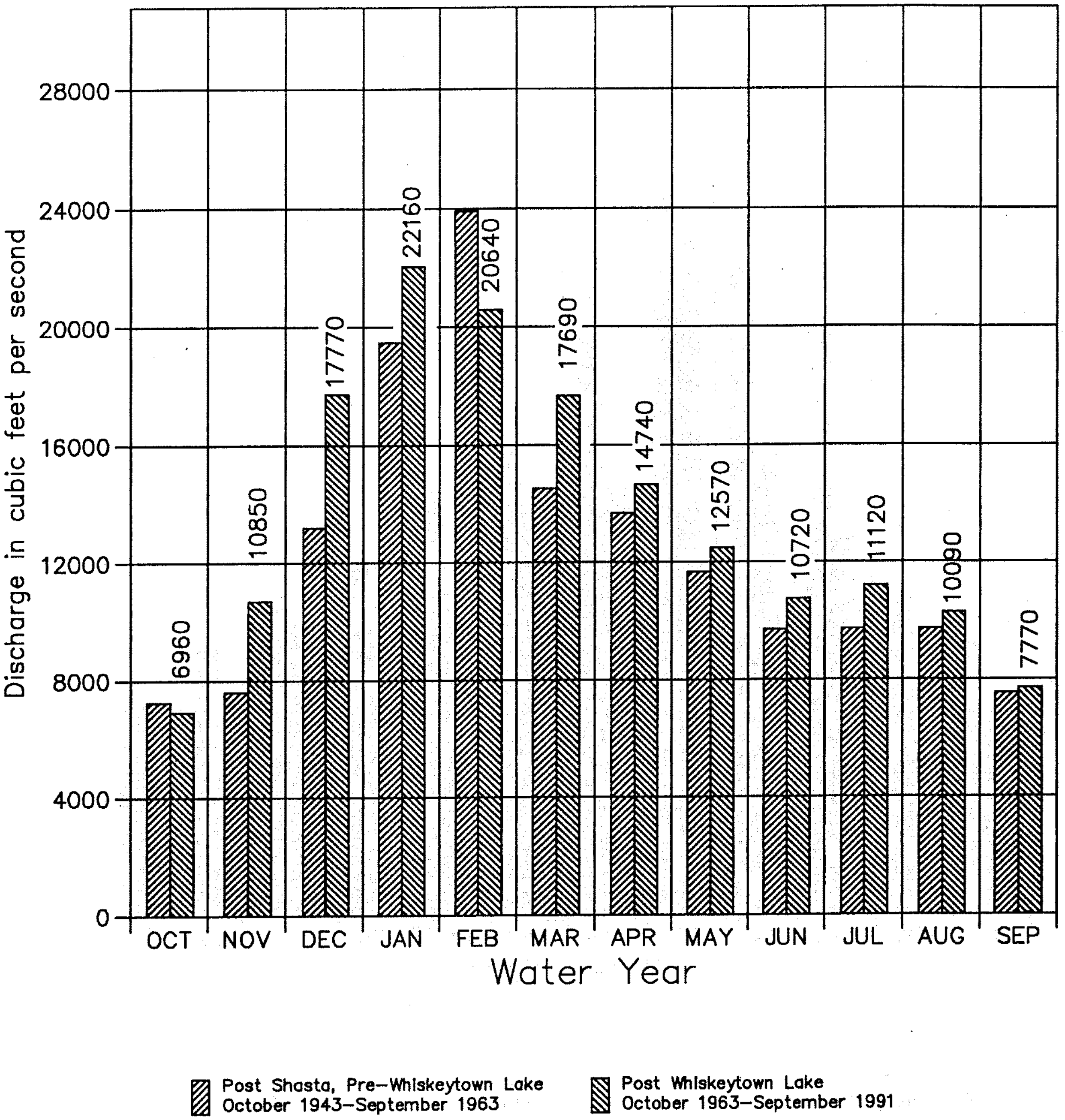
2. Increase the number of moderate discharges and reduce the number and the volume of very high flows.

Figure 7

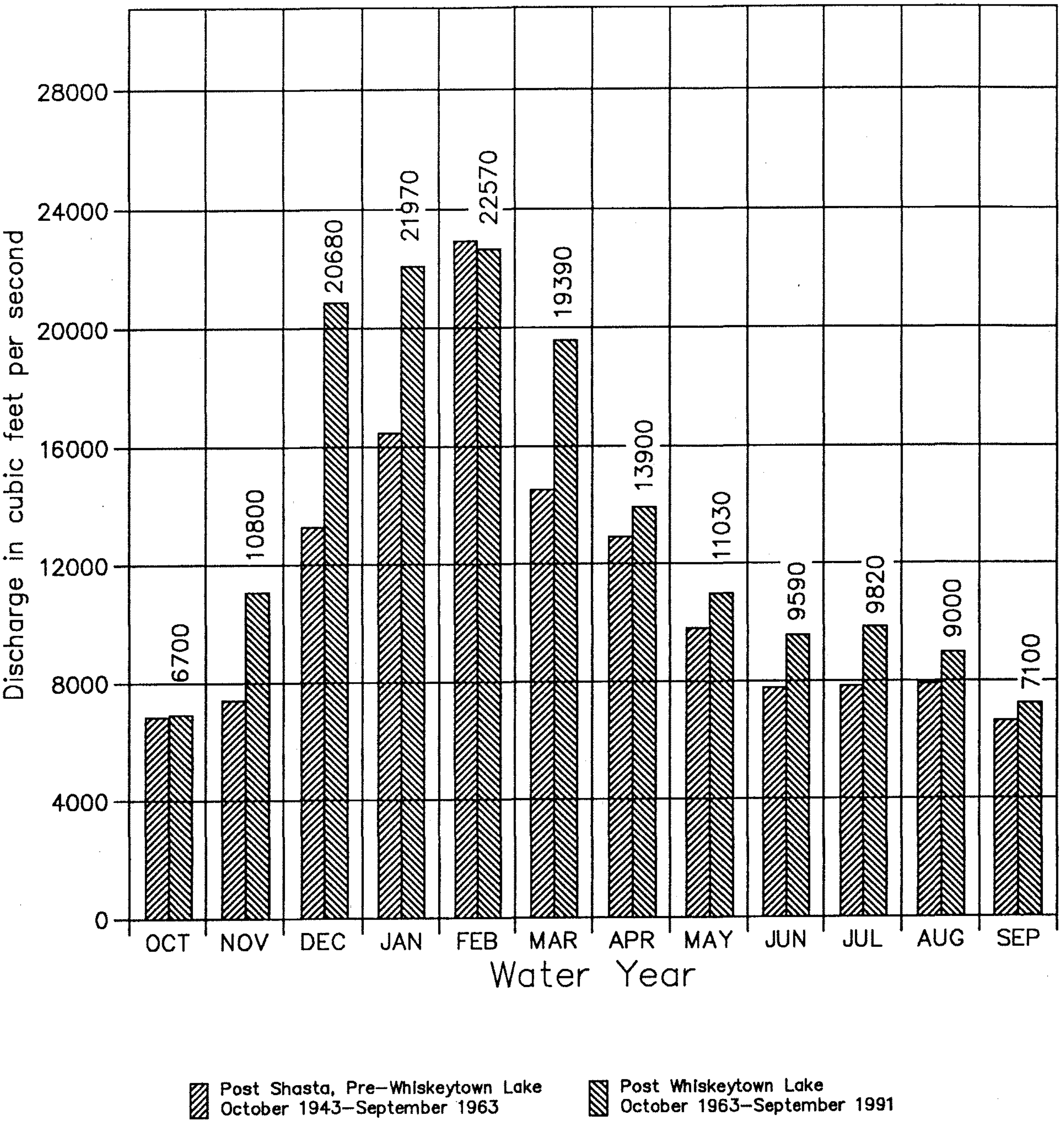


Sacramento River Bank Erosion Investigation
Changes in Mean Monthly Discharge
Sacramento River Above Bend Bridge

Figure 8

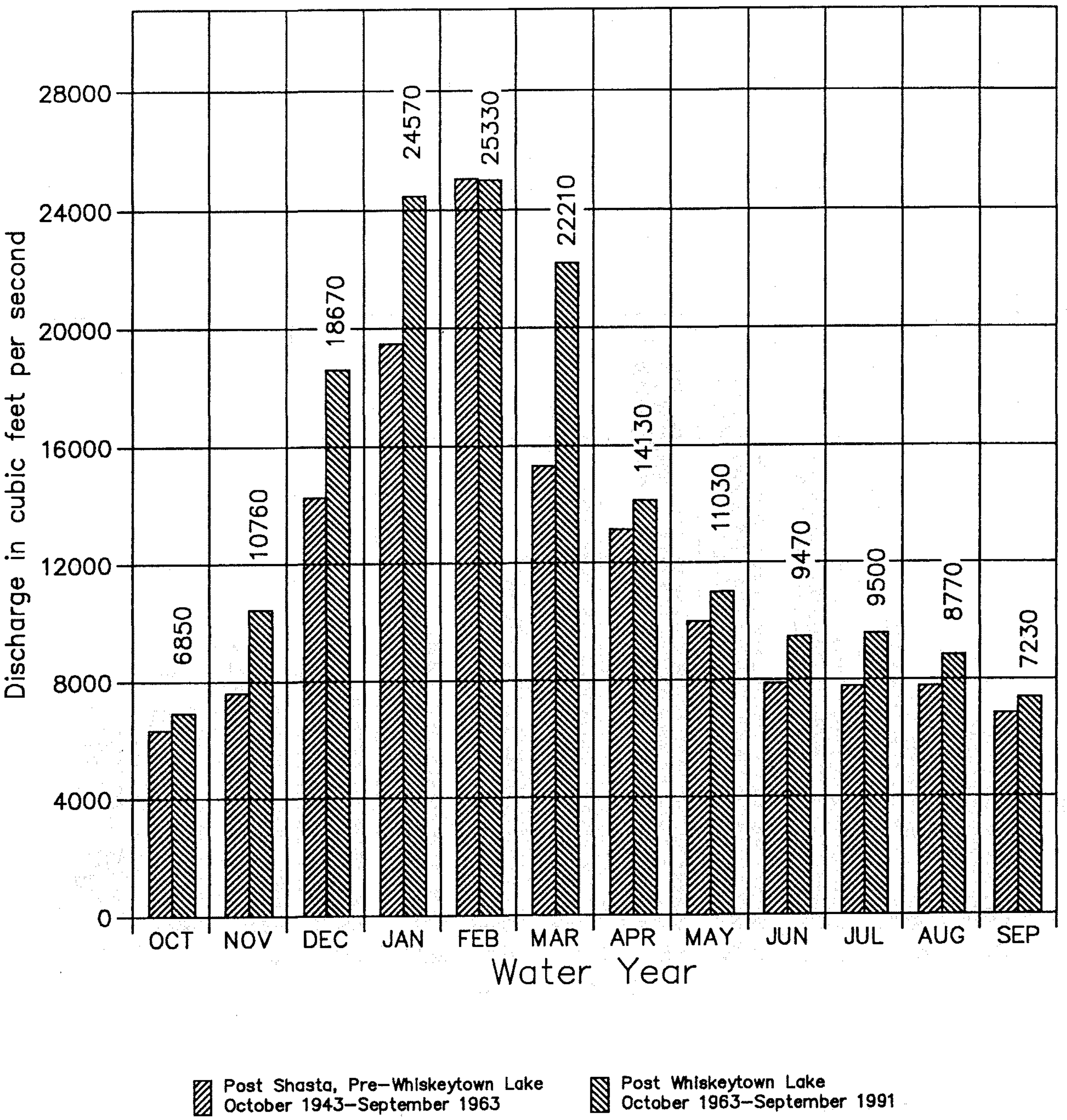


Sacramento River Bank Erosion Investigation
Changes in Mean Monthly Discharge
Sacramento River at Vina Bridge



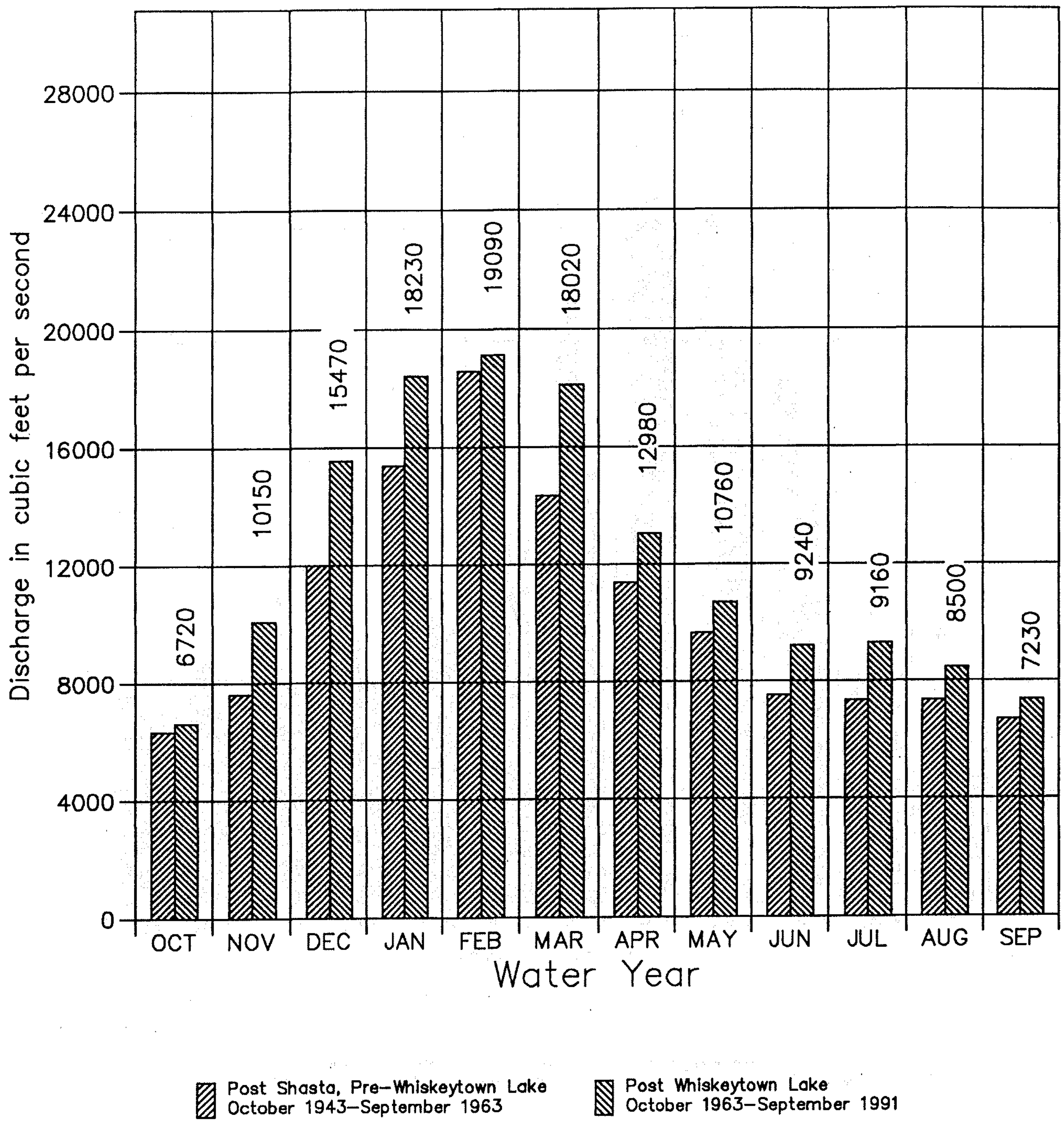
Sacramento River Bank Erosion Investigation
Changes in Mean Monthly Discharge
Sacramento River at Hamilton City

Figure 10

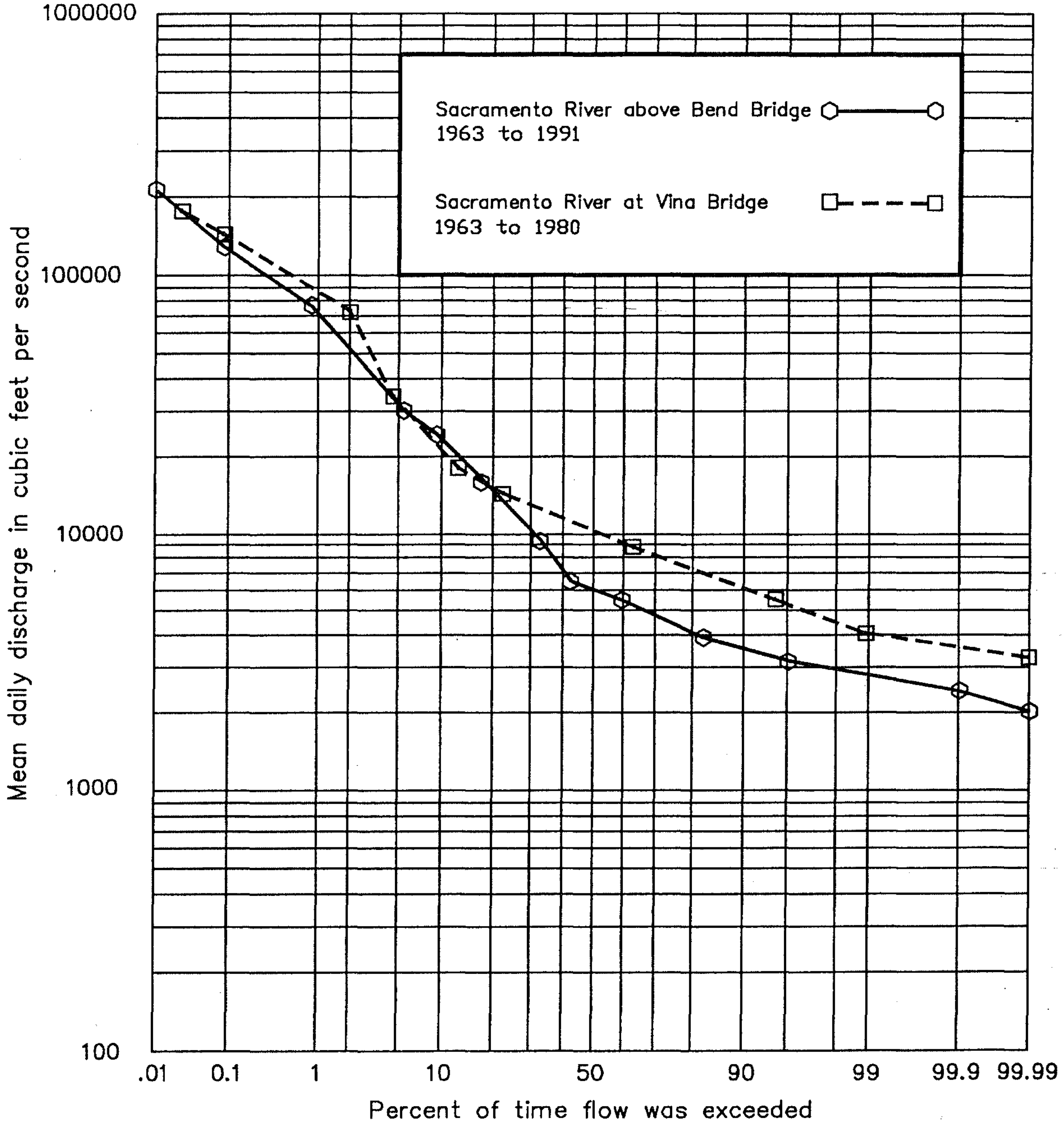


Sacramento River Bank Erosion Investigation
Changes in Mean Monthly Discharge
Sacramento River at Butte City

Figure 11



Sacramento River Bank Erosion Investigation
Changes in Mean Monthly Discharge
Sacramento River at Colusa



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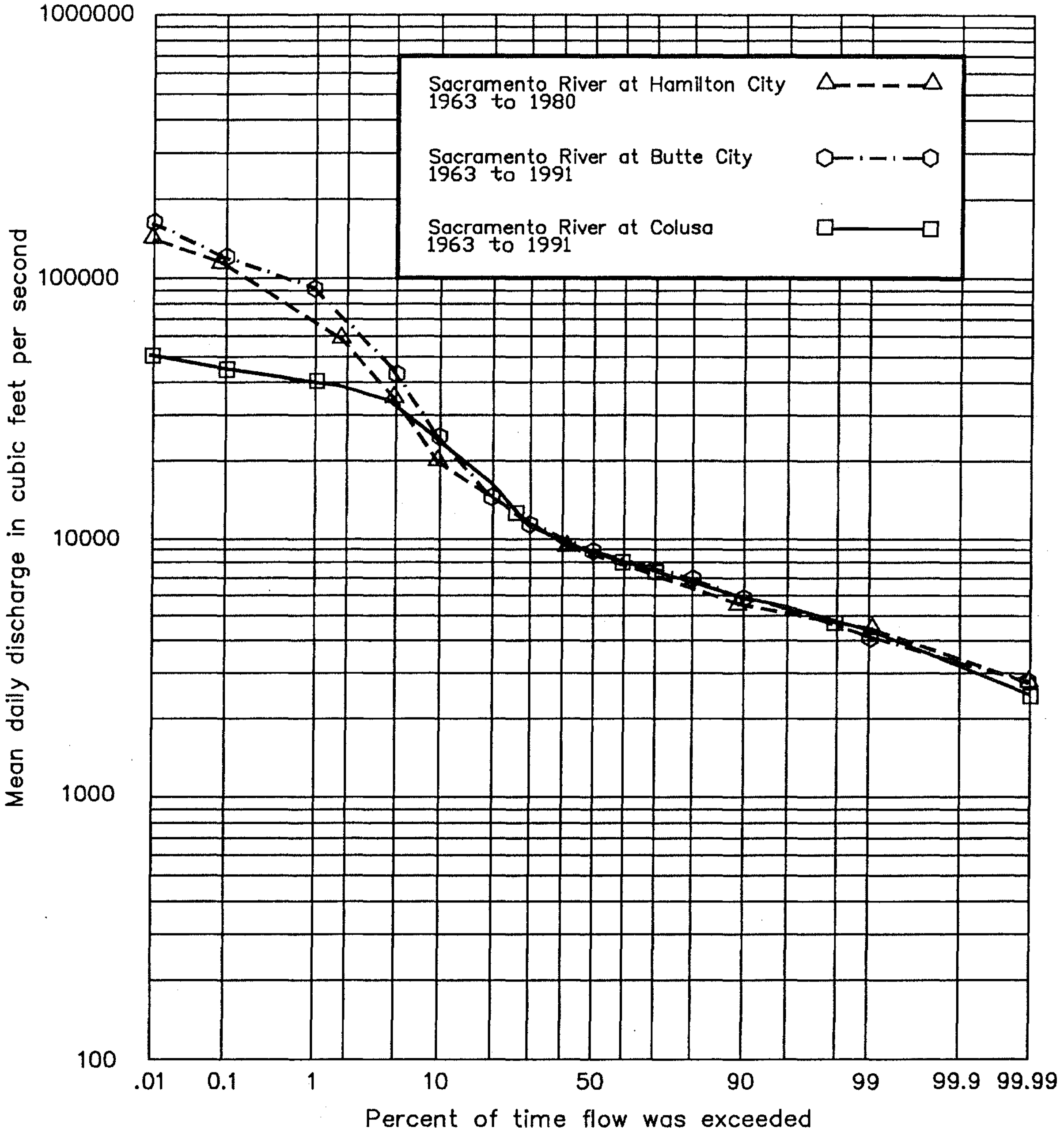
Sacramento River Bank Erosion Investigation
Flow Duration
Sacramento River above Bend Bridge and at Vina Bridge



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Sacramento River Bank Erosion Investigation
Flow Duration
Sacramento River at Hamilton City, Butte and Colusa

The effect of the Trinity diversion on post Shasta flows has been to increase the discharge for any particular exceedence frequency. For example, between 1981 and 1991, the average discharge at the Bend Bridge gage has been increased by 1250 cfs, a 26 percent increase.

Flood Hydrology

Peaks in the hydrograph generally occur in response to intense winter rainstorms. Winter flooding from runoff above Red Bluff and in the study area is intensified when the soil mantle is saturated, when the ground is frozen or when warm rain on snow adds snowmelt to runoff. Flooding on the tributary streams is characterized by high peak flows of moderate duration (USCE, 1978).

The flood hydrology of the Sacramento Basin changes in the downstream direction as tributaries combine with the Sacramento River. Before construction of Shasta Dam, the main Sacramento River flood peak formed above Shasta for most storms. Since construction of Shasta, the flood peak is usually generated in the tributaries between Redding and Red Bluff. The tributaries below Red Bluff generally peak before the upstream peak on the Sacramento River arrives and consequently have a lesser effect.

In the few years before construction of Shasta Dam, great floods occurred in 1937, 1940, 1941 and 1942. Table 6 shows the peak flows. The storms of December 1937 were, to that date, the most destructive in the history of Northern California, and the Sacramento River reached its highest level in 42 years. An eyewitness account described the orchards in the Jelly District as completely under water except for the very tops of the trees, and the entire lower portion of Bend was inundated. Many cattle and sheep were lost, and massive amounts of debris from upstream lodged in the study reach. The greatest natural Sacramento River flow of record occurred in 1940 when severe flooding again occurred in the study area. According to the February 29, 1940 edition of the Red Bluff Daily News, floodwater was 2-1/2 feet over the deck of Bend Bridge, and "The Jelly District was under several feet of water as the river there yesterday reached an all-time high of 41 feet, nearly three feet higher than the 1937 flood."

Floods that occurred before Shasta Dam are essentially of historical interest only, but flow conditions and the pattern of inundation during the 1940 flood would be very similar to the flow and the overflow pattern expected during a 100-year flood with Shasta Dam in operation (USCE, 1977).

Flood frequency diagrams are used to predict the number of floods within a specified range of magnitude which could be expected to occur during any long period of time. The magnitude of 10- and 100-year, and other events may be read directly from the graph with the reliability depending on the length of record. The above Bend Bridge near Red Bluff gage has the longest record in Northern California, with 101 years (1892-present).

TABLE 6 - PEAK FLOWS OF HISTORICAL FLOODS

in Thousands of Cubic Feet per Second

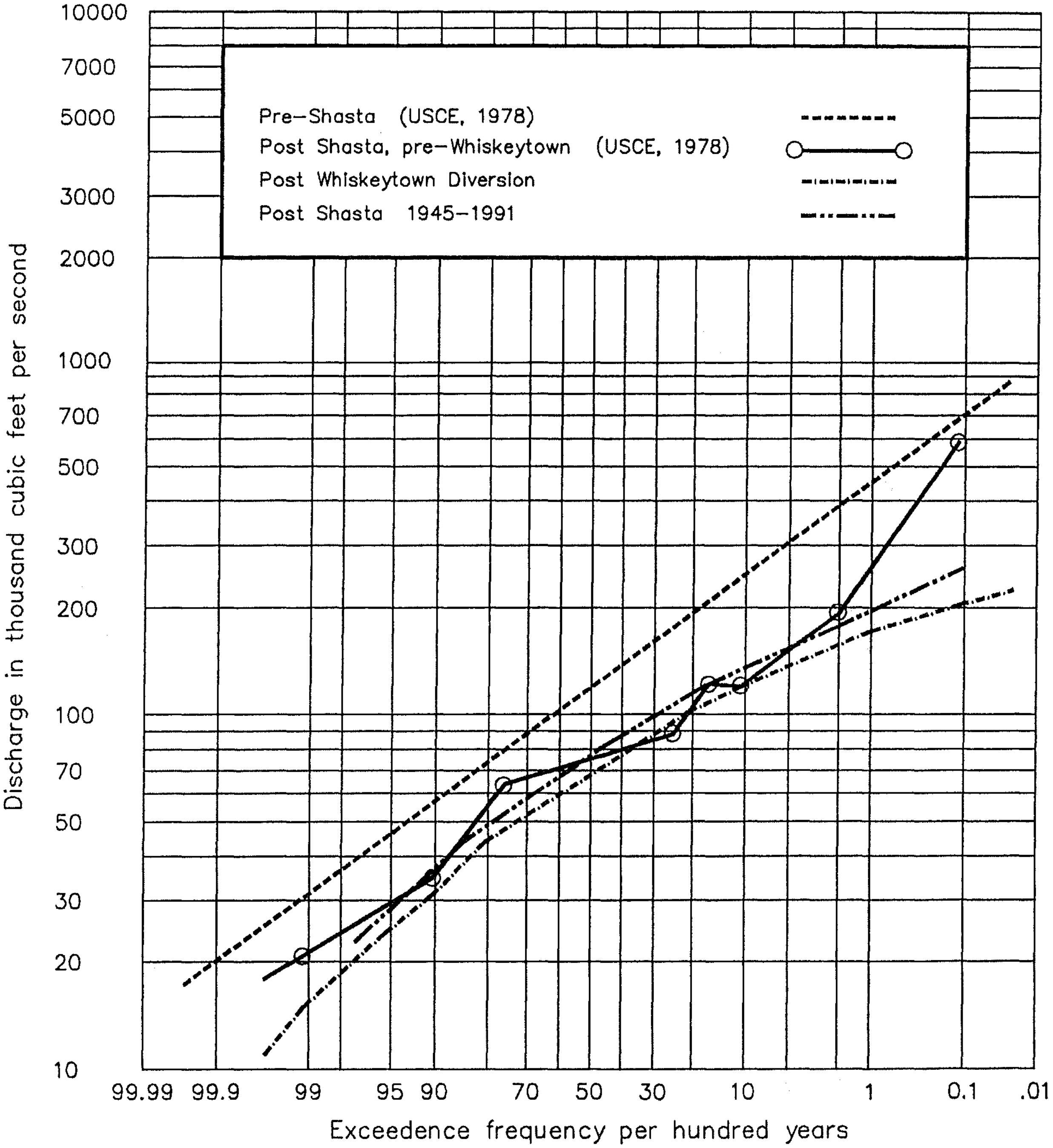
Station	12/37	02/40	04/41	02/42	12/51	01/56	02/58	12/64	01/69	01/70	01/74	01/78	02/80	03/83	02/86
Sacramento River above Bend Bridge (11377100)	262	291	157	203	137	115	139	156	92	157	133	106	104	152	134
Red Bank Creek (11378800)	-	-	-	-	-	5.6	-	9.7	9.2	8.7	6.7	9.3	8.4	10.5	-
Antelope Creek (11379000)	-	-	7.9	10.4	6.5	4.1	2.5	9.0	9.4	17.2	8.4	3.0	6.1	-	-
Elder Creek (11380500)	10.7	13.1	14.1	N/R	4.7	2.5	11.3	10.3	3.8	7.2	8.9	5.0	6.7	5.9	-
Mill Creek (11381500)	36.4	11.4	7.3	11	5.3	4.8	2.2	16	12.4	17.1	10.1	3.3	6.7	7.8	11.8
Thomes Creek (11382000)	16.5	17	5.6	8.1	5.7	10.9	11.4	37.8	9.3	18	29.4	7.3	6.7	7.1	32.9
Sacramento River at Vina (11383730)	-	-	-	-	146	135	-	163	139	171	159	121	132	174	-
Deer Creek (11383500)	23.8	18.4	8.0	11	6.7	6.6	8.7	18.8	15	21.1	10.3	4.3	-	11.3	16.1
Sacramento River at Hamilton City (11383800)	-	350	-	-	-	-	-	151	126	156	158	123	-	176	-
Sacramento River at Butte City (11389000)	-	-	-	170	111	149	160	126	120	152	136	121	124	157	145
Sacramento River at Colusa (11389500)	-	-	-	49	39.7	43.2	45.8	-	42.7	48.4	48.6	45.2	45.8	51.8	50.1

Figure 14 shows the flood frequency curve for the three hydrologic periods at the above Bend Bridge gage. The pre-Shasta Dam and the post Shasta pre-Whiskeytown graphs were calculated by the U.S. Army Corps of Engineers (USCE, 1977) using Log Pearson Type III analysis and by assuming Shasta Dam operations for the entire period of record. The post Shasta graph was derived using Weibull flood frequency analysis on the 45 years of available record. Note the large discrepancy at higher flows between the post Shasta, pre-Whiskeytown and post Whiskeytown hydrologic periods. The flows with a recurrence interval of 100 years and more were calculated by the USCE by assuming the operation of Shasta Dam for the entire period of record. The post Shasta curve was calculated using actual flows. The 1945-1991 graph is probably the best since it has the longest period of record, and the Whiskeytown diversion does not affect floodflows. This graph indicates that a peak with a 2-year recurrence interval has a flow of 79,000 cfs, a 10-year peak of 125,000 cfs and a 100-year of 200,000 cfs.

The effect of Shasta Dam under normal operating conditions is greatest on flood peaks near Keswick. The 100-year flood of 300,000 cfs at Keswick is reduced to 26 percent of the natural flow (DWR, 1984). Shasta Lake is not nearly as effective at controlling higher peak flows downstream because of tributary inflow. The uncontrolled 100-year flood at Red Bluff is 420,000 cfs. This flow would be reduced to 66 percent (277,000 cfs) of the natural flow by the dam. The uncontrolled flows at Vina, Hamilton City, Butte City and Colusa are not known because pre-dam data are not available.

Figures 15 and 16 show the same for the Vina and Hamilton City gages. At Vina Bridge the equivalent 2-, 10- and 100-year peak storm flows are 90,000 cfs, 135,000 cfs, and 205,000 cfs, and at Hamilton City the flows are 90,000, 135,000 and 200,000 cfs. Figure 17 shows the flood frequency curves for the Butte City and Colusa gages. For the Butte City gage the storm flows are 90,000, 128,000 and 185,000 cfs. The equivalent Colusa gage flows are 36,000, 47,000 and 57,000 cfs. Note that overbank flow is not gaged and does not show up on the flood frequency curves.

Note: See Table 5 for source and period of record



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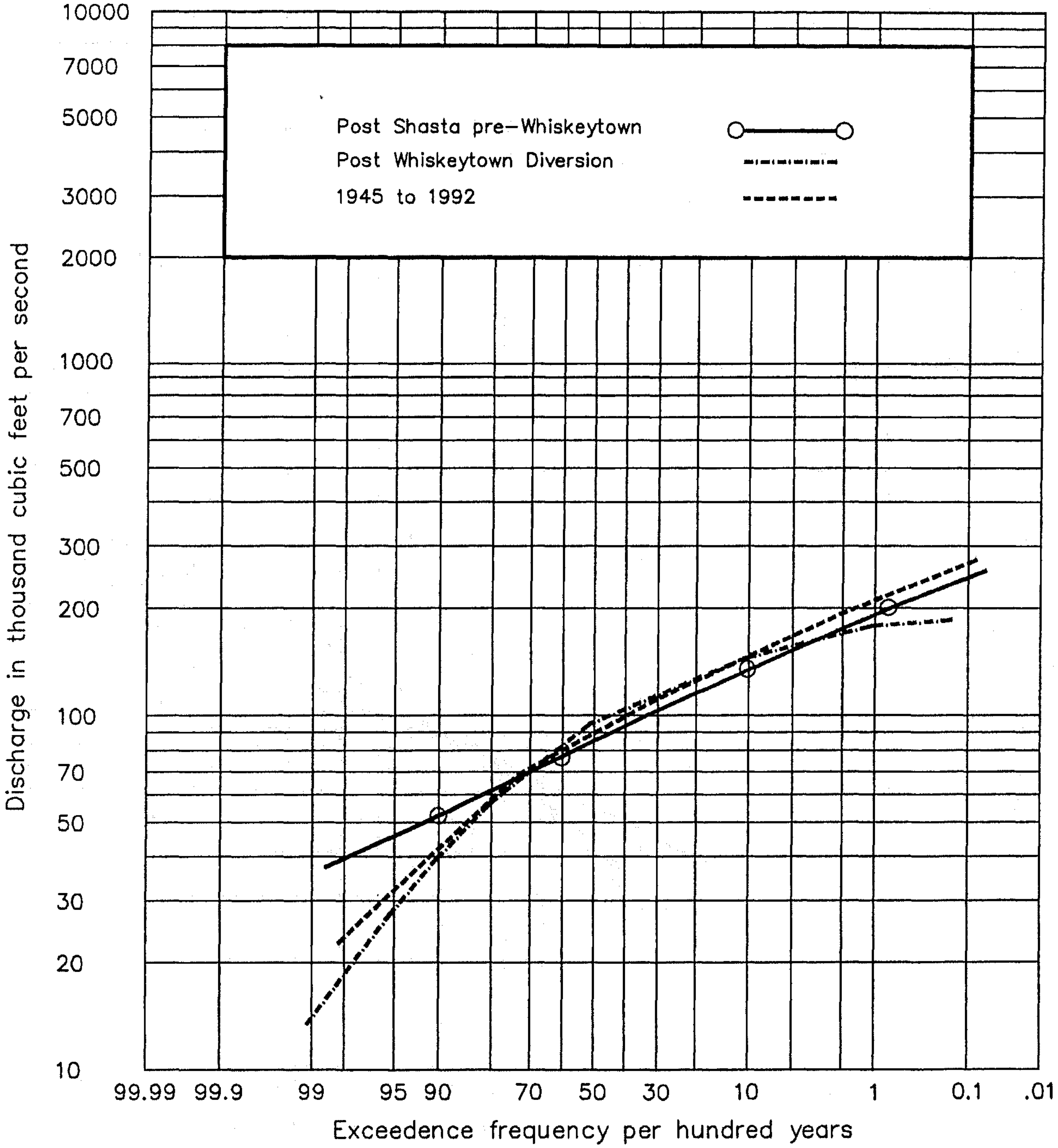
Sacramento River Bank Erosion Investigation
Peak Flood Flow Frequency
Sacramento River above Bend Bridge

Figure 15



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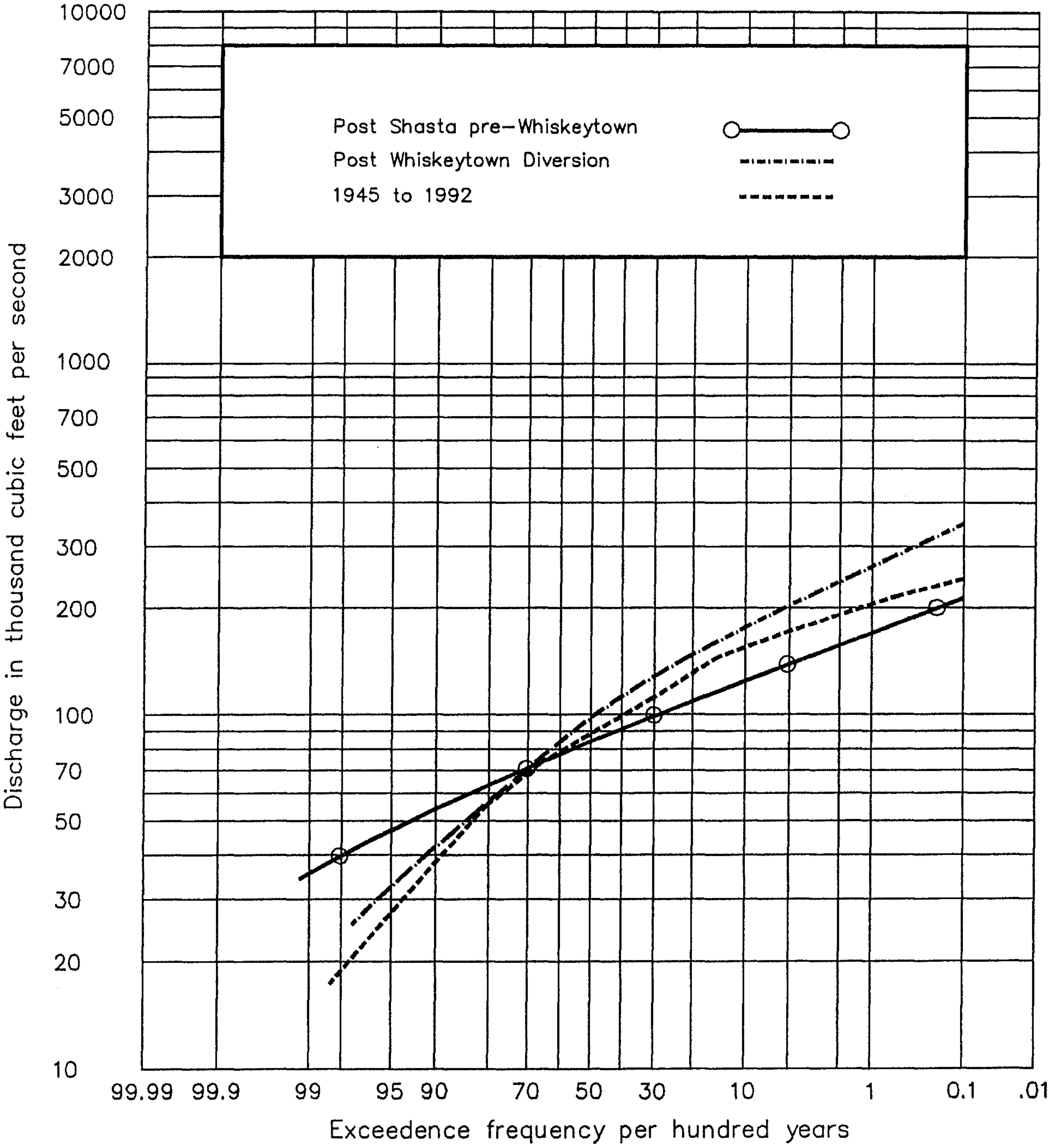
Sacramento River Bank Erosion Investigation
Peak Flood Flow Frequency
Sacramento River at Vina Bridge

Figure 16



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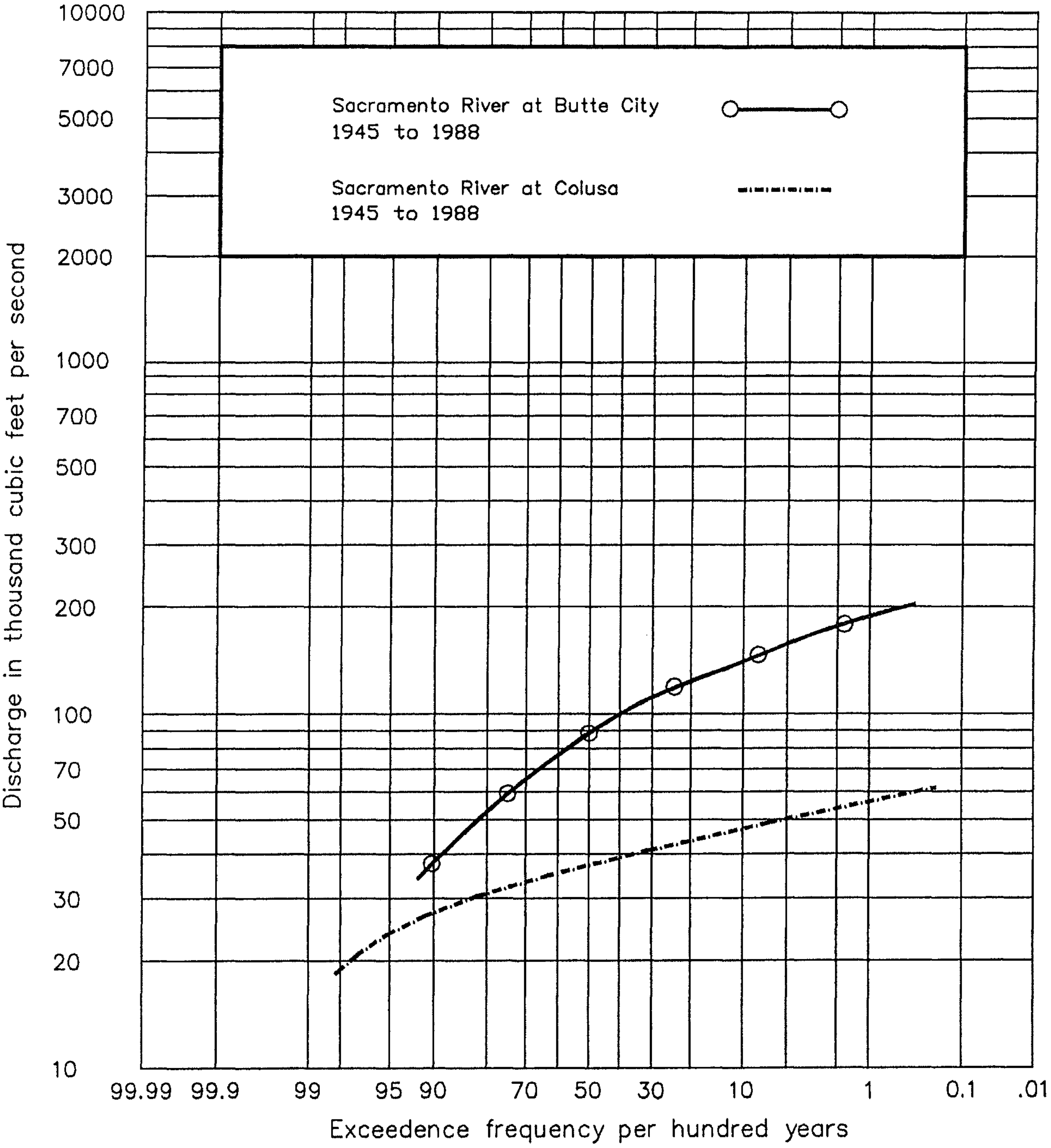
Sacramento River Bank Erosion Investigation
Peak Flood Flow Frequency
Sacramento River near Hamilton City



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Sacramento River Bank Erosion Investigation
Peak Flood Flow Frequency
Sacramento River at Butte City and Colusa

PART III: EROSION AND DEPOSITION OBSERVATIONS

SACRAMENTO RIVER BANK EROSION
FLOODPLAIN DEPOSITION
LAKE RED BLUFF DEPOSITION
GAGING STATION CROSS SECTIONS
THALWEG DEPTHS AND RIVER WIDTHS

SACRAMENTO RIVER BANK EROSION

A river erodes both its banks and bed. Bed erosion leads to degradation and grading of the stream profile. In a bedrock stream, this process is relatively slow, even during periods of geologically rapid rejuvenation and uplift. In alluvial river systems, banks erode and sediments are deposited. Floodplains, islands, and side channels will undergo modification with time. Bed erosion also occurs in alluvial streams, but the erosion is generally balanced by deposition over a period of years.

Bank erosion is generally of much more interest and concern to people. Bank erosion is dependent on channel shape, bed and bank material, and river hydraulic characteristics. Because of the generally stable banks of the Sacramento River between Keswick and Red Bluff, bank erosion is slight in most places. Between Red Bluff and Colusa, however, significant bank erosion occurs. Downstream of Colusa, flood flows and associated velocities are greatly reduced by overflow occurring upstream (both overbank flow and flow at the Moulton and Colusa overflow weirs). In addition, downstream the flatter slopes of the channel bed minimize the erosion potential.

Bank erosion generally occurs on the outside of meander bends. Here, banks are susceptible to erosion because high-flow velocities impinge directly into banks and turbulent motion along the channel thalweg undercuts the banks. Eroding banks may be either high-terrace or low terrace. High terrace banks normally have a deep soil profile containing mostly loamy sand and silt. Below the soil is a thicker deposit of sand and gravel. A low-terrace bank consists mostly of a sand and gravel with a thin silt profile on top.

The fish, wildlife, and riparian vegetation are adjusted to the cycle of erosion, deposition and changing channel pattern in which the river swings slowly back and forth across a broad meander belt. The health and productivity of the system at any one point is dependent on the periodic rejuvenation associated with these changes.

Salmon prefer to spawn in fresh, uncompacted gravel that has recently moved. These spawning beds tend to occur in wide, shallow riffle areas such as areas with multiple channels or chute cutoffs. Salmon spawn here because of increased flow velocity, shallower depths and greater hydraulic diversity. Gravel in the lower horizons of an eroding bank provides fresh gravel to spawning beds. Between Red Bluff and Colusa, bank erosion is estimated to contribute about 85 percent of the total available spawning gravel (DWR 1984; 1985). Much of the sand and silt from the soil horizon is redeposited in the riparian forests downstream.

Bank erosion is also the driving force for riparian plant succession. On the outside of bends, high-terrace banks with a mature forest typically consisting of valley oak, box elder, and black walnut are eroded. On the opposite side is a point bar consisting of sand and gravel. Willows, alders and cottonwoods become established here. The rapid invasion of riparian vegetation slows flood flow velocities and allows sand and silt to deposit. With time, riparian stages with a succession of different plant species occurs as the point bar becomes higher and farther away from the river.

Various birds and other wildlife use different riparian stages for feeding, nesting, and reproduction. The climax valley oak forests are relatively sterile compared to the younger riparian stages. Therefore, bank erosion and riparian rejuvenation are necessary to maintain a healthy and productive ecosystem.

Sediment deposition is inextricably linked to bank erosion. Without deposition, the channel would simply widen until it was so large that erosion would terminate. However, the coarser material eroded from the bank is deposited on point bars downstream. The point bars constrict the bend and enable erosion to continue.

DWR (1979) observed bank erosion over a 2-1/2-year period at six sites in the Red Bluff-to-Colusa reach. Bank erosion was divided into summer (low-flow) erosion and winter (high-flow) erosion. Only two of the six sites showed any erosion during the summer. Average bank recession between April and October 1977 was 11.4 and 2.2 feet, respectively.

In contrast, high flows were far more conducive to erosion. A major storm occurred in January 1978. Erosion was greatest during the period that included this storm, with bank recession ranging from 30 to 50 feet. During the storm itself, Woodson Bridge State Recreation Area below Thomes Creek lost over 40 feet in a single 24-hour period.

Our bank erosion study was divided into two phases. The Phase I- Aerial Photography Bank Erosion Study identified 67 eroding bank sites between Red Bluff and Ord Ferry. The amount of erosion at these sites over a 11-year period (1976-1987) were measured using aerial photography. In the Phase II-Bank Erosion Monitoring Sites Study, we surveyed 15 eroding bank sites between 1986 and 1993 in the reach from Red Bluff to Colusa. These are resurveyed semi-annually.

Phase I-Aerial Photography Bank Erosion Study

The purpose of this phase of the study was to determine total bank erosion, bank composition, gravel and silt produced from bank erosion, and bank recession rates. A total of 67 bank erosion sites were identified and evaluated by comparing 1976 and 1987 aerial photographs. All visibly eroded areas from Red Bluff to Ord Ferry were measured using a planimeter.

Of the 67 identified eroding banks between Ord Ferry and Red Bluff, 30 were sampled. Three bulk gravel samples were taken near the middle of the eroding bend to estimate gravel size distributions in the lower bank. One bulk sample was obtained at the toe of the bank near the summer waters edge, another approximately halfway up to the top of the gravel-floodplain contact, and the last just below this contact. No samples were taken of overlying silt and sand floodplain deposits.

The three samples were combined and mechanically sifted in the field and each fraction weighed. Fractions less than 0.375 inch sieve size were brought back to the office for further analysis. At each site, about 400-600 pounds of gravel were sifted and weighed. Weights of sediment fractions were noted on a data analysis sheet and these data in turn were plotted on an Autocad-generated mechanical analysis diagram, shown in Appendix A.

Eroded bank sediment volumes were determined by measuring bank heights and lengths, area of the bank eroded, and gravel thicknesses. Bank heights (defined as the distance from the bottom of the river thalweg to the top of the bank) and gravel thicknesses were measured using a combination of sonar measurements and stadia and level measuring. Bank lengths were measured using a tape along the bank edge, and the distances from bank edge to the top of the gravel layer were obtained. Gravel thickness was assumed to extend from the top of the gravel layer to the bottom of the thalweg.

Eroded bank areas were determined by overlaying 1987 aerial photos of the channel on 1976 aerial photos and measuring the change in river bank location using a planimeter. Bank lengths and maximum bank recession were also measured on the photos. Data from the surveyed sites were averaged by geomorphic reach and applied to the unsurveyed sites.

Table 7 is a summary of bank erosion data for the Red Bluff to Ord Ferry reach during this 11-year period. In general, there are a number of observations that can be made from this table. The average bank height from the bottom of thalweg to the top of the bank is about 25 feet, with 16 feet of gravel and 9 feet of silt. The average eroding bank cross-section between Red Bluff and Ord Ferry is shown pictorially in Figure 18.

The average bank recession of an actively eroding bank is about 20 feet per year, ranging from a few feet to nearly 80 feet. The average length of a contiguous eroding bank is about 3,000 feet, for a total of about 197,000 linear feet in this reach. This represents 34 percent of the bank. Another 18 percent was eroding but has been protected with riprap. More specific observations include:

- The mean bank height in 1987 was 25.1 feet, ranging from a minimum of 15.4 feet to a maximum of 33.7 feet. Two banks were higher, at 40.2 and 47.9 feet but these banks are composed of Pliocene Modesto Formation and not recent gravel deposits.

- The mean gravel thickness in 1987 was 16.1 feet, ranging from a minimum of 6.0 feet to a maximum of 23.7 feet. Two greater gravel thicknesses occur but these are Pleistocene Modesto Formation deposits.

- The mean eroded bank area per site is 802,000 square feet, ranging from a minimum of 32,000 square feet to a maximum of 3,140,000 square feet.

- The average per site gravel volume eroded is 429,200 cubic yards, ranging from a minimum of 16,800 cubic yards to a maximum of 2,028,400 cubic yards.
- The average per site volume of fines eroded is 294,000 cubic yards, ranging from a minimum of 4,400 cubic yards to a maximum of 2,228,900 cubic yards.
- The average per site total bank volume eroded is 723,200 cubic yards, ranging from a minimum of 24,500 cubic yards to a maximum of 3,118,000 cubic yards.
- The average length of an eroding bank from 1976-1987 is 2,939 feet, ranging from a minimum of 620 feet to a maximum of 8,860 feet.
- The average per site maximum bank recession is 443 feet, ranging from a minimum of 40 feet to a maximum of 1,280 feet.
- The average per site total bank recession is 235 feet, ranging from a minimum of about 30 feet to a maximum of 830 feet.
- The average annual bank recession from 1976 to 1987 is 21.4 feet, ranging from a minimum of 2.7 feet to a maximum of 75.2 feet.

Phase II-Bank Erosion Monitoring Sites Study

Beginning in 1986, ten bank erosion monitoring sites were surveyed using a theodolite and an electronic distance meter. Six more were added in 1988, for a total of sixteen sites. Each site is surveyed twice yearly. Successive bank lines are plotted and the eroded bank area calculated. The Phelan Island and Golden State Island sites were riprapped during the summer of 1988 and are no longer monitored. The sixteen sites are shown on Figure 19 and described in order from upstream to downstream.

Coyote Creek

Coyote Creek is at River Mile 232.5, on the west bank, about one mile above Mill Creek. Plate 7 shows the Coyote Creek erosion site. The upstream two-thirds of this site is high terrace cultivated fields and orchards, and the lower third is low terrace riparian vegetation. The bank is fairly straight, except for a sharply curved lower third of the site.

The downstream third of the area is underlain mostly by silt, versus sand and gravel overlain by silt and sand for the upstream two-thirds of the site.

TABLE 7

SACRAMENTO RIVER EROSION SITE PARAMETERS, RED BLUFF DIVERSION DAM TO ORD FERRY 1975 TO 1986

REACH	EROSION SITE***	RIVER MILE	AVERAGE BANK HEIGHT (FEET)	AVERAGE GRAVEL THICKNESS (FEET)	ERODED BANK AREA (SQUARE FEET X 1,000)	TOTAL GRAVEL VOLUME ERODED (CUBIC YARDS X 1,000)	TOTAL FINE VOLUME ERODED (CUBIC YARDS X 1,000)	TOTAL BANK VOLUME ERODED (CUBIC YARDS X 1,000)	LENGTH OF ERODED BANK (FEET)	MAXIMUM BANK RECESSION (FEET)	AVERAGE BANK RECESSION (FEET)	AVERAGE ANNUAL BANK RECESSION (FEET)
	ERODING BANK	240.5	20.7*	14.2*	336	176.7**	80.9**	257.6**	3680	160	91.3	8.3
	SACT 1	239.9	21.1	13.7	236	119.7	64.7	184.4	1770	240	133.3	12.1
6A	ERODING BANK	239.5	20.7*	14.2*	141	74.2**	33.9**	108.1**	1960	160	71.9	6.5
	ERODING BANK	239.0	20.7*	14.2*	63	33.1**	15.2**	48.3**	1280	80	49.2	4.6
	ERODING BANK	239.0	20.7*	14.2*	32	16.8**	7.7**	24.5**	800	100	40.0	3.6
	SACT 2	238.5	20.3	14.7	742	404.0	153.9	557.9	3360	520	220.8	20.1
	ERODING BANK	237.0	19.9*	13.1*	3140	1519.6**	798.6**	2318.2**	6640	800	556.7	50.6
	SACT 3	236.5	15.4	12.0	485	215.6	61.1	276.6	3200	228	151.6	13.8
	ERODING BANK	236.0	19.9*	13.1*	96	46.5**	24.4**	70.9**	1090	135	88.1	8.0
	ERODING BANK	235.5	19.9*	13.1*	85	41.1**	21.6**	62.8**	1100	100	77.3	7.0
6B	SACT 4	235.0	23.3	13.2	1614	789.1	603.8	1392.8	4800	700	336.3	30.6
	ERODING BANK	234.0	19.9*	13.1*	666	321.8**	169.1**	491.0**	4520	240	147.1	13.4
	ERODING BANK	233.0	19.9*	13.1*	253	122.4**	64.3**	186.8**	1860	190	136.0	12.4
	SACT 5	232.9	21.1	14.0	468	242.7	123.1	365.7	3530	400	132.6	12.1
	ERODING BANK	232.0	19.9*	13.1*	96	46.5**	24.4**	70.9**	970	200	99.0	9.0
	ERODING BANK	231.5	19.9*	13.1*	371	179.5**	94.4**	273.9**	2220	320	167.1	15.2
6C	ERODING BANK	231.0	19.9*	13.1*	193	93.4**	49.1**	142.5**	1514	250	127.5	11.6
	SACT 6	228.9	33.9	16.9	144	90.1	90.7	180.9	2480	88	58.1	5.3
	ERODING BANK	227.5	27.2*	15.4*	786	447.3**	345.5**	792.8**	3840	460	204.7	18.6
	ERODING BANK	226.0	27.2*	15.4*	645	367.1**	283.5**	650.6**	3960	360	162.9	14.8
	SACT 7	225.5	30.7	14.8	44	24.1	26.9	50.0	1480	40	29.7	2.7
	SACT 8	224.4	20.8	19.9	131	96.6	4.4	100.9	2220	136	59.0	5.4
	SACT 9	223.3	26.8	14.2	264	138.8	123.2	262.0	3400	144	77.6	7.1
6D	ERODING BANK	223.0	27.2*	15.4*	605	344.3**	265.9**	610.2**	1980	560	305.6	27.8
	TOOMES 1 & 2	222.0	27.0	7.7	3118	889.2	2228.8	3118.0	5100	1080	611.4	55.6
	ERODING BANK	221.7	27.2*	15.4*	228	129.8**	100.2**	230.0**	1950	210	116.9	10.6
	SACT 28	221.3	24.4	20.5	407	309.0	58.8	367.8	2260	480	180.1	16.4
	ERODING BANK	221.0	27.2*	15.4*	257	146.3**	113.0**	259.2**	1900	260	135.3	12.3
	PALISADES	219.0	33.7	15.1	633	354.0	436.1	790.1	2880	440	219.8	20.0
6E	ERODING BANK	217.5	27.2*	16.2*	155	93.0**	63.1**	156.1**	1740	110	89.1	8.1
	ERODING BANK	216.0	27.2*	16.2*	1893	1135.8**	771.2**	1907.0**	8860	870	213.7	19.4
	SACT 12	213.1	19.0	6.4	1968	466.5	918.4	1384.9	2380	1280	826.9	75.2
	SACT 13	212.5	28.4	13.9	624	321.2	335.1	656.4	920	1280	678.3	61.7
	SACT 10	211.9	21.0	16.8	430	267.6	66.9	334.4	2350	312	183.0	16.6
	SACT 14	211.2	20.9	11.0	1469	598.5	538.6	1137.1	5100	620	288.0	26.2
	SACT 15	210.6	30.4	23.7	1161	1019.1	288.1	1307.2	3000	760	387.0	36.2
	SACT 16	210.4	23.9	13.6	1476	743.5	563.1	1306.5	4750	568	310.7	28.2
6F	ERODING BANK	209.0	27.1*	17.0*	547	343.8**	205.8**	549.6**	4620	240	118.4	10.8
	ERODING BANK	208.0	27.1*	17.0*	251	157.8**	94.5**	252.2**	1710	225	146.8	13.3
	SACT 17	207.2	40.2	35.0	41	53.1	7.9	61.0	620	120	66.1	6.0
	ERODING BANK	207.0	27.1*	17.0*	511	321.2**	192.3**	513.5**	2500	300	204.4	18.6
	ERODING BANK	206.0	27.1*	17.0*	401	252.0**	150.9**	402.9**	1850	330	216.8	19.7
	SACT 18	204.2	23.3	20.2	330	246.9	37.9	284.8	2660	220	124.1	11.3
	SACT 19	203.2	31.5	7.3	144	38.9	129.1	168.0	1700	140	84.7	7.7
	ERODING BANK	203.0	27.1*	17.0*	2333	1466.3**	877.9**	2344.2**	5220	1225	446.9	40.6
	ERODING BANK	202.0	27.1*	17.0*	610	383.4**	229.5**	612.9**	2500	375	244.0	22.2
	SACT 20	201.5	32.7	21.8	1235	997.1	498.6	1495.7	3230	600	382.4	34.8
6G	ERODING BANK	201.0	27.1*	17.0*	169	106.2**	63.6**	169.8**	1360	220	124.3	11.3
	ERODING BANK	199.0	26.5*	19.1*	245	173.3**	67.1**	240.5	1900	215	128.9	11.7
	ERODING BANK	198.0	25.8*	21.2*	188	147.3**	32.4**	179.6**	2000	170	94.0	8.5
	ERODING BANK	196.0	25.8*	21.2*	1074	841.3**	185.0**	1026.3**	2580	695	416.3	37.8
	ERODING BANK	195.5	25.8*	21.2*	1110	869.5**	191.2**	1060.7**	2970	840	373.7	34.0
6H	ERODING BANK	195.5	26.8*	21.2*	1220	955.7**	210.1**	1165.8**	2560	680	476.6	43.3
	ERODING BANK	194.5	25.8*	21.2*	682	534.2**	117.5**	651.7**	2820	475	241.8	22.0
	SACT 21	194.0	23.3	21.9	294	238.5	15.2	253.7	2220	220	132.4	12.0
	ERODING BANK	193.5	25.8*	21.2*	285	223.3**	49.1**	272.3**	1800	220	168.3	14.4
	SACT 24	193.0	28.3	20.4	576	435.2	168.5	603.7	2820	320	204.3	18.6
	ERODING BANK	192.0	22.8*	12.1*	2321	1040.2**	918.1**	1958.2**	5810	520	399.5	36.3
	PHELAN ISL.	191.5	27.0	6.5	1955	470.6	1484.4	1955.0	4620	920	423.2	38.5
	GOLDEN STATE	190.0	26.0	6.0	1598	355.1	1183.7	1538.8	4080	652	391.7	35.6
	ERODING BANK	190.0	22.8*	12.1*	439	196.7**	173.6**	370.4**	3195	250	137.4	12.5
7A	SACT 23	189.0	47.9	43.7	102	165.1	15.9	181.0	1200	300	85.0	7.7
	SACT 25	187.7	21.9	13.6	1440	725.3	442.7	1168.0	3980	576	361.8	32.9
	ERODING BANK	187.0	22.8*	12.1*	1707	765.0**	675.2**	1440.2**	3400	1000	502.1	45.6
	ERODING BANK	187.0	22.8*	12.1*	2616	1172.4**	1034.8**	2207.1**	4200	1070	622.9	56.6
	SACT 26	186.5	21.4	21.0	2608	2028.4	38.6	2067.1	5800	1200	449.7	40.9
	R. D. FARWELL	185.5	17.6	13.4	1264	627.3	196.6	823.9	6140	500	245.9	22.4
	TOTAL		1678.4	1076.7	53750	28755.7	19698.0	48453.8	196909	29699	15768.0	1433.6
	AVERAGE		25.1	16.1	802	429.2	294.0	723.2	2939	443	235.3	21.4

* MEAN VALUES OF SURVEYED DATA BY GEOMORPHIC REACH

** GENERATED FROM MEAN VALUES OF SURVEYED DATA

*** LOCATIONS IDENTIFIED BY RIVER MILE

SACT 1-26 ARE BULK GRAVEL SAMPLE LOCATIONS, SHOWN IN APPENDIX A

Plate 4 shows that the site has had about 1,500 feet of erosion in the last 100 years. Over the long-term, erosion has progressed westward at an average rate of 15 feet per year at the center of the site, although only minor erosion has occurred here since 1946. Several hundred feet of private riprap is in the bend above the site.

The river has not occupied the eroding high terrace bank in the last 100 years, although there is some subtle evidence of meander scrolls and channel deposits several thousand feet west of the present bank. The east bank consists of gravel point bar deposits. Plate l shows that about 1,000 feet downstream, the east bank is constrained by a cemented volcanic gravel mapped as Upper Modesto Formation by Helley and Harwood (1985).

The bank's radius of curvature is about 3,700 feet. Average bank erosion between June 1988 and August 1993 is 11 feet. The maximum erosion occurred at the sharply curved lower end, where 19 feet of recession occurred between November 1992 and August 1993. Only a few feet of recession occurred along the straight upper stretch.

Toomes Creek # 1

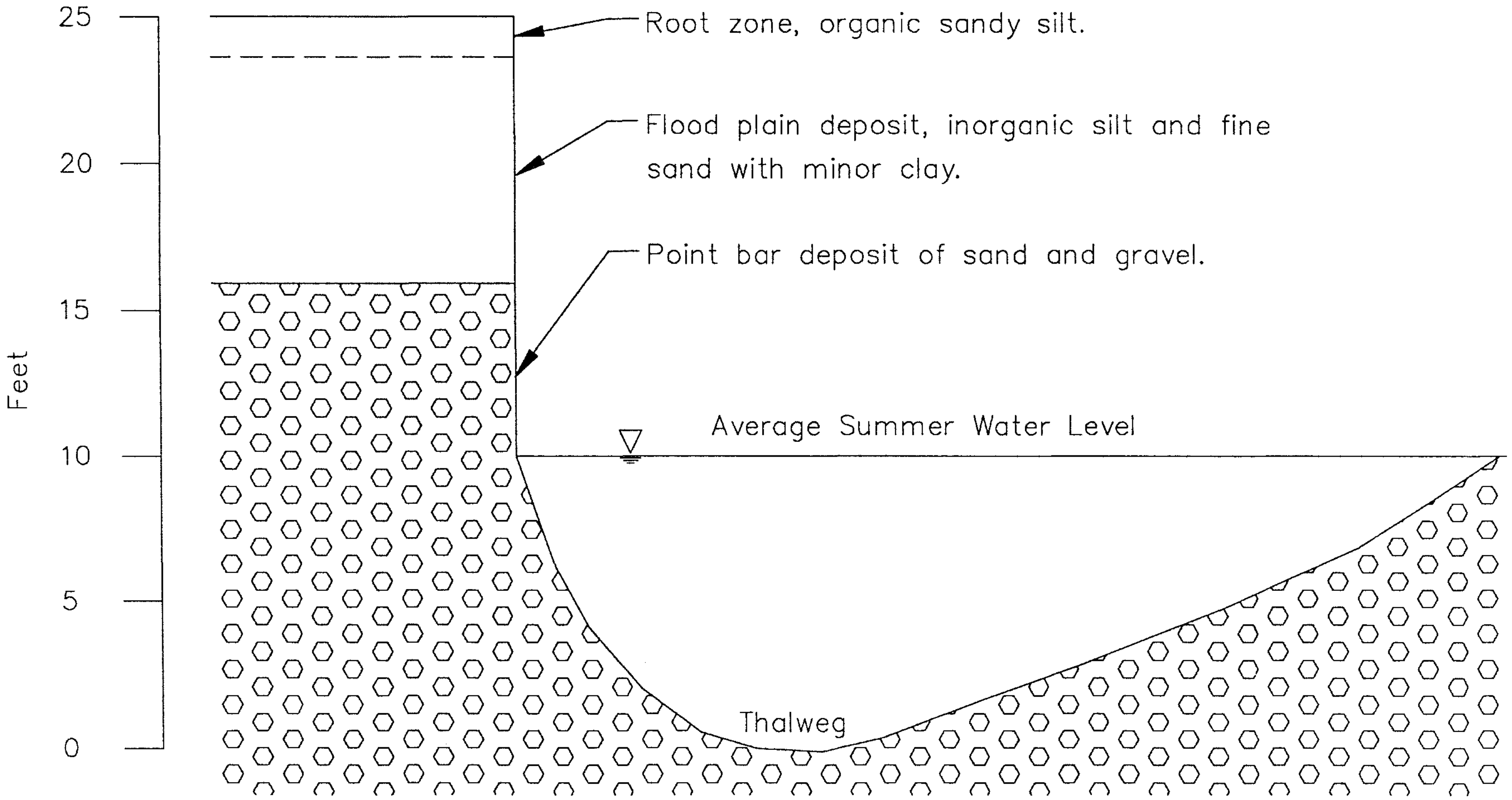
This site is at River Mile 222 on the east bank, about 4 miles upstream from Woodson Bridge, as shown on Plate 8. The mouth of Toomes Creek is at the upstream end of the site. Toomes #1 and #2 have a bend radius of curvature of about 2,500 feet. The entire bank area is planted with field crops. The west bank consists of low terrace gravel point bar deposit.

The eroding eastern bank consists of well consolidated clayey silty sand and clayey silt. Plate 4 shows that the one-hundred year meander belt is only about 2,000 feet wide. The Middle Sacramento River Spawning Gravel Atlas (DWR, 1984) shows that the 1896 river channel bifurcated in this area, with the eastern channel about 200 west of the present channel bank. Most of the erosion has occurred since 1969, with about 200 feet of eastward migration. There are no obvious channel features visible on aerial photographs in this area.

Toomes Creek #1 is on the upper end of a long sweeping curve. Only minor erosion has occurred here, with the maximum erosion at less than 4 feet between August 1986 to November 1992. However, between November 1992 and August 1993, a maximum 9 feet and an average 5 feet of bank recession occurred. Plate 1 shows the site geology. The eroding bank was mapped as Upper Modesto Formation by Helley and Harwood (1985). This would explain the slow rate of erosion.

Toomes Creek # 2

This site is a continuation of Toomes Creek # 1 and was considered to be a single site for the calculation of the radius of curvature. Plate 9 shows that erosion only occurred on the upstream half of the site. The lower half is in a slough area at low flows. Row crops and fallow grasslands are the predominant overbank vegetation. The bank profile is complex, consisting of

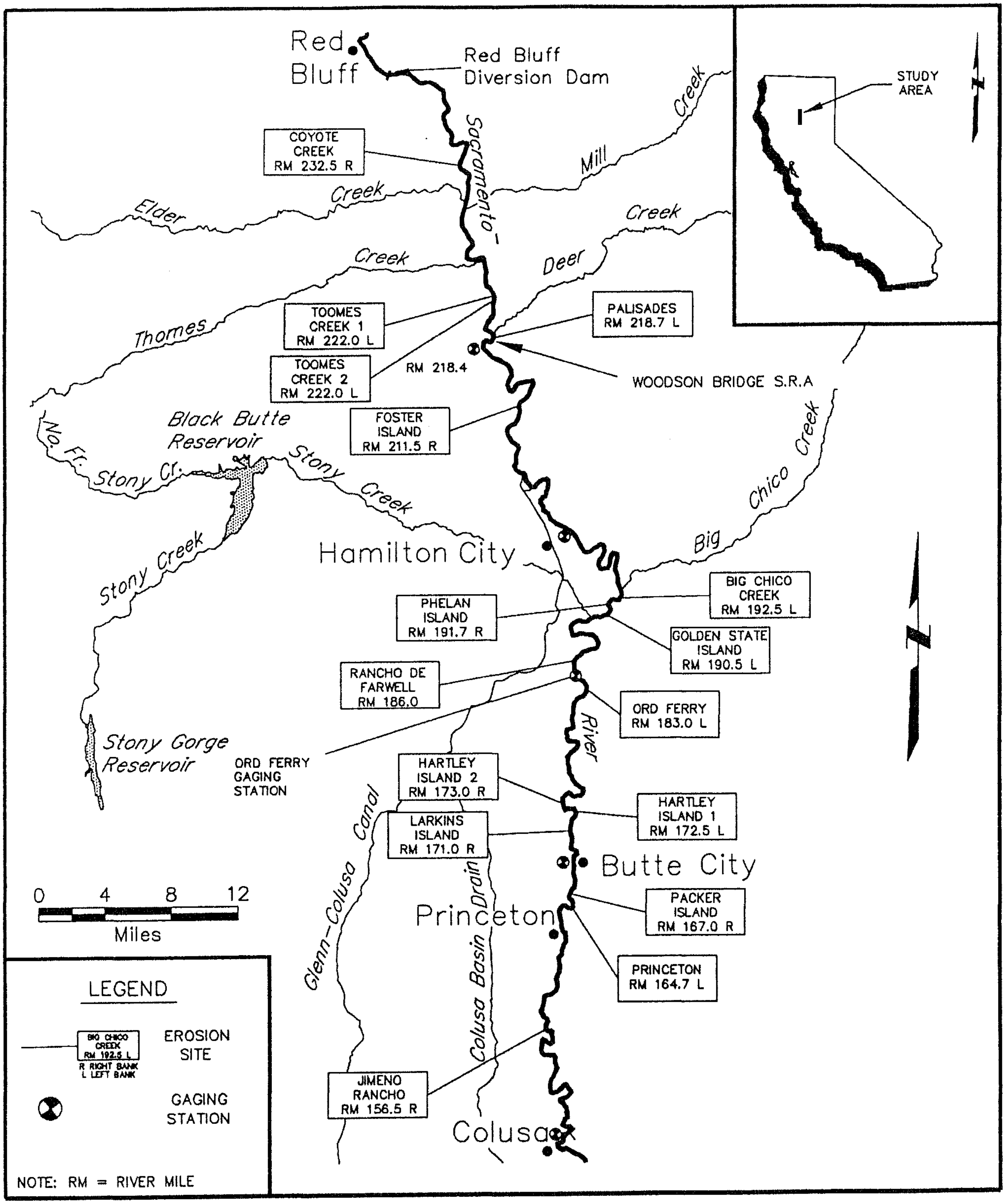


Sacramento River
Bank Erosion Investigation

Average Eroding Bank Cross-Section Red Bluff to Ord Ferry

Figure 18

Figure 19



STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

Sacramento River Bank Erosion Investigation
Erosion Site Locations
Sacramento River from Red Bluff to Colusa

a silt layer, underlain by a silty sand, underlain by a sandy gravel. Some of the bank layers extend further out into the river indicating that they are more resistant to erosion.

The bank was surveyed between August 1986 and December 1993. Most of the erosion occurred between stakes 6 and 9. Maximum erosion was at stake 8, with 46 feet of recession. Only minor erosion occurred on the upper and lower parts of the site.

Palisades

The Palisades erosion site, shown on Plate 10, is about one-half mile upstream of Vina Bridge on the southeast bank, in Woodson Bridge State Recreation Area. It was surveyed between August 1986 and November 1993. The Palisades bank protection method was installed along the eroding bank in the summer of 1986 before the surveying began. The area above the park has been unstable, with a 100-year meander belt of about 5,000 feet. Bank protection was installed directly above the erosion site in 1963. Plate 1 shows the west bank directly below the site is controlled by Tehama Formation overlain by (Upper) Riverbank Formation. This bank has not moved significantly in the last 100 years.

Plate 4 shows that the eroding bank was nearly straight in 1955, but since then has developed a radius of curvature of about 2800 feet.

The park has some unique morphology, with floodplain channeling trending parallel to the floodflow direction. These are probably formed by scouring from high-velocity floodflows. Large valley oaks line these flood channels. The area was mapped by Helley and Harwood (1985) as Recent stream channel deposits.

A typical cross-section of the bank is composed of three layers. The top one foot consists of dark gray, somewhat organic silt, underlain by about 20 feet of light brown silt with thin lenses of sandy silt and sand. These two units are floodplain deposits, commonly referred to as the Columbia soil series. Below the flood plain deposits are sand and gravel. These represent older stream channel and point bar deposits from previous meandering episodes. Well completion reports from nearby wells indicate that the sand and gravel continues to depths of 40 to 60 feet. This was the tallest eroding bank measured in the Red Bluff to Colusa reach of the river. Only minor bank recession was measured at this site. Most of this was caused by bank slumping behind the Palisades. Silt and sand deposited between the nets to depths of 3 to 7 feet.

Foster Island

This site is at River Mile 211.5, on the right bank on the upper part of Foster Island. The site is approximately 9 miles south of Woodson Bridge, as shown on Plate 11. Plate 4 shows that at this site, the river has been slowly moving from the east side of the meander belt downstream to the west. Vegetation alternates between grassland and dense riparian vegetation in about equal amounts. The bank consists of an upper layer of mostly silt with some sand, underlain by mostly gravel with some sand. The bank is mildly curved, with a radius of curvature of 3,800 feet. Plate 1 shows that the river is eroding sediments mapped as part of the historic meander belt.

The hundred-year meander belt is only 1,500 feet wide at this point, although the historic meander belt is much wider, probably in the order of 12,000 feet. The site has had about 1,000 feet of erosion in the last 100 years.

There was very little bank erosion at this site between June 1988 and November 1992, with a maximum of 4 feet, occurring at stake 11 in the upper third of the site. Average bank erosion between June 1988 and June 1990 is less than one foot. During the winter storms of the 1993 water year, a maximum of 32 feet of bank erosion was recorded on the lower third of the site.

Big Chico Creek

This erosion site is a bit more than a mile below Big Chico Creek on the east bank, at River Mile 192.5 (Plate 12). It is about two miles above the confluence of the Sacramento River and Stony Creek. Bank erosion was measured here between June 1988 and August 1993. Plate 2 shows that the eroding bank is part of the historic meander belt.

It is mostly a riparian site, with large, mature trees and thick riparian jungle over much of the bank. The site is 3,200 feet long. The bank consists of a thick layer of sandy silt underlain by a sandy gravel. The geologic units are shown on Plate 2.

This is an area where the river has moved more than 3,000 feet in the past 100 years (Plate 5). The river bank has receded about 500 feet since 1969. Riprap occurs upstream of the site. The site has no clearly defined radius of curvature because of irregularities in the bank, but the eroding portion is nearly straight.

The west bank is a gravel bar that has constricted the river near the head of the erosion site. Most of the erosion is occurring in this constricted reach. Between June 1988 and November 1992, maximum erosion occurred at stake 15, with about 67 feet of erosion. During the 1993 water year, a maximum of 25 feet eroded.

Phelan Island

The Phelan Island site is on the west bank at River Mile 191.7 about one mile above the confluence of the Sacramento River and Stony Creek. Details of the site are shown on Plate 13 and the geology on Plate 2. The bank vegetation is orchard along the entire length. The site was surveyed from August 1986 until June 1988. It was riprapped during the fall of 1988 and the site was discontinued. The radius of curvature is about 2,200 feet. The river has not migrated through Phelan Island in the last 100 years, but geomorphic evidence suggests that the river migrated through the area shortly before that (Plate 5).

Golden State Island

Golden State Island is at River Mile 190.5 on the east bank about one-half mile north of Stony Creek (Plate 14). The geology is shown on Plate 2. The site was surveyed between August 1986 and June 1988. The site was riprapped in the fall of 1988. Golden State Island is an old meander loop that was cut off in the late 1930s (Plate 5). No information is available on bank composition because the site was riprapped prior to bank sampling. Dense riparian jungle occurs near the top and at the bottom of the site. Grass and an open field occur in the middle.

The 100-year meander belt is about 5,500 feet wide at this point. There is evidence of a wider zone of historic meandering. The river moved about 900 feet eastward into the old meander loop between 1969 and 1988.

The radius of curvature is about 1,900 feet. Rapid erosion was occurring at the site prior to riprapping. The maximum erosion between August 1986 and June 1988 was 53 feet.

Most of the erosion occurred in the middle and lower part of the site.

Rancho de Farwell

This site is on the west bank at River Mile 186, about 1.5 miles above Ord Ferry Bridge, as shown on Plate 15. The entire site is in orchard. The bank material varies, with sandy silt underlain by sandy gravel in the upper and lower third of the site. The midportion of the site with the majority of the erosion, consists predominantly of an unconsolidated sandy gravel. The radius of curvature is about 2,200 feet and the site is 4,800 feet long. The site was surveyed between August 1986 and August 1993.

The river has not been at this location in the last 100 years (Plate 5), but geomorphic evidence suggests that the river was there shortly before that. The 100-year meander belt is only about 3,000 feet wide at this point. Meander scrolls and arcuate geomorphic features indicate that the historic meander belt is much wider, on the order of 12,000 feet.

Plate 2 shows that the river is presently eroding the historic meander belt along most of the erosion site. Stereo aerial photo pairs confirms that the lower bank is higher in elevation.

This site is highly erodible. A maximum of about 80 feet of erosion occurred toward the middle of the site between August 1986 and November 1992. During the winter of 1992-1993, a maximum of 190 feet of erosion occurred. The maximum combined erosion was 262 feet.

Ord Ferry

The Ord Ferry site is on the east bank at River Mile 183, about one mile downstream from Ord Ferry Bridge (Plate 16). It is in an area where the river has steadily and consistently eroded the east bank, for a total of about 3,000 feet in the last one hundred years (Plate 5). Riprap extends down to the site's upstream end. The site has been surveyed between August 1986 and December 1993.

Riparian jungle occurs on the upstream one-half of the eroding bank, with grass on the second half. Much of the upstream bank is underlain by an erosion resistant clay plug, the remnants of an oxbow lake deposit. Helley and Harwood (1985) mapped this deposit as stream channel deposits. Plate 2 shows that older stream channel deposits occur along the upstream end; however there is a thin sliver of historic meander belt deposits along the bank that is too thin to map. Meander belt deposits occur at the lower end. The hydraulic radius is about 2,300 feet. The west bank consists of a large gravel bar with emergent riparian vegetation. The bank receeded a maximum of about 34 feet between August 1986 and November 1992. The maximum amount of erosion recorded between November 1992 and December 1993 was 43 feet.

Hartley Island # 2

This site is on the right bank at River Mile 173 about 4 miles upstream from Butte City (Plate 17). The site is on the downstream end of the meander around Hartley Island. Bank erosion has been measured here between June 1988 and December 1993. The vegetation consists of, from upstream to downstream, orchard, riparian, cropland, riparian, grass and riparian. The opposite bank on the inside of the bend is mostly gravel bar and young riparian vegetation. The Hydraulic radius is about 2,800 feet.

The bank erosion is occurring in deposits mapped as historic meander belt on Plate 3 and by Helley and Harwood (1985) as stream channel deposits. The upstream part of the eroding bank is in the historic meander belt but not in the 100-year meander belt (Plate 6). The downstream part has been eroded at various times as the river migrated from west to east.

A maximum of about 11 feet of erosion occurred at this site between June 1988 and November 1992. Between November 1992 and December 1993 the maximum amount of erosion was 27 feet.

Hartley Island # 1

Hartley Island # 1 is at River Mile 172.5 on the east bank about 3.5 miles upstream from Butte City (Plate 18). The eroding site is in a walnut orchard with some riparian toward the middle of the site. Bank composition has not been mapped at this site. The site has been surveyed from August 1986 to August 1993.

The river has migrated steadily eastward a distance of about 2,500 feet for the last 100 years and the meander belt is 3,500 feet wide (Plate 6). The point bar developing on the inside of the bend is mostly young riparian vegetation. The hydraulic radius is about 2,200 feet.

The bank erosion is occurring on historic meander belt deposits (Plate 3). These deposits are over 100 years old.

Most of the erosion appears to occur at the downstream end of the bend. Maximum erosion is about 112 feet, with 52 feet occurring between November 1992 and August 1993.

Larkins Island

Larkins is at River Mile 171.0 on the west bank about 2.5 miles above Butte City (Plate 19). The site has been surveyed since 1986 to the present. The river has been slowly migrating westward through the historic meander belt (Plate 3). Bank vegetation is entirely orchard. Bank composition has not been mapped at this site.

The 100-year meander belt is only about 2200 feet wide in this area and the river has eroded westward about 1,000 feet during this time (Plate 6). The vegetation is mostly field crops at the upstream end and orchards in the lower end. The hydraulic radius of the eroding bank is 2,000 feet. The opposite bank is a gravel point bar with incipient riparian vegetation.

Most of the erosion during the 1986-1992 drought occurred in the midportion of the bend. A maximum of 24 feet of bank recession occurred between July 1986 and November 1992. During the winter of 1992-1993, a maximum 54 feet of recession occurred on the downstream end of the meander bend.

Packer Island

This site is on the right bank at River Mile 167.0 (Plate 20). It has been surveyed since June 1988. The site has a wide variety of vegetation, including riparian, grassland and orchards in patches. The river is eroding westward, about 2,000 feet since 1896 (Plate 6). The meander belt is about 4,000 feet wide at this point. The hydraulic radius is about 2,000 feet. The east bank is mostly an open gravel bar with a band of riparian vegetation along a recent river cutoff. A maximum of about 142 feet were eroded during the survey period, of which 120 feet eroded between November of 1992 and August 1993. Most of the erosion occurred on the downstream end of the bend. Plate 3 shows that the river is eroding the historic meander belt.

Princeton

The Princeton site is on the southeast bank at River Mile 164.7, about one mile upstream of the town of Princeton, as shown on Plate 21. The site was monitored between August 1986 and August 1993. This site was also monitored between 1977 and 1979 (DWR, 1979). The site is the most erodible site measured, and at present probably also the most erodible bank on the Sacramento River. The meander belt is about 3,500 feet wide (Plate 6). Contrary to most banks, the Princeton site is eroding laterally southward, and is not showing typical meander development. The river has moved in this direction more than 3000 feet since 1896, and as much as 2,200 feet since 1935.

The river is eroding a meander loop that was cut off prior to 1896 (Plate 3). The banks consist of a thick layer of unconsolidated silt underlain by medium to fine gravel. According to Helley and Harwood (1985), the eroded deposit is Quaternary Alluvium. The bank vegetation is prune orchard. Several buildings and an equipment yard have been lost in the last five years. The northwest bank is low terrace riparian vegetation. The eroding bank is scalloped but fairly straight. No definable radius of curvature can be assigned to this bank. A maximum of about 150 feet of bank recession occurred between August 1986 and November 1992. In the winter of 1992-1993, a maximum 150 feet of erosion occurred.

Jimeno Rancho

Jimeno Rancho erosion site is at River Mile 156.5 on the west bank (Plate 22). The site is about 2 river miles south of Moulton Weir. This site has been surveyed between June 1988 and August 1993. Orchards occur on the overbank area. The radius of curvature is about 1,600 feet. A point bar with gravel and riparian vegetation has developed on the east bank.

The meander belt is narrow, less than 2,000 feet (Plate 6). The river is eroding historic meander belt material (Plate 3) deposited more than 100 years ago, mapped as stream channel deposits by Helley and Harwood (1985). A maximum of 44 feet eroded during the monitoring period.

Results

Table 8 shows the results from the sixteen erosion sites.

A number of other variables other than duration and magnitude of discharge affect bank erosion rates. Some of those suggested include the resistance to entrainment by the bank materials (bank composition), radius of curvature of the bend, bed material sediment transport capacity of the flows, bank height, and degree of root reinforcement of the bank by vegetation.

Our bank erosion study began in 1986, at the same time as California's extended seven year drought. Most of the data gathered were from low-flow erosion. High flows occurred in the winter and spring of 1993. These data are included in the report, but detailed analysis were not done in time for this report.

Bank composition has been identified as one of the factors influencing bank erodibility.

Our preliminary results indicate a significant positive correlation between the amount of bank erosion and discharge. It was noted that more erosion occurred during discharge events above base flow than at base flow alone. The amount of erosion attributable to these peak events will be quantified by subtracting base flow erosion (low flow) from peak event erosion (high flow) and developing discharge vs. erosion relations. Base-flow erosion from May through November 1987 averaged 1.0 feet per site with values ranging from a low of 0 feet erosion at Toomes Creek to a high of 3.8 feet at Princeton erosion site. This corresponded to an average base flow of 8,370 cubic feet per second over 180 days. Erosion from December 9, 1986 through May 18, 1987 ranged from a low of 0 feet at Toomes erosion site to a high of 12.6 feet at Princeton. This corresponded to an average flow of 19,020 cfs during 54 days when discharge exceeded base flow during this 157-day period. Erosion from November 21, 1987 through June 7, 1988 averaged 5.1 feet per site from a low of 0 feet at Toomes Creek erosion site to a high of 18.9 feet at Princeton. This corresponded to an average flow of 18,180 cfs during 58 days when discharge exceeded base flow during this 196-day period.

Princeton and Golden State Island erosion sites had the most active erosion, averaging 15.1 feet during the two high-flow periods and 2.5 feet during the one base-flow period.

There is the possibility that survey benchmarks may be lost during flooding.

Golden State Island and Phelan Island were riprapped by the Corps of Engineers and have therefore been dropped from DWR's erosion monitoring project. However, it may prove useful to continue monitoring these locations in other ways. Some of the first surveys were done using angles that were not repeated in later surveys. It was found that the resulting data could not be used for comparative purposes. Consequently, the most recent erosion surveys also included these old angles in order to use the initial surveys.

TABLE 8 SACRAMENTO RIVER BANK EROSION SITES

Site Name	Years Surveyed	Maximum Erosion (Feet)	Mean Erosion (Feet)	Eroded Silt (Yard^3)	Eroded Gravel (Yard^3)	Average Eroding Bank Length (Feet)
Coyote Creek	1988-93	19	11	14310	18310	2960
Toomes Creek I	1986-93	9	5.2	8000	1310	1650
Toomes Creek II	1986-92	37	18	42660	9990	3100
Palisades 1	1986-89	10	3.4	29770	5430	2640
Palisades 2^	1990-91	1.2	1.2	3150	570	2690
Palisades 3^	1991-92	1.4	0.7	1940	350	2710
Foster Island	1988-93	32	12	39970	15250	5260
Big Chico Creek	1988-93	77	41	89510	41350	3490
Phelan Island 1	1986-87	2.6	1.2	*	*	3930
Phelan Island 2^	1987-88	3.8	0.9			3970
Golden State Island	1986-88	53	29	*	*	3200
Rancho de Farwell	1986-93	262	128	297540	256560	5000
Ord Ferry	1986-92	34	23	*	*	3620
Hartley Island II	1988-92	11	3.9	*	*	5510
Hartley Island I	1986-93	112	54	*	*	5660
Larkins Island	1986-93	54	26	*	*	4340
Packer Island	1988-93	142	69	*	*	4150
Princeton 1	1986-91	140	103	*	*	2070
Princeton 2^	1991-93	182	89	*	*	3040
Jimeno Rancho	1988-92	44	35	*	*	3740

^ Same erosion site but different survey backsights

* Silt and gravel volumes not available

FLOODPLAIN DEPOSITION

Floodplain deposition regenerates high-terrace soils lost by bank erosion. Bank erosion occurs year-round. The floodplain deposition occurs during large floods on an episodic basis. An average of 3 to 6 inches to, in places, several feet of silt may be deposited during a single flood. The deposition process can rebuild high-terrace soils at a fairly rapid rate. Areas that were river bottom in the 1940s are presently being farmed. The rate of formation of high terrace soils has been reduced by flood control.

It was believed (USCE 1978) that through bank erosion, high-terrace lands were being replaced by low-terrace point bars because Shasta Dam reduced deposition of soils on the floodplain. Observations made during this study indicate that this may not be the case. After the flood of March 1983 and February 1986, floodplain deposition was observed in a number of places. Deposition varied from zero inches to over 2 feet, with an average of several (3-6) inches within the flooded area. Although the incidence of floodplain deposition has decreased, so has the rate of bank erosion. In a study of land use changes in the Sacramento River Riparian Zone, DWR (1983) came to a similar conclusion:

> "....there has been no overall loss of high-terrace prime soils from 1946 through 1982. Erosional losses of soil, both in orchard and riparian vegetation, have been severe, but natural soil building processes have created an equal or slightly greater amount of prime high-terrace soil."

It is not known if the present high terrace soils are at a lower elevation than pre-Shasta Dam high terrace soils.

Floodplain Cross-Sections

Five cross-sections were surveyed during the summer of 1986. These extend from one side of the floodplain or centerline of a project levee, across the floodplain, across the Sacramento River to the opposing side of the floodplain or project levee. These surveys re-established historic profiles done by the U. S. Geological Survey during the mid-1970s. Cross-sections were located at the Glenn-Colusa Irrigation Canal, Pine Creek, Jacinto, Butte City and Moulton Weir. Elevations were run at intervals of 20.0 feet and read to tenths of a foot. All level loops were closed and checked.

In the summer of 1988, five additional cross-sections were surveyed. These include cross-sections at the Red Bluff Diversion Dam, Sacramento Bar, Tehama-Los Molinos, Woodson Bridge and Hamilton City. These cross-sections are compared to U.S. Army Corps of Engineers cross-sections surveyed between 1917 and 1923. The locations of the ten floodplain cross-sections are shown on Figure 20 and summarized on Table 9.

TABLE 9 SURVEYED FLOODPLAIN CROSS-SECTIONS

SURVEYED CROSS-SECTION	RIVER MILE	YEARS SURVEYED	
Red Bluff Diversion Dam	243.0	1917	1988
Sacramento Bar	235.6	1923	1988
Tehama-Los Molinos	227.5	1923	1988
Woodson Bridge	218.4	1917	1988
Hamilton City	206.0	1917	1988
Glenn-Colusa Irrigation Canal	201.2	1977	1986
Pine Creek	197.7	1980	1986
Jacinto	175.4	1972	1986
Butte City	168.5	1979	1986
Moulton Weir	158.7	1976	1986

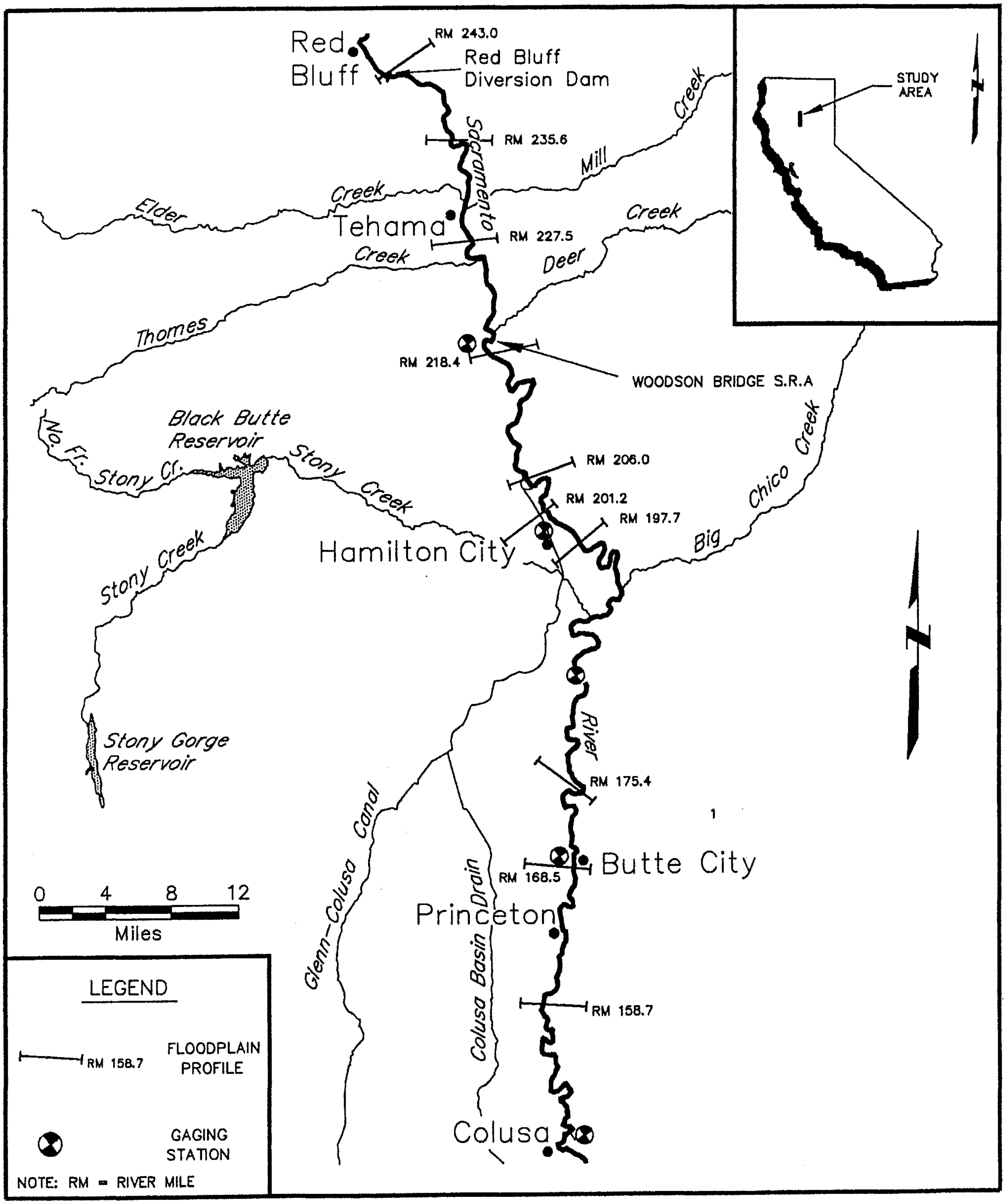
Red Bluff Diversion Dam - River Mile 243.0

This cross-section was originally surveyed by the U.S. Corps of Engineers in 1917. The River Mile 243.0 cross-section is at the Red Bluff Diversion Dam (Figure 21). The cross-section crosses the dam axis and traverses across open and tilled fields. Elevations are only shown on the east bank of the river. The section showing elevations is about 8,600 feet long. Survey monuments were established in the parking lot of the diversion dam and near the right abutment. Maximum silt deposition in floodplain swales is 15 feet. The river moved about 500 feet eastward between the two surveys.

Elevations were taken from a U.S. Geological Survey monument on the east abutment of the diversion dam.

Sacramento Bar - River Mile 235.6

The River Mile 235.6 cross-section crosses Sacramento Bar, about 9.5 miles south of Red Bluff (Figure 22). The cross-section begins on the east side near the intersection of Antelope Creek and Clement Avenue and extends about 6,600 feet across the floodplain to the levee on the west side of the Sacramento River. Comparison of the 1988 and the 1923 cross-sections shows that the river has moved about 2,500 feet southeast by meander cutoff, and the old channel has been filled in by an average of about 20 and a maximum of 26 feet of sediment.



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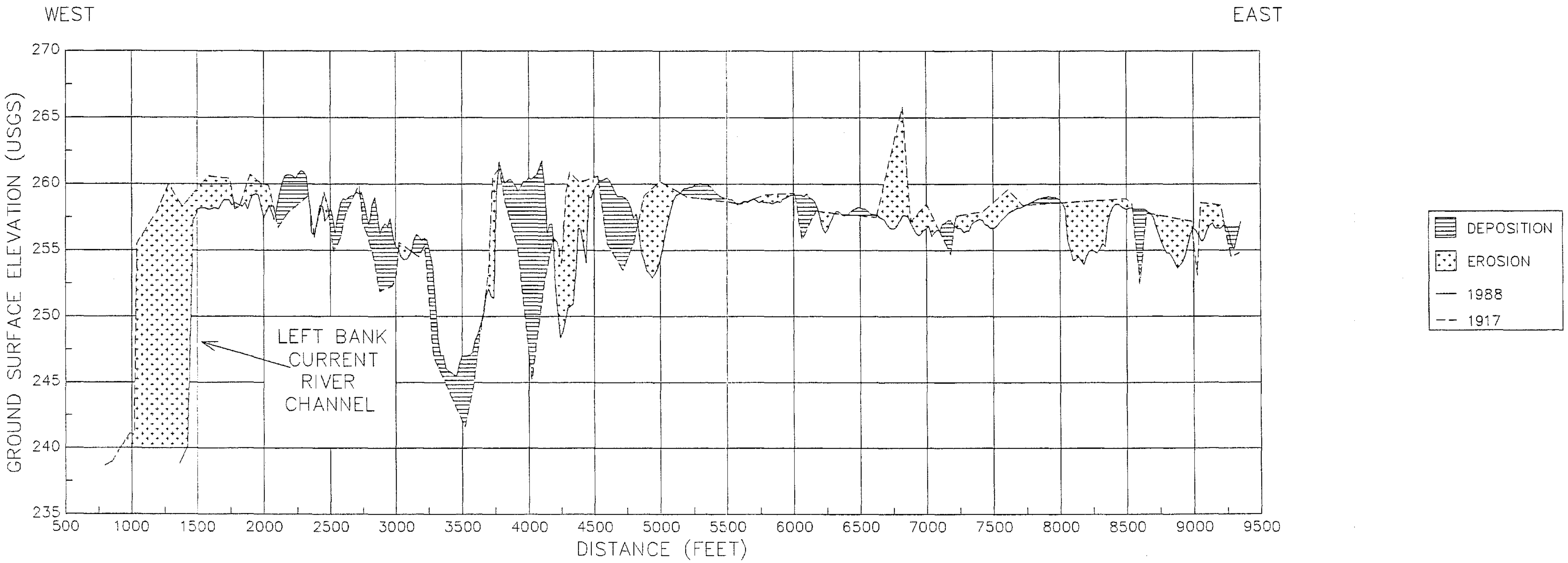
Sacramento River Bank Erosion Investigation
Floodplain Profile Locations
Sacramento River from Red Bluff to Colusa

Figure 21



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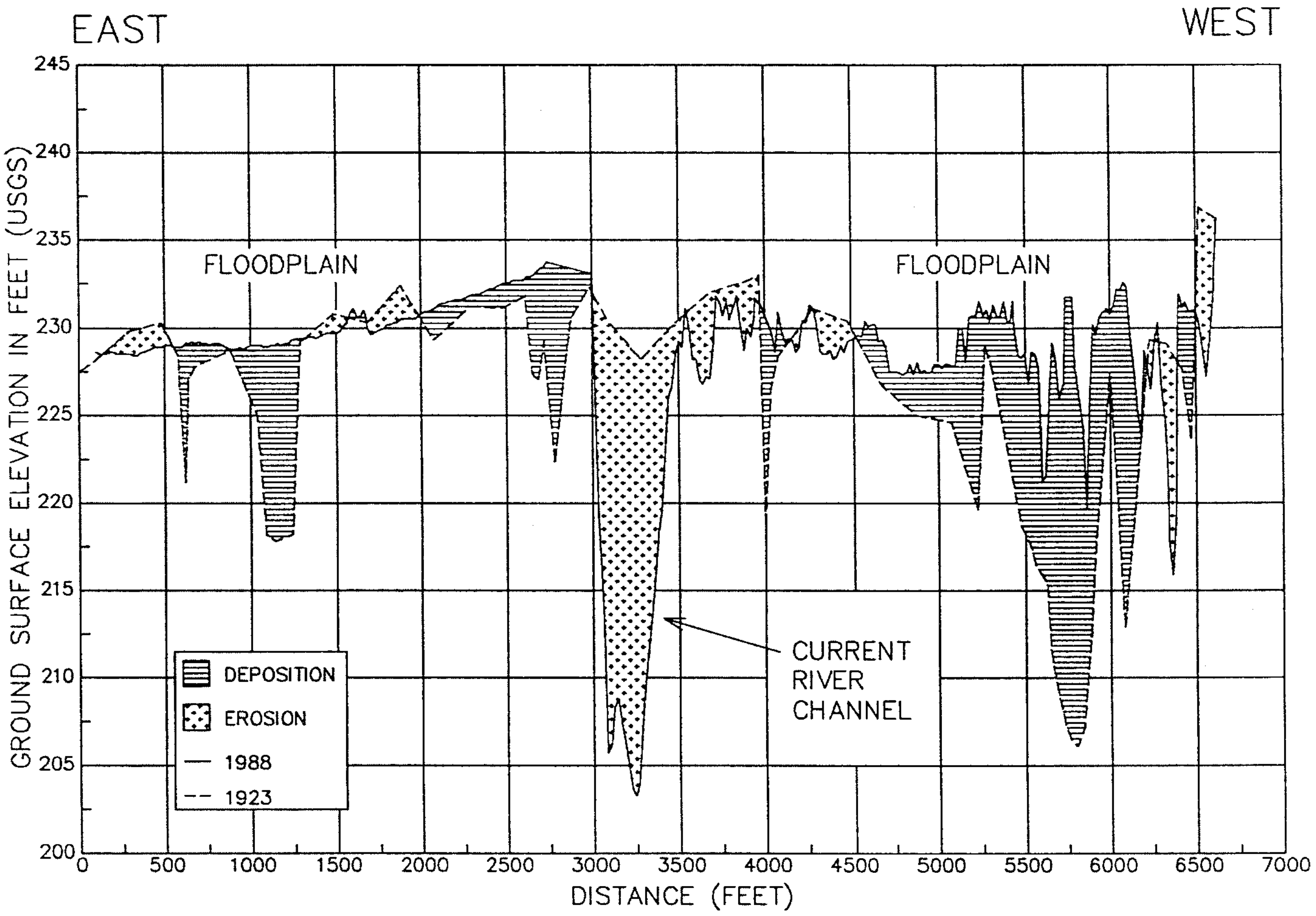
Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross Section
River Mile 243.0



Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross-Section at River Mile 235.6

Figure 22

The highest part of the profile is on the east side adjacent to the present river channel. The channel thalweg is three feet deeper in 1988 than in 1923. The maximum depth of erosion is 25 feet, and the maximum depth of deposition is also 25 feet. The yearly average deposition rate is 4.6 inches (0.38 feet). During the 65 years between the two sections, a net deposition of 1.24 feet occurred.

Tehama- Los Molinos - River Mile 227.5

This cross-section is about 5,900 feet long and located 1.5 miles downstream from the bridge in Tehama at River Mile 227.5 (Figure 23). It consists of orchards, a densely vegetated island, open fields and riparian land.

Some extensive changes have taken place at this profile. In 1923, the river had multiple channels through this area. The eastern channel is now an oxbow lake and the main western channel is now a slough. The main river channel has moved about 600 feet to the east. A maximum of about 25 feet of deposition has occurred in the old channel. The old oxbow on the eastern part of the floodplain, about 2,000 feet from the present channel, has filled with an average of about 14 and a maximum of 25 feet of sediment. During the 65 years between the two sections a net deposition of 1.05 feet occurred.

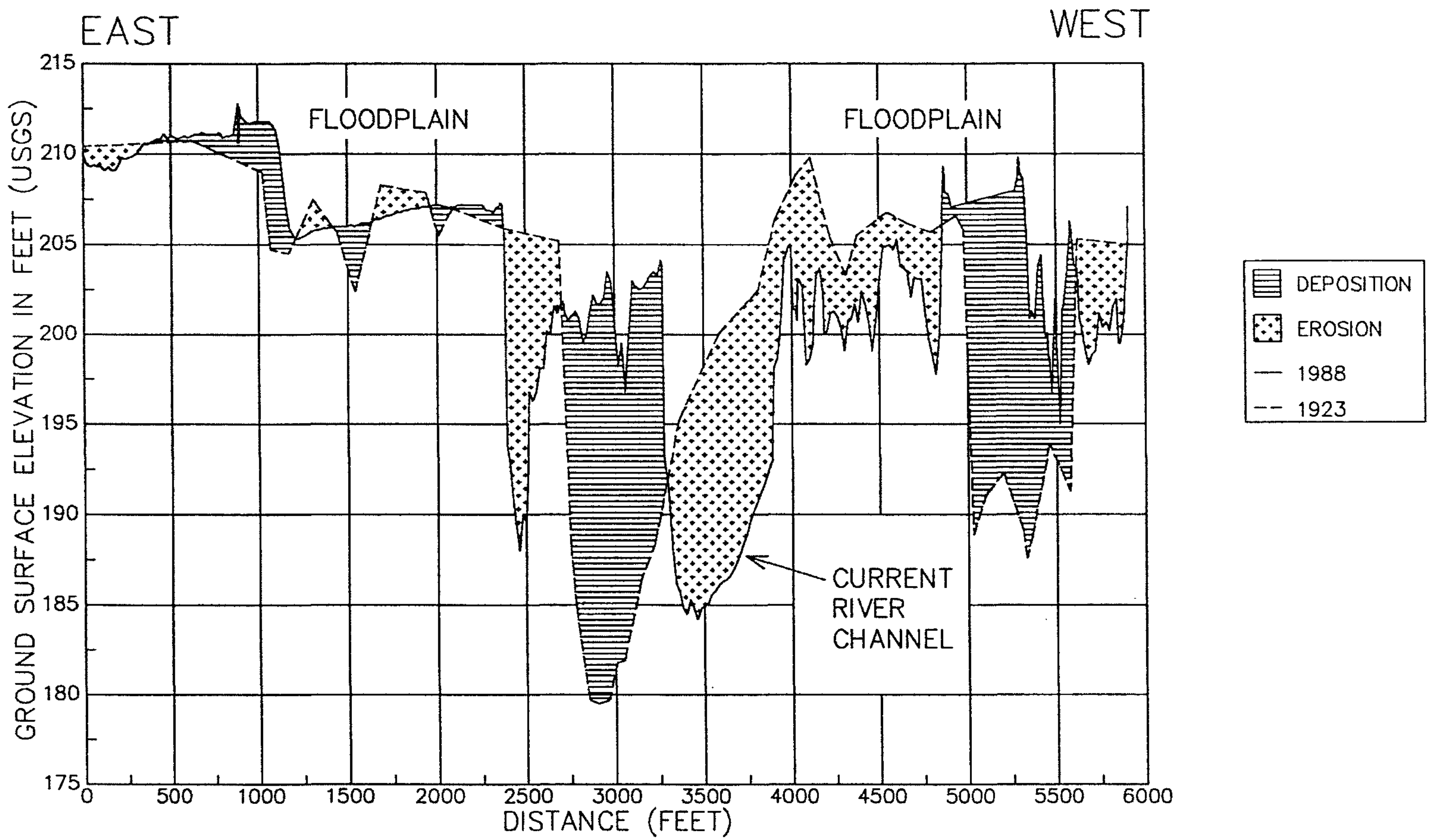
Woodson Bridge - River Mile 218.4

This section is near Woodson Bridge State Recreation Area (S.R.A.) (Figure 24). The Sacramento River has not moved substantially at this site because of outcrops of Tehama Formation on the west bank. The cross-section is about 13,230 feet long and includes orchards, riparian land and Woodson Bridge S.R.A.. The west end is on the west bank of the river just upstream from Woodson (Vina) Bridge and follows the north side of Gardiner Ferry Road (South Avenue) to the Southern Pacific Railroad.

USGS datum elevations were established on the section using benchmark number F842 at elevation 200.94 feet and an elevation from DWR of 177.44. Comparison of the 1988 versus the 1917 cross-section shows that at this point the river and floodplain have remained fairly stable. There has been 5,400 square feet of erosion and 45,900 square feet of deposition, mostly on the floodplain. Between 1917 and 1988, an average of about 3.1 feet of silt deposition occurred over the entire section.

Hamilton City - River Mile 206.0

This section (Figure 25) is about 5 miles north of Hamilton City. It crosses the river just north of the Glenn-Colusa Irrigation District pumps. The floodplain consists mostly of orchards with some gravel bars near the river. The cross-section extends from Canal Road on the east side to the intersection of Cutting Avenue and Second Street on the west side.

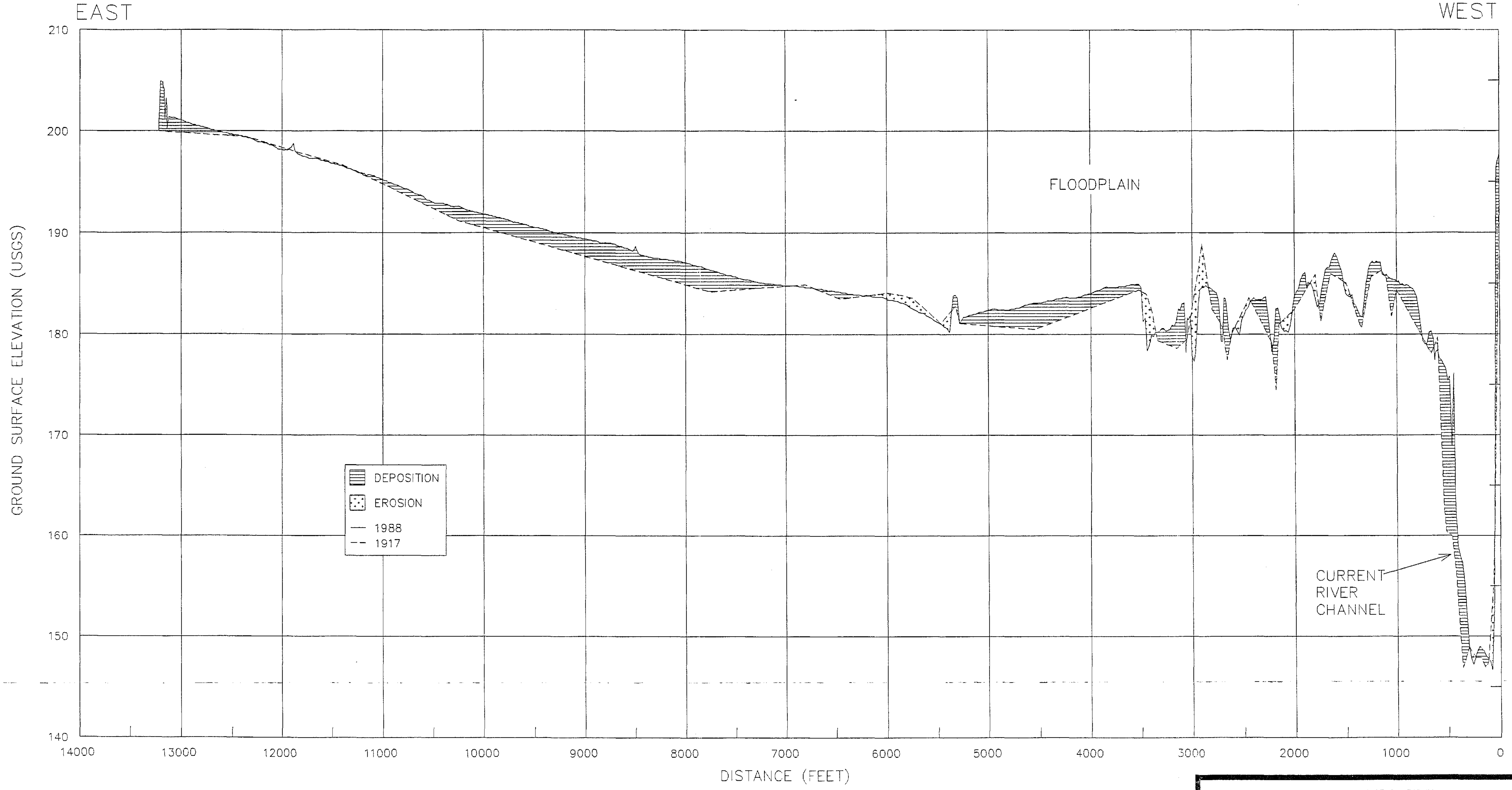


Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross-Section at River Mile 227.5

Figure 23

Figure 24



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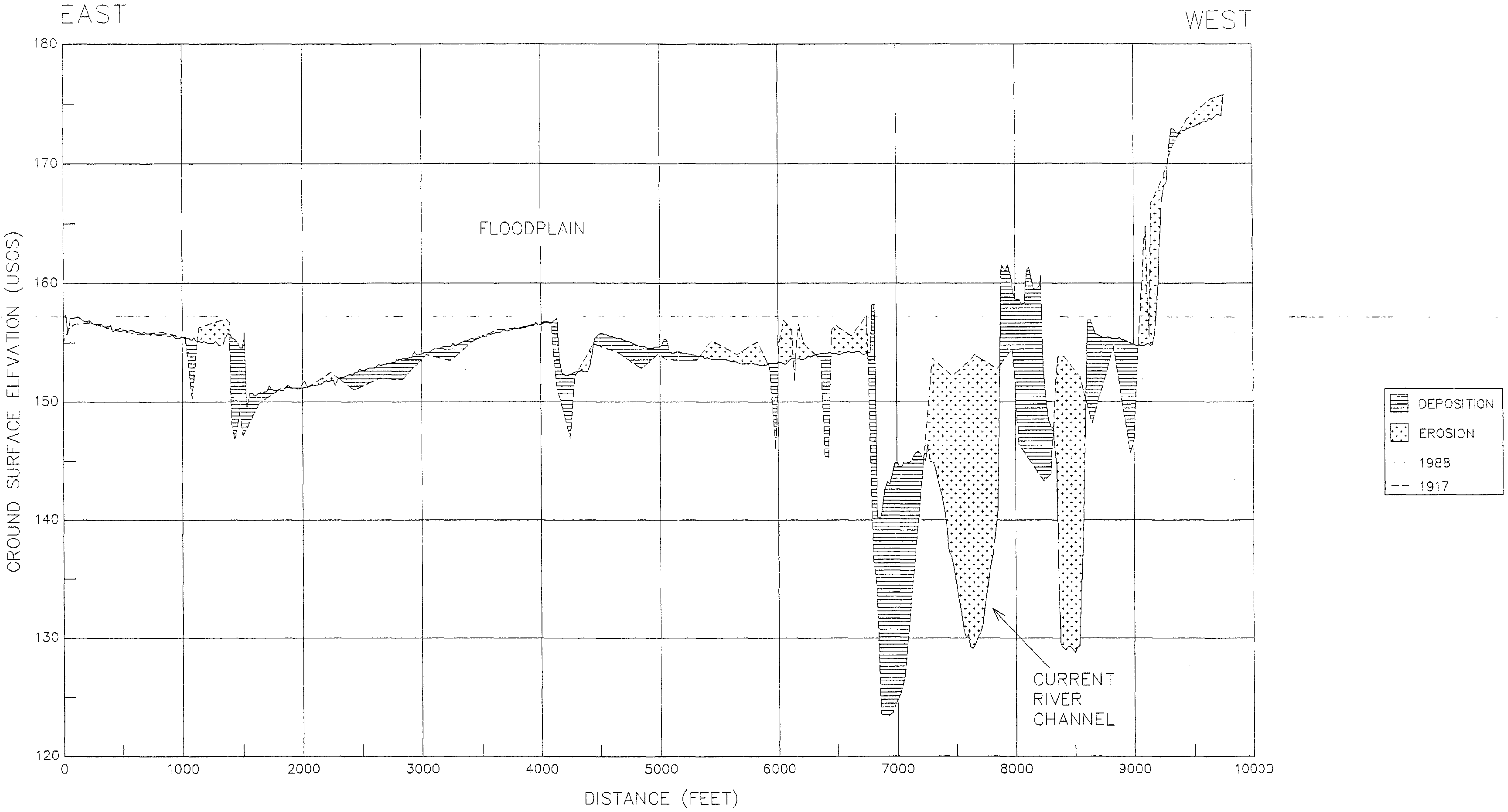
Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross-Section
River Mile 218.4



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Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross-Section
River Mile 206.0

USGS elevations were brought in from the west side of the pumps. Comparing the 1986 cross-section to the 1917 shows that the river has moved about 600 feet west and deposition has occurred behind it. It also shows a second channel on the west side that serves as the inlet to the pumps. This channel is maintained by dredging and depositing the material on the island between the two channels. Overbank deposition also appears to be occurring on the east side floodplain. Some of this may be due to leveling and infilling prior to orchard planting.

About 20 feet of deposition has occurred in the 1917 channel and about 23 feet of erosion has occurred in the location of the 1988 channel. The thalweg of the 1917 channel is about 7 feet lower than the 1988 channel.

Glenn-Colusa Irrigation Canal - River Mile 201.2

The section at River Mile 201.2 is only about 2,000 feet long (Figure 26). It extends from a riprapped levee road on the eastern river bank, across the river, through an orchard to the levee on the west bank. The cross-section was first surveyed by the USGS in 1977 and resurveyed by DWR in the summer of 1986. A considerable amount of channel erosion appears to have occurred during that period. The east bank is stable because of the riprap and no lateral erosion has occurred. This cross-section has degraded overall by 0.68 feet mostly because of the channel erosion, but the floodplain appears to have neither aggraded or degraded substantially.

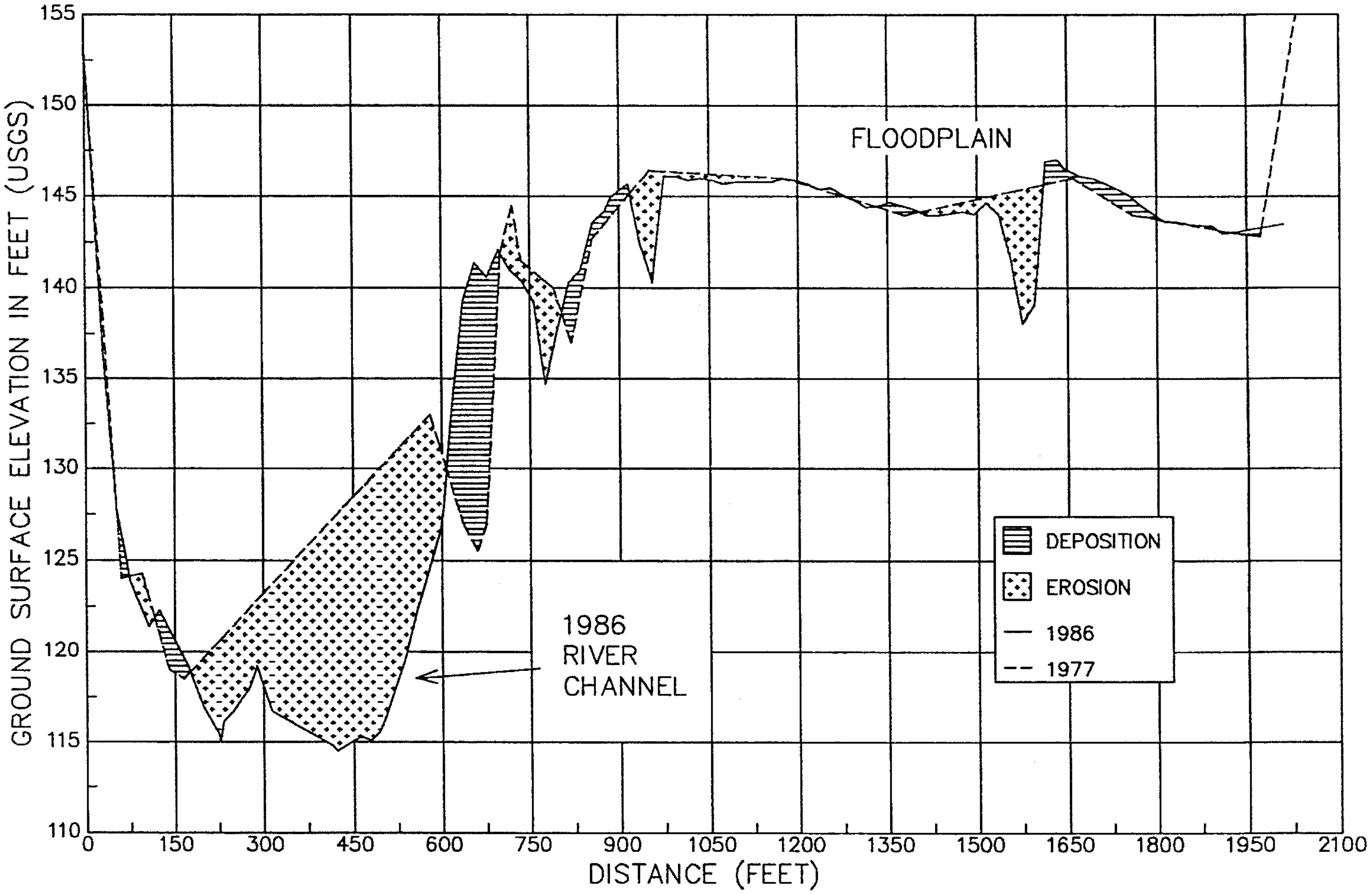
Pine Creek - River Mile 197.7

This cross-section is about one and a half miles below the Hamilton City Bridge (Figure 27). It extends from an elevated levee road on the west side, through some orchards to the riprapped bank of the Sacramento River. The east side consists mostly of riparian vegetation with alternating strips of trees and grass. The cross-section terminates on a levee road. Total distance is about 4,500 feet.

The channel section appears to be stable because of the riprapped bank. The maximum depth increased about 2 feet during this time period. Both deposition and erosion occurred on the east side and deposition on the west side. Overall, the profile lost 0.3 feet between 1980 and 1986, although the floodplain had net deposition.

Jacinto - River Mile 175.4

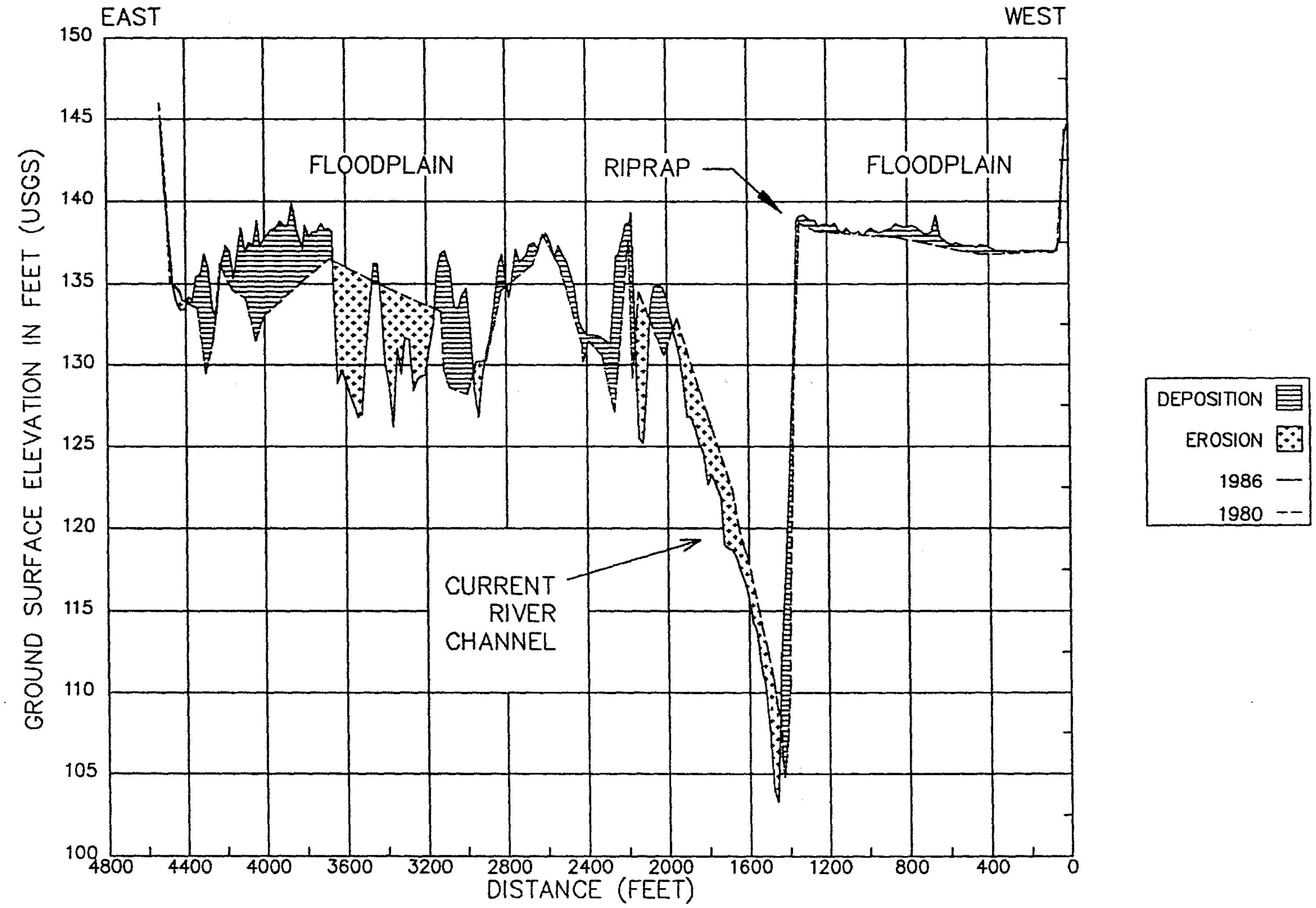
River Mile 175.4 cross-section is directly north of Hartley Island, a few miles north of the town of Glenn (Figure 28). Only the channel section was surveyed in 1988, but the old section extends from the project levee on the west side, across the Sacramento River onto a meander loop cutoff, across a slough and an orchard to the project levee on the east side.



Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross Section – River Mile 201.2

Figure 26



Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross-Section at River Mile 197.7

Figure 27

Butte City - River Mile 168.5

Cross-section 168.5 is a few hundred feet above the Butte City Bridge and follows parallel to State Highway 162 for a distance of about 4,600 feet (Figure 29). The east side of the cross-section begins on the levee, crosses a river terrace, and intersects the riprapped bank of the Sacramento River. The west side has 3,800 feet of orchards before crossing Rasor Slough and minor riparian vegetation. The 1979 section was surveyed by the U.S. Geological Survey and resurveyed by DWR in 1986.

The river has not been eroding in this area in the last 100 years. The east bank is stable because of geologic control and riprap. There is abundant evidence that the river had previously meandered all the way to the western end of the cross-section, at Razor slough. As much as 4 feet of silt was deposited on the west side floodplain between the time of the two cross-sections. The thickness decreased away from the river, until at about 2,800 feet, where some erosion occurred. A maximum of 6 feet was also deposited in Rasor Slough. A maximum of about 20 feet of erosion also occurred in the channel, and the thalweg lowered about 14 feet. This channel section is the deepest of the ten cross-sections surveyed. Overall, an average of 0.3 feet of aggradation occurred between 1979 and 1986.

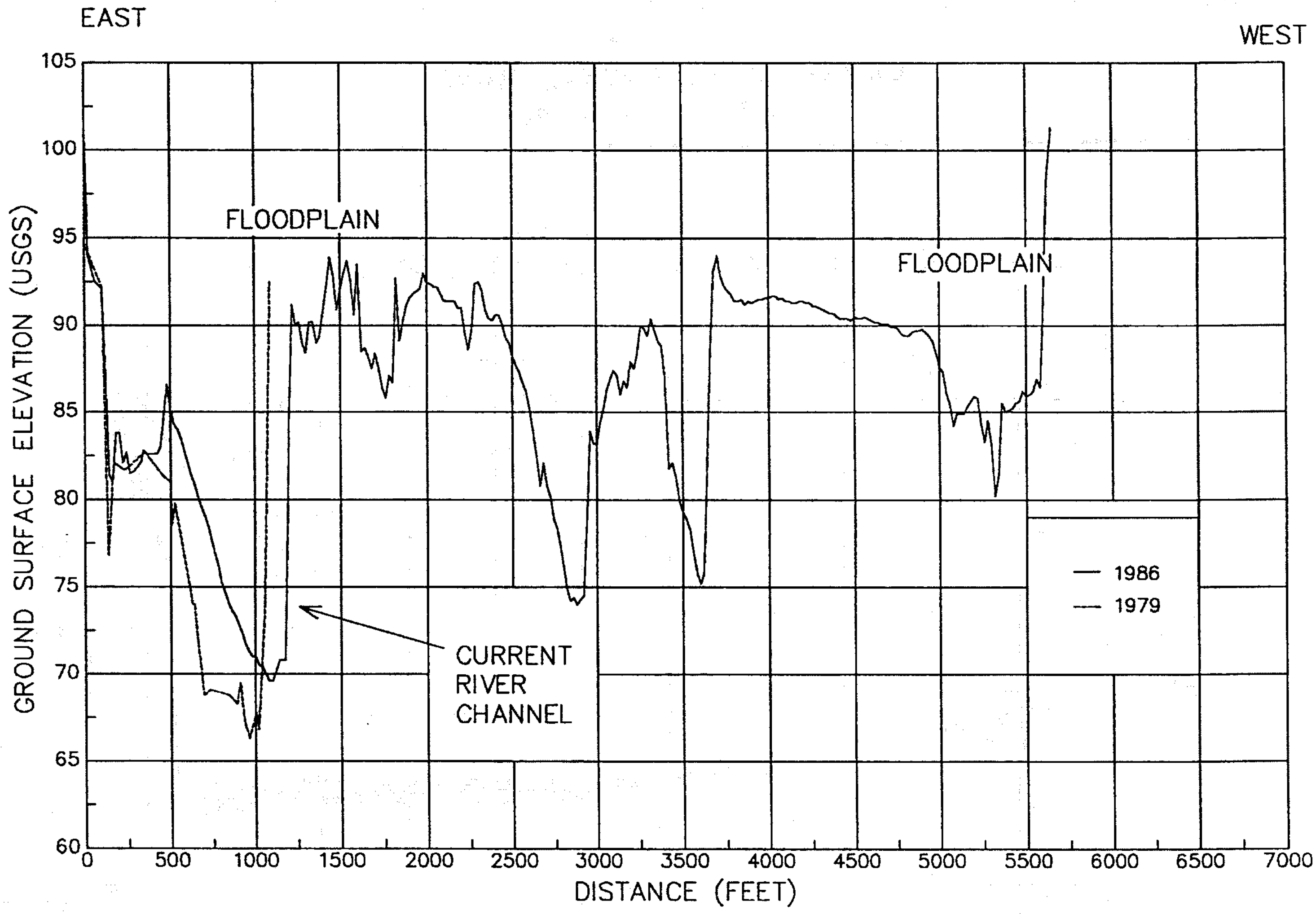
Moulton Weir - River Mile 158.7

This cross-section is short, only about 2,100 feet long. It is about 1,000 feet upstream of Moulton Weir (Figure 30). The cross-section begins on the project levee on State Highway 45. It traverses a short section of riparian vegetation, then crosses the river, open grassland and some more riparian. The river has actively meandered over the entire cross-section in the last 100 years.

According to the cross-section, about 300 feet of bank recession has occurred on the west bank in the 10 years between the two surveys. During the same time, maximum depth also increased about 10 feet. Deposition occurred in the Riparian forest to the west and on the gravel bar and riparian to the east. Near the river, as much as 15 feet of sediment deposited on the gravel bar.

Results

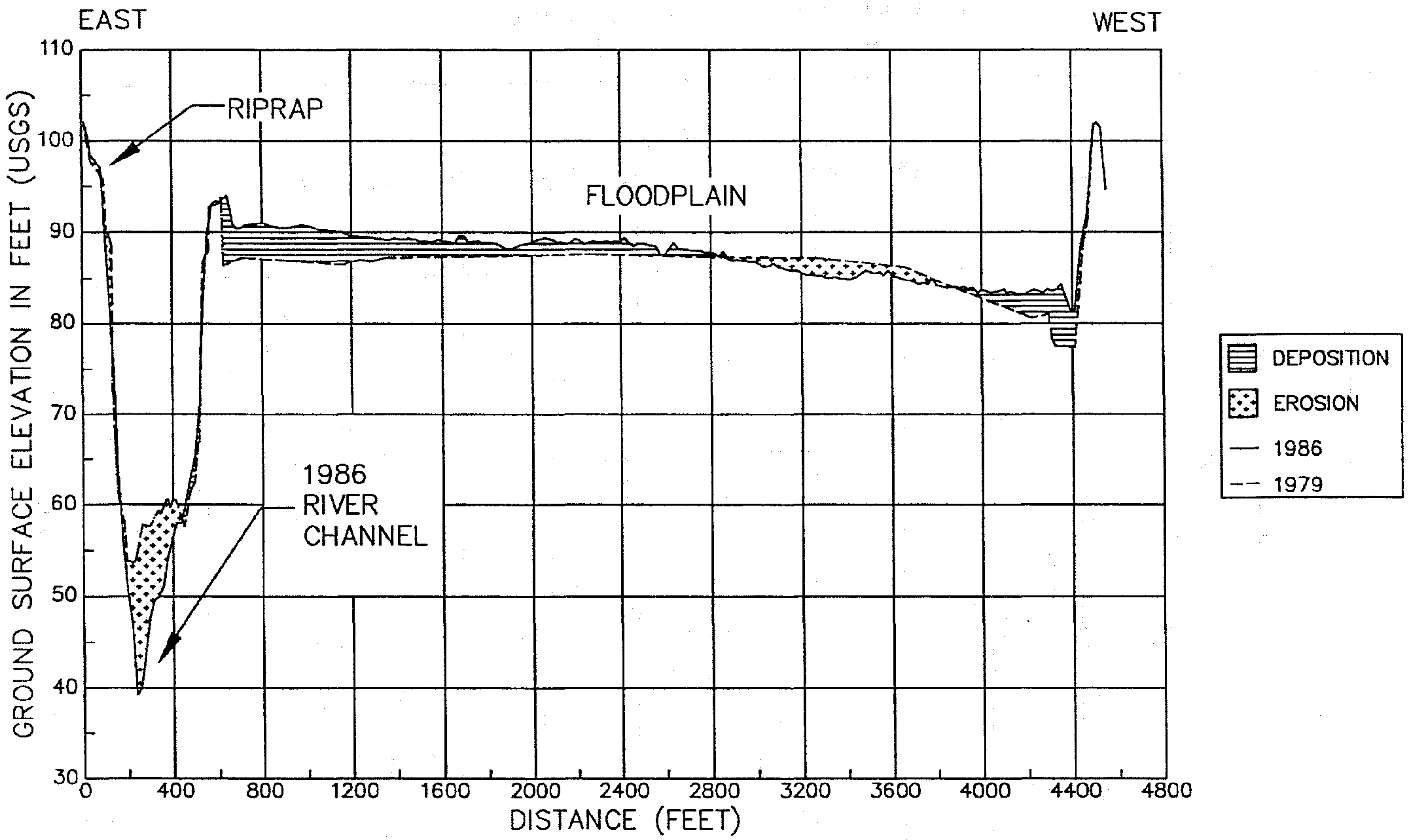
By comparing the various cross-sections it is clear that the amount of deposition is related to the elevation. Older stream channels and oxbows close to the river will fill relatively fast, with 25 feet of deposition in 70 years, while the stable floodplain far from the river will only deposit or erode a few feet during the same time period. Floodplain erosion also occurs. This happens mostly in areas with narrow floodplains or where the river channel is more stable. Table 10 summarizes the data for the floodplain cross-sections.



Sacramento River
Bank Erosion Investigation

Changes in Floodplain Cross-Section at River Mile 175.4

Figure 28



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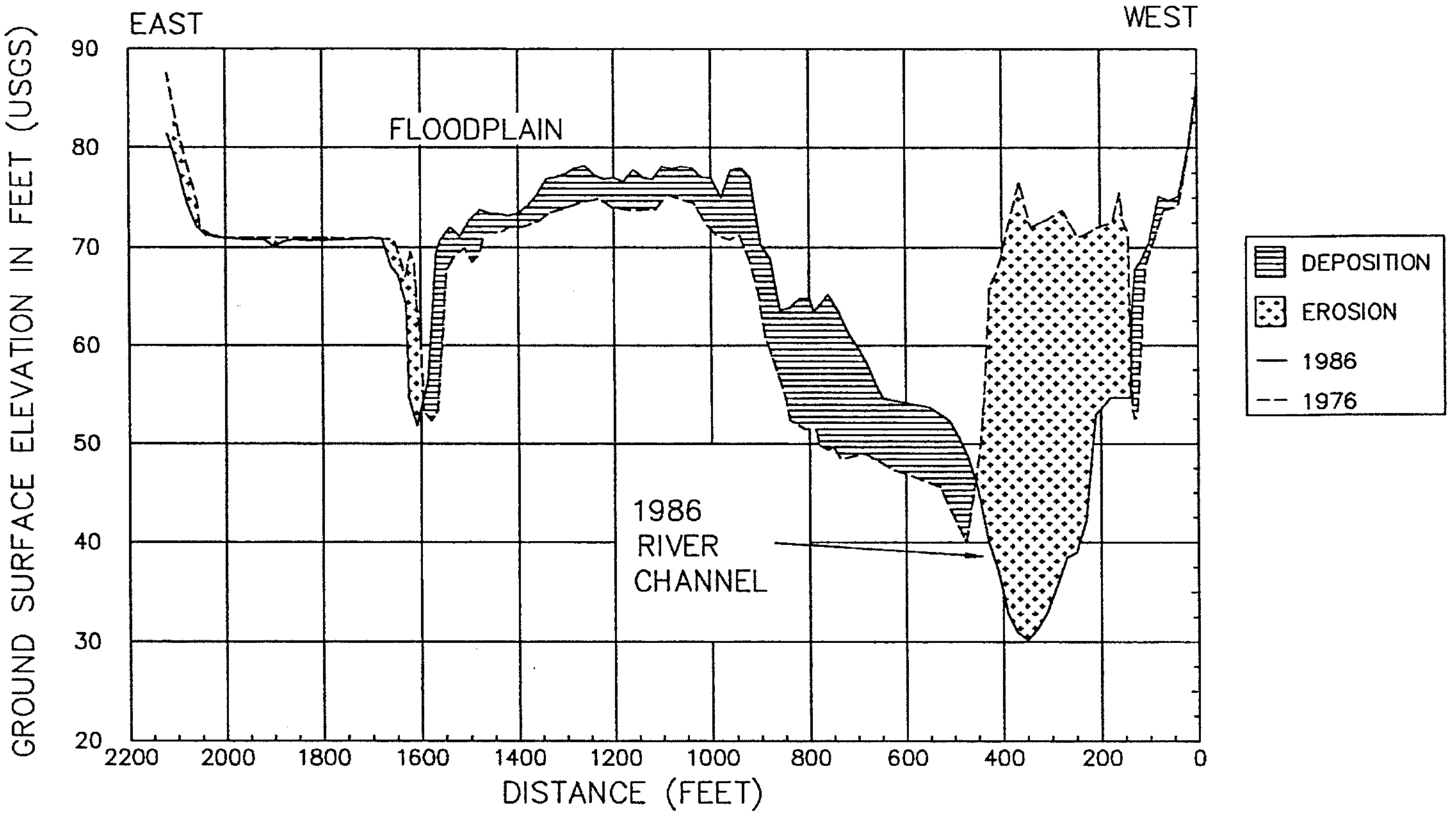
Changes in Floodplain Cross-Section at River Mile 168.5

Figure 29



Sacramento River
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Changes in Floodplain Cross-Section at River Mile 158.7

Figure 30

TABLE 10 FLOODPLAIN CROSS-SECTIONS
CHANGES IN ELEVATION IN FEET

years	River Mile 227.5		River Mile 235.6		River Mile 158.7		River Mile 168.5		River Mile 175.4		River Mile 197.7		River Mile 201.2	
	Average Depth	Elevation Change	Average Depth	Elevation Change	Average Depth	Elevation Change	Average Depth	Elevation Change	Average Depth	Elevation Change	Average Depth	Elevation Change	Average Depth	Elevation Change
1917-1923	24.05	0	12.83	0	-	-	-	-	-	-	12.42	0	-	-
1976	-	-	-	-	22.61	0	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-	-	-	-	-	6.37	0
1979	-	-	-	-	-	-	12.30	0	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-	4.47	0	-	-	-	-
1986	-	-	-	-	23.88	-1.27	12.00	+0.30			12.12	+0.30	7.05	-0.68
1988	23.00	+1.05	11.59	+1.24	-	-	-	-	-	-	-	-	-	-

LAKE RED BLUFF DEPOSITION

The Red Bluff Diversion Dam is on the Sacramento River immediately below the mouth of Red Bank Creek (Figure 31). The dam was completed in 1966 and is operated by the U.S. Bureau of Reclamation.

Releases to the river are controlled by eleven 60- by 18-foot regulating gates. One of these is the sluice gate located at the right end of the spillway. This gate is provided with automatic controls to aid in maintaining a constant water surface elevation and to sluice sediment from in front of the canal headworks.

The dam maintains Lake Red Bluff at a normal pool elevation of 252.5 feet during the summer and 251.5 during the winter, except when flows exceed 50,000 cubic feet per second and rising. At that point the gates are lifted over a period of two hours until the gates clear the water. The gates are slowly lowered when flows are 50,000 cubic feet per second and declining. Beginning in 1986, the gates were open between October and March to improve fish passage. Backwater effects occur at flows less than 50,000 cubic feet per second. Minor effects from the diversion dam's gate supports occur above this flow.

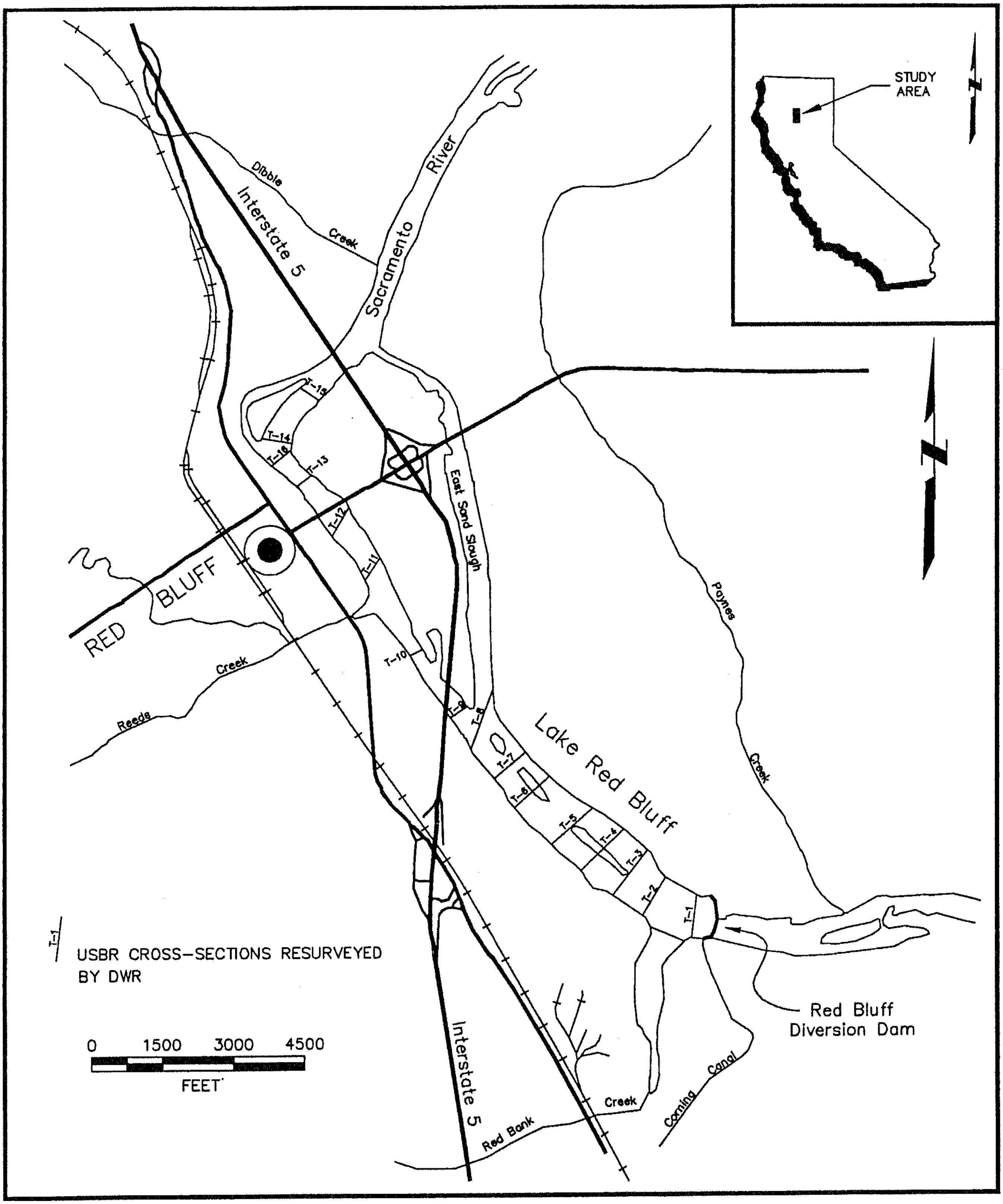
The U.S. Bureau of Reclamation surveyed cross-sections across Lake Red Bluff in 1951, 1962, and 1968 and computed water surface elevations for various flows. They also computed sediment deposition in Lake Red Bluff between December 1966 and February 1968 as 3,600 tons, assuming that all sediment in suspension was sluiced through the dam.

DWR performed sonar surveys at 16 of the original USBR cross-sections of Lake Red Bluff. These were done in 1982, 1986, and 1988 to quantify the backwater effects on sediment deposition during high flow. Aggradation and degradation in the lake is an indicator of the amount of sediment transport in the Sacramento River.

The goals of this program are to examine the backwater effects on in-channel sedimentation and determine the amount of bedload moving down the Sacramento River. Thirty-two monuments were set to mark the ends of the cross-sections in the fall of 1986. These are shown in Figure 31. These monuments are composed of galvanized pipe set in concrete. The distance between monuments was measured using an electronic distance measuring device. The profiles were established by using a paper- feed, depth sounder mounted on a boat. The collected data are plotted to calculate changes in cross-sectional area of the channel at each profile location.

Changes in the Diversion Dam Operation

The effect of the changes in operation of the Red Bluff Diversion Dam on aggradation on Reeds Creek was investigated as part of the ***Sacramento Valley Westside Tributary Watersheds Erosion Study--Reeds Creek Watershed*** (DWR, 1991). Figure 32 shows the



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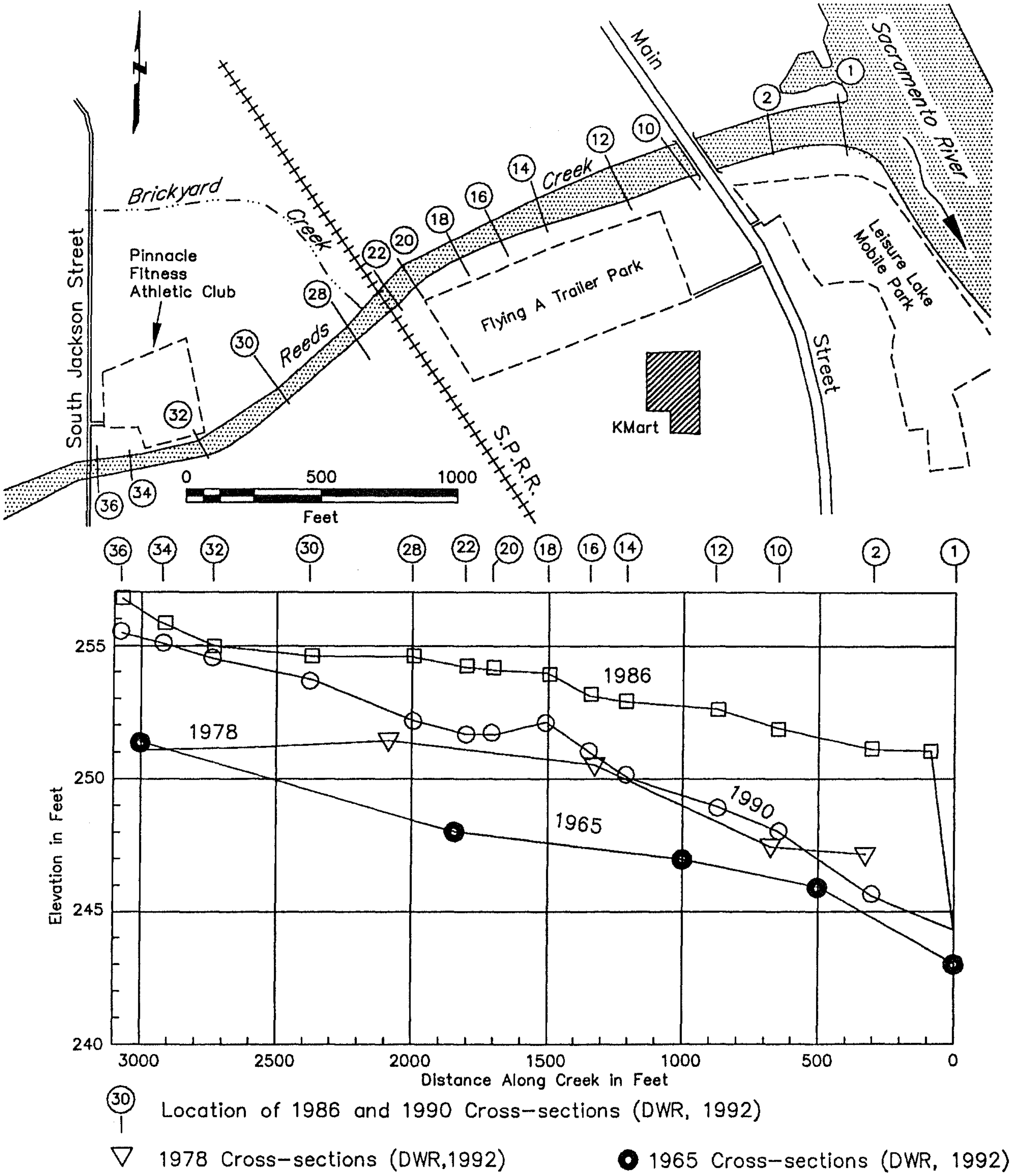
Sacramento River Bank Erosion Investigation
Cross-Section Profile Locations
Red Bluff Diversion Dam

Figure 32



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Sacramento River
Bank Erosion Investigation

Changes in the Stream Profile
Reeds Creek

profile of the lower 3,200 feet of the Reeds Creek channel. About 4 feet of aggradation is evident between the completion of the dam in 1966 and 1986, for a total of about 56,000 cubic yards of sediment. Major stormflows in March 1983 and February 1986 contributed the majority of this sediment. The U.S. Bureau of Reclamation dredged the mouth of Reeds Creek several times to remove accumulated sediment. Since the fall of 1986, the dam has been opened during the winter months and the accumulated sediments are beginning to scour out of the reach.

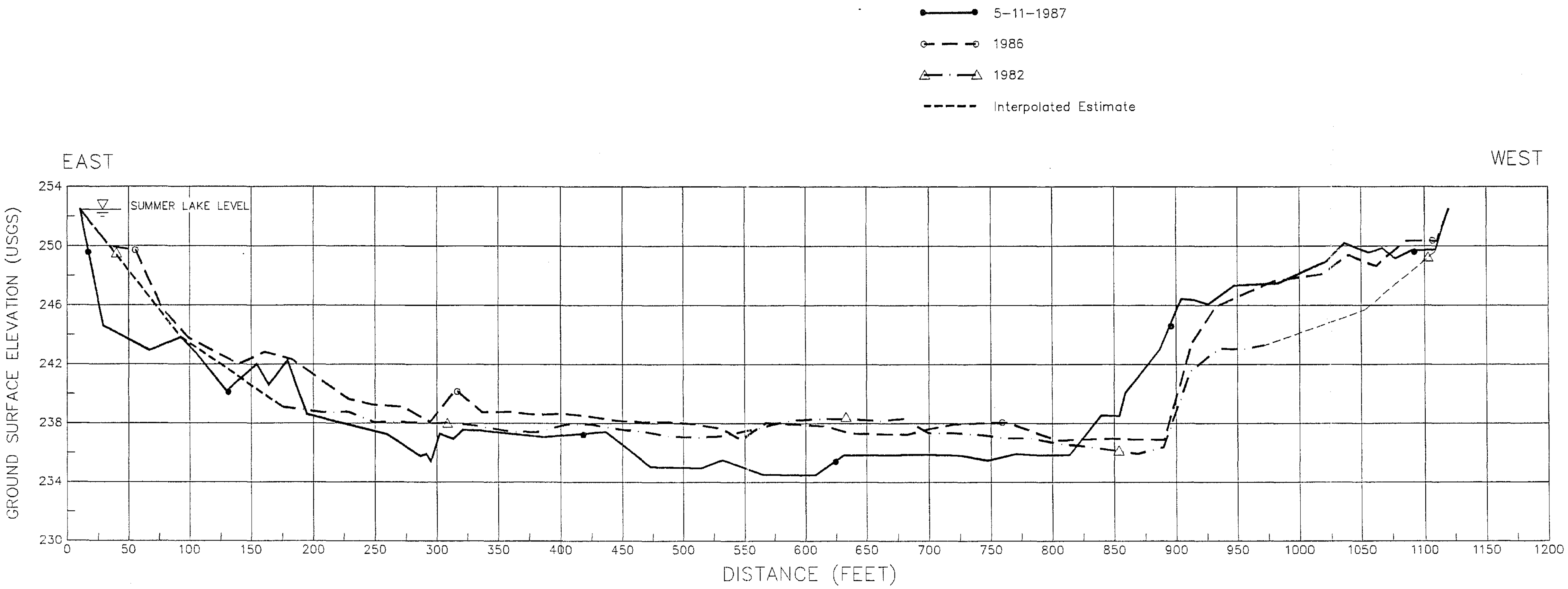
In March 1990, DWR (1991) re-surveyed Reeds Creek, as also shown on Figure 32. The profiles show that, since the dam began opening its gates during the winter runoff, about 35,000 cubic yards of gravel has been flushed out of this section. It would be expected that similar results are occurring on the Sacramento River.

Lake Cross-Sections

The name of each section and the survey dates are shown in Table 11. The cross-sections are shown in Figures 33 to 48.

The U.S. Bureau of Reclamation has reported a continuing problem with concrete erosion above and below the crest of the spillway. The abrasive action of sand and gravel passing over the crest at flood stage is thought to be the cause of this erosion (USBR, 1970).

Calculations by the Bureau suggest low bedload sediment transport and low rates of deposition in the reservoir area. Table 12 shows the change in the average depth with time of the different cross-sections. In general, there was aggradation between 1968 and 1986. Between 1986 and 1987, there was degradation. This was the first year that the gates were left open during the winter months. Clearly a new survey should be done to see how effective this is in keeping the reservoir sediment-free.



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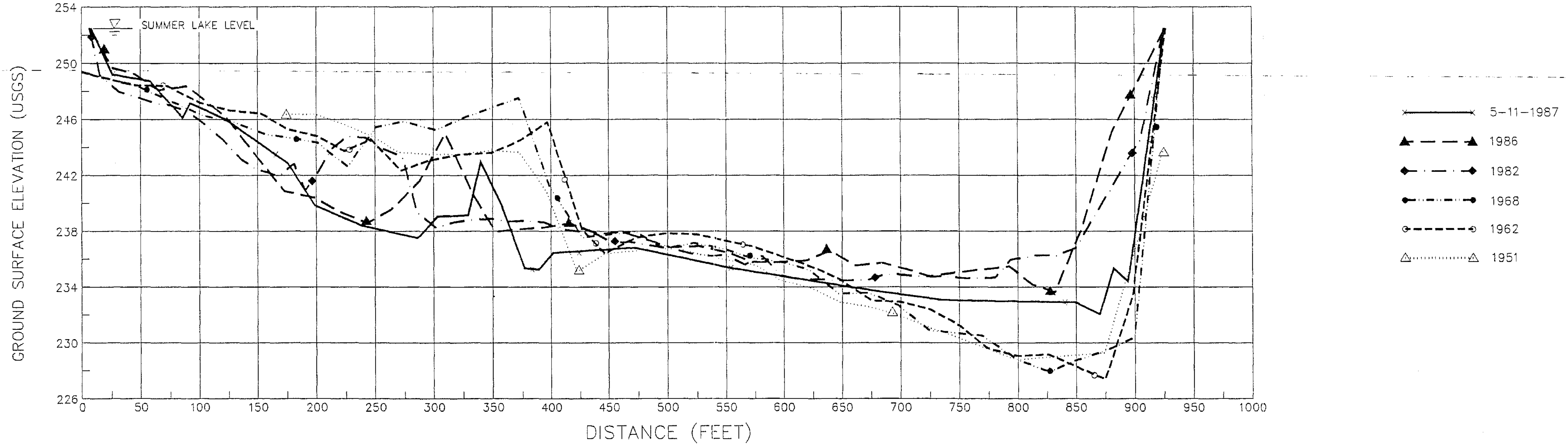
Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-1

Lake Red Bluff



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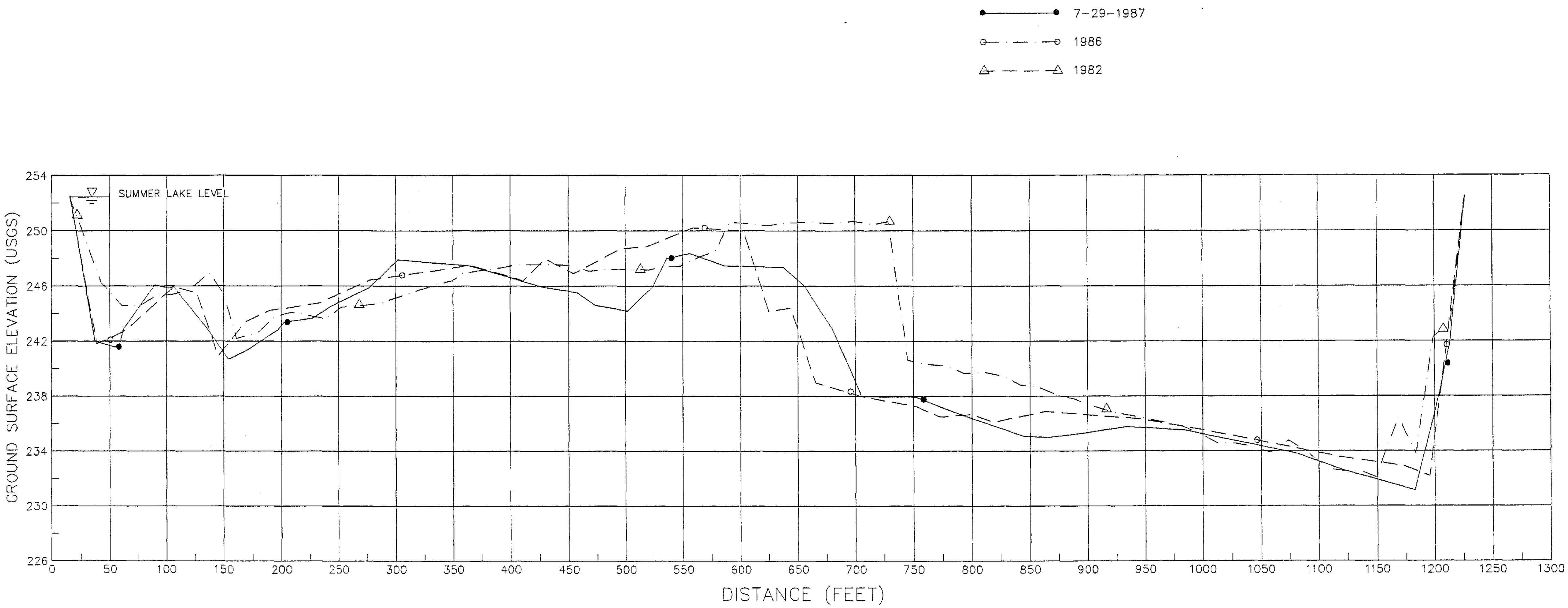
Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-2
Lake Red Bluff



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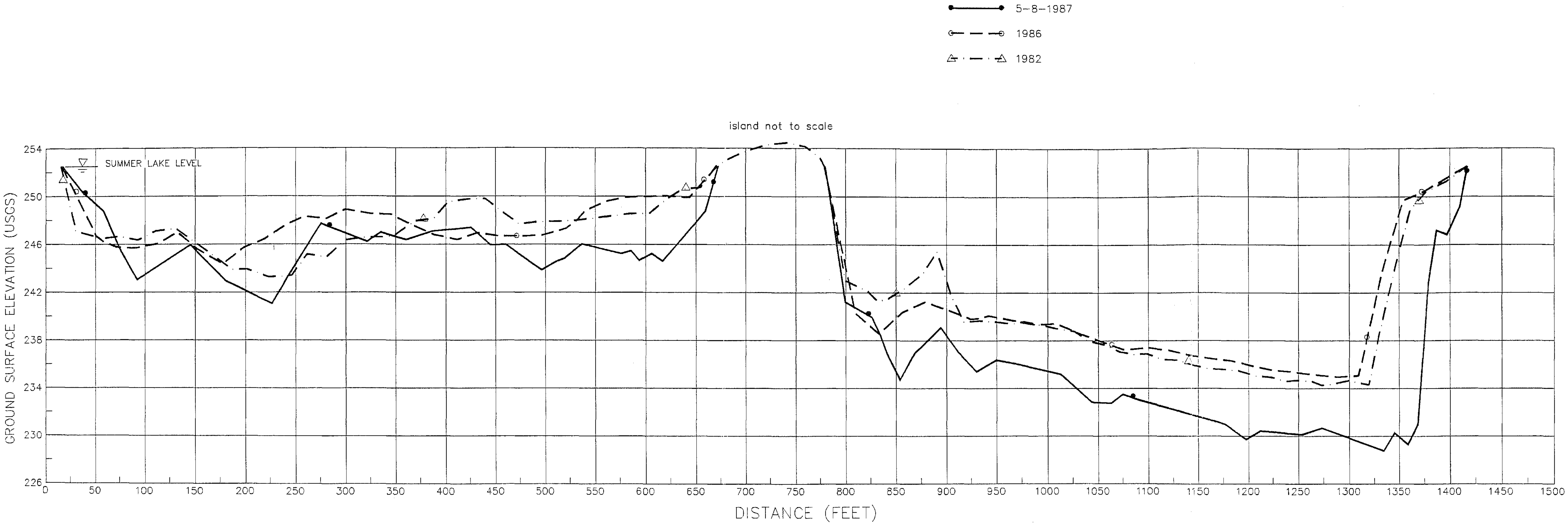
Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-3

Lake Red Bluff



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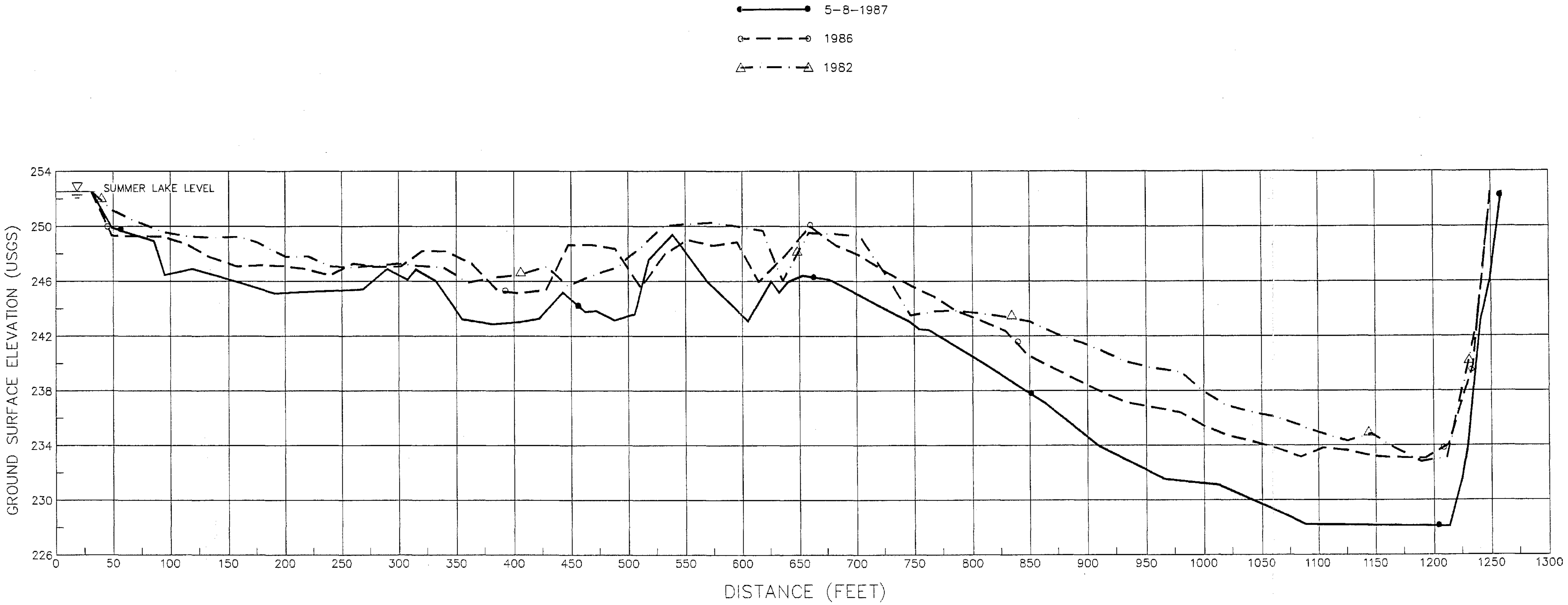
Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-4
Lake Red Bluff



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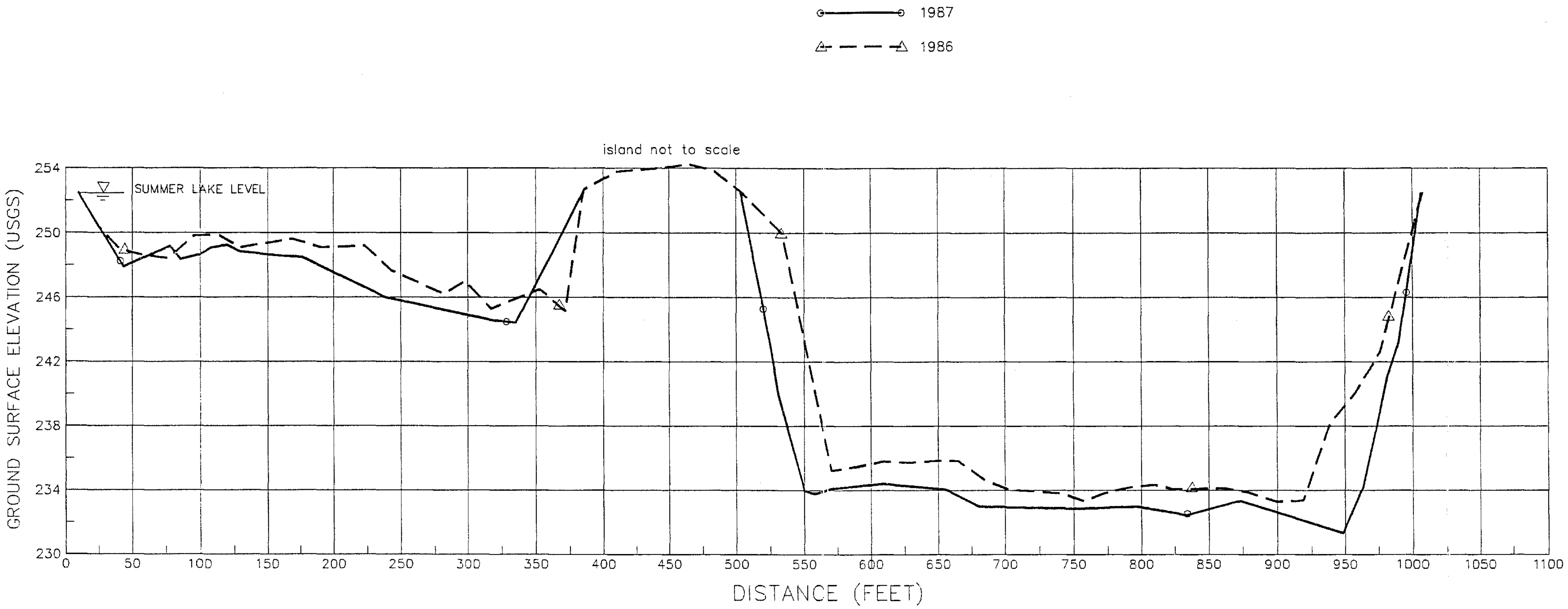
Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-5
Lake Red Bluff

Figure 38



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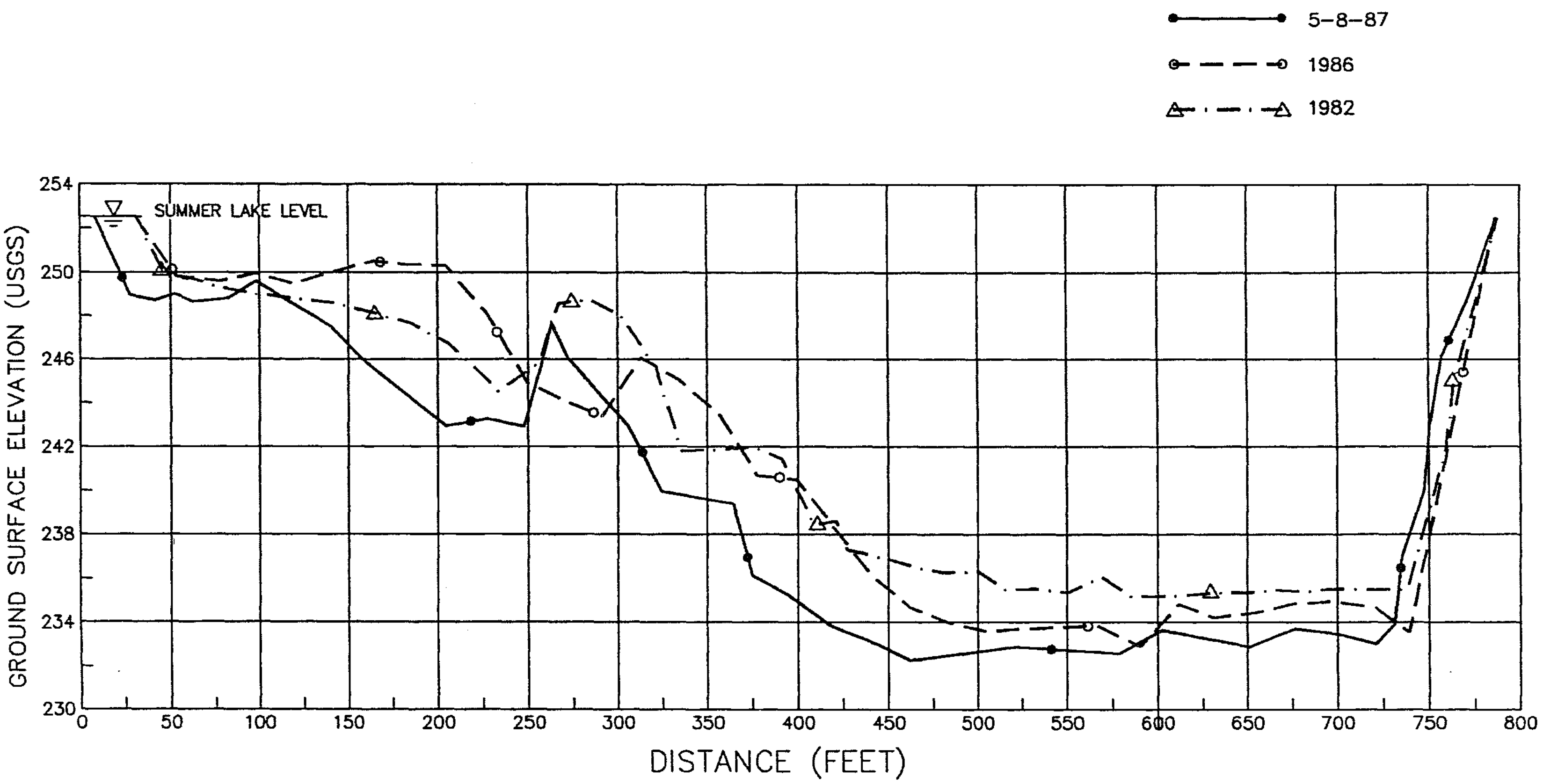
NORTHERN DISTRICT

Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-6
Lake Red Bluff

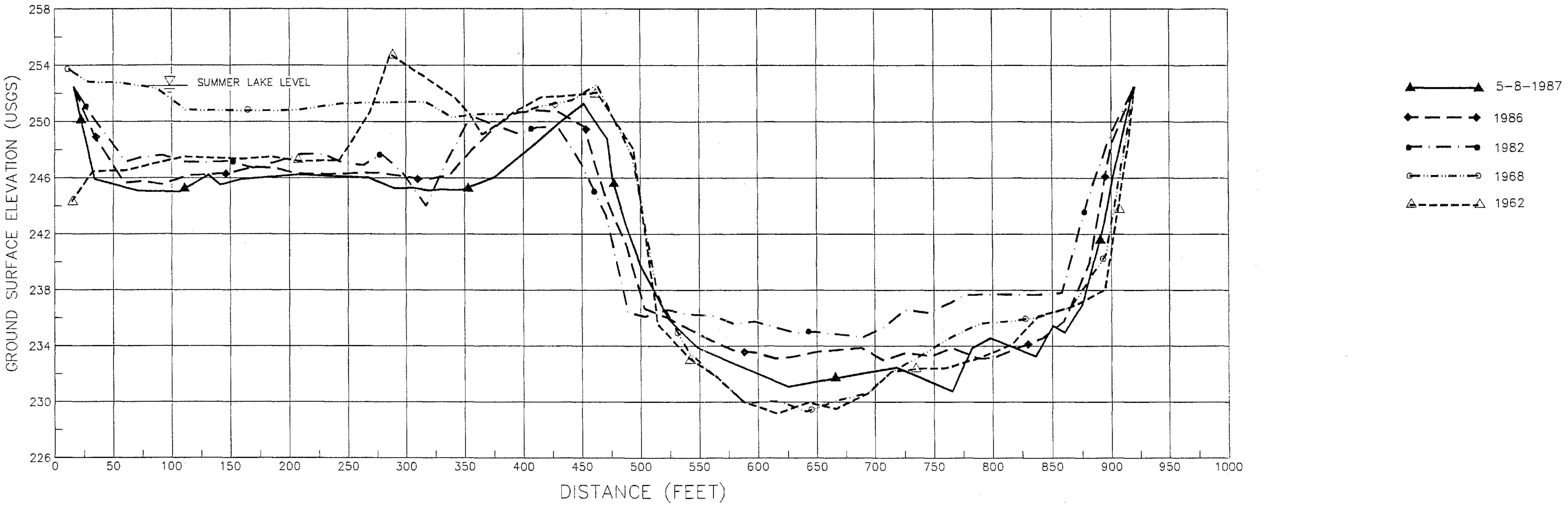


Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-7 Lake Red Bluff

Figure 39

Figure 40



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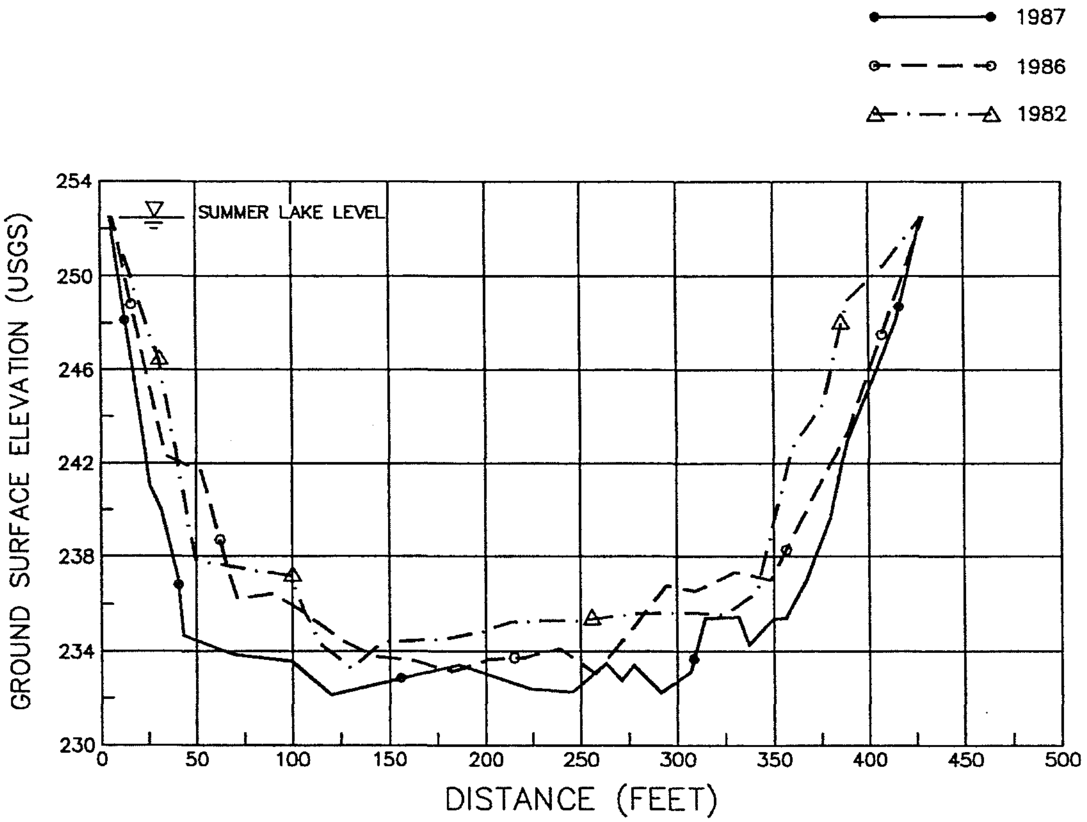
NORTHERN DISTRICT

Sacramento River
Bank Erosion Investigation

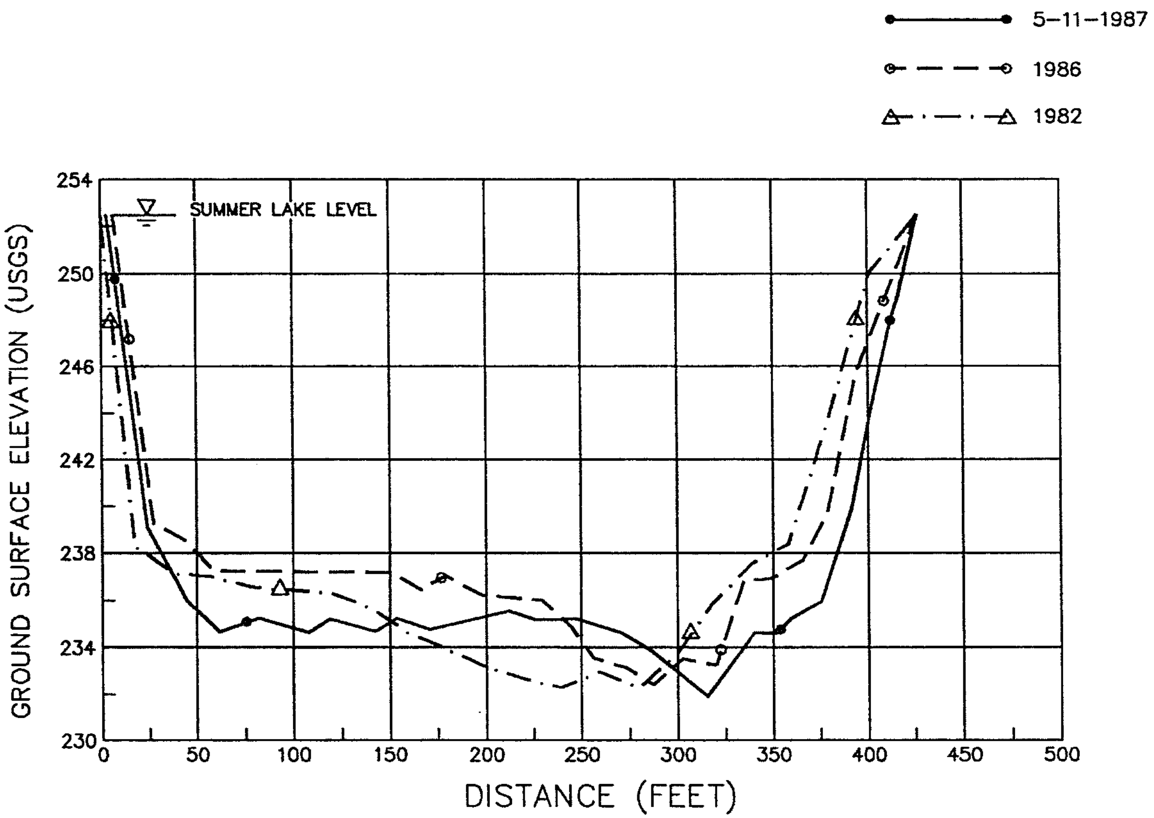
Changes in Cross-Section T-8
Lake Red Bluff



Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-9 Lake Red Bluff

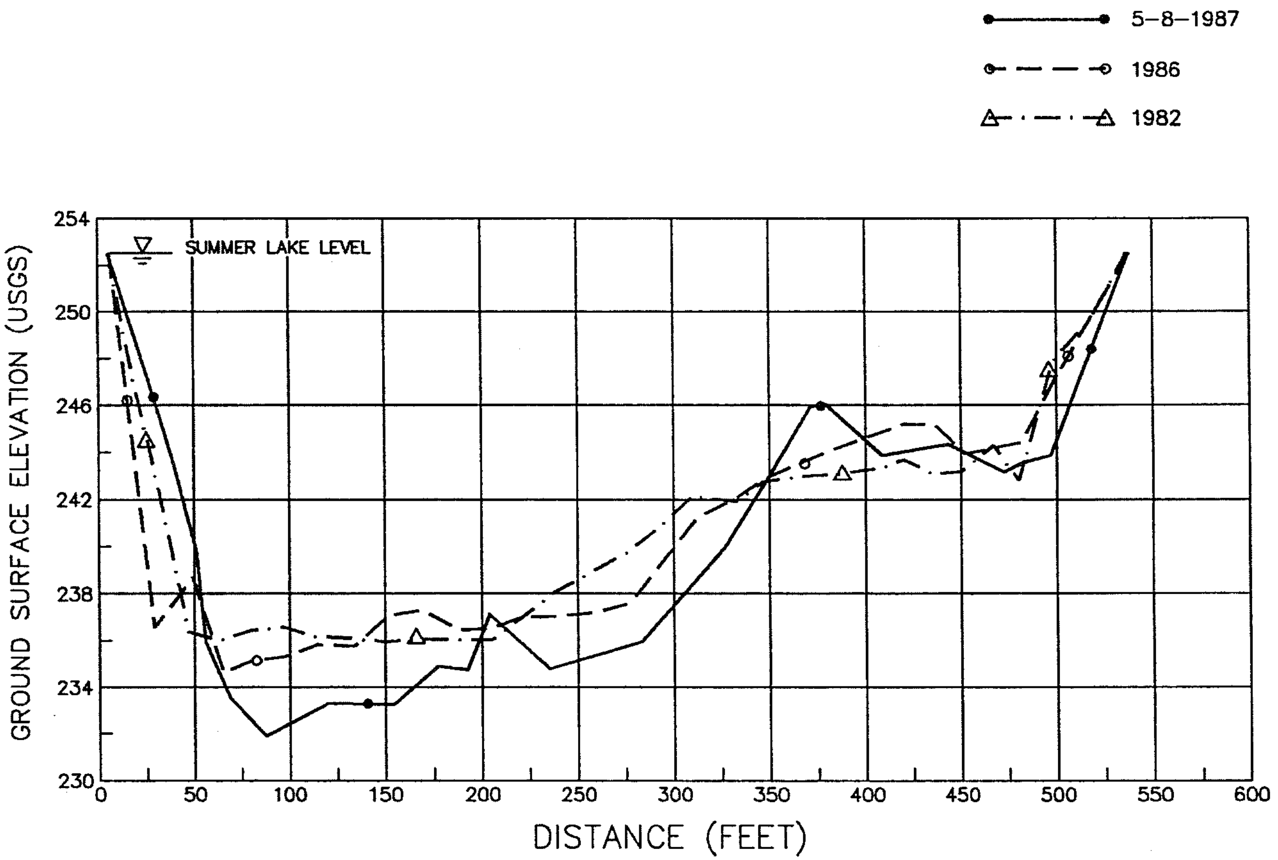
Figure 41



Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-10 Lake Red Bluff

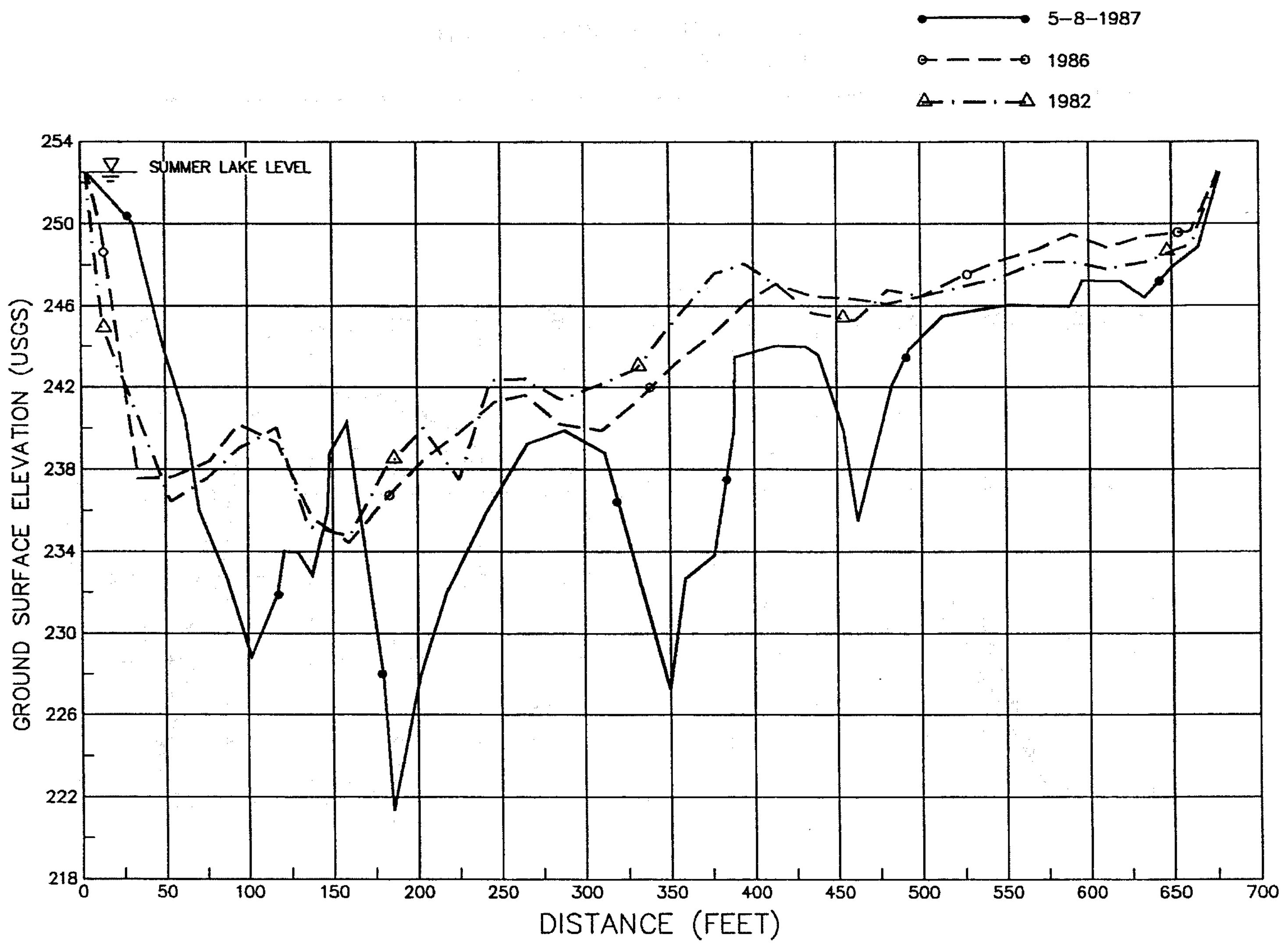
Figure 42



Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-11 Lake Red Bluff

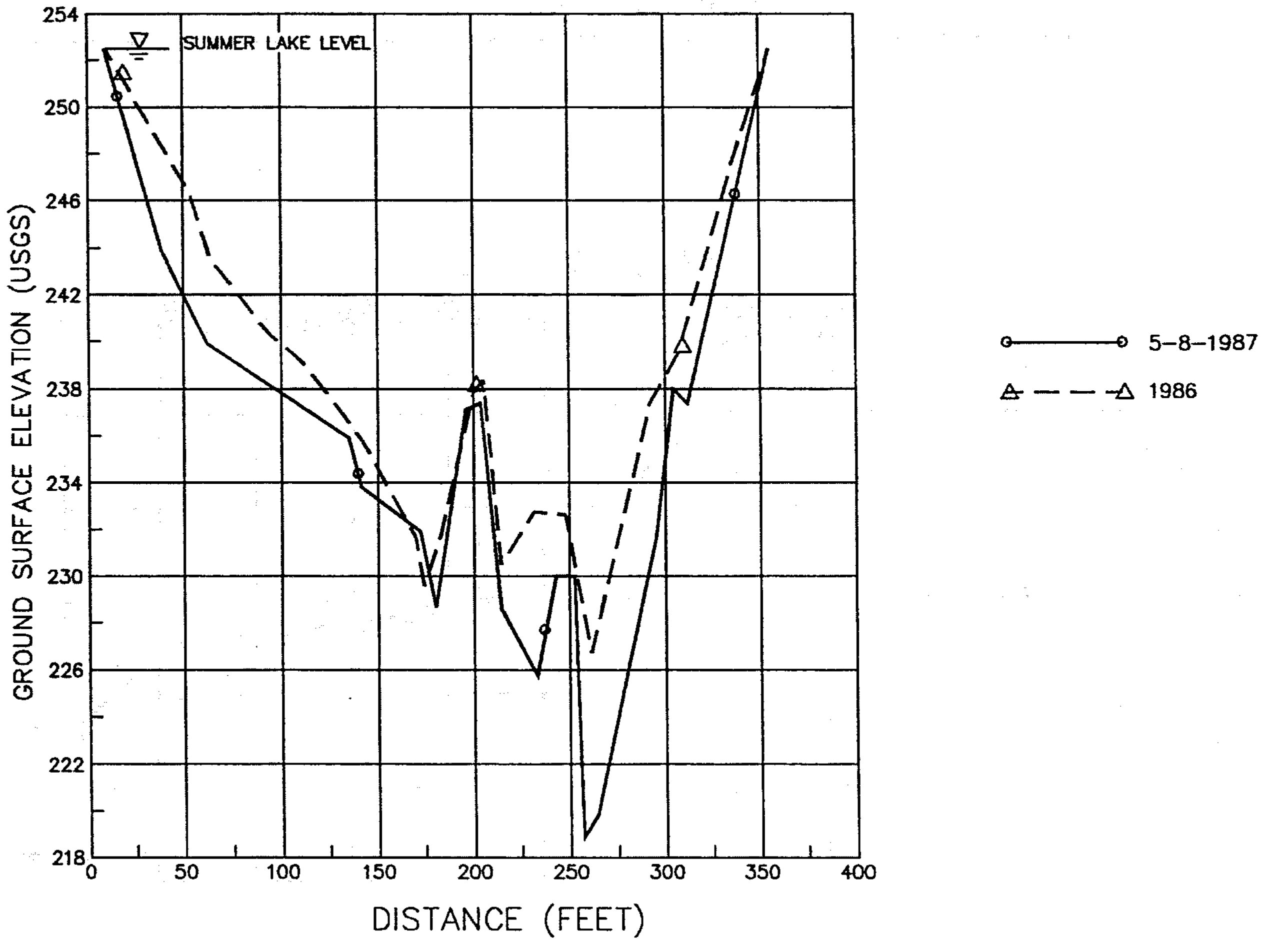
Figure 43



Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-12 Lake Red Bluff

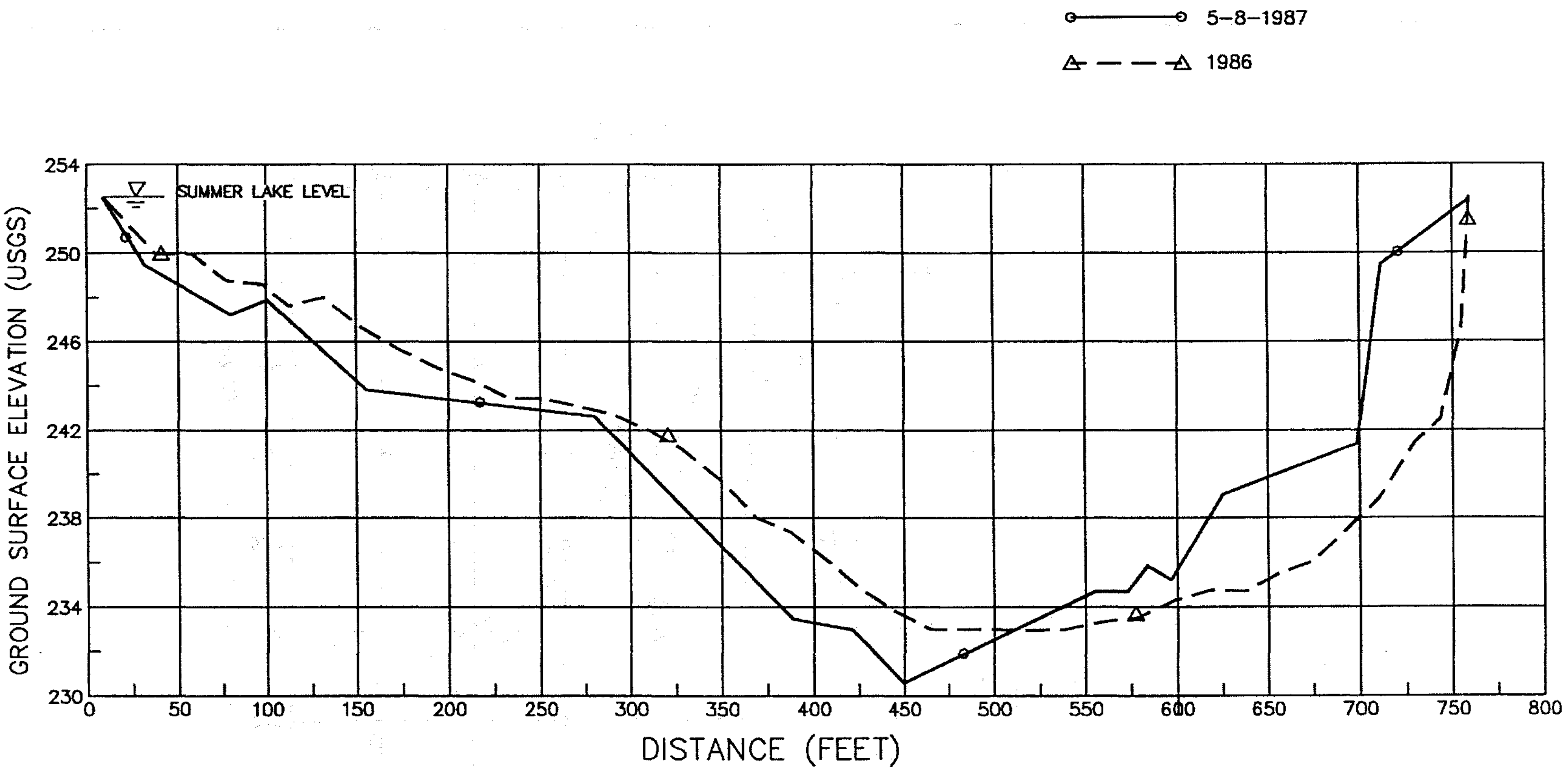
Figure 44



Sacramento River
Bank Erosion Investigation

Changes in Cross–Section T–13 Lake Red Bluff

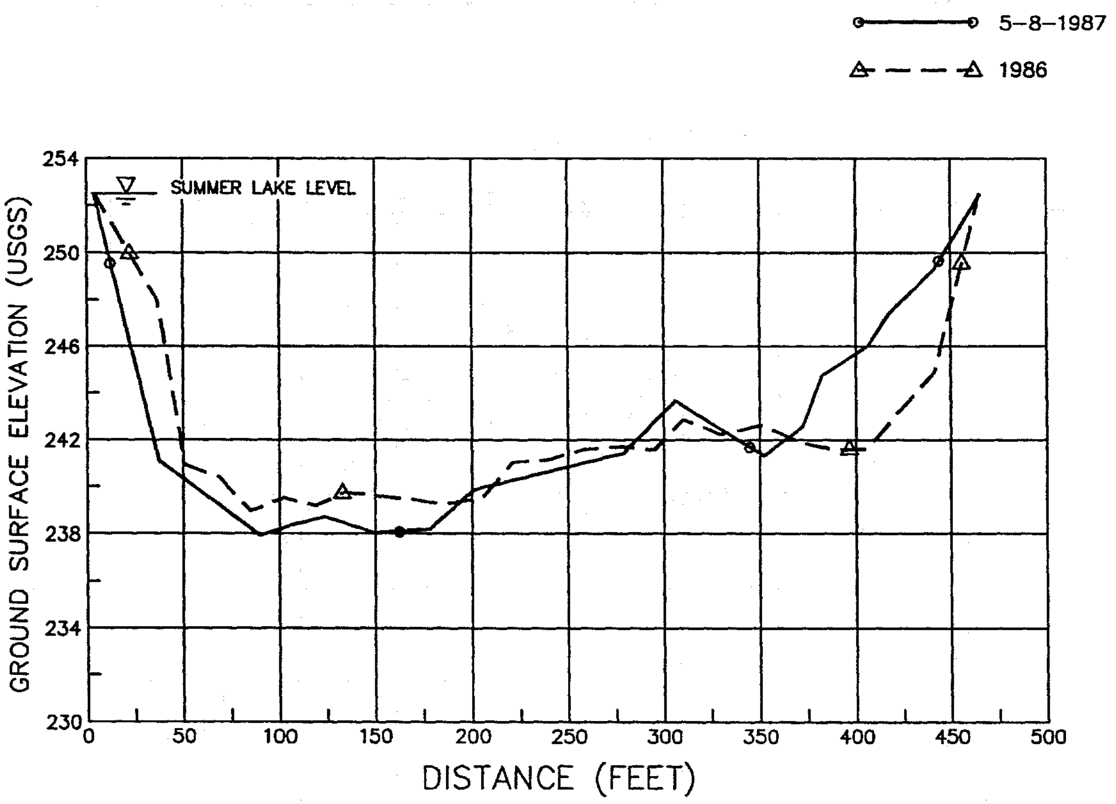
Figure 45



Sacramento River
Bank Erosion Investigation

Changes in Cross–Section T–14 Lake Red Bluff

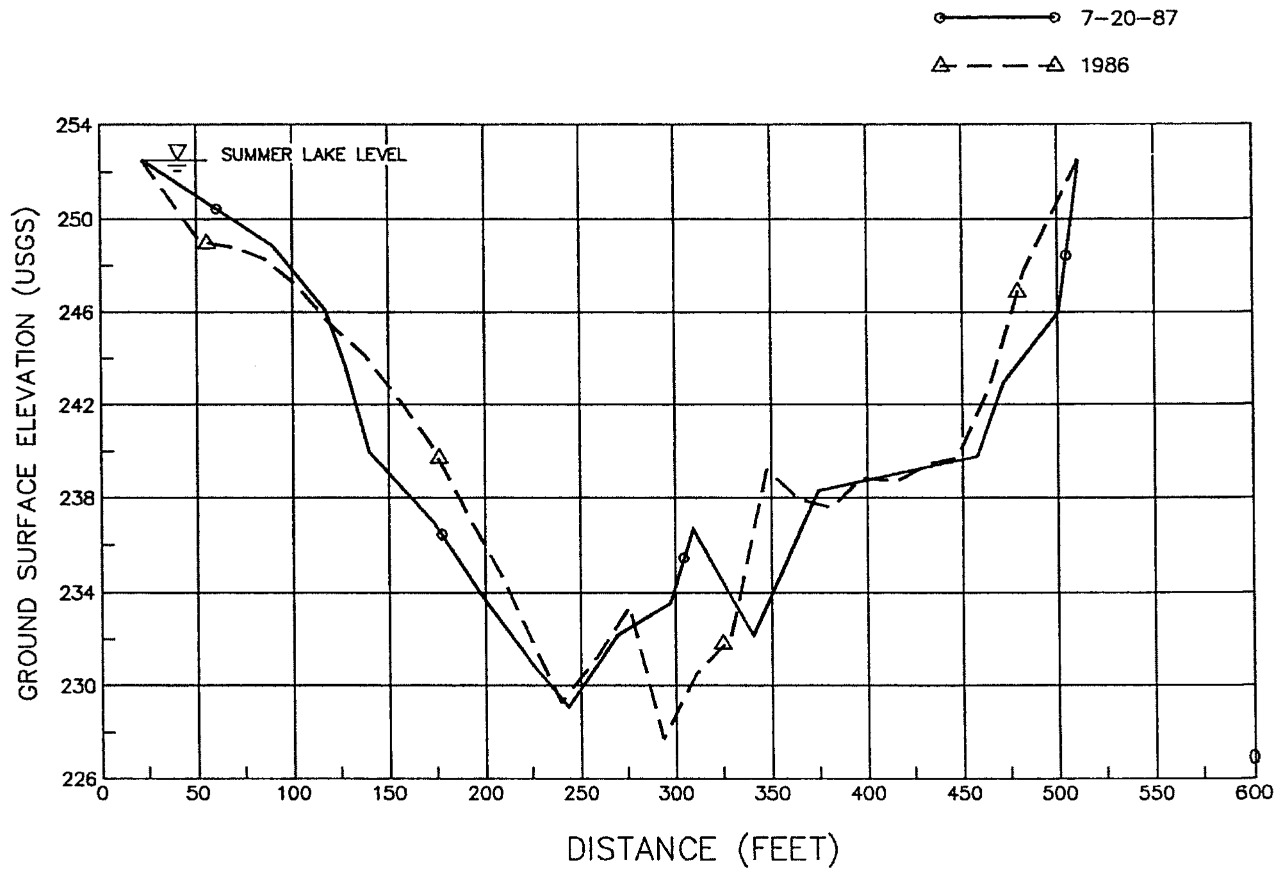
Figure 46



Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-15 Lake Red Bluff

Figure 47



Sacramento River
Bank Erosion Investigation

Changes in Cross-Section T-16 Lake Red Bluff

Figure 48

TABLE 11 LAKE RED BLUFF CROSS-SECTIONS

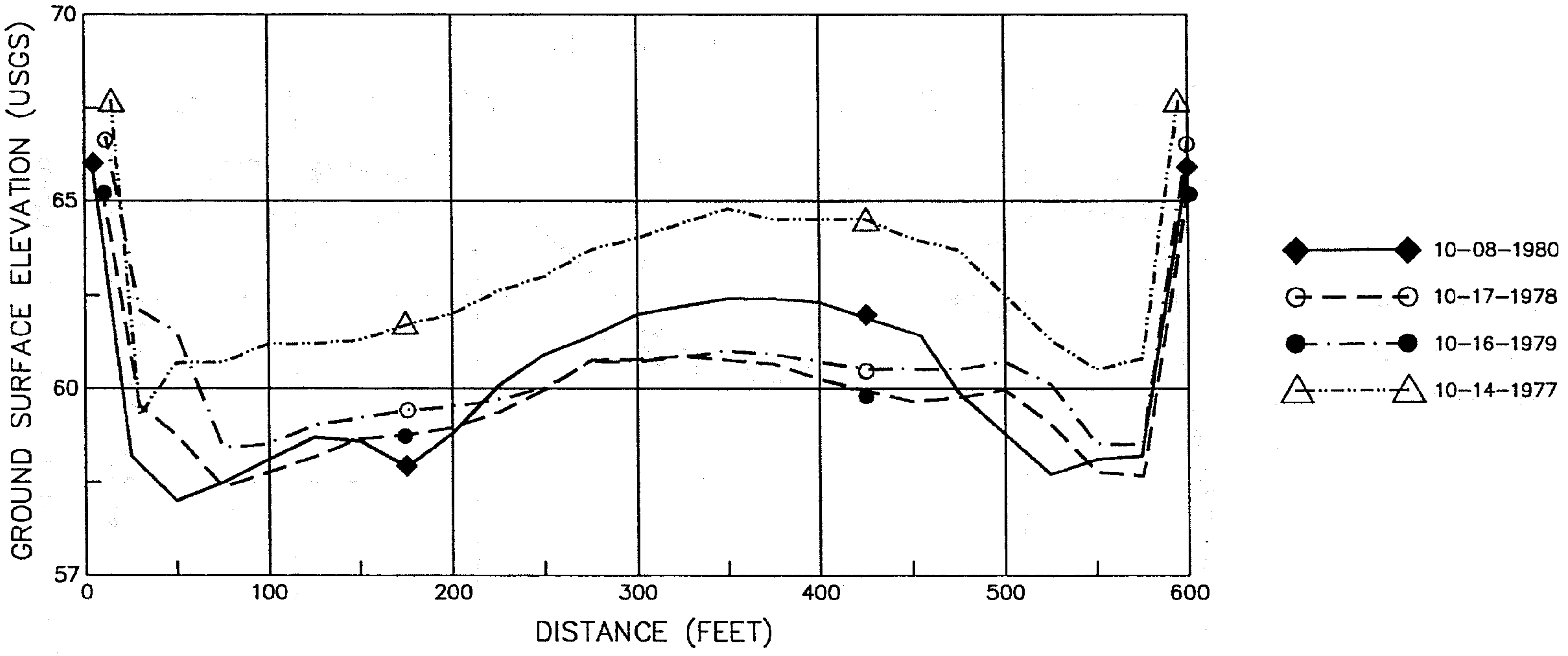
Profile Number	USBR Survey Dates Average Depth, in Feet			DWR Survey Dates Average Depth, in Feet		
	1951	1962	1968	1982	1986	1987
T1				12.37	11.24	12.47
T2	13.39	13.27	13.35	12.99	12.60	14.32
T3				9.53	10.95	11.41
T4				8.90	8.60	12.1
T5				8.07	8.97	11.91
T6					10.5	12.2
T7				10.44	10.85	12.75
T8		9.38	9.17	11.77	13.36	14.30
T9				13.63	14.56	16.59
T10				15.13	14.38	15.90
T11				11.63	11.85	12.7
T12				8.98	9.11	12.58
T13					13.58	16.46
T14					12.12	11.94
T15					10.30	10.32
T16					12.42	12.96

GAGING STATION CROSS-SECTIONS

Gaging station data from DWR's Sutter Yard Hydrology Section in Sutter, California were used to plot cross-sections. Cross section bottom elevations were collected using a tag line while making instream flow measurements. The elevation of each profile is tied into a gage reading in the vicinity of each site. For that reason, the elevation of each profile has not been established in terms of mean sea level. The resulting data should only be used for comparison purposes. The location of each plot is shown in Figure 20. The years of record are listed in Table 12 below. Figures 49 to 54 show the changes in channel cross-section at the gaging stations. Table 13 shows the change in elevation of gaging station cross-sections.

TABLE 12 LOCATION OF GAGING STATION CROSS-SECTIONS

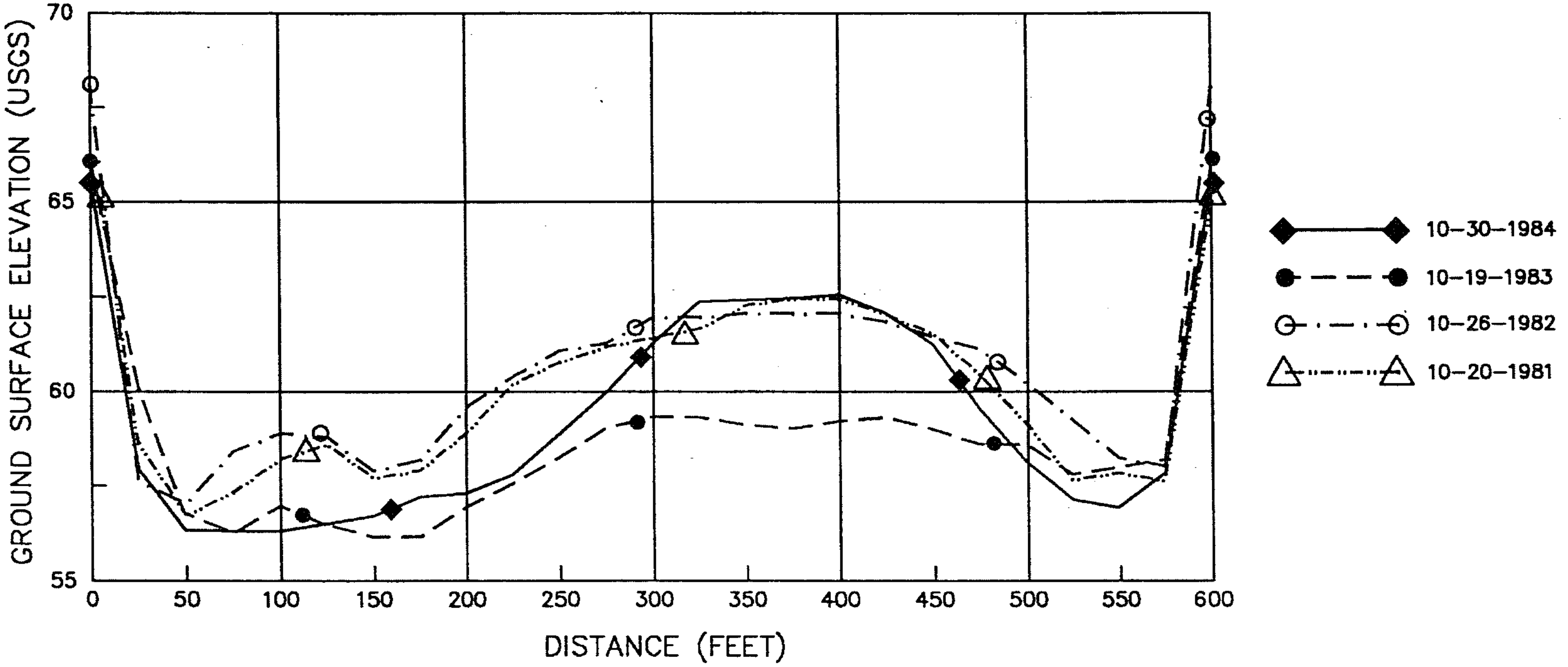
Section Location	Survey Dates
Vina Bridge, 1300 feet below gage	1977, 1978, 1979, 1980
Vina Bridge, 1500 feet below gage	1981, 1982, 1983, 1984
Hamilton City, 1700 feet above gage	1976,1977, 1978, 1979, 1981,1982, 1984
Hamilton City, 800 feet above gage	1980, 1985
Ord Ferry, 1300 feet above gage	1977, 1978, 1979, 1980, 1981, 1982
Ord Ferry, 1000 feet above gage	1983, 1984, 1985
Butte City	1957, 1962, 1967



Sacramento River
Bank Erosion Investigation

Changes in Channel Cross-Section 1300 feet below Vina Gage

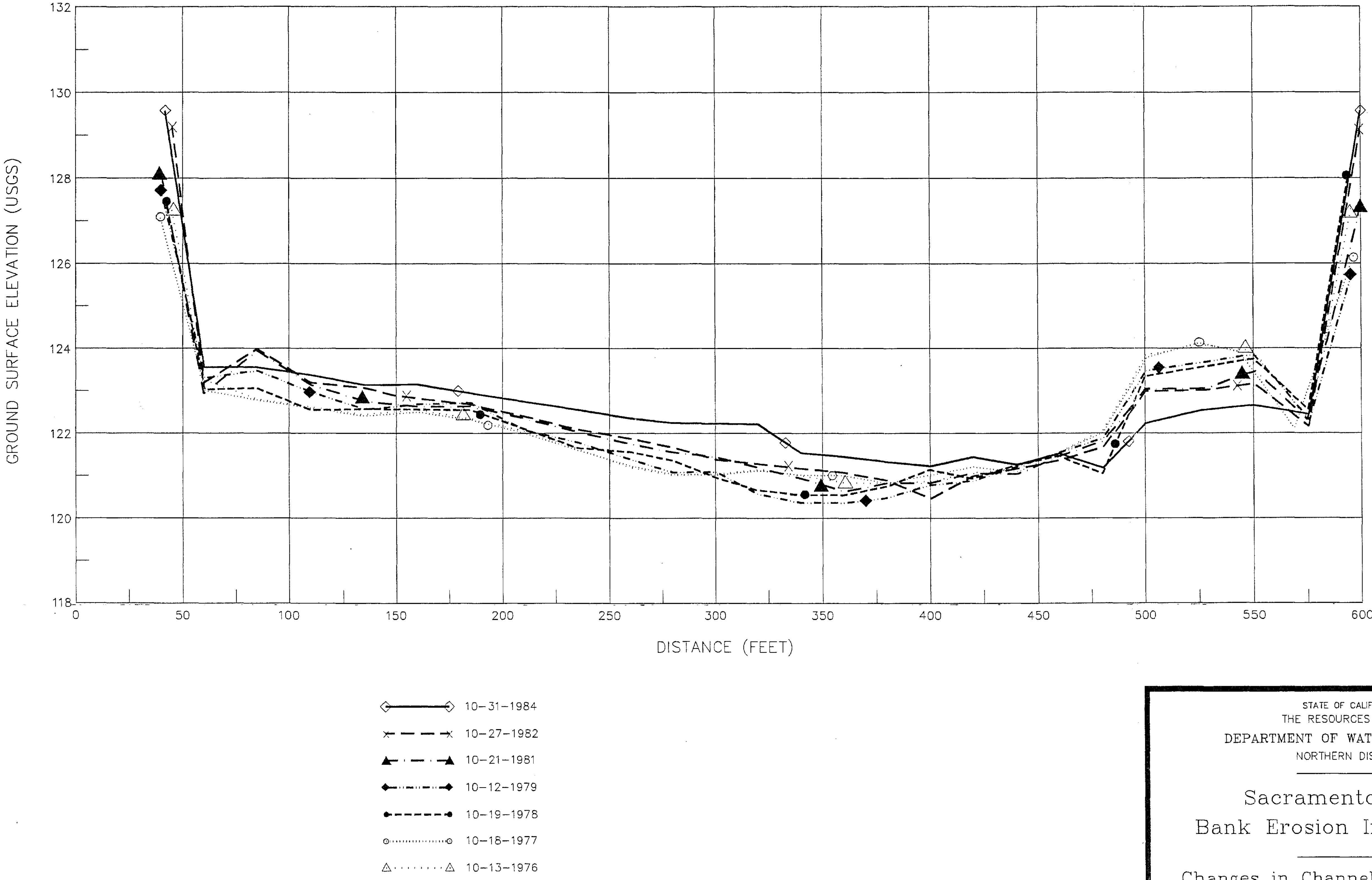
Figure 49



Sacramento River
Bank Erosion Investigation

Changes in Channel Cross-Section 1500 feet below Vina Gage

Figure 50



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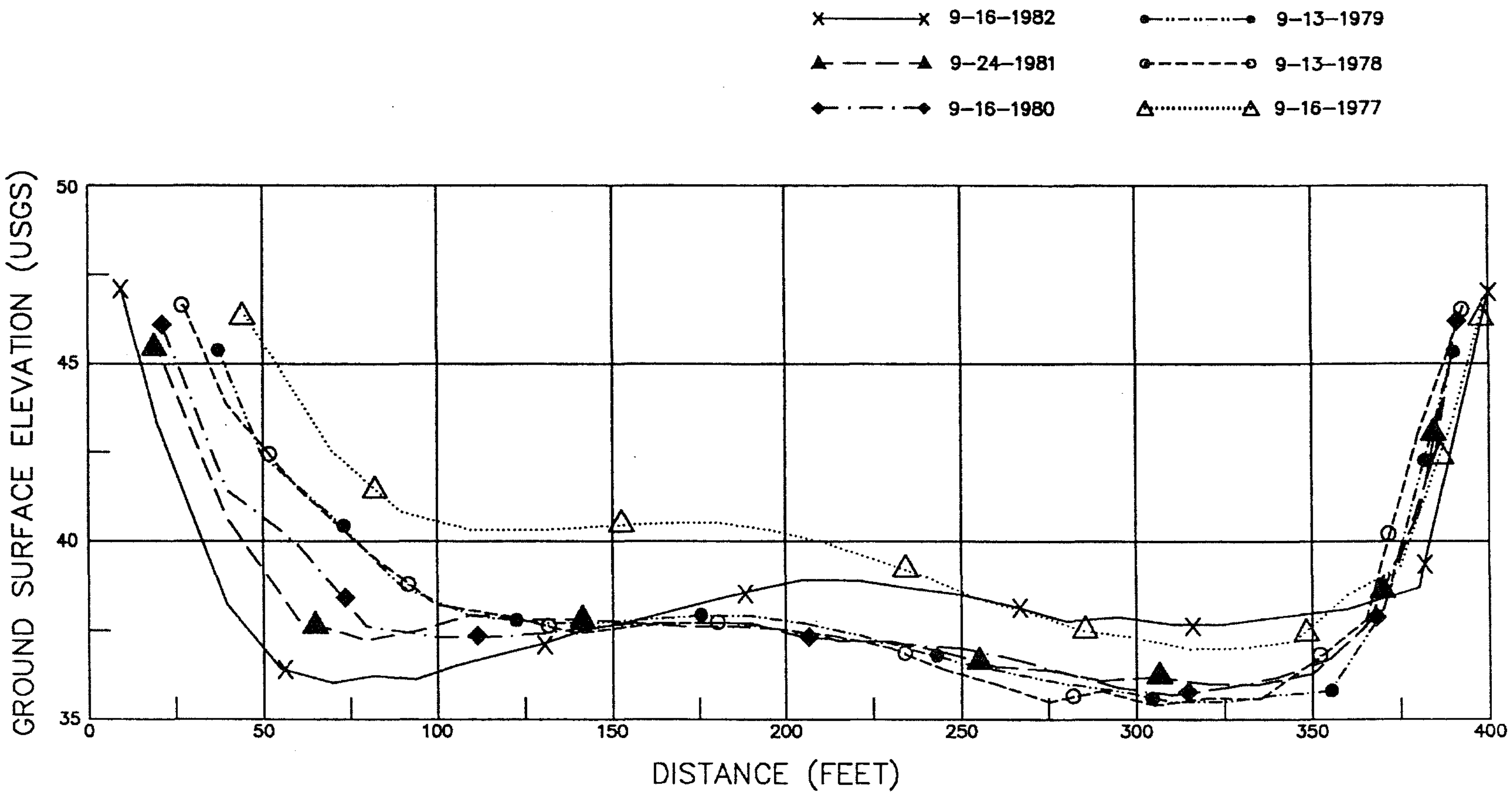
Sacramento River
Bank Erosion Investigation

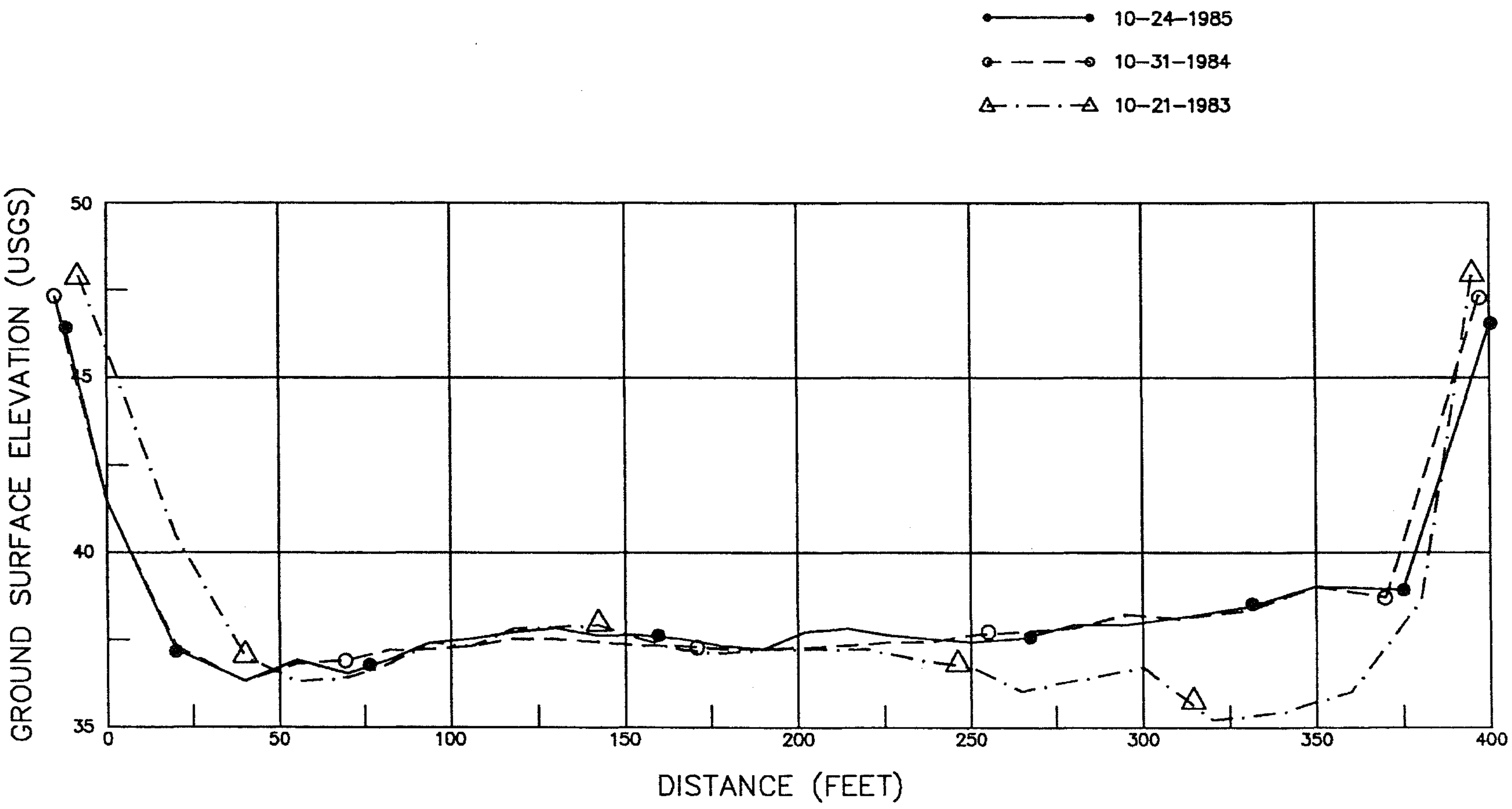
Changes in Channel Cross-Section
1700 feet above Hamilton City Gage



Sacramento River
Bank Erosion Investigation

Changes in Channel Cross-Section 1300 feet above Ord Ferry Gage

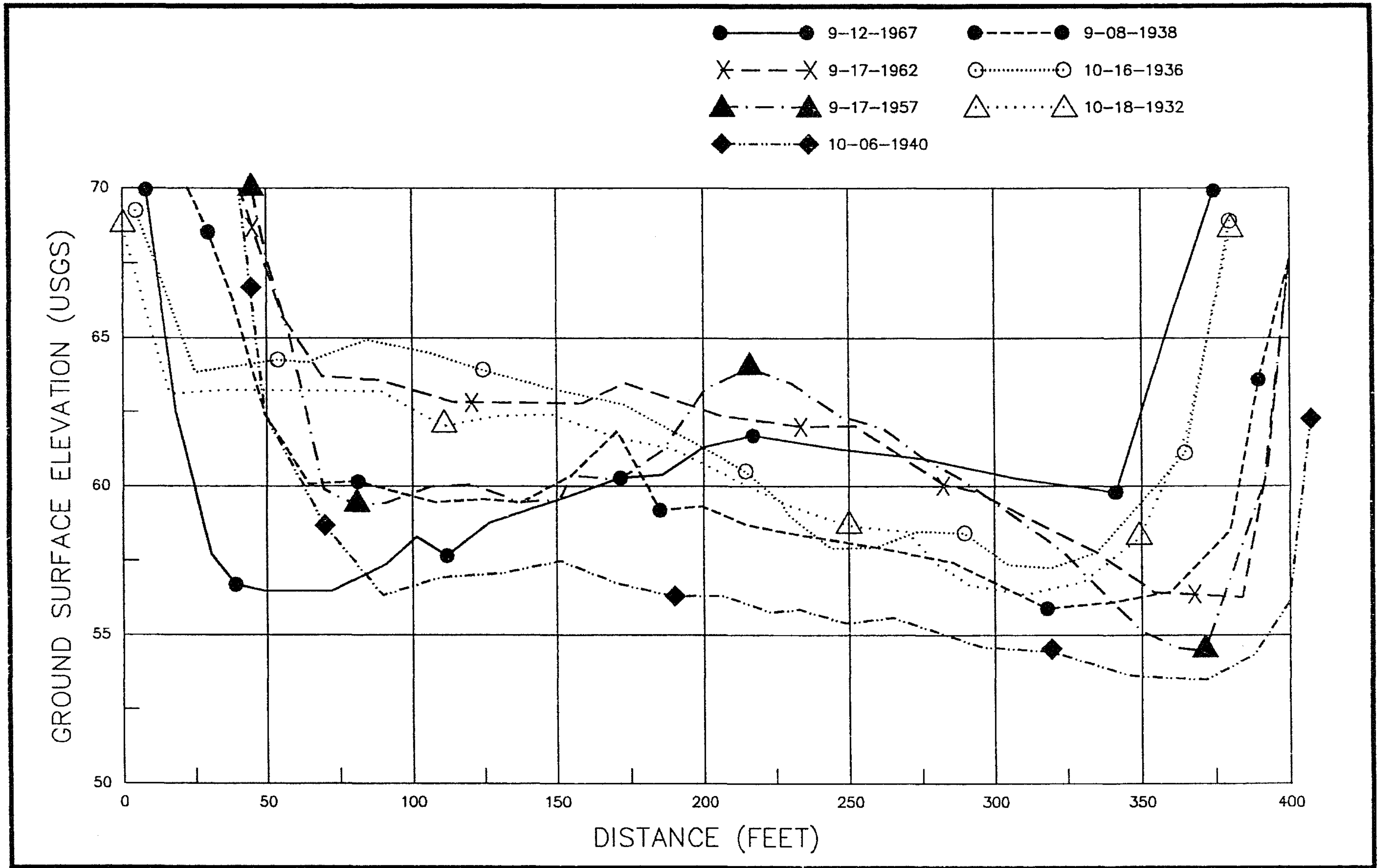
Figure 52



Sacramento River
Bank Erosion Investigation

Changes in Channel Cross–Section 1000 feet above Ord Ferry Gage

Figure 53



Sacramento River
Bank Erosion Investigation

Changes in Channel Cross-Section Butte City Gage

Figure 54

TABLE 13 CHANGE IN ELEVATION OF GAGING STATION CROSS-SECTIONS

years	1000 feet above Ord Ferry Gage		1300 feet above Ord Ferry Gage		Butte City Gage		1300 feet below Vina Gage		1500 feet below Vina Gage		700 feet above Hamilton City Gage	
	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*
1932	-	-	-	-	8.50	0	-	-	-	-	-	-
1936	-	-	-	-	7.68	+0.82	-	-	-	-	-	-
1938	-	-	-	-	9.84	-2.16	-	-	-	-	-	-
1940	-	-	-	-	12.38	-2.54	-	-	-	-	-	-
1957	-	-	-	-	8.47	+3.91	-	-	-	-	-	-
1962	-	-	-	-	7.55	+0.92	-	-	-	-	-	-
1967	-	-	-	-	8.84	-1.29	-	-	-	-	-	-
1976	-	-	-	-	-	-	-	-	-	-	7.23	0
1977	-	-	6.55	0	-	-	5.14	0	-	-	7.31	-0.08
1978	-	-	8.32	-1.77	-	-	7.57	-2.43	-	-	7.30	+0.01
1979	-	-	8.35	-0.03	-	-	8.30	-0.73	-	-	7.32	-0.02
1980	-	-	8.69	-0.34	-	-	7.93	+0.37	-	-	-	-
1981	-	-	8.85	-0.16	-	-	-	-	8.16	0	7.22	+0.10
1982	-	-	8.70	+0.15	-	-	-	-	7.80	+0.36	7.10	+0.12
1983	10.05	0	-	-	-	-	-	-	9.69	-1.89	-	-
1984	9.67	+0.38	-	-	-	-	-	-	8.92	+0.77	6.91	+0.19
1985	9.71	-0.04	-	-	-	-	-	-	-	-	-	-

* Change in average elevation of cross-section, in feet. + Aggradation - Degradation

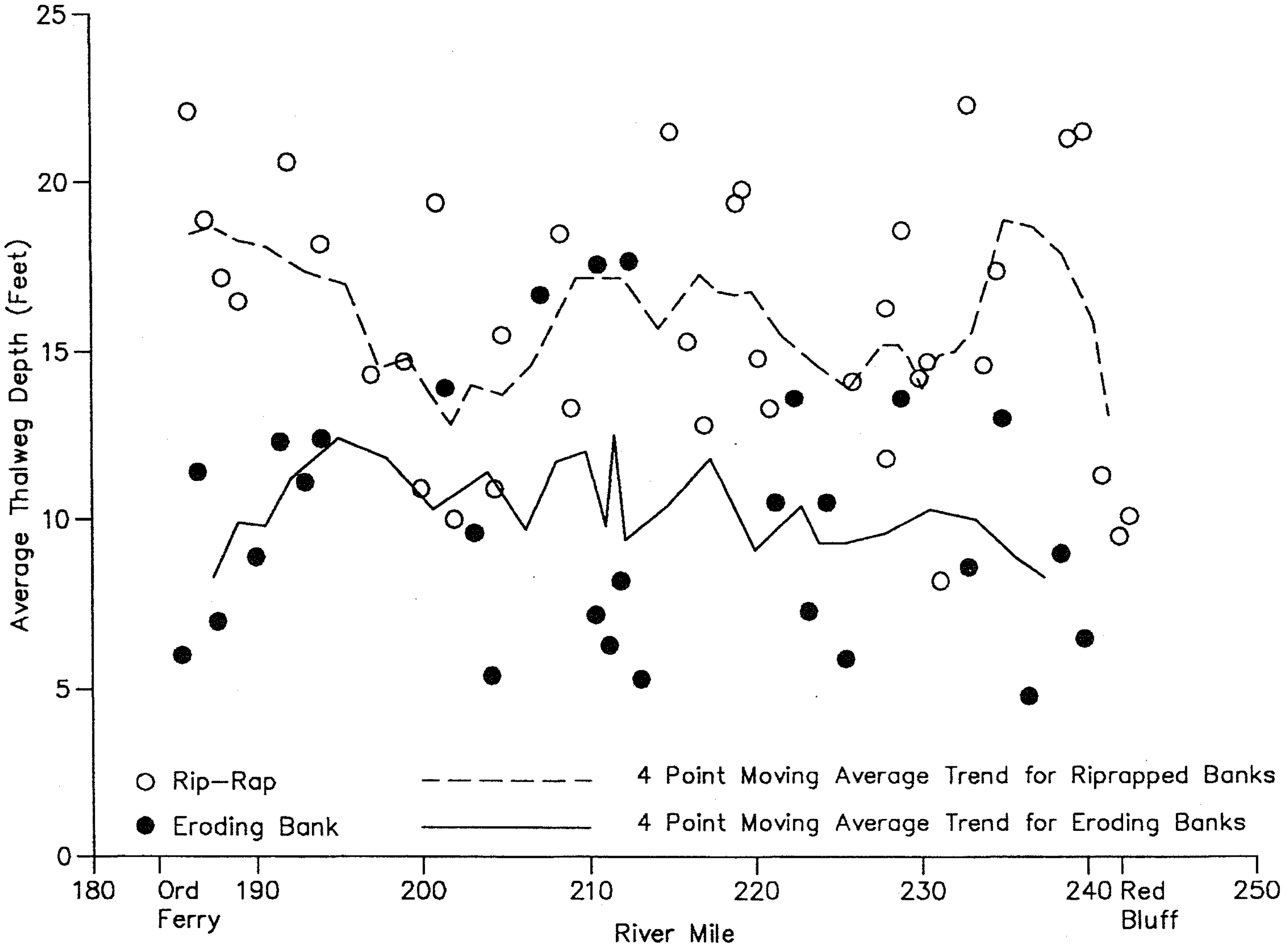
THALWEG DEPTHS AND RIVER WIDTHS NEAR ERODING AND RIPRAPPED BANKS

The Department of Water Resources (1984) theorized that bank protection would cause the channel to narrow and deepen. When a channel is stabilized, it will no longer erode its banks but will erode its bed. Deposition will continue on the inside of the bend, causing the channel to narrow and deepen. Such a channel will have less hydraulic diversity and salmon spawning area.

In conjunction with DWR's bank erosion monitoring program, thalweg depths were measured in 1987 opposite 30 eroding banks between Red Bluff and Ord Ferry. Depths were obtained by using a sonar depth-finding instrument mounted on the back of a jet boat. Individual surveys were started at the downstream end of the site and continuous soundings recorded as the boat followed a sinusoidal path across the thalweg adjacent to each bank. The resultant strip chart recordings were analyzed and an average thalweg depth for each site was obtained. The same procedure was used for measuring thalweg depths opposite 37 riprapped sites between Red Bluff and Ord Ferry. These data were entered into spreadsheets for analysis. Eroding bank and riprapped thalweg depths were then plotted by river mile. Four-point moving average trends were then derived and plotted for both erosion and riprap sites. The area between these two curves was divided by measured river length to yield mean river depth over the measured Sacramento River reach. Figure 55 shows that in 1987 the mean thalweg along riprapped banks average 6 feet deeper than comparable eroding banks. The average thalweg depth for riprap has a mean of 15.8 feet, ranging from a minimum of 8 feet to a maximum of 23 feet. The average thalweg depth for eroding banks has a mean of 10.0 feet, ranging from a minimum of 5 feet to a maximum of 18 feet.

A similar study was done in 1991 to test the results of our 1987 study. The resulting plot, shown on Figure 56, is remarkably similar to the 1987 results.

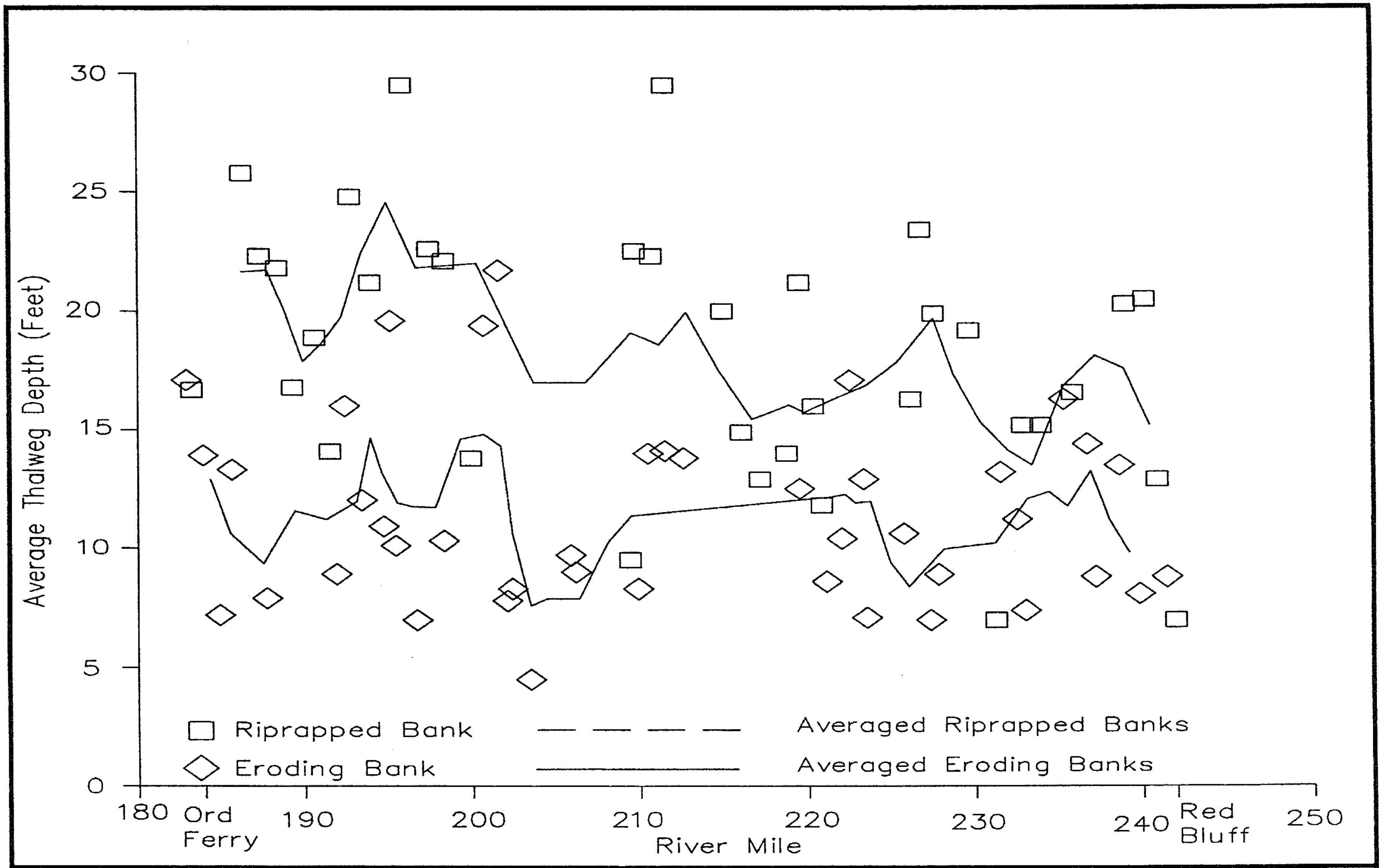
River channel widths were measured every 400 feet from 1987 aerial photos between Red Bluff and Ord Ferry. River widths opposite eroding and riprapped banks were averaged to yield a mean width opposite each eroding bank and a mean width opposite each riprapped bank. These mean values were then plotted by river mile (Figure 57). Four-point-moving-average trends were also calculated and plotted. The area between these two curves was divided by measured river length to yield mean river width over the measured Sacramento reach. Widths opposite erosion sites are generally greater than at riprap sites by an average of 65 to 90 feet, depending on how the average is calculated. Eroding banks have a mean of 480 feet, ranging from a minimum of 325 feet to a maximum of 600 feet. Riprap widths were narrower, with a mean of 410 feet, ranging from a minimum of 290 feet to a maximum of 600 feet. The difference in widths appears to remain fairly constant from Ord Ferry (RM 184.3) to RM 223; upriver from there, the difference decreases until from RM 235 to Red Bluff, it is essentially nonexistent.



Sacramento River
Bank Erosion Investigation

1987 Thalweg Depths Next to Eroding and Riprapped Banks

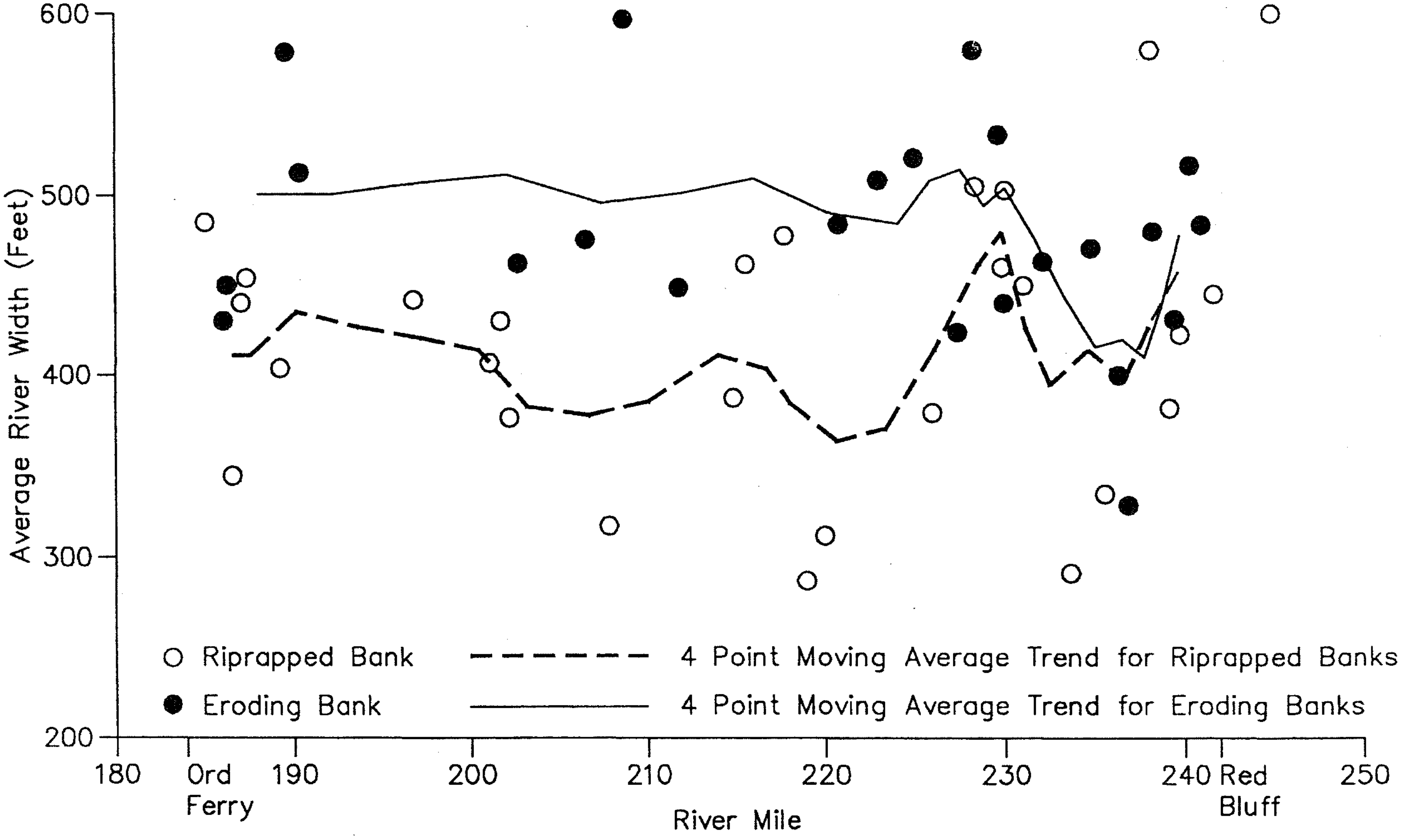
Figure 55



Sacramento River
Bank Erosion Investigation

1991 Thalweg Depths Next to Eroding and Riprapped Banks

Figure 56



Bank Erosion Investigation

1987 River Widths Next to Eroding and Riprapped Banks

Figure 57

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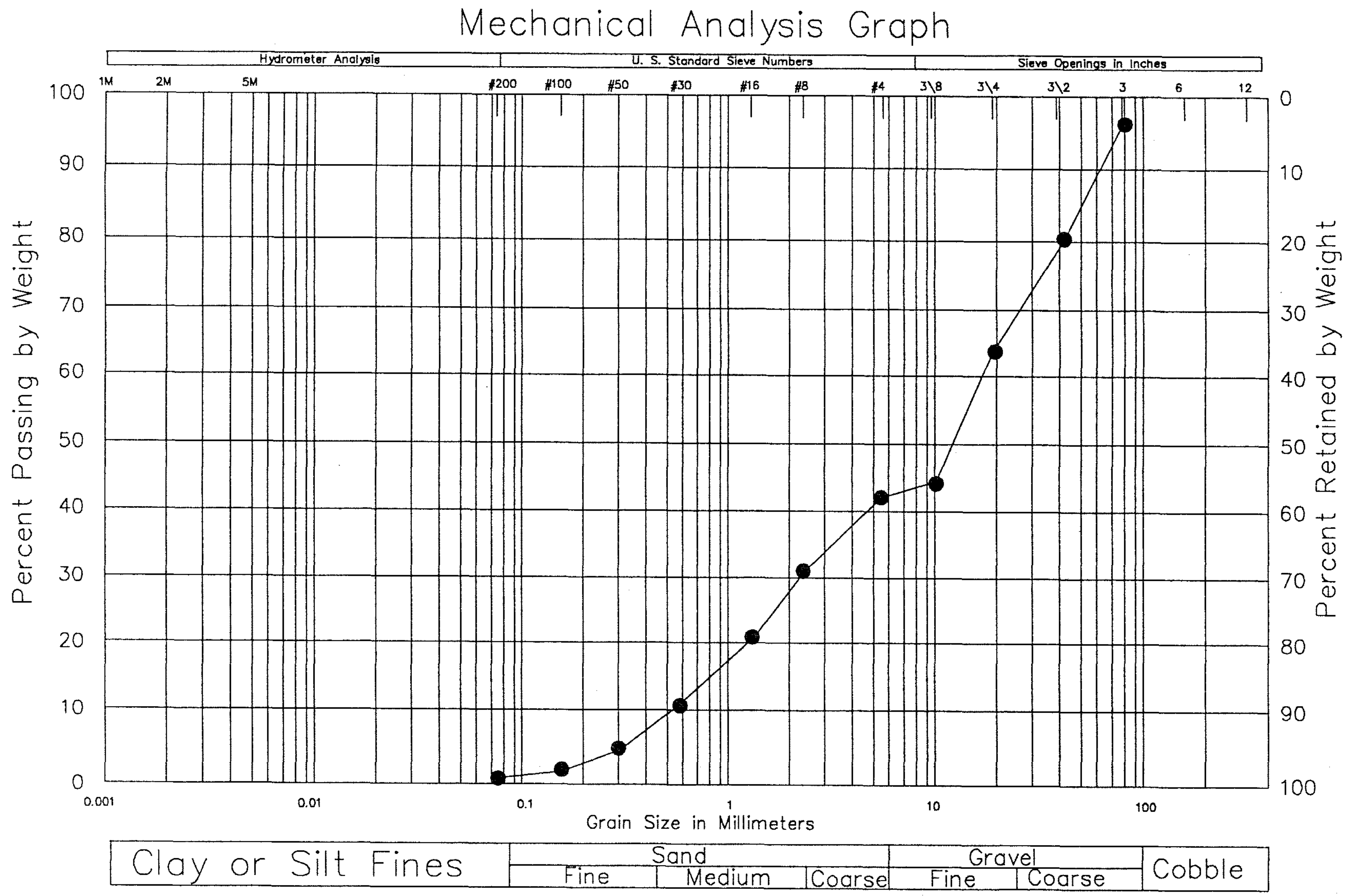
APPENDIX A

SACRAMENTO RIVER BANK BULK SAMPLES



MECHANICAL ANALYSIS OF THE
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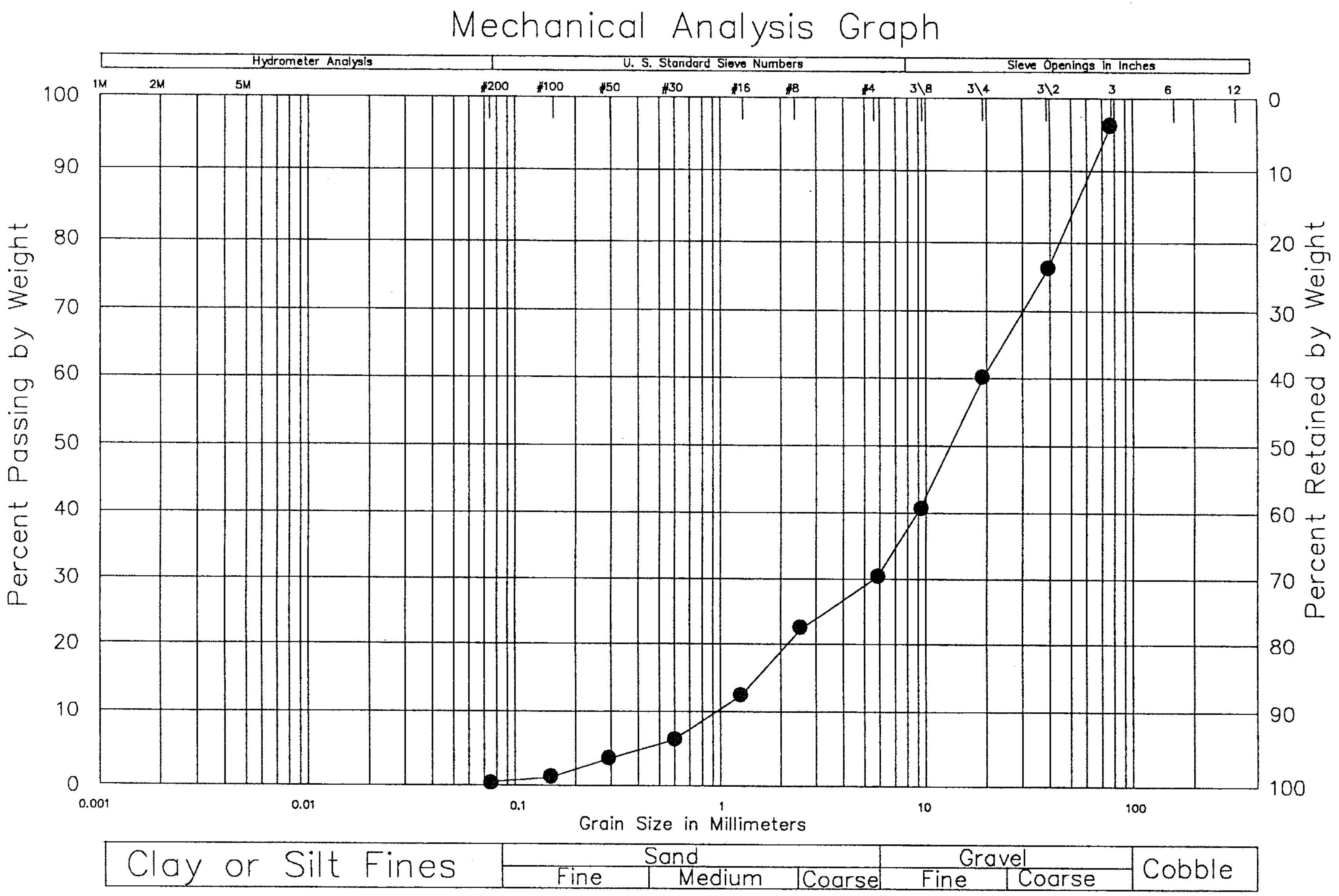
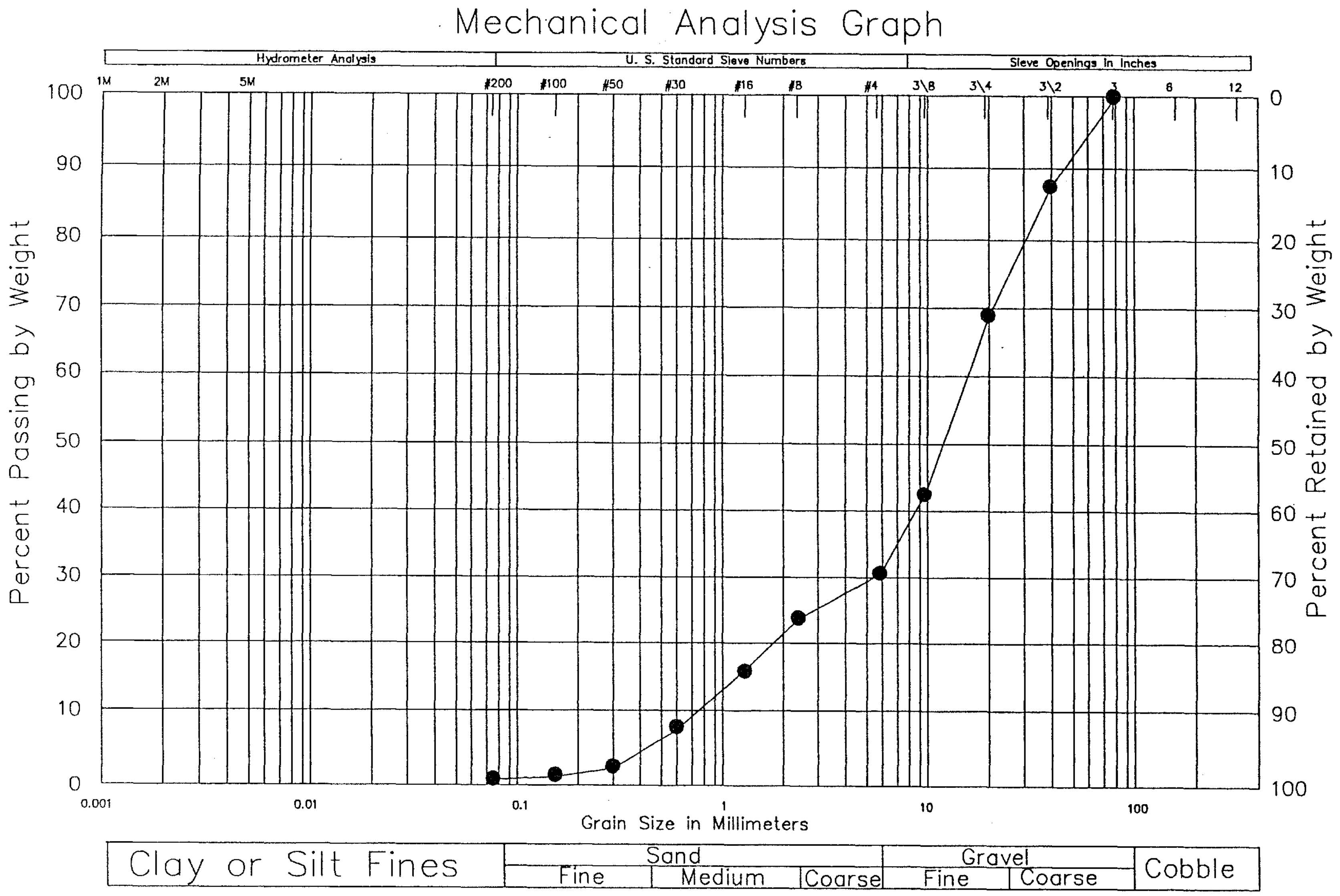
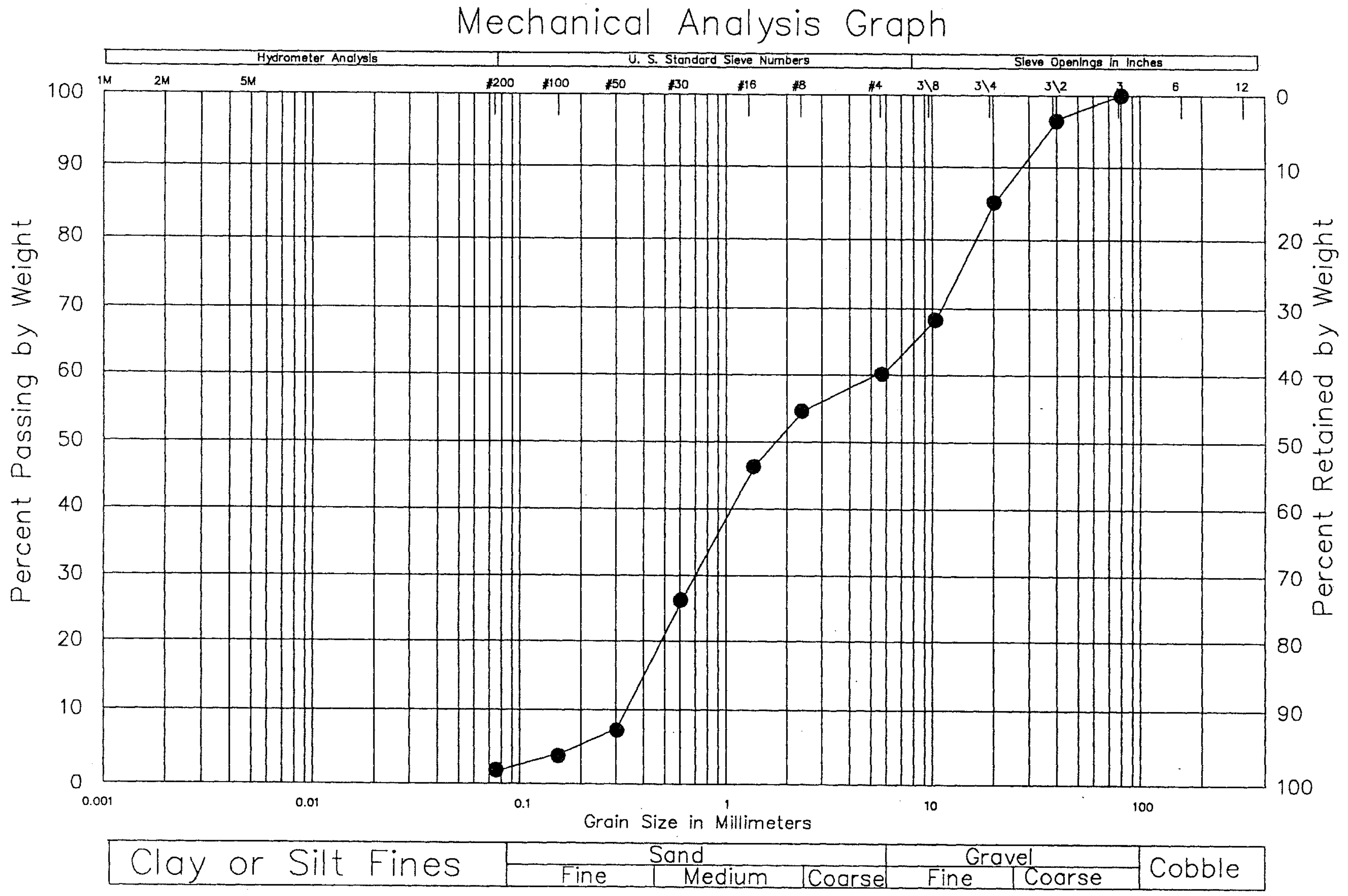


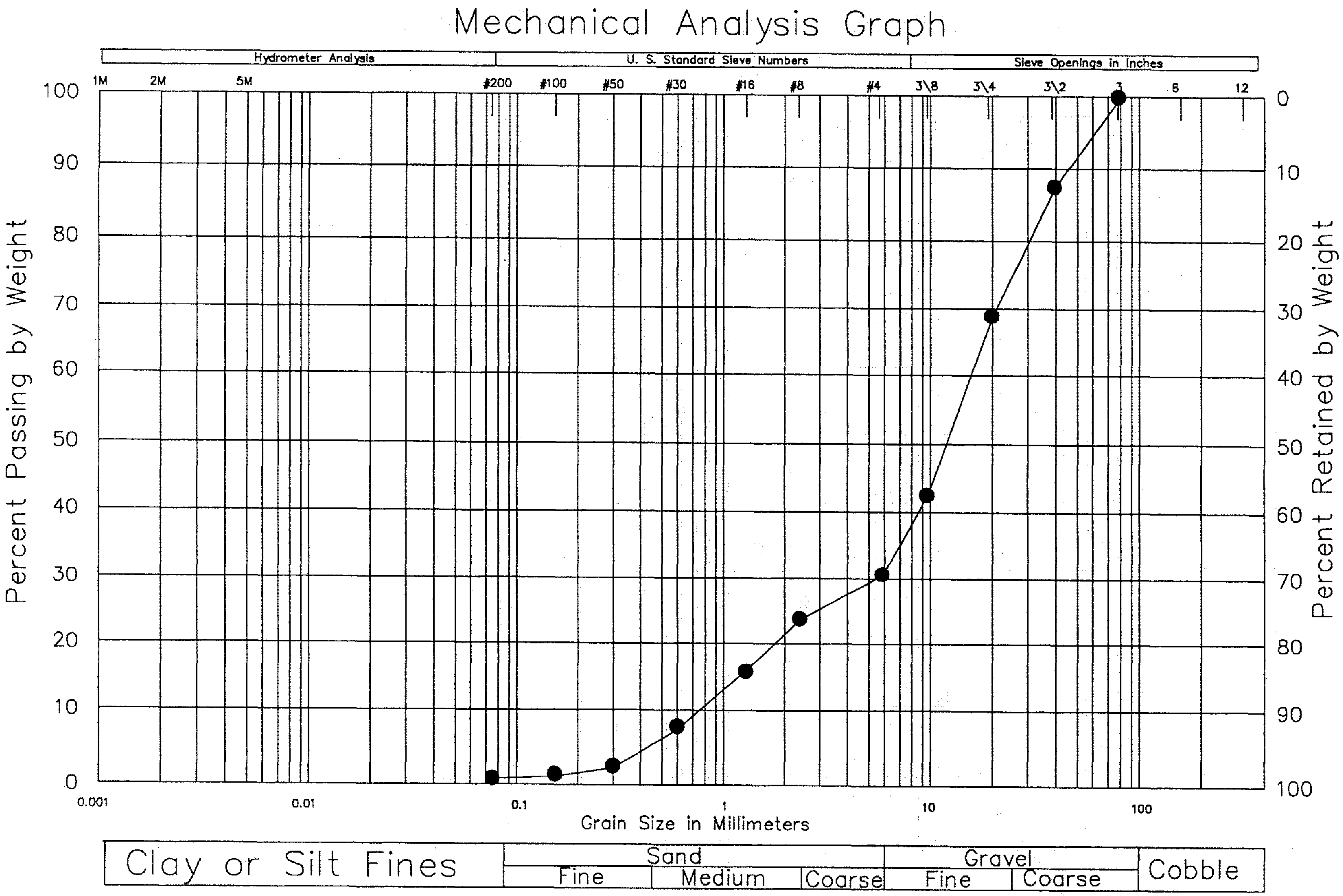
MECHANICAL ANALYSIS OF THE
TOOMES CREEK #1 EROSION SITE



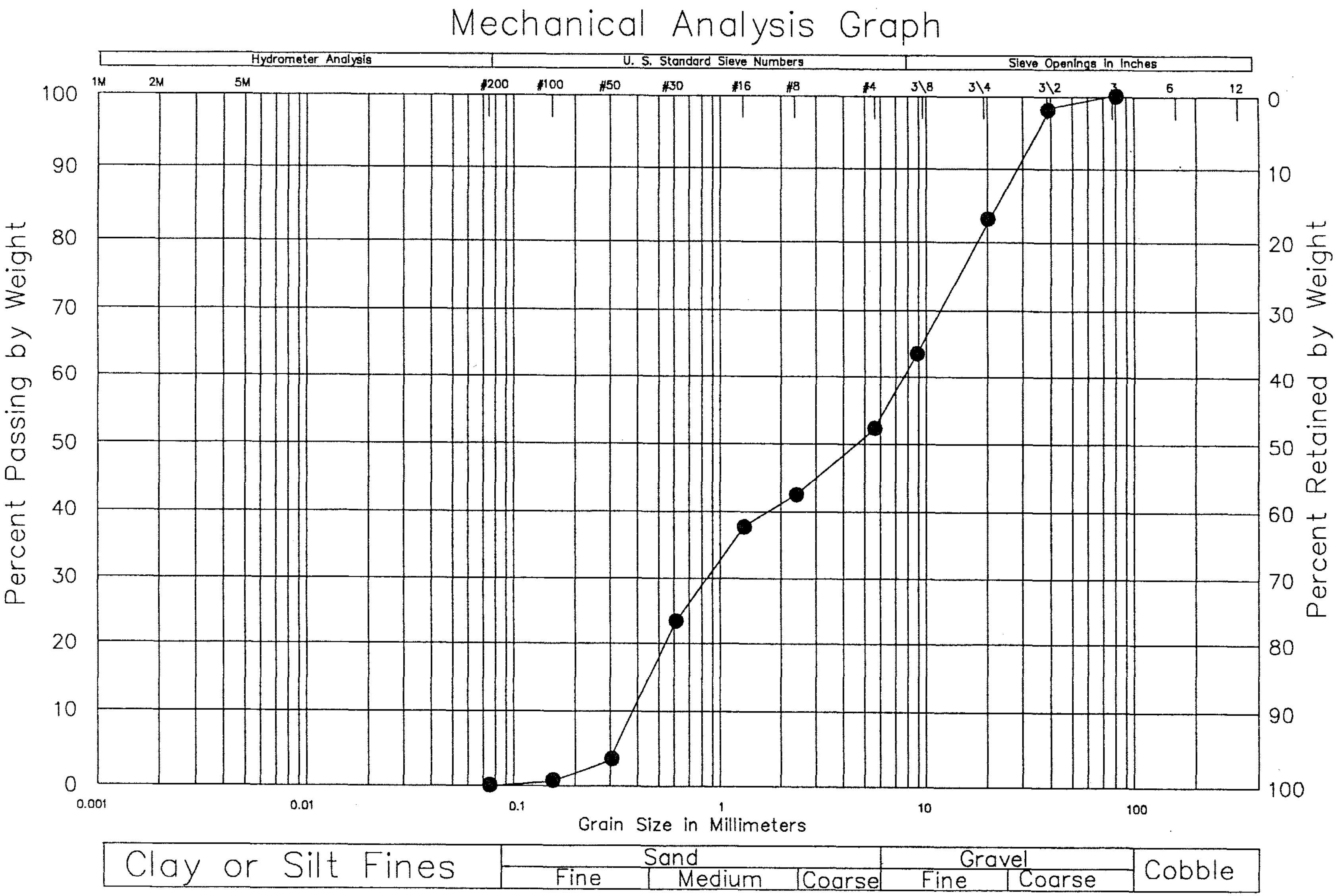
MECHANICAL ANALYSIS OF THE
PALISADES EROSION SITE



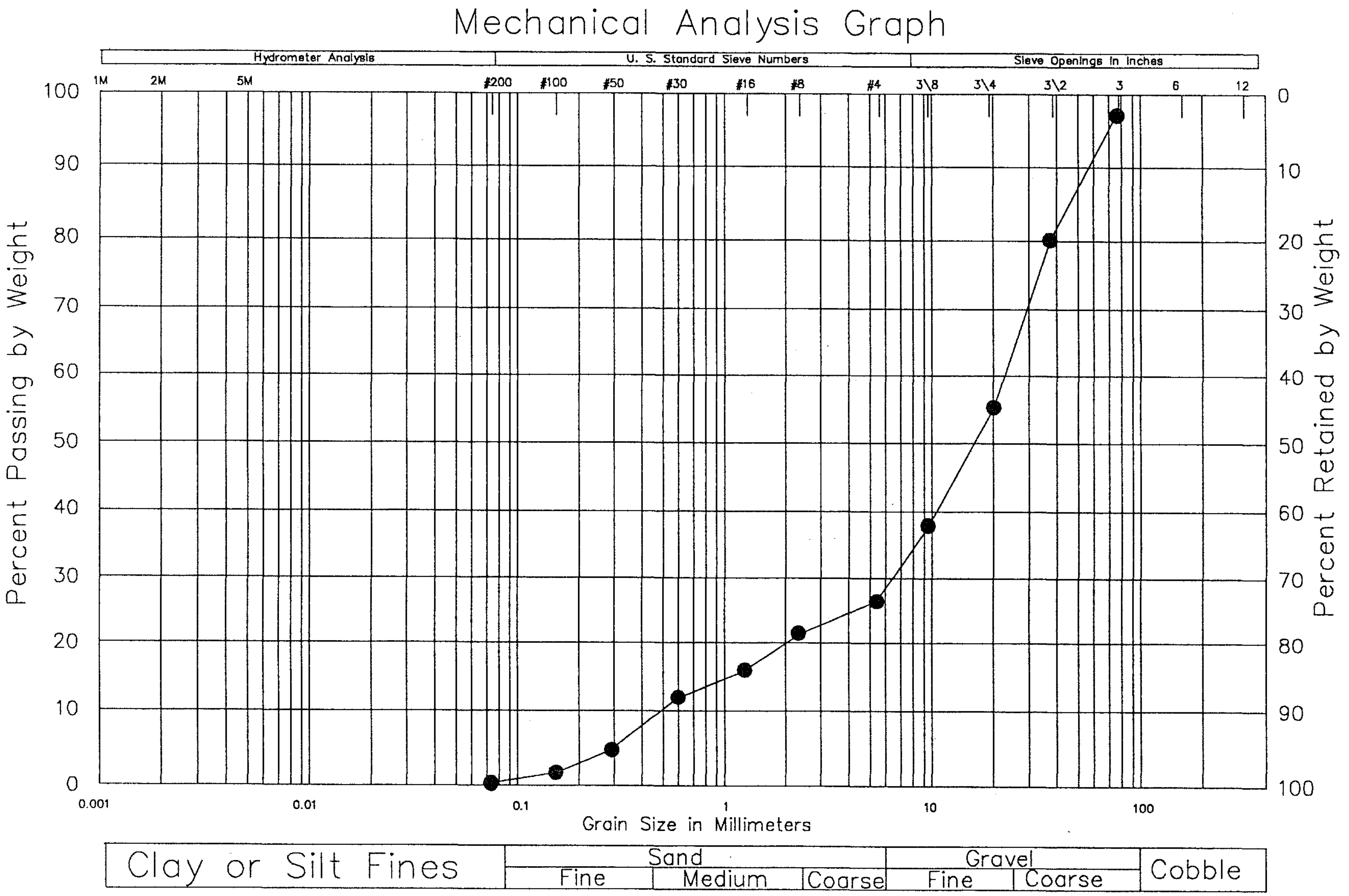
MECHANICAL ANALYSIS OF THE
TOOMES CREEK #2 EROSION SITE



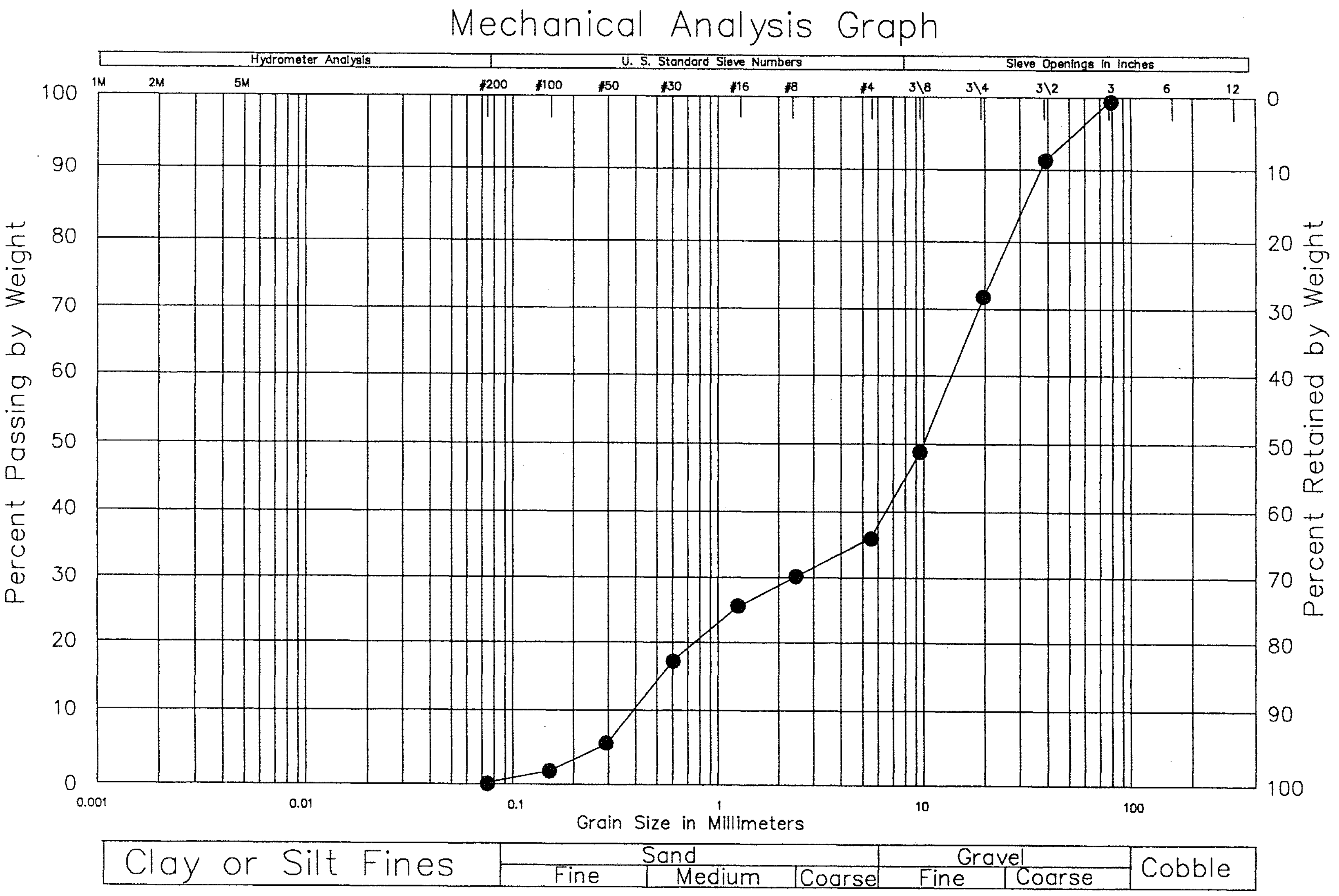
MECHANICAL ANALYSIS OF THE
PALISADES EROSION SITE



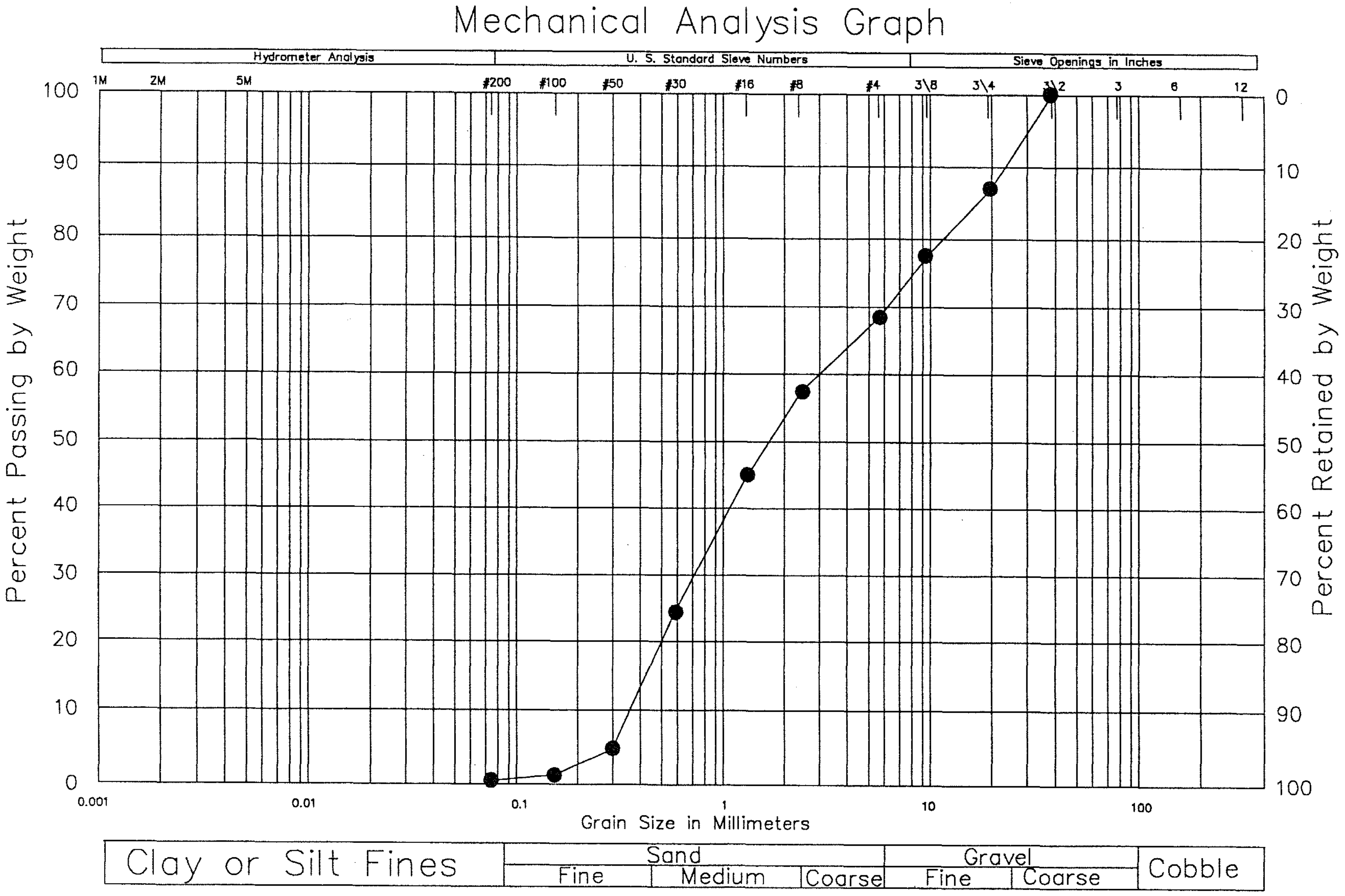
MECHANICAL ANALYSIS OF THE
BIG CHICO CREEK EROSION SITE



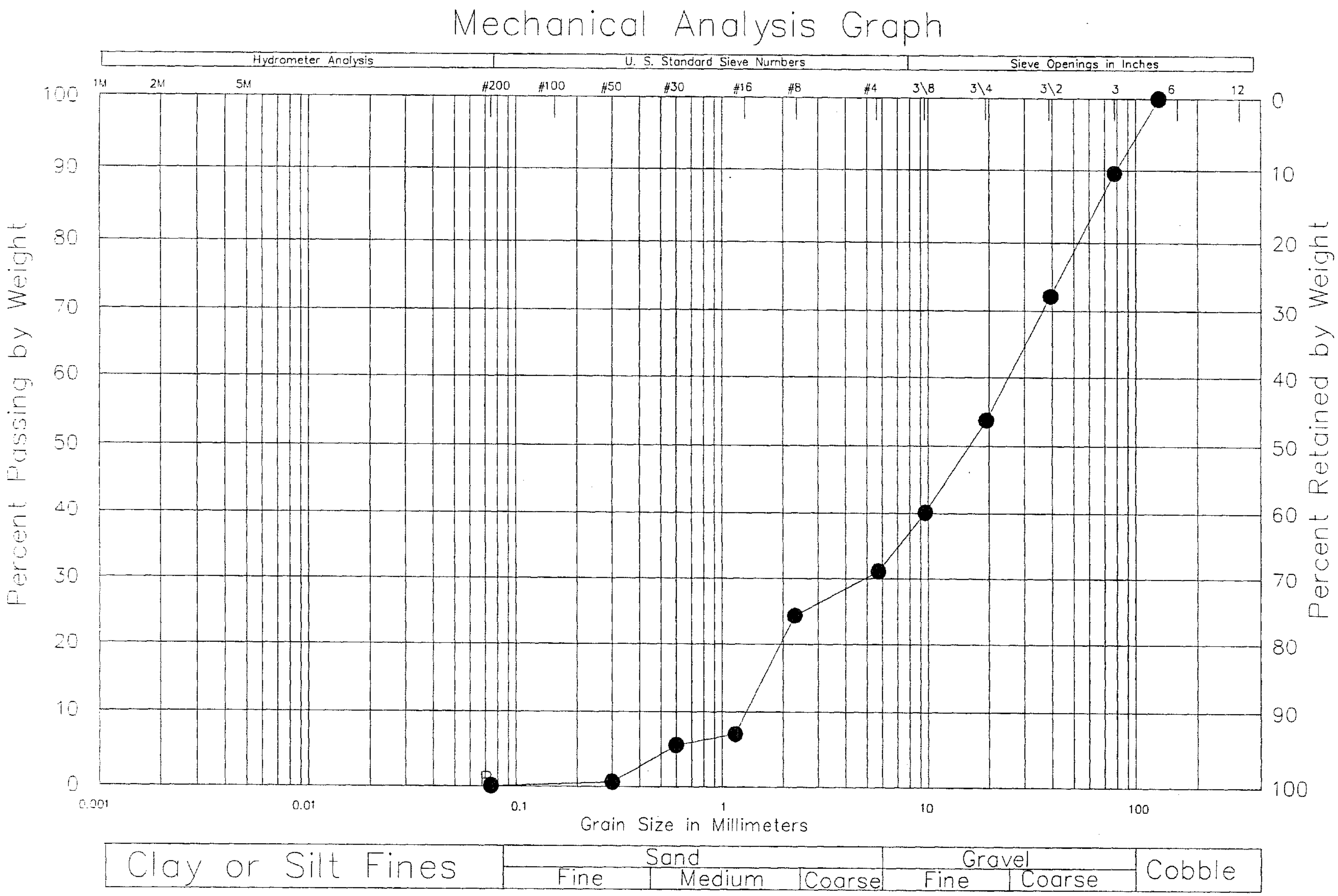
MECHANICAL ANALYSIS OF THE
RANCHO DE FARWELL EROSION SITE



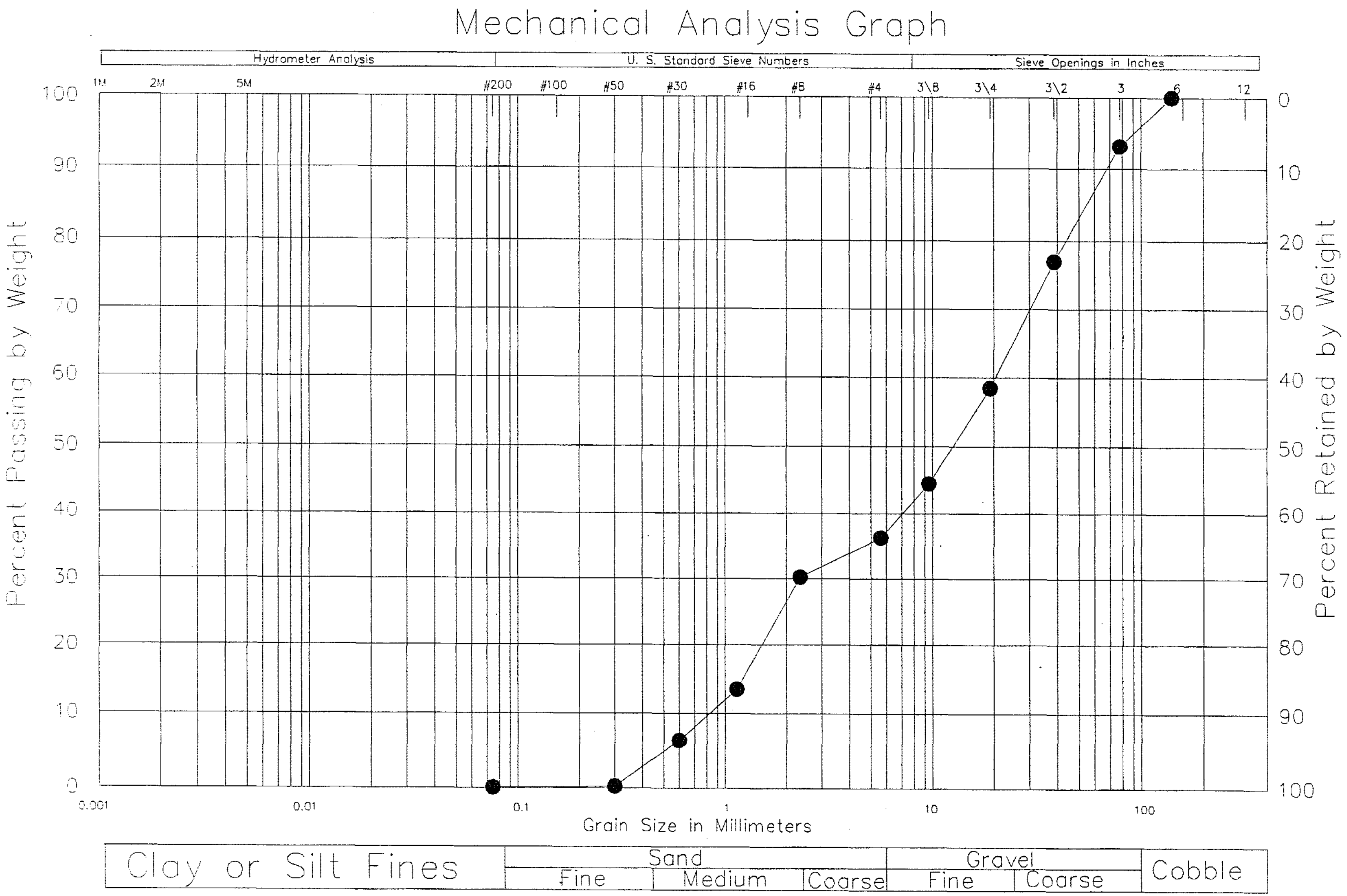
MECHANICAL ANALYSIS OF THE
FOSTER ISLAND EROSION SITE



MECHANICAL ANALYSIS OF THE
ORD FERRY EROSION SITE

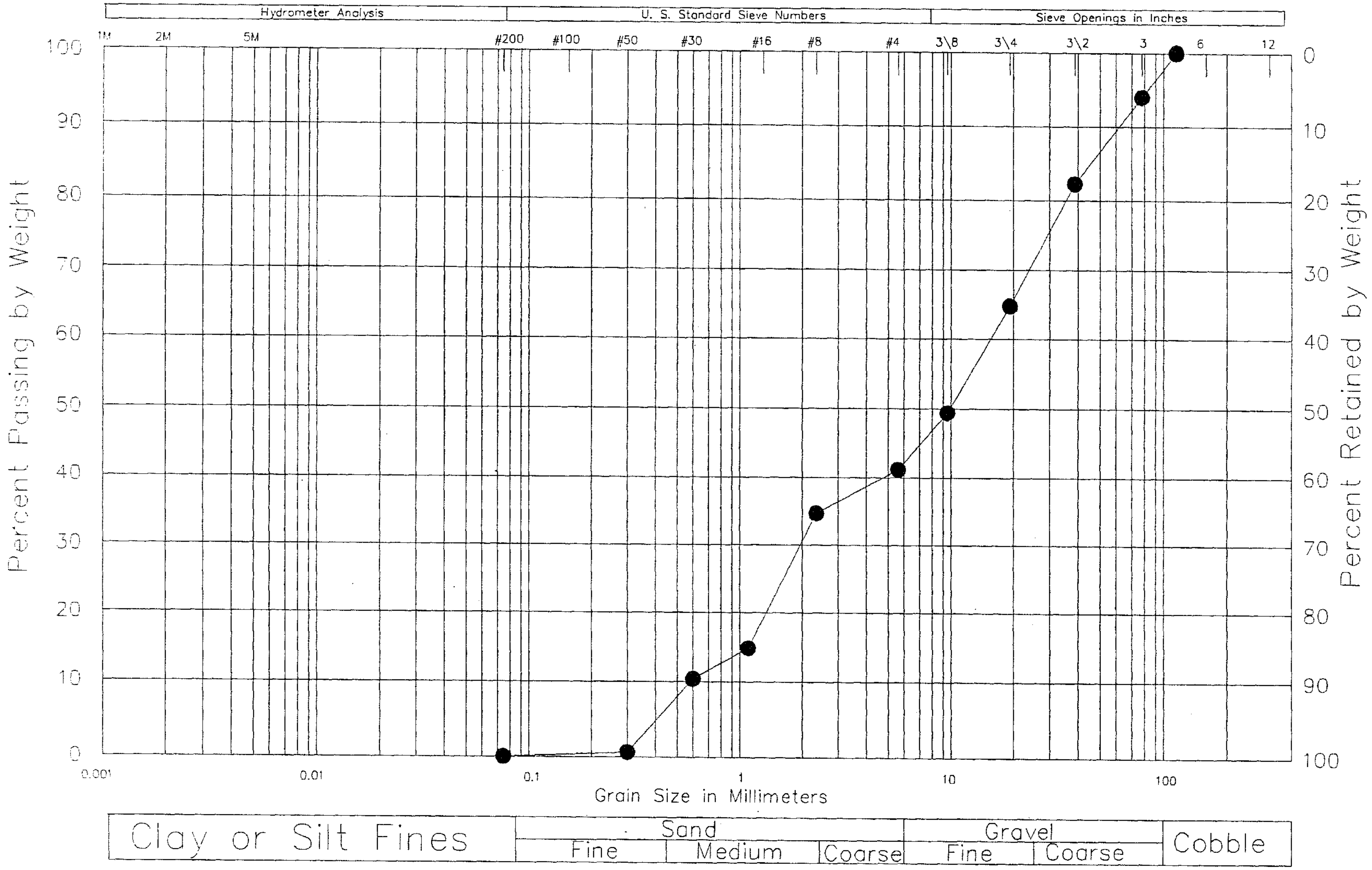


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT01

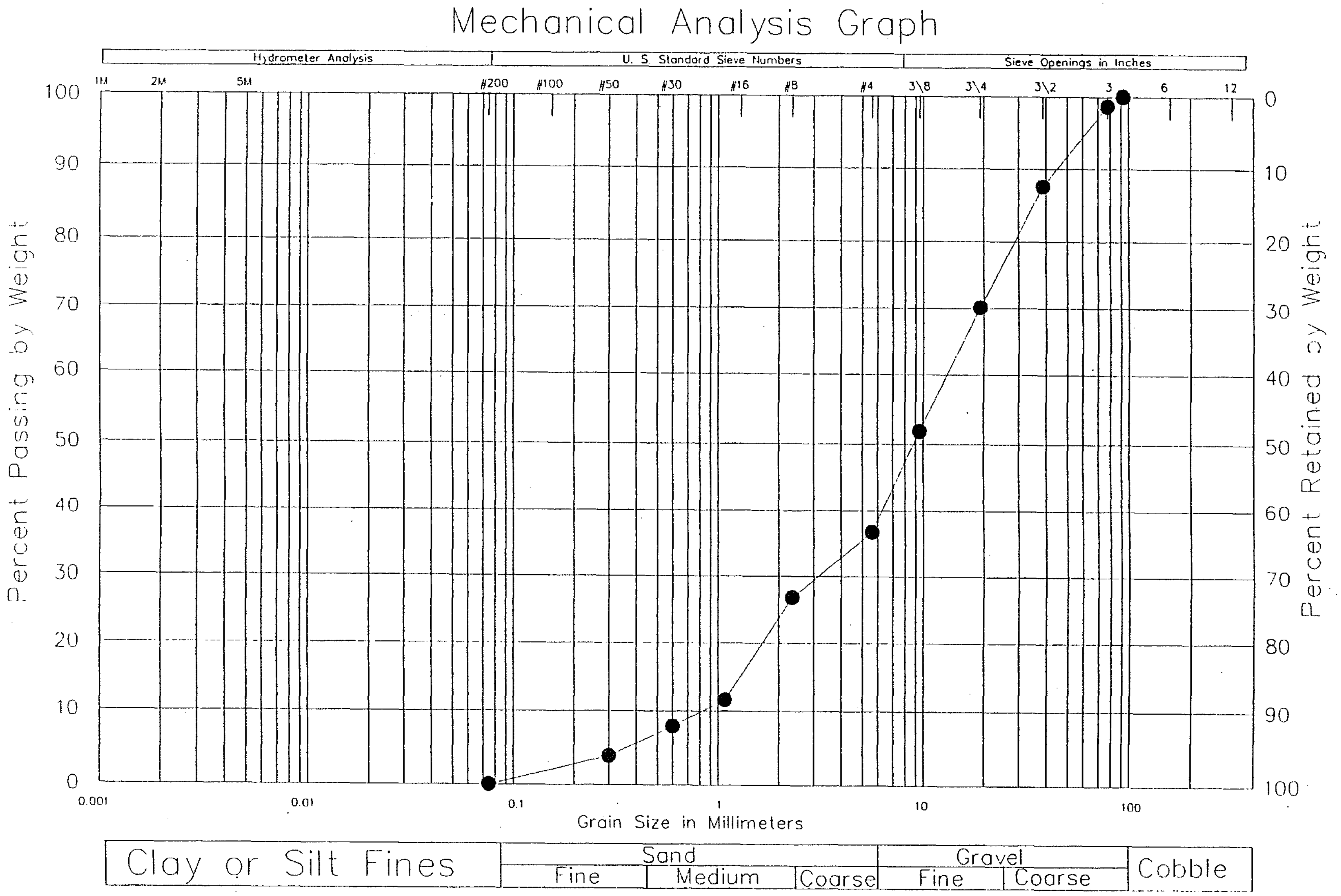


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT02

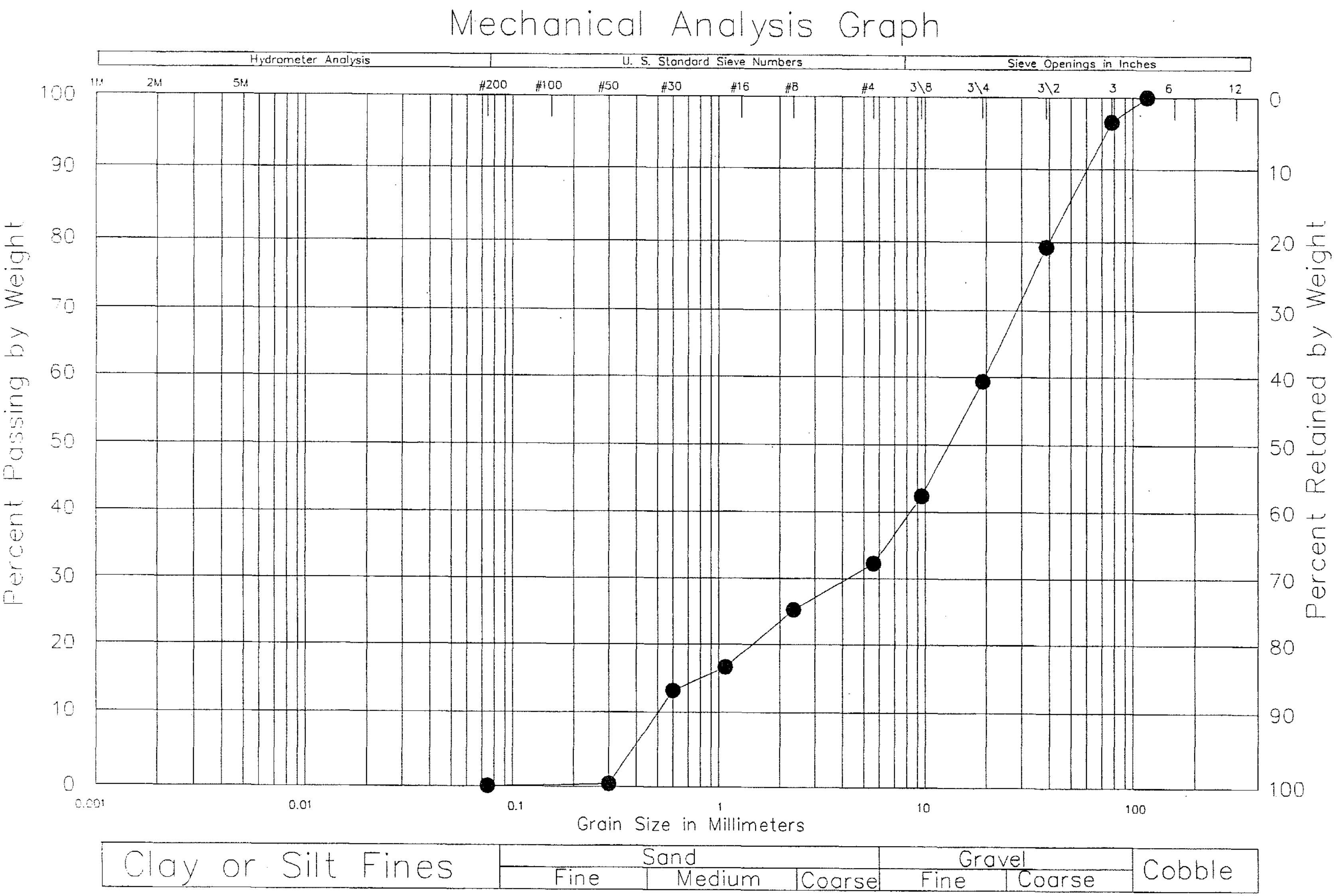
Mechanical Analysis Graph



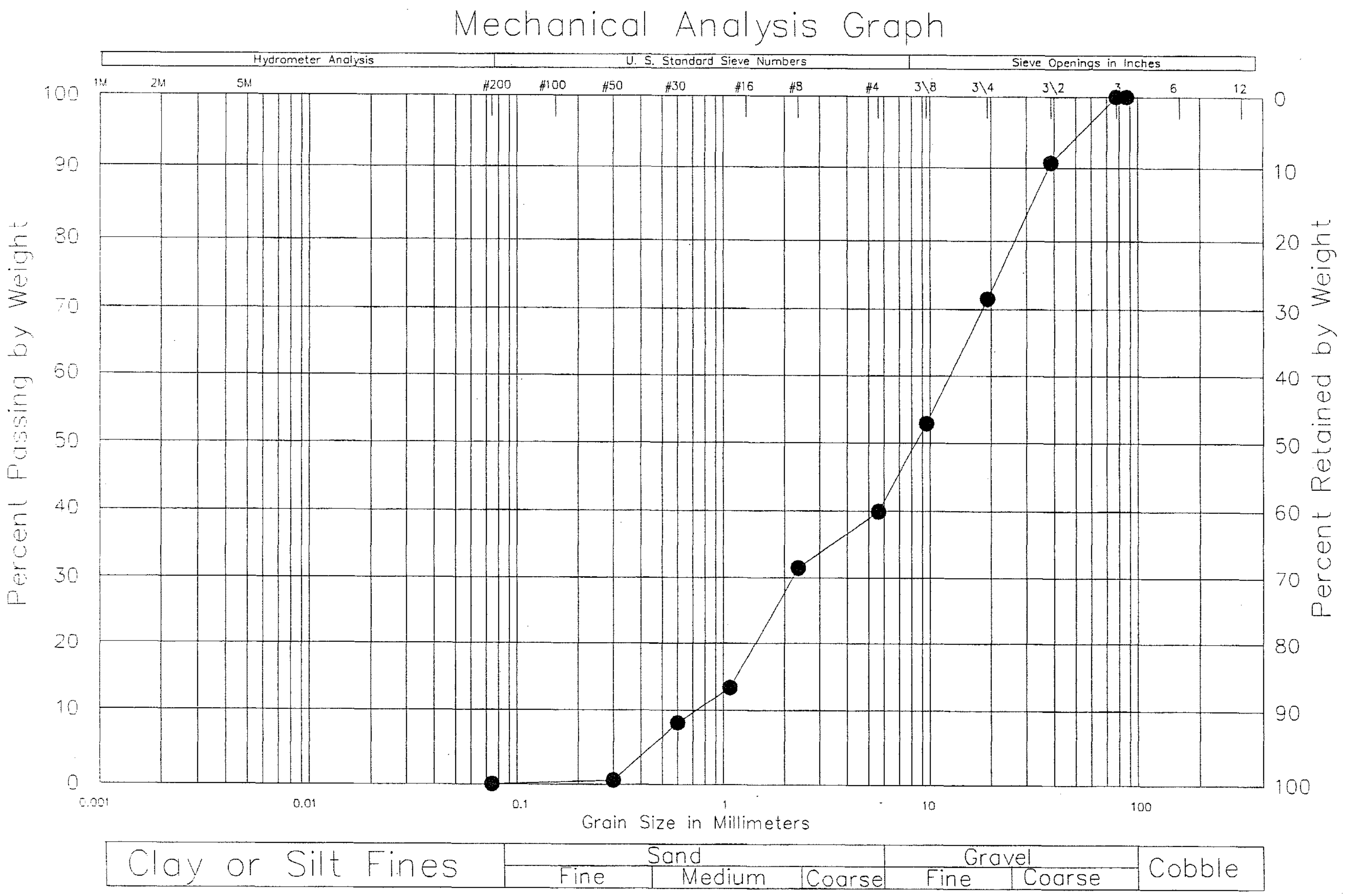
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT03



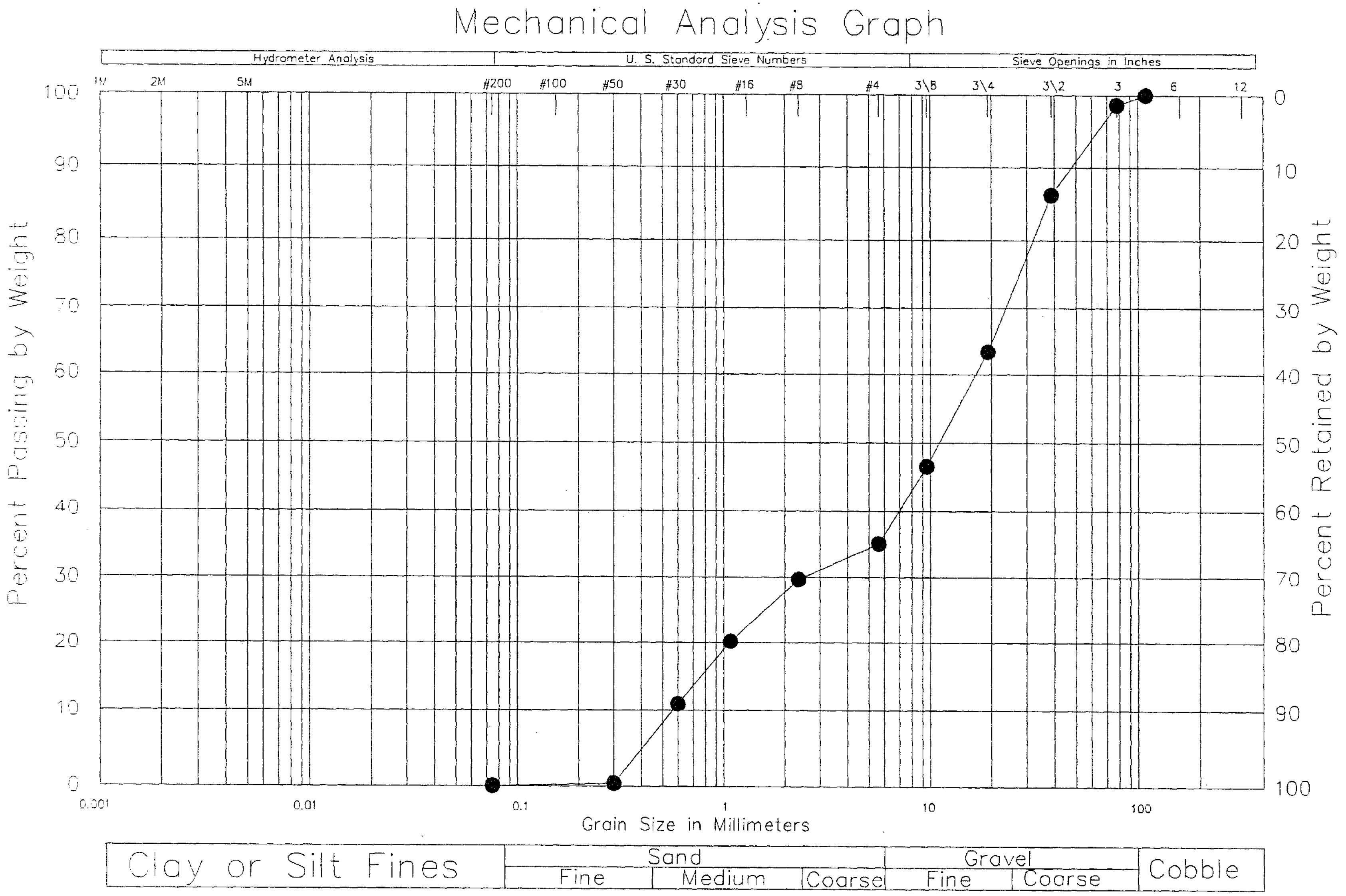
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT04



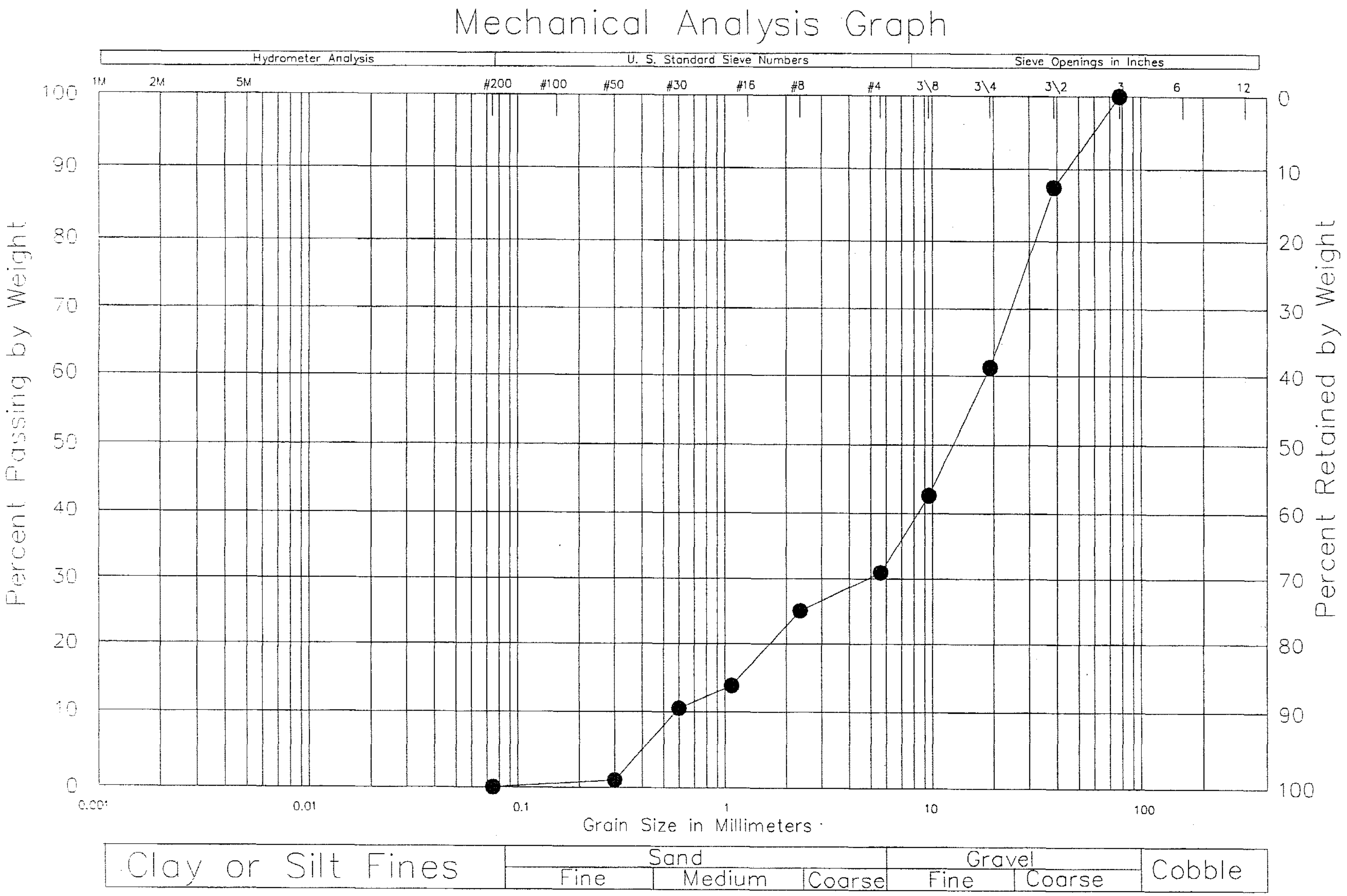
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT05



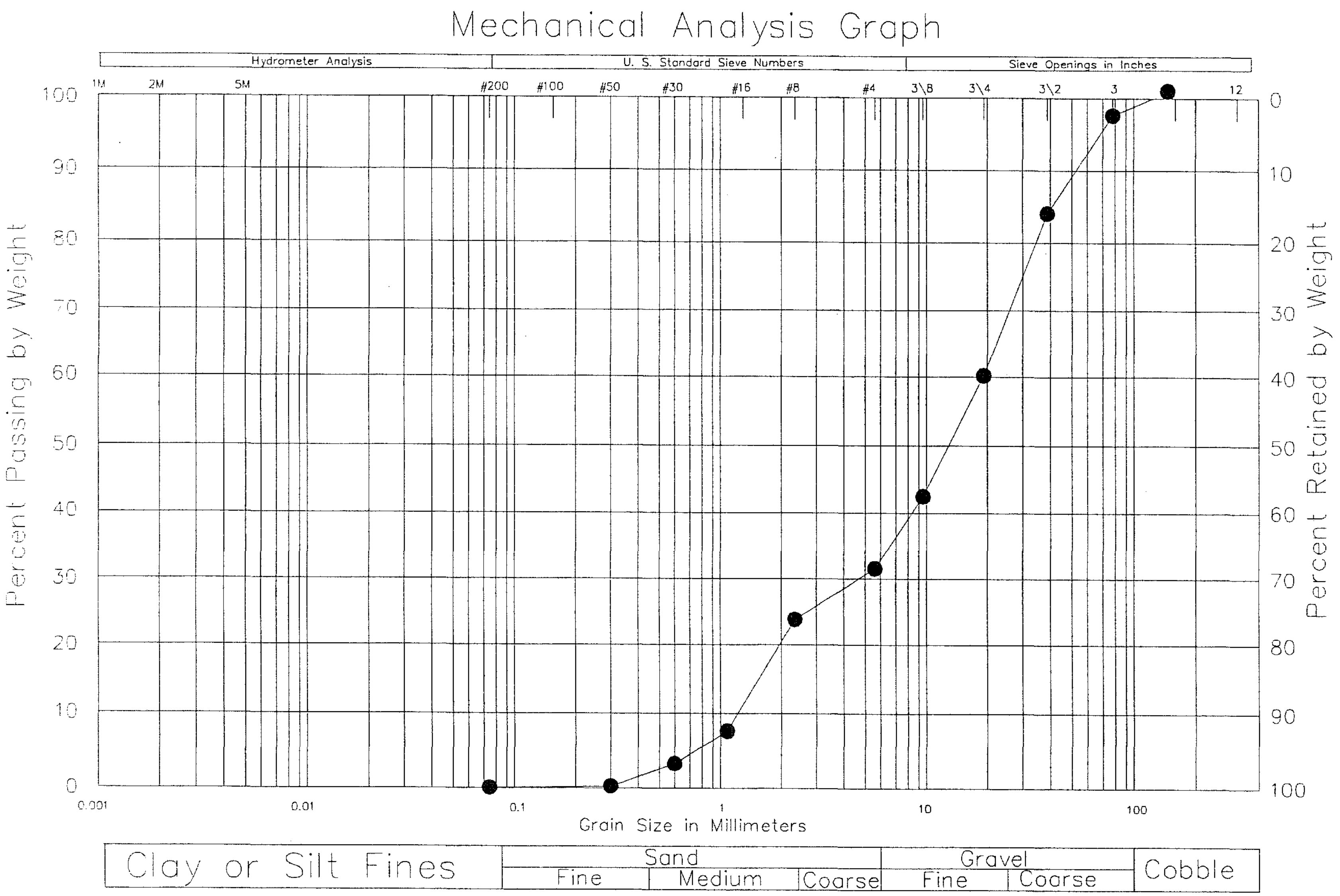
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT06



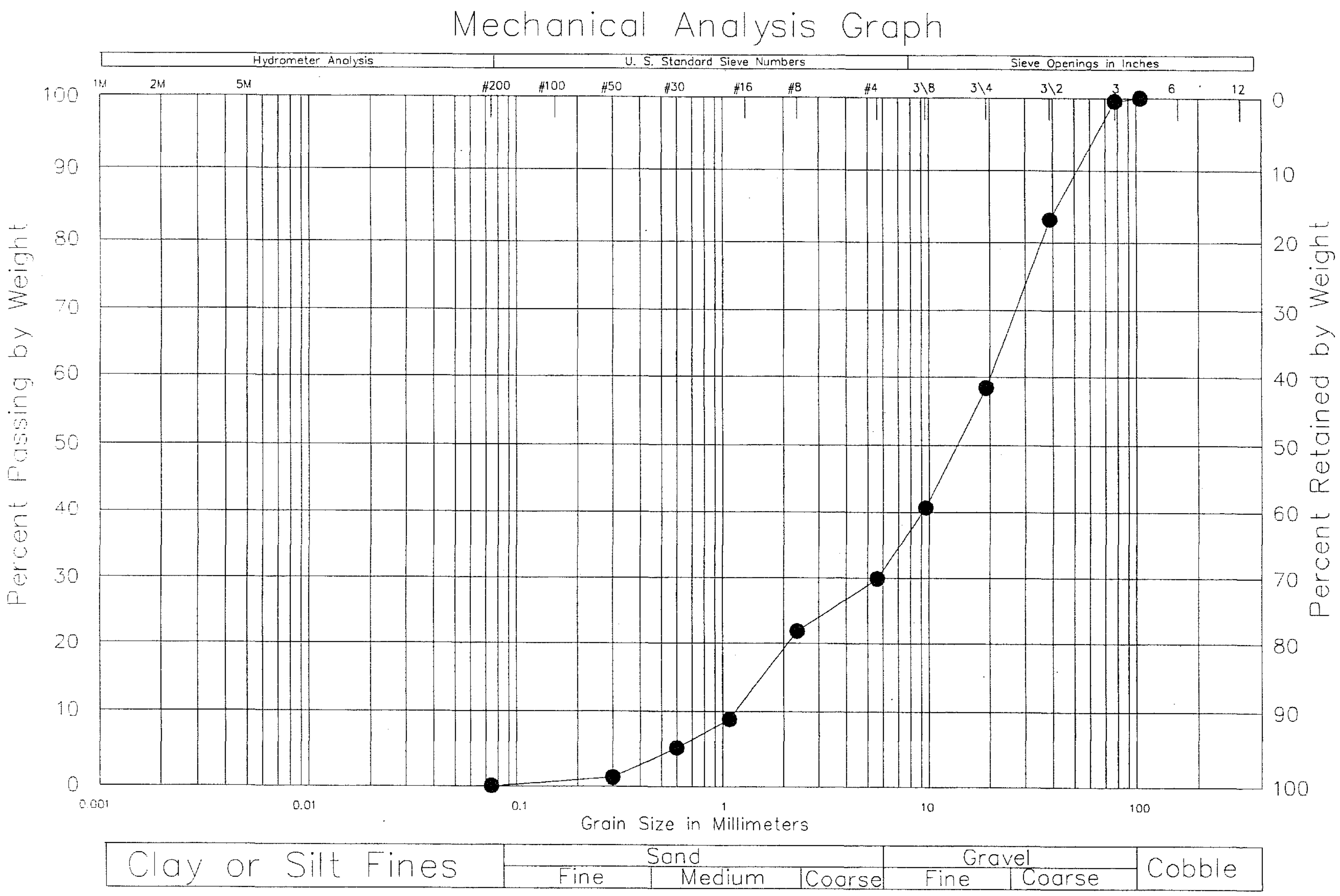
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT07



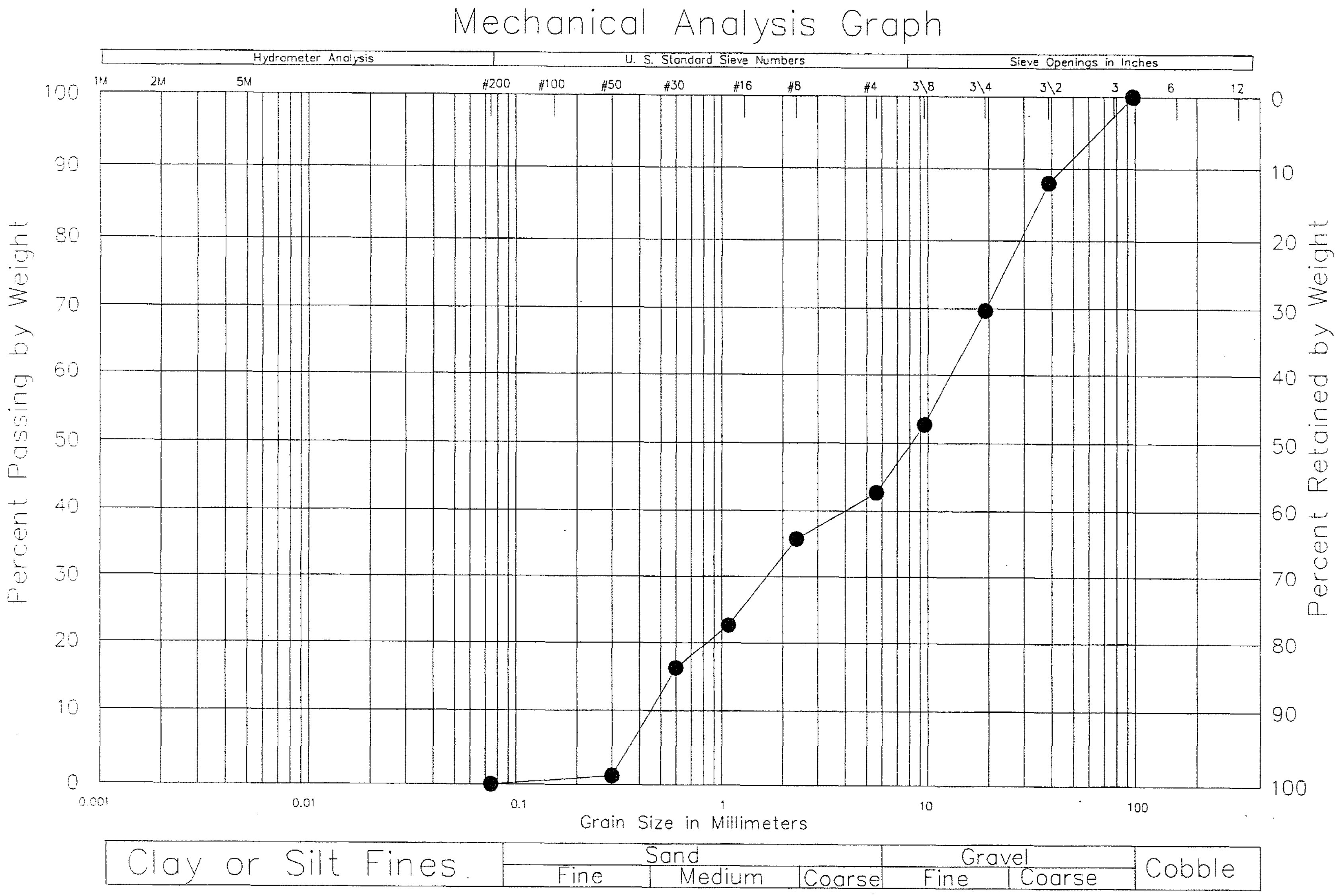
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT08



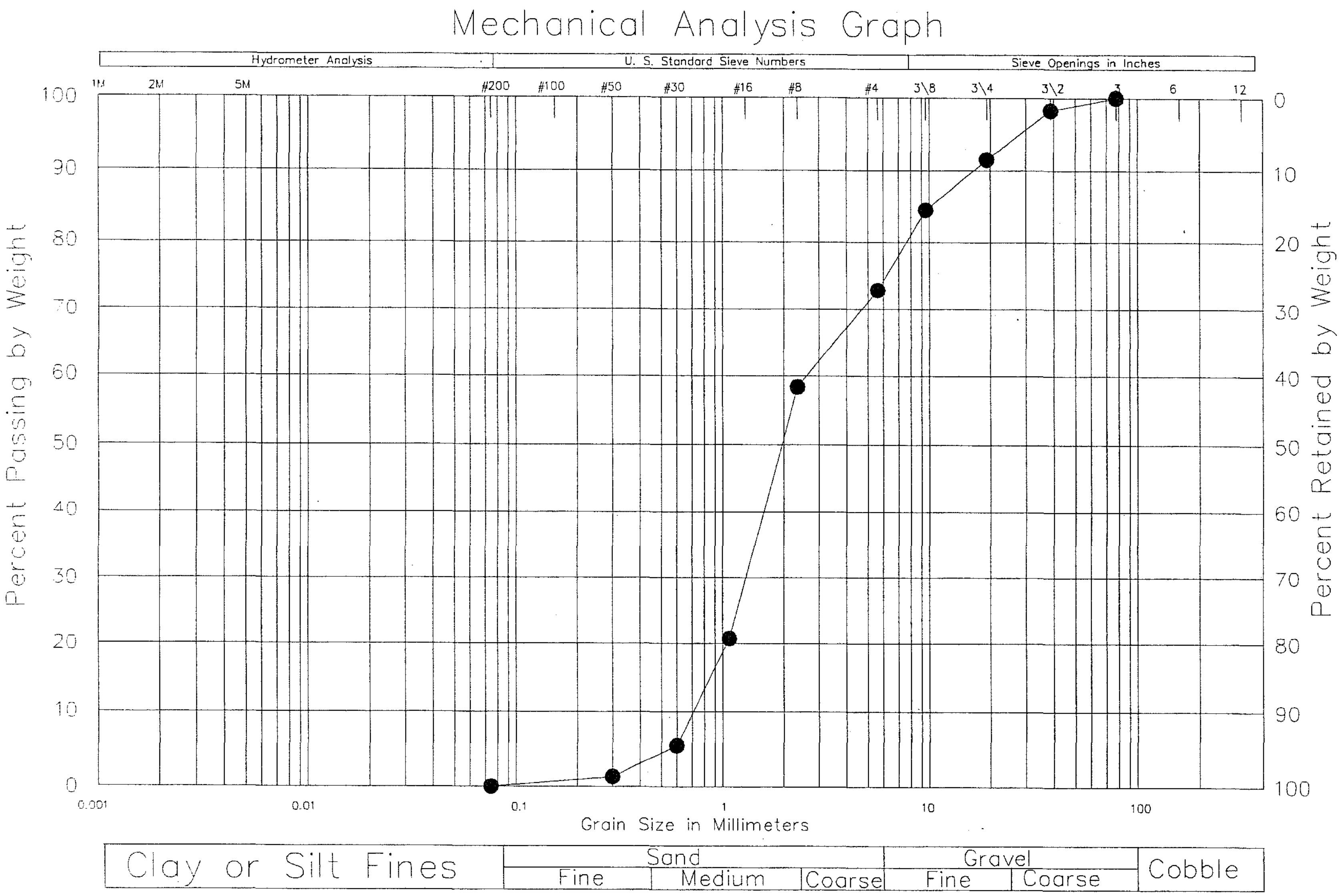
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT09



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT10

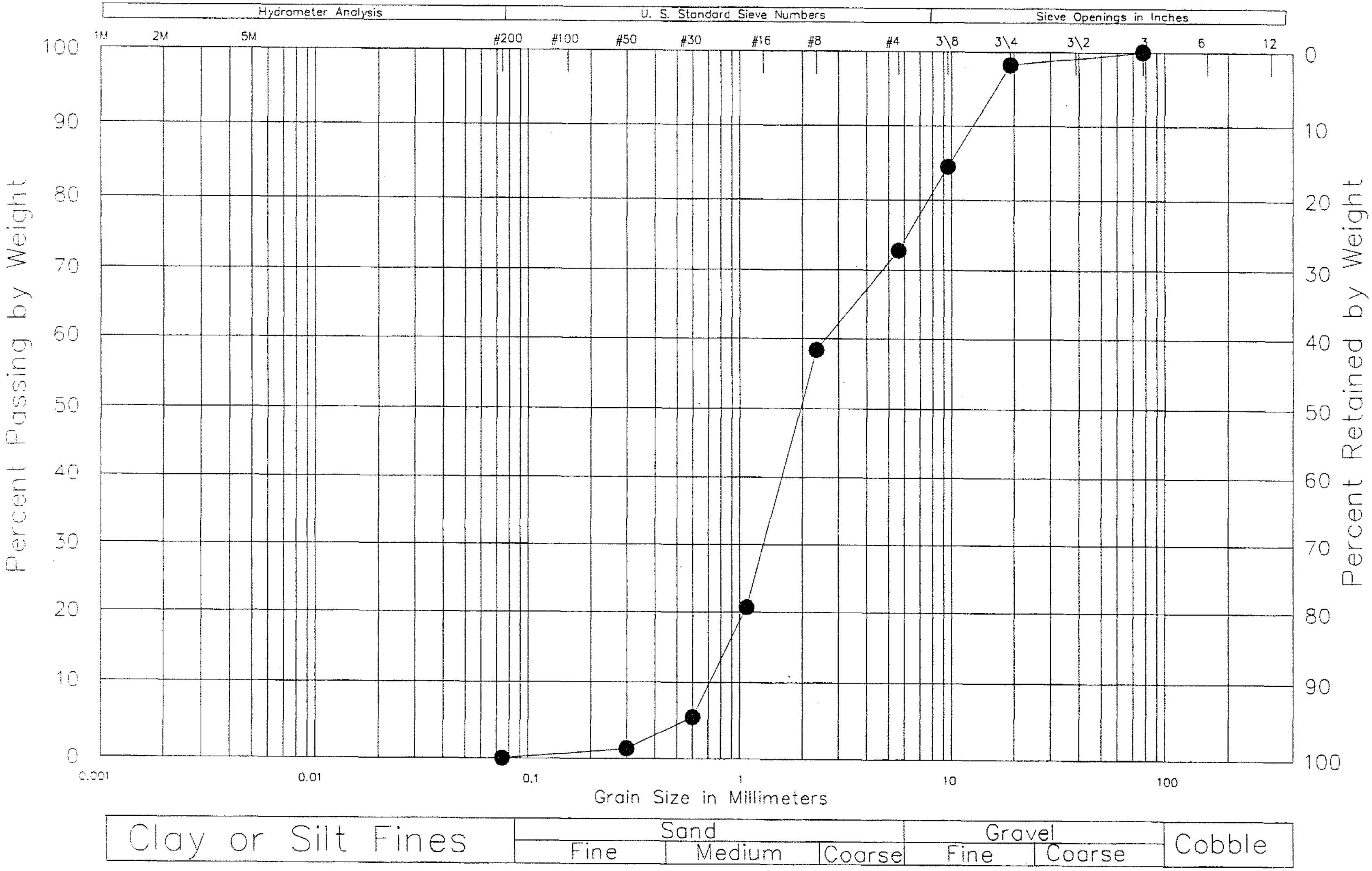


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT11



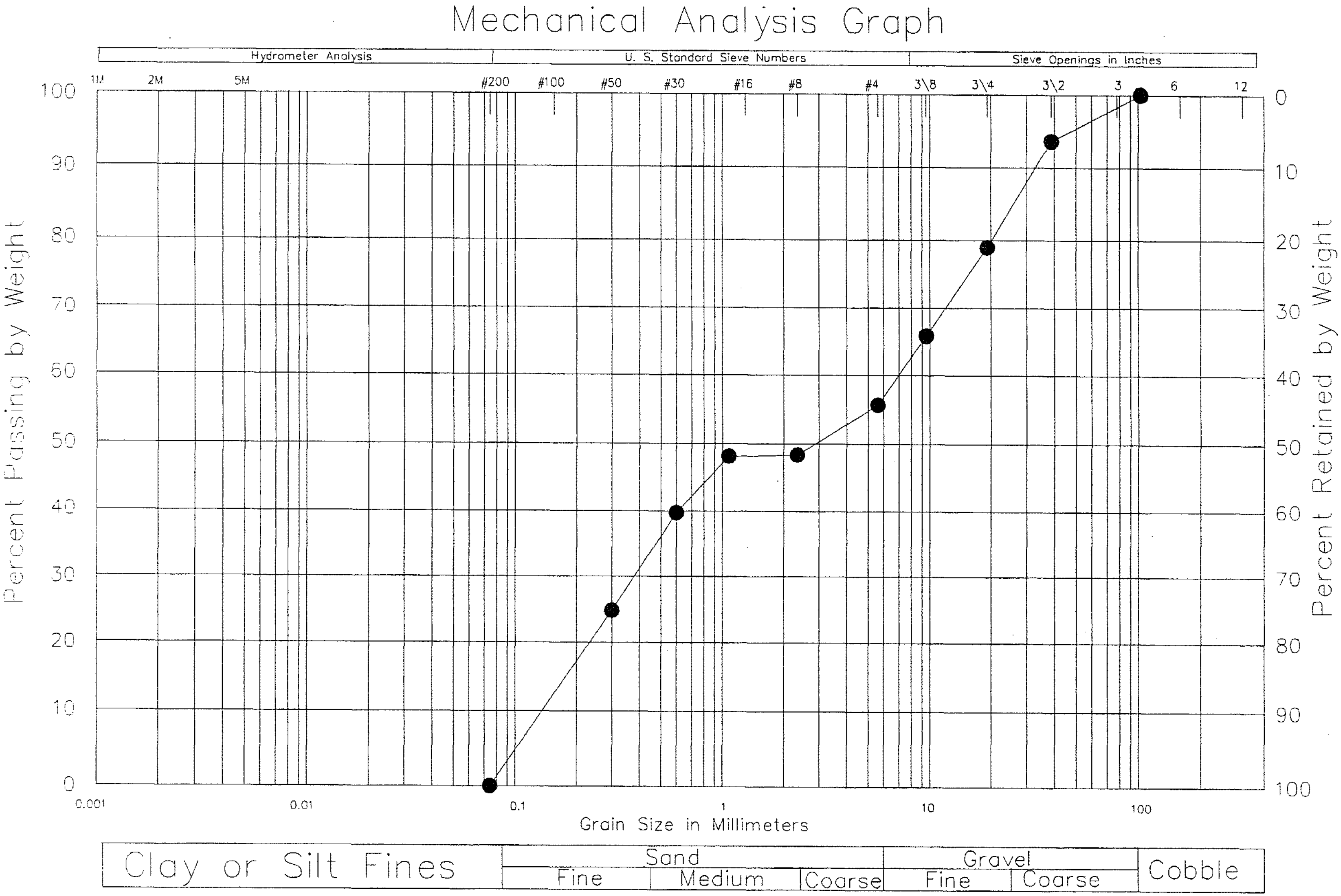
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT12

Mechanical Analysis Graph

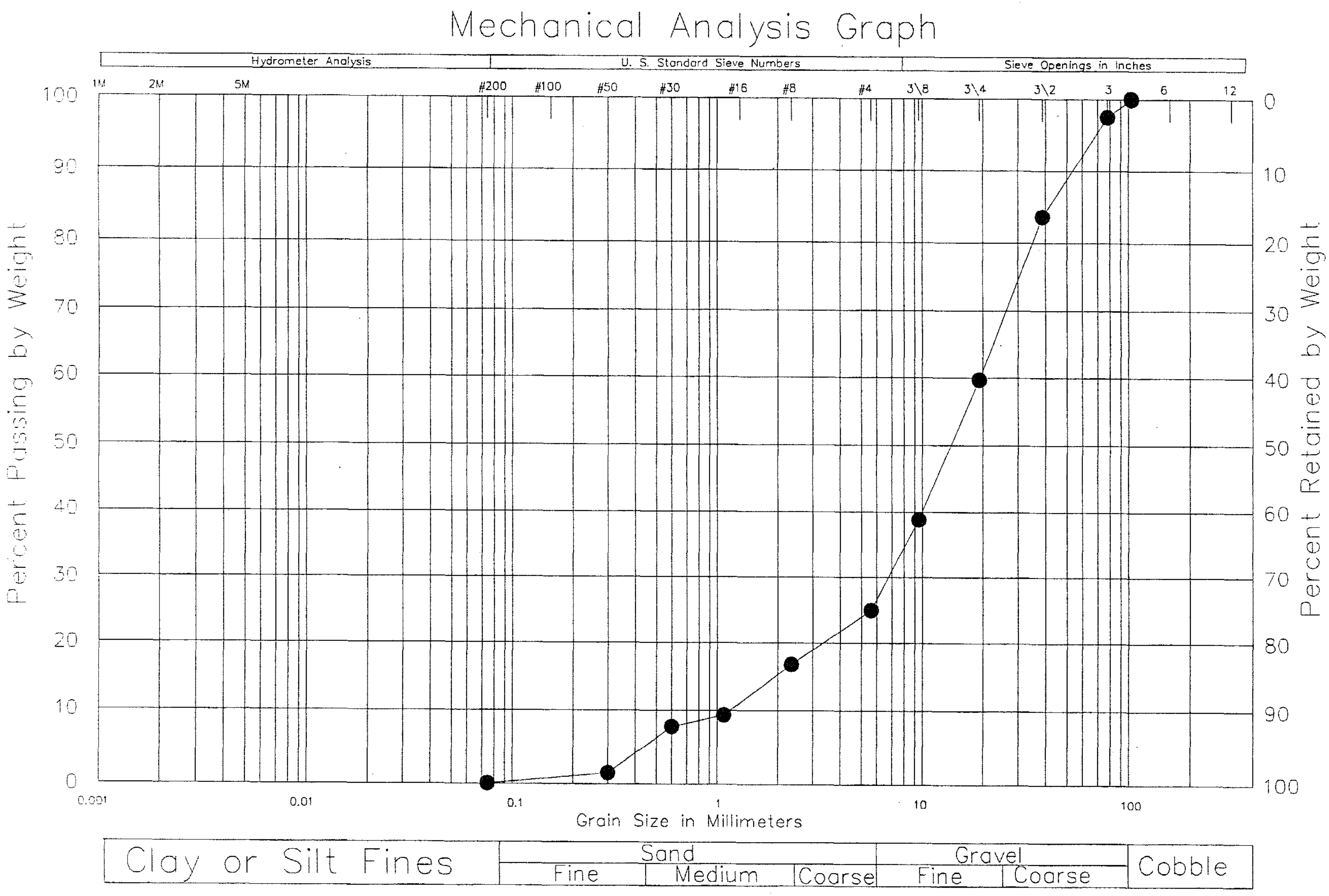


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER

SITE: SACT13

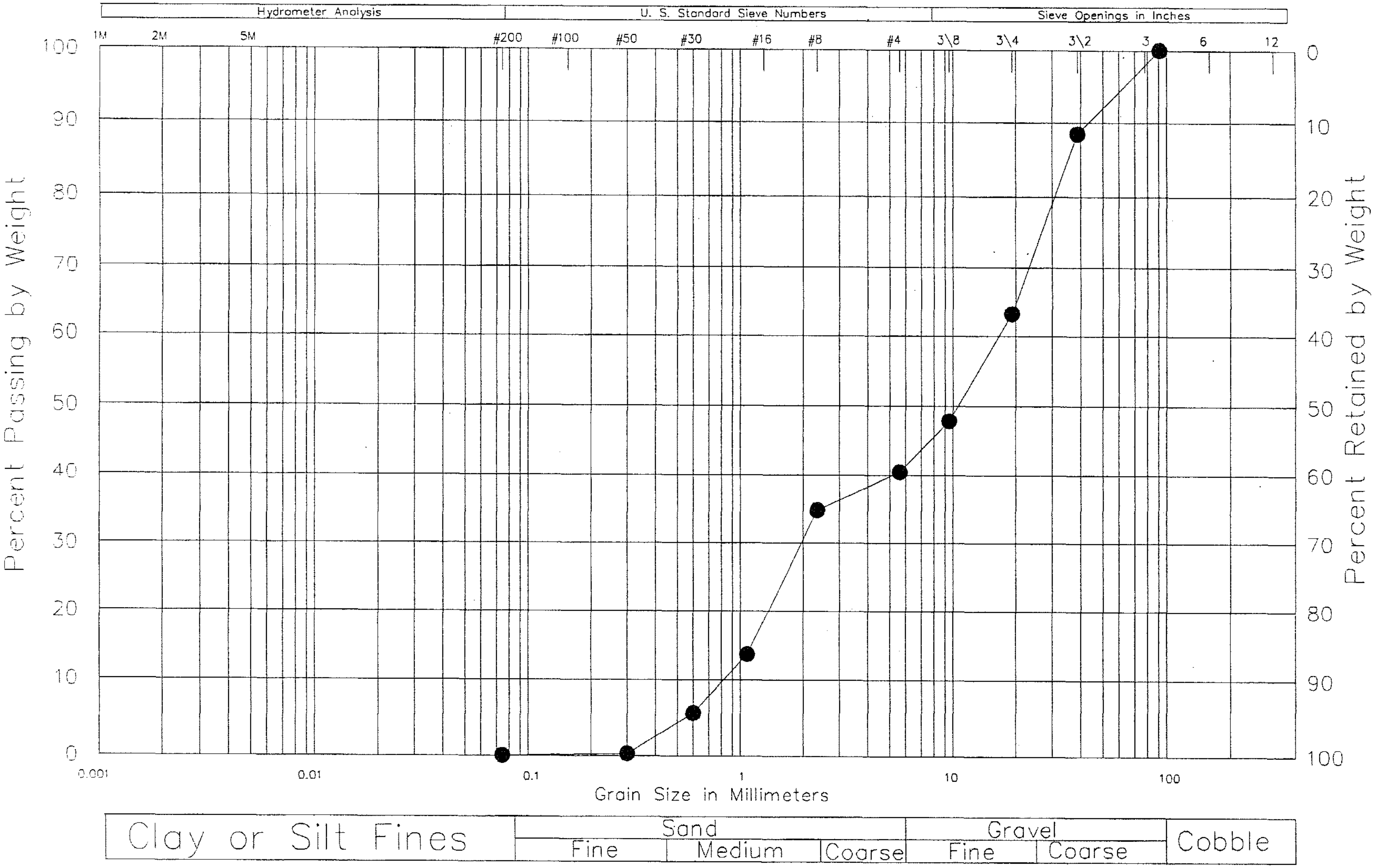


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT14

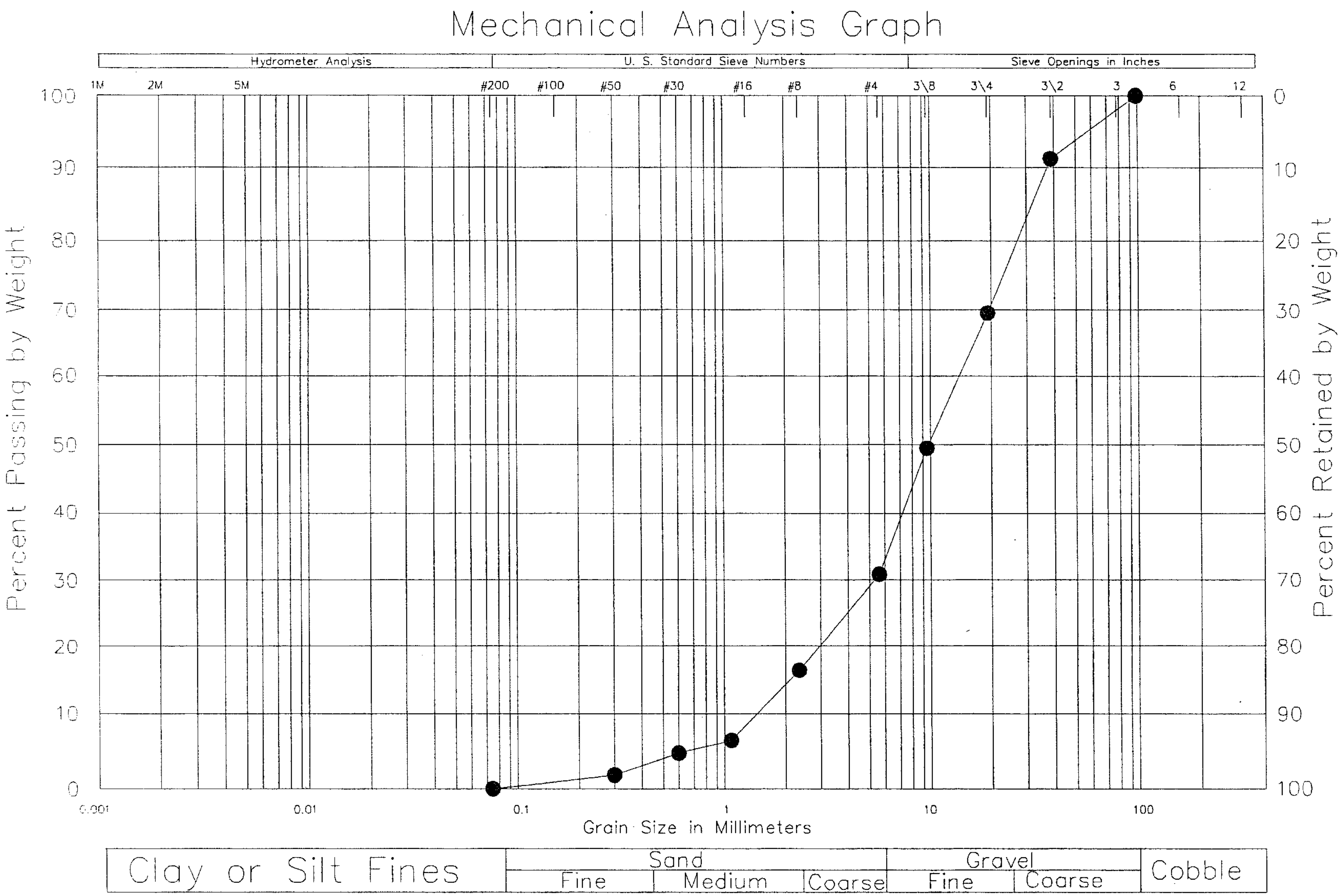


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT15

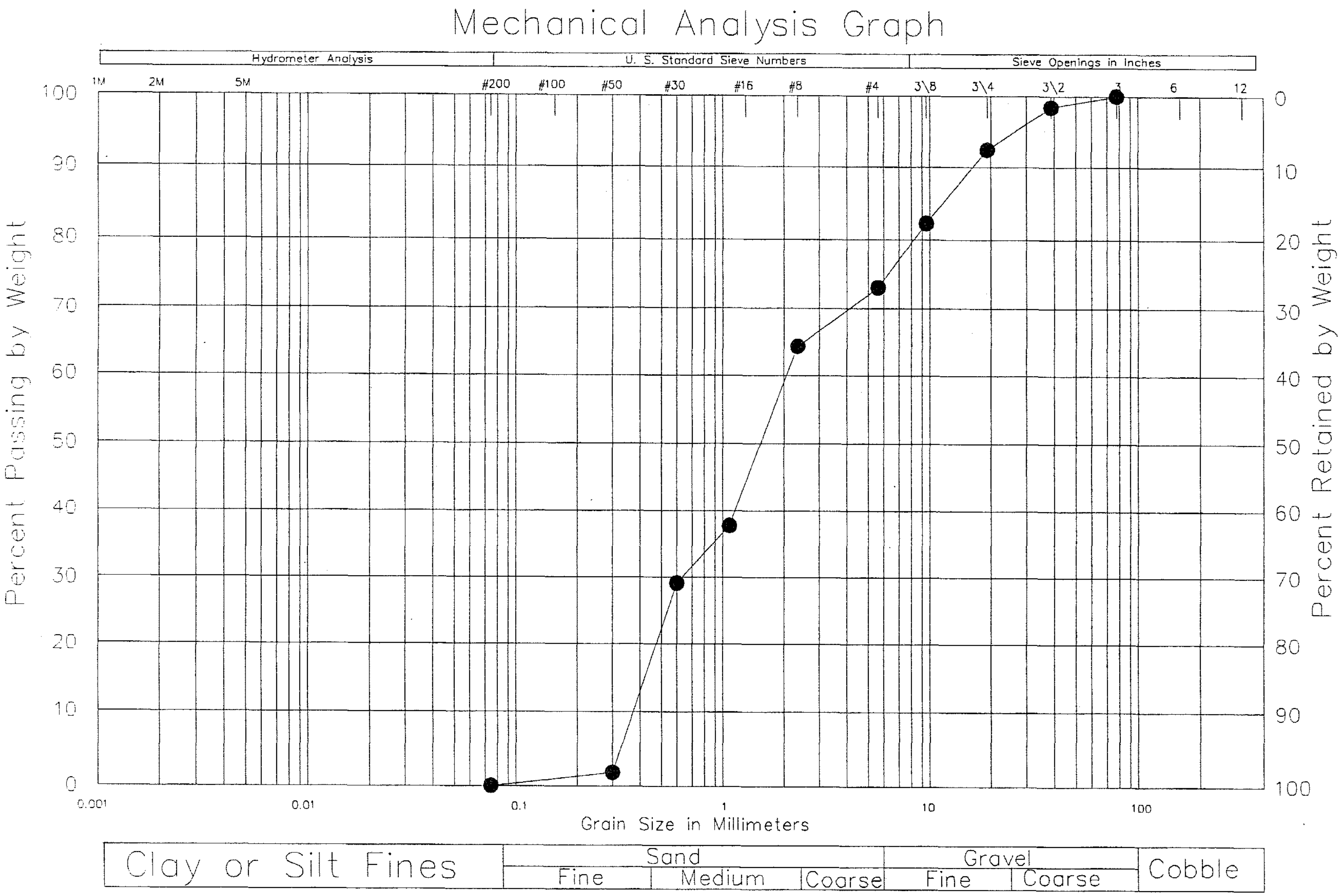
Mechanical Analysis Graph



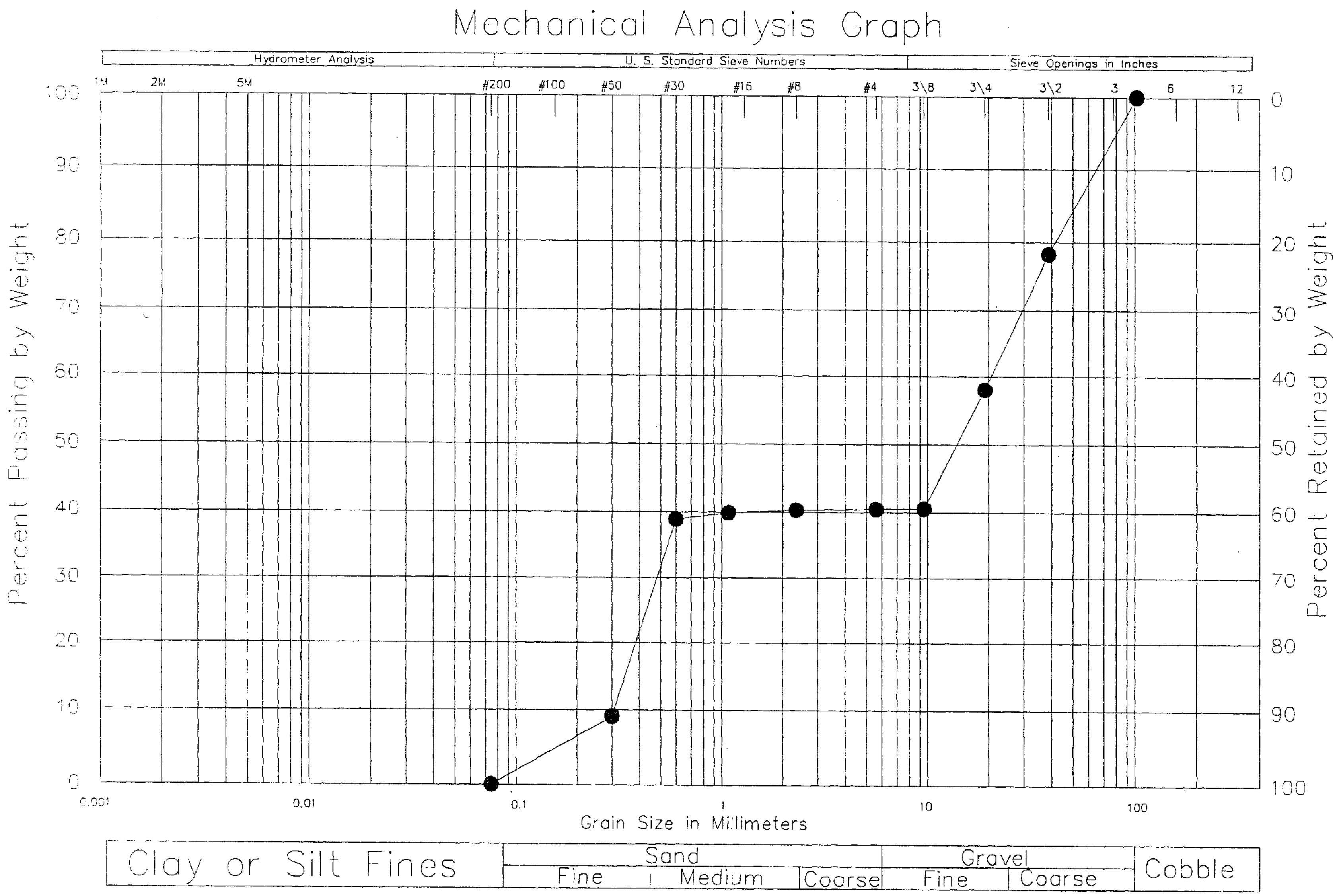
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT16



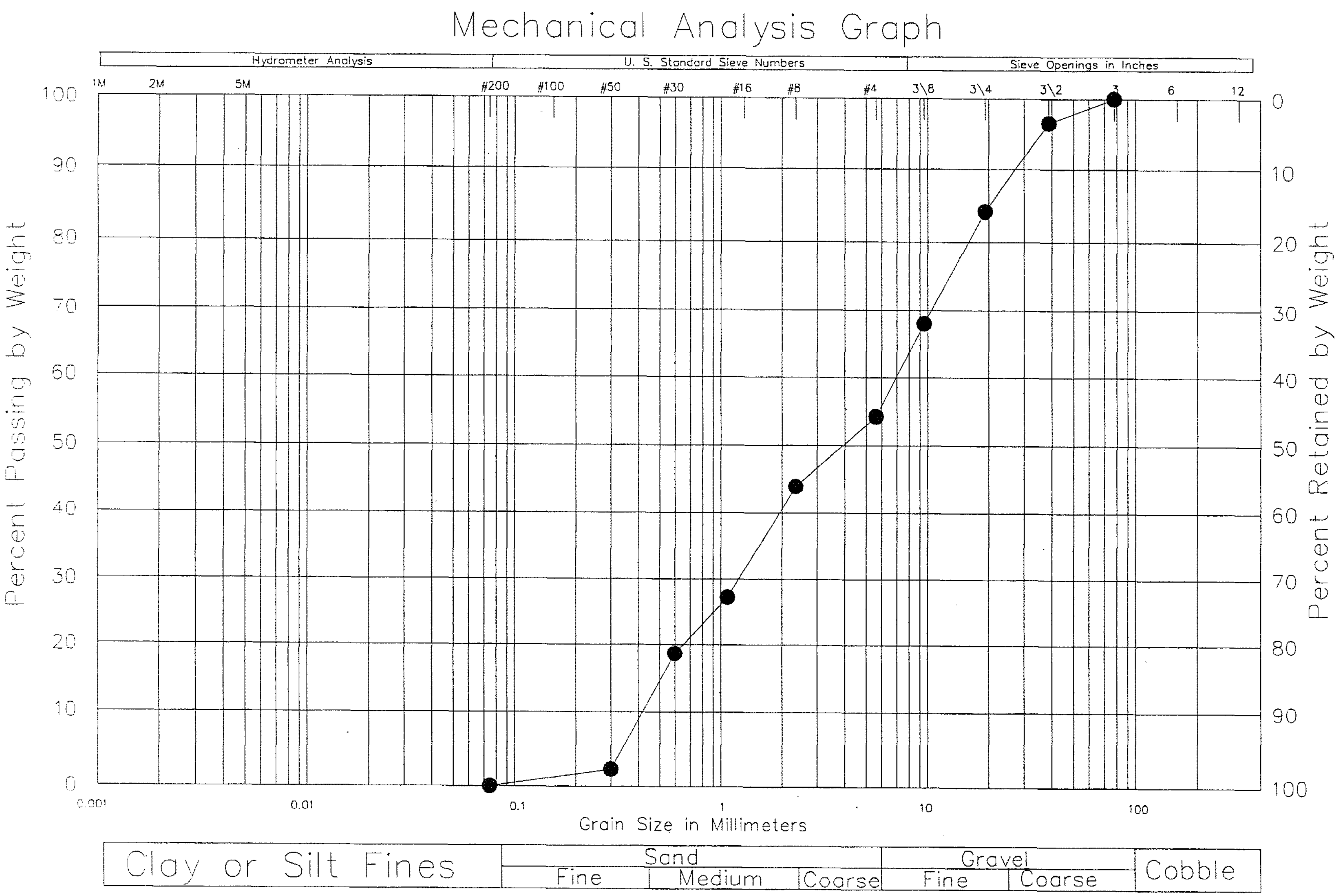
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT17



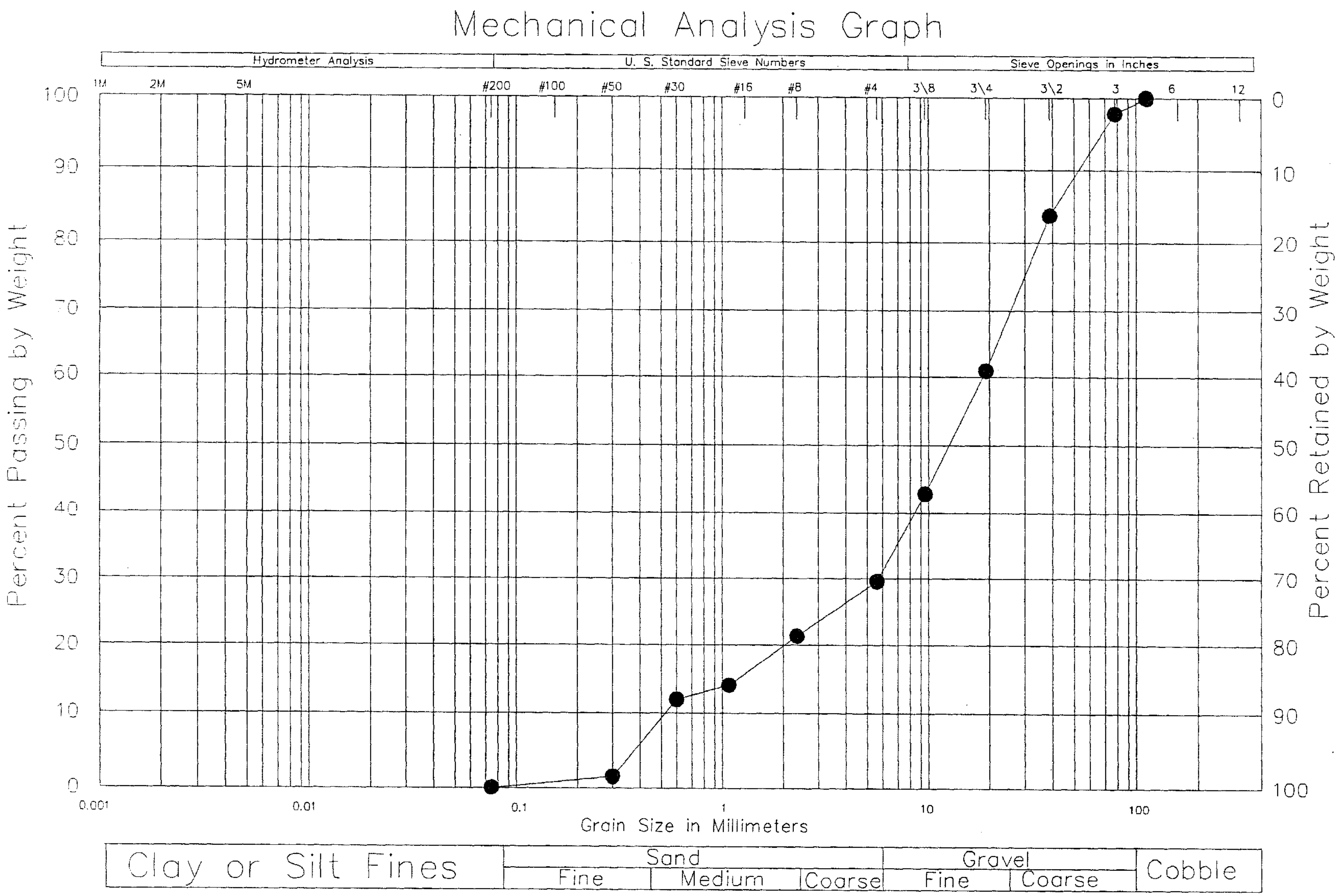
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT18



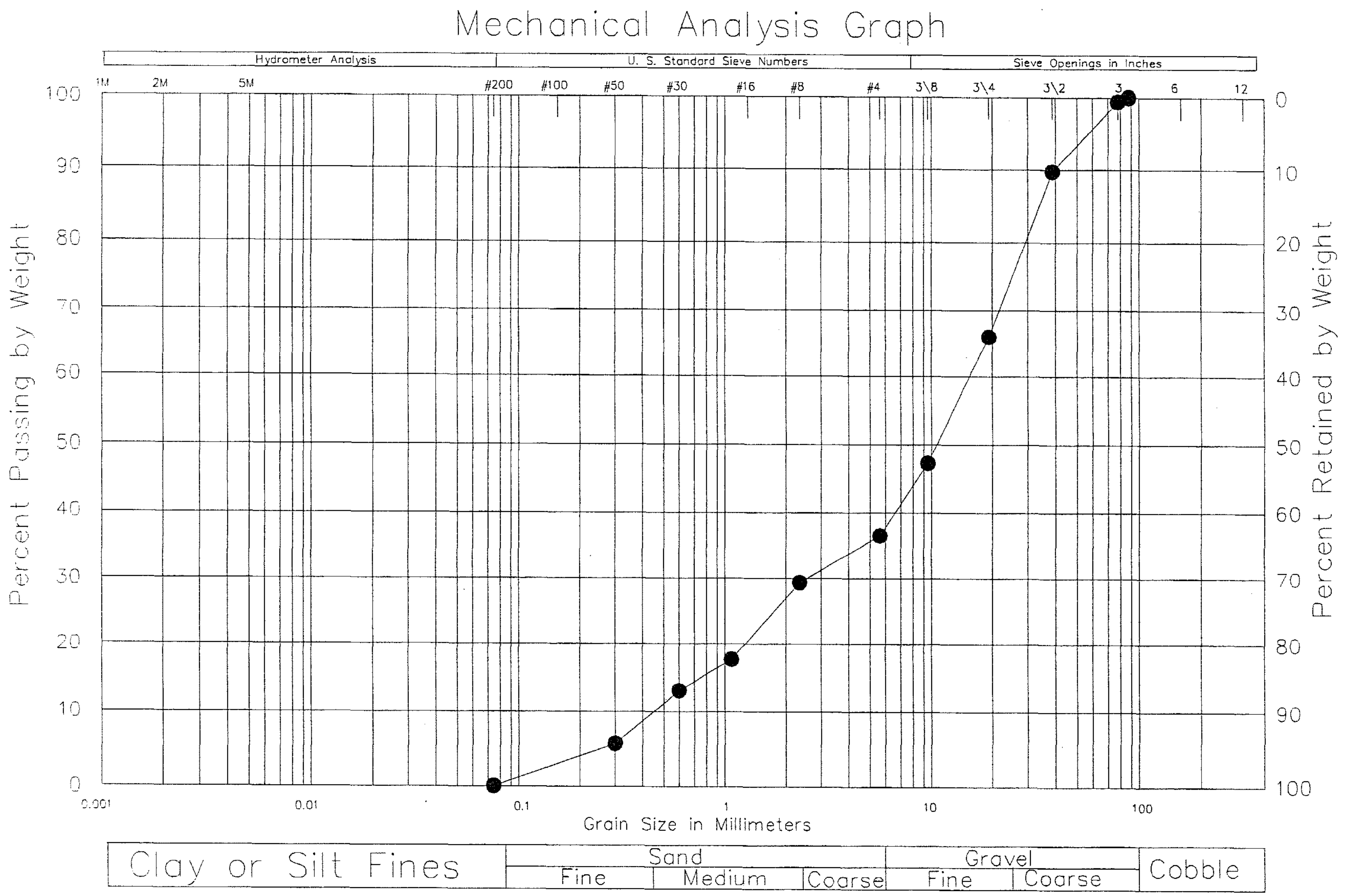
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT19



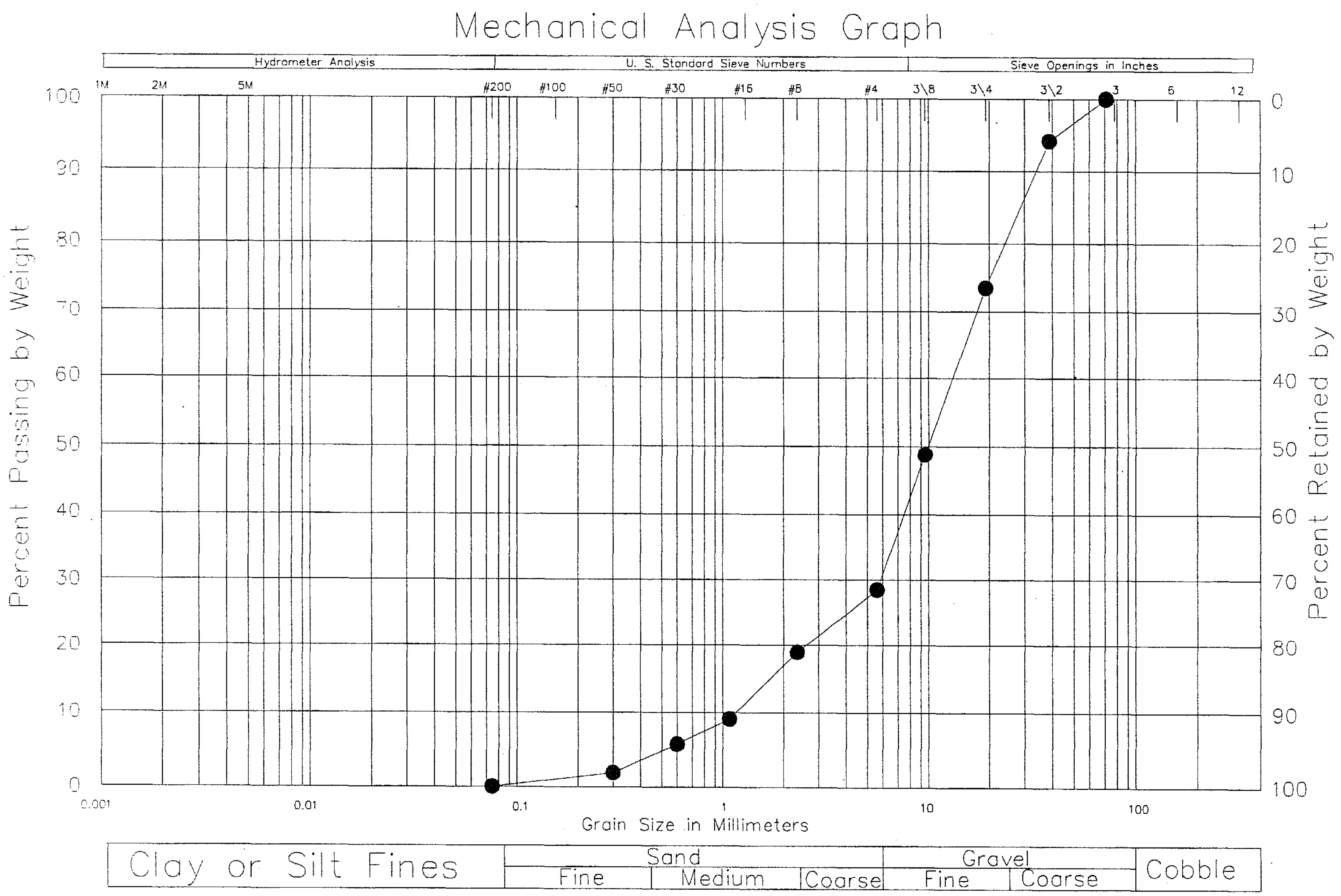
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT20



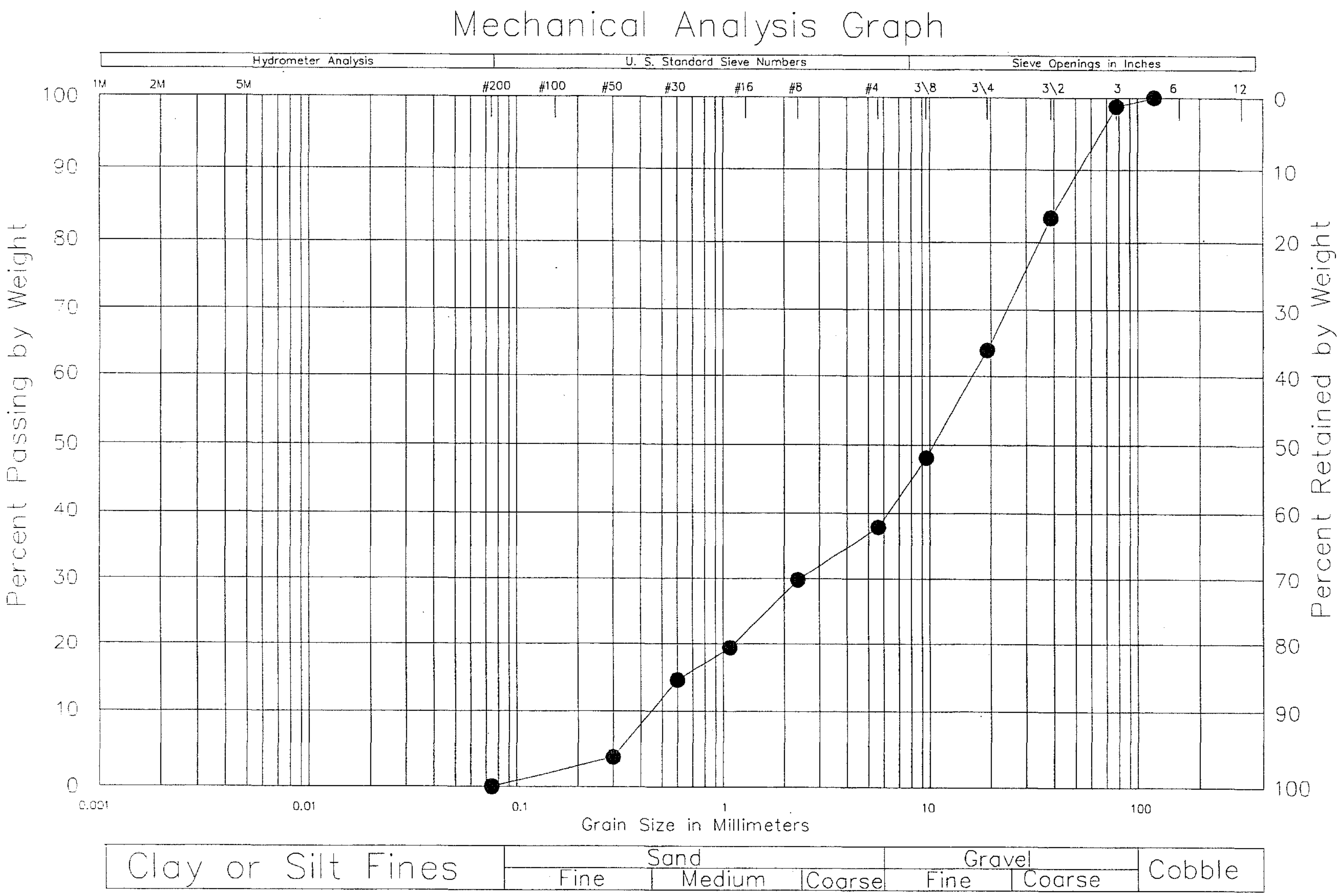
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT21



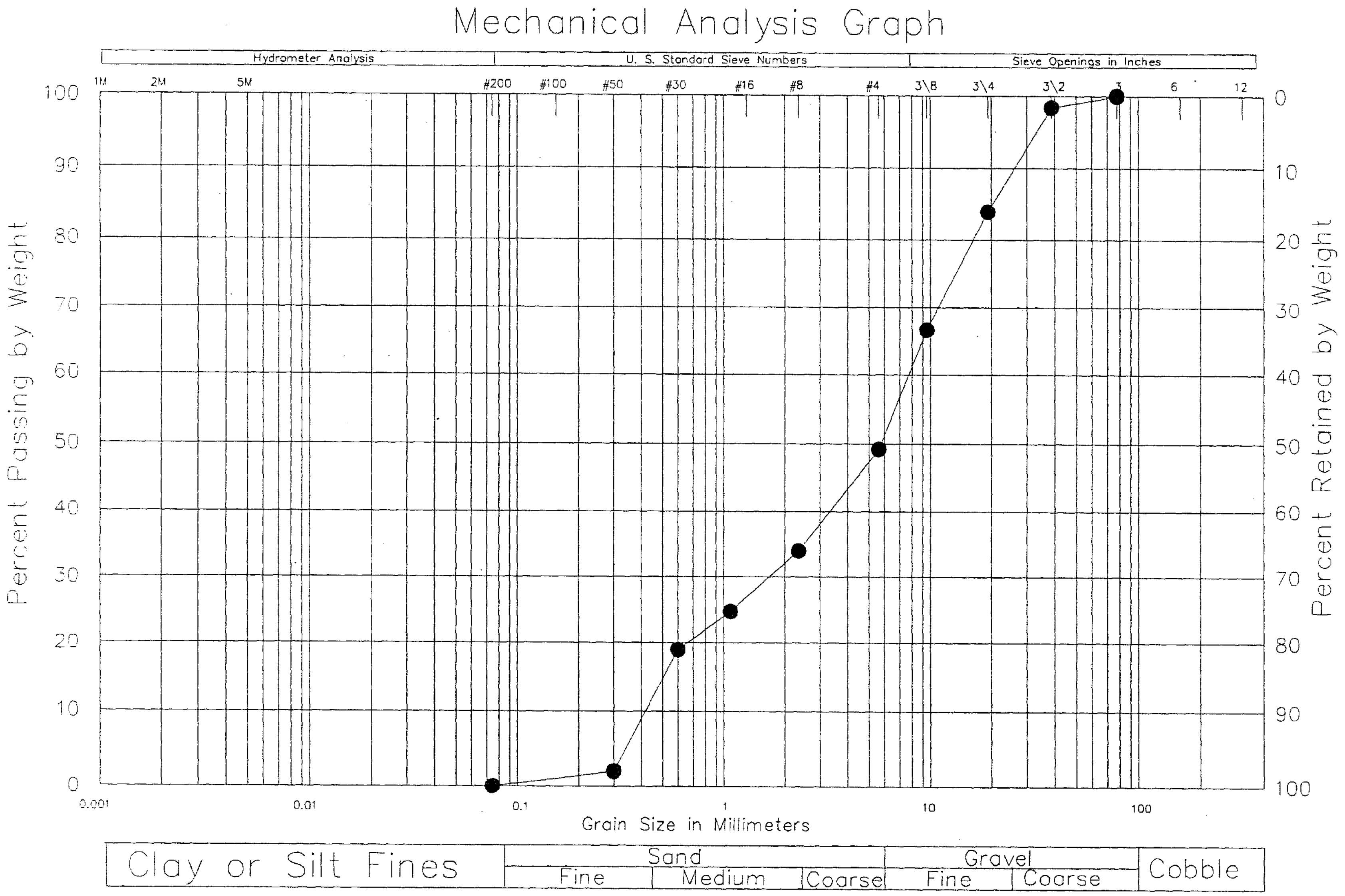
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT22



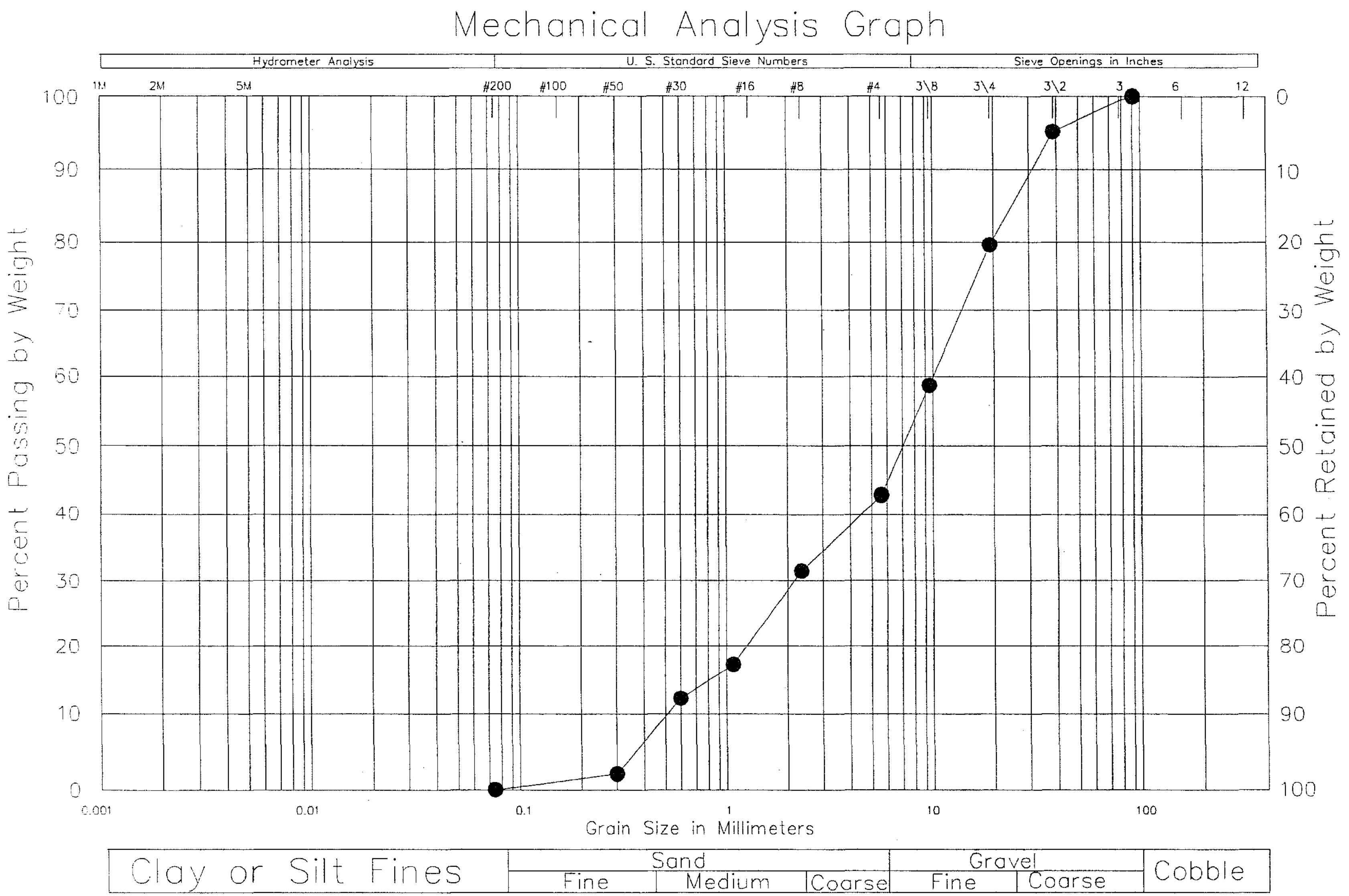
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT23



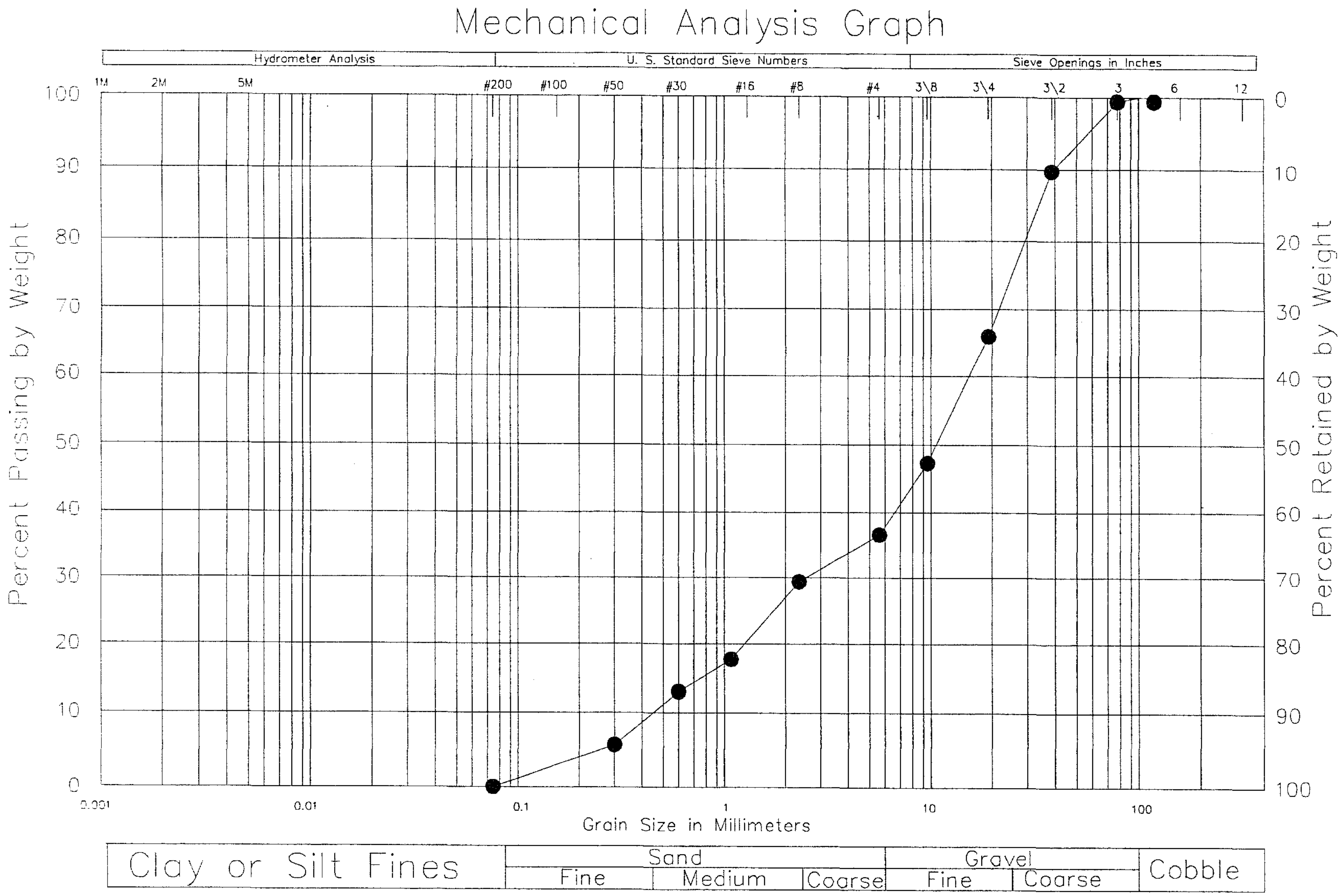
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT24



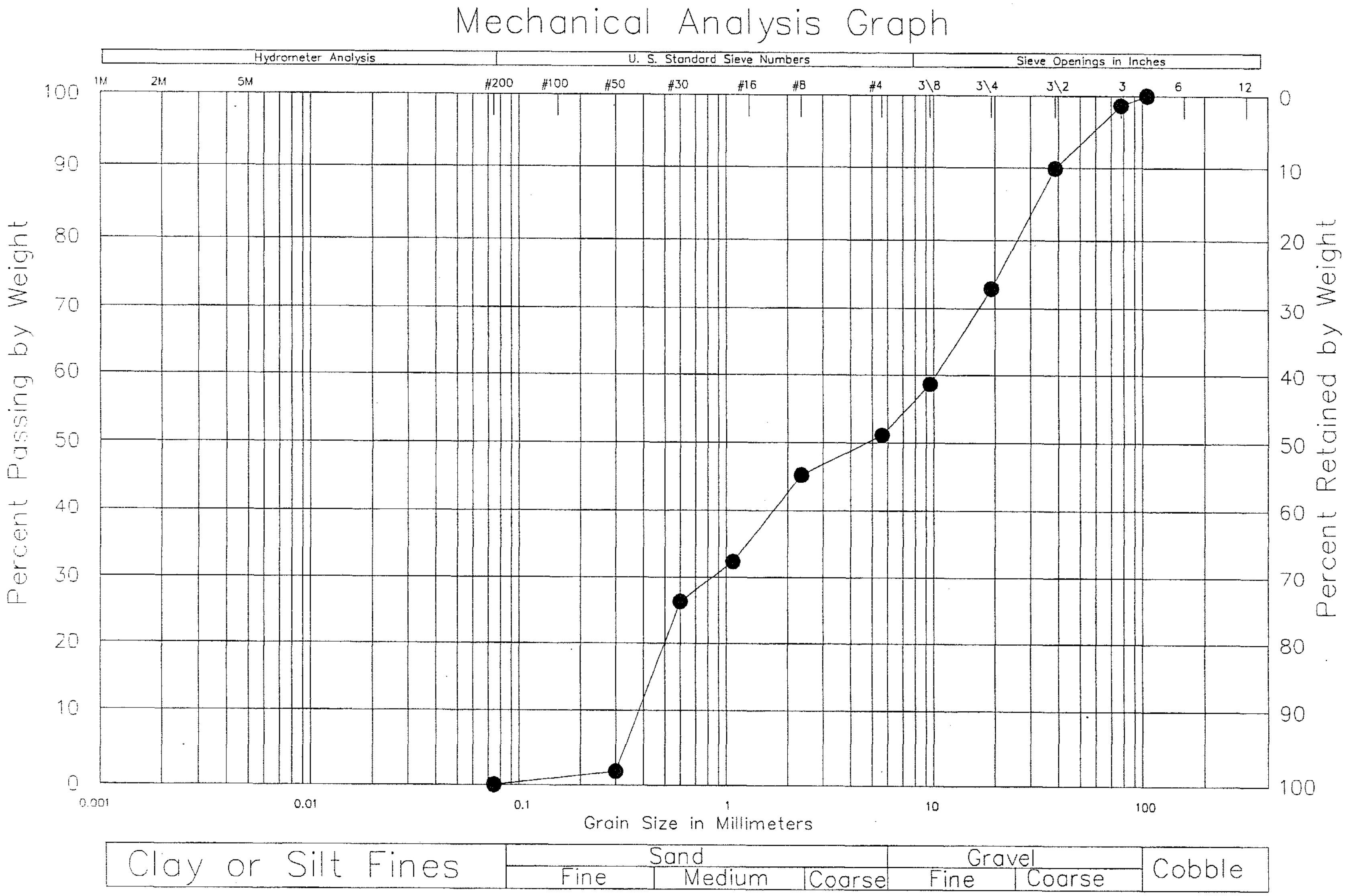
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT25



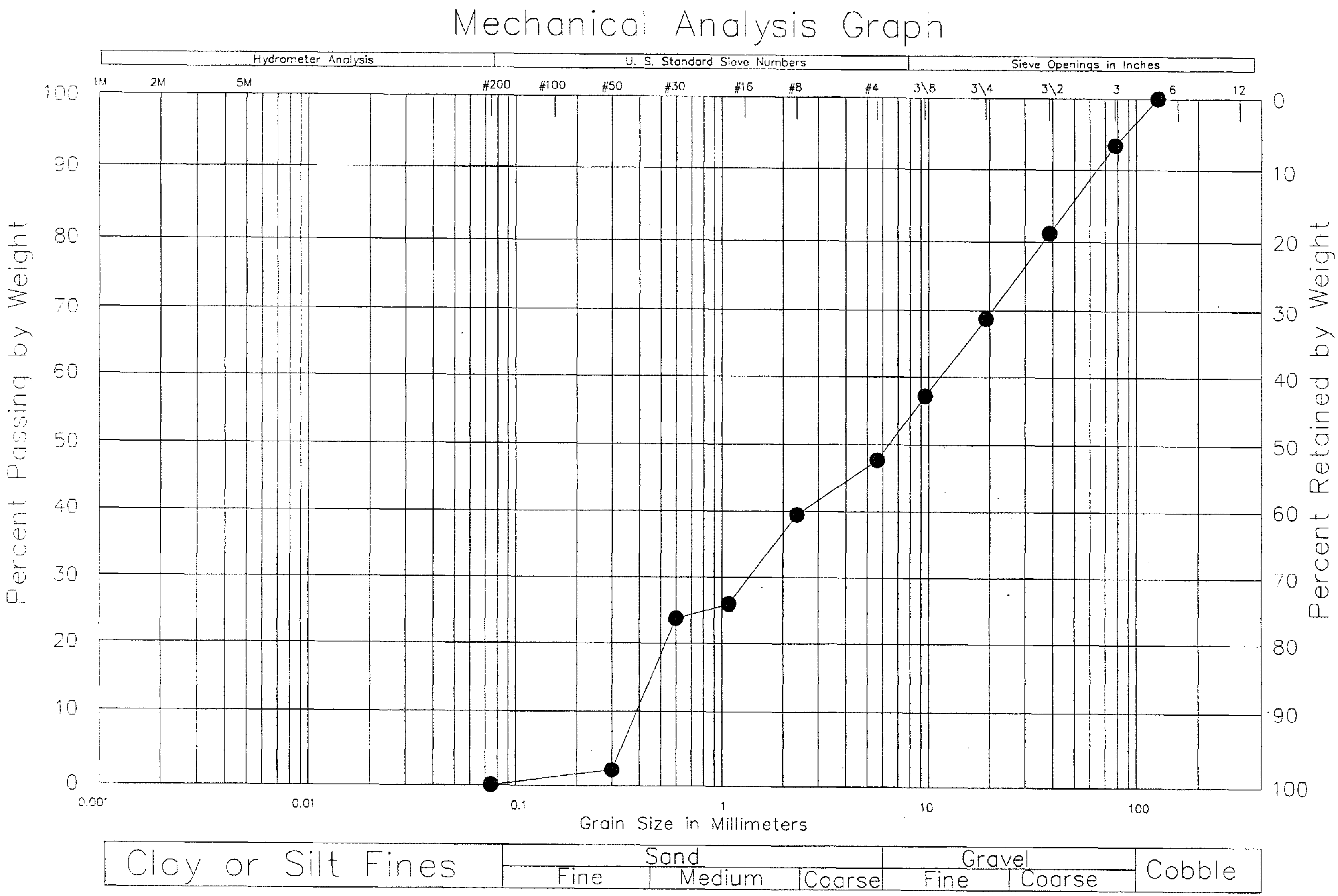
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT26



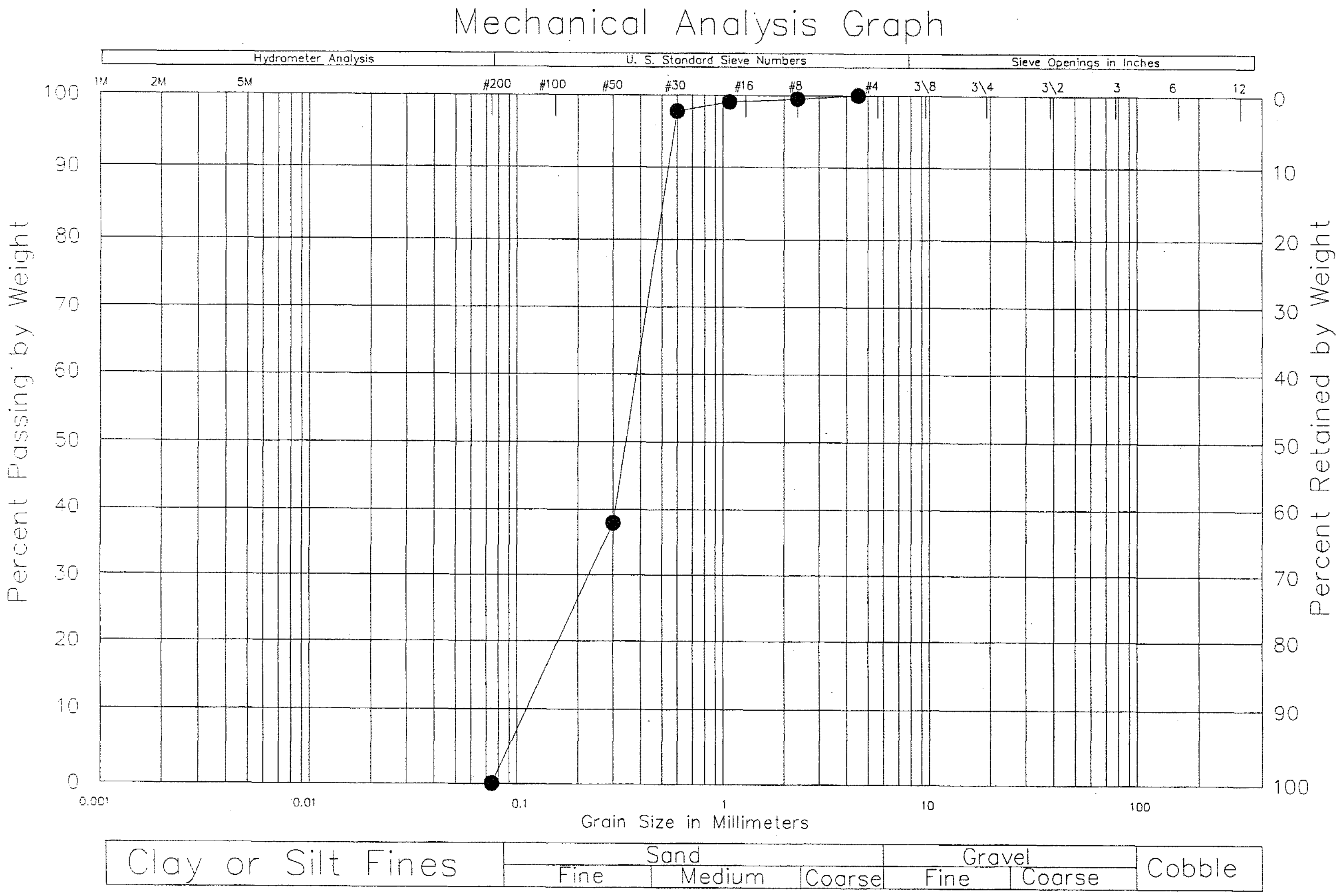
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT27



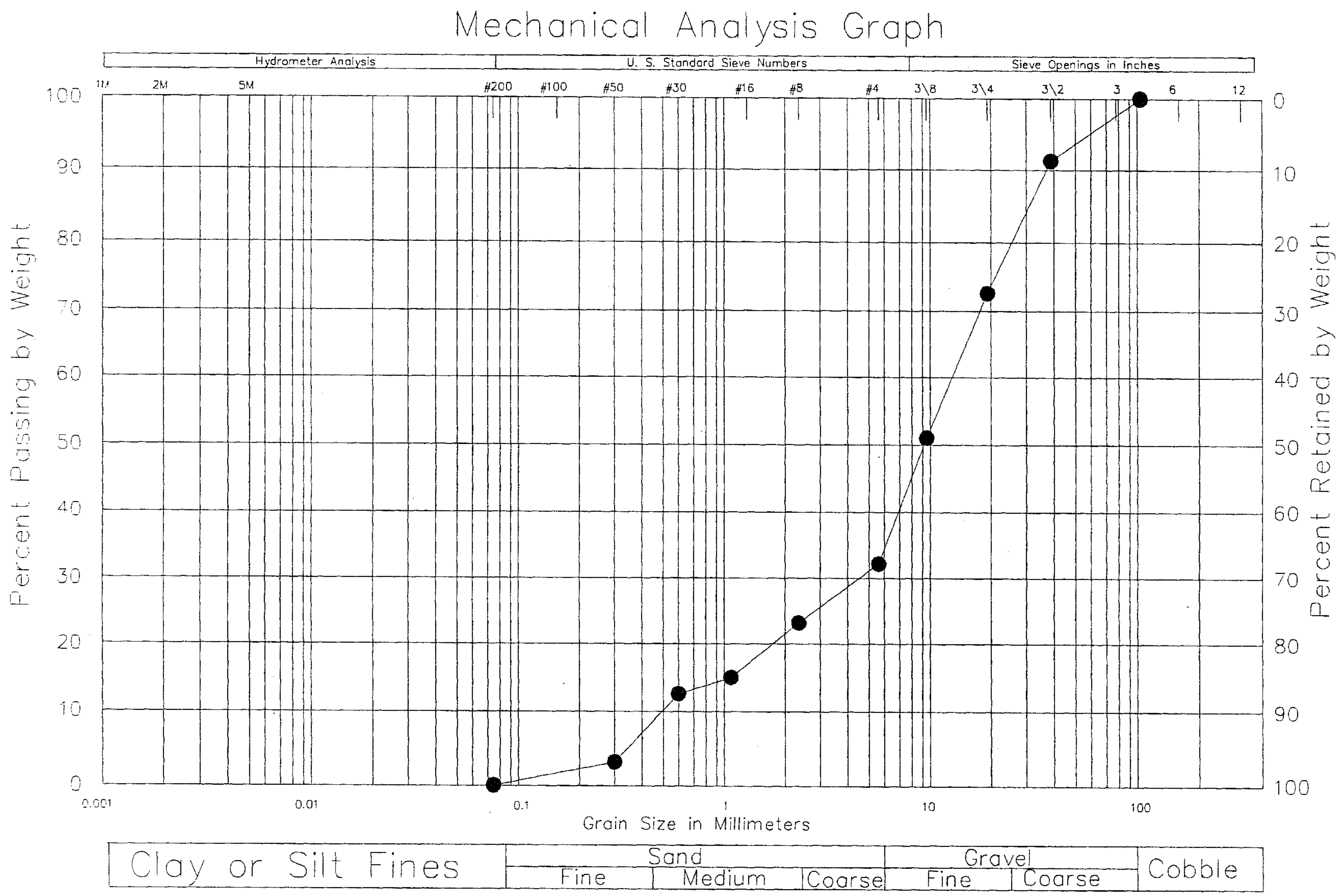
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT28



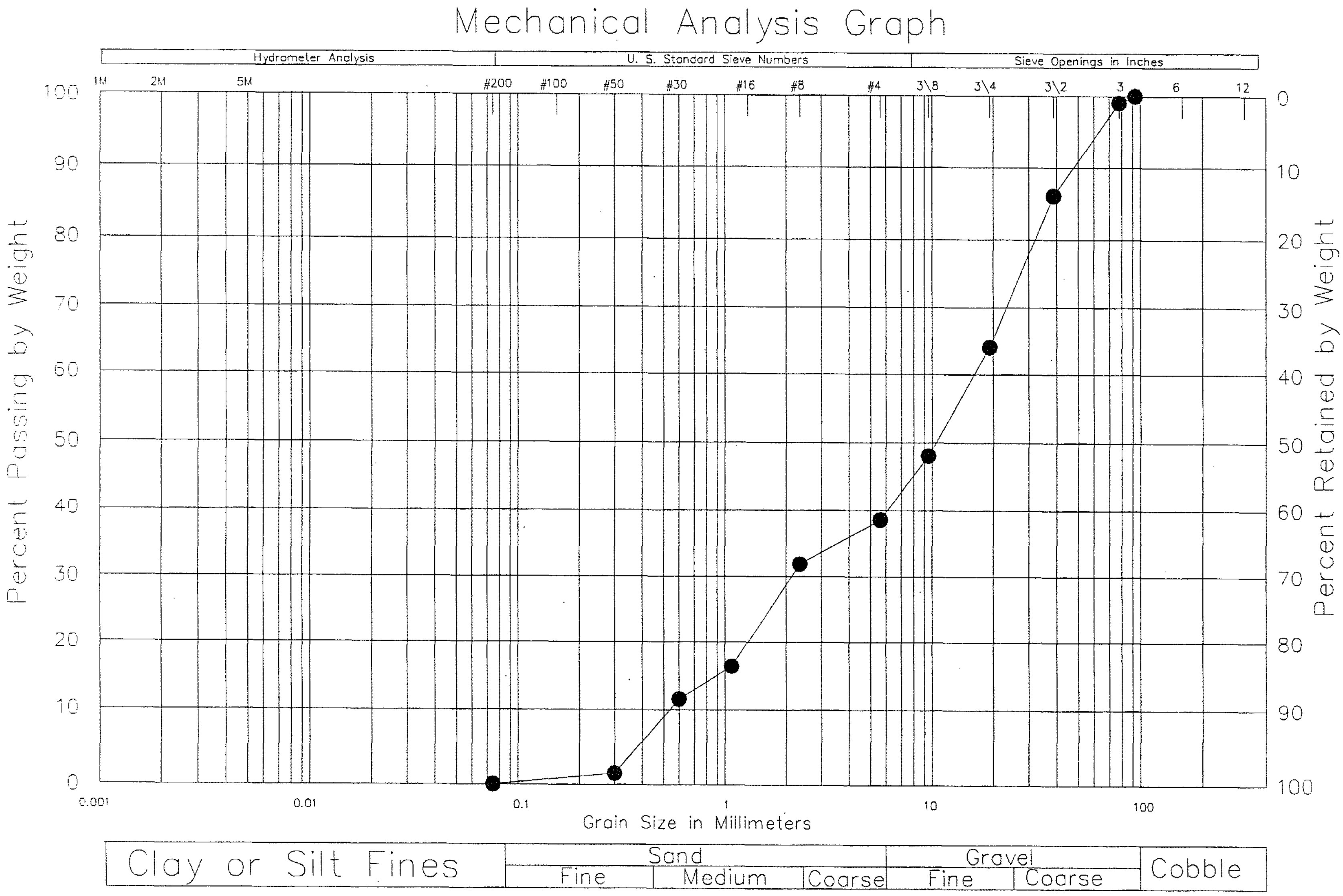
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT29



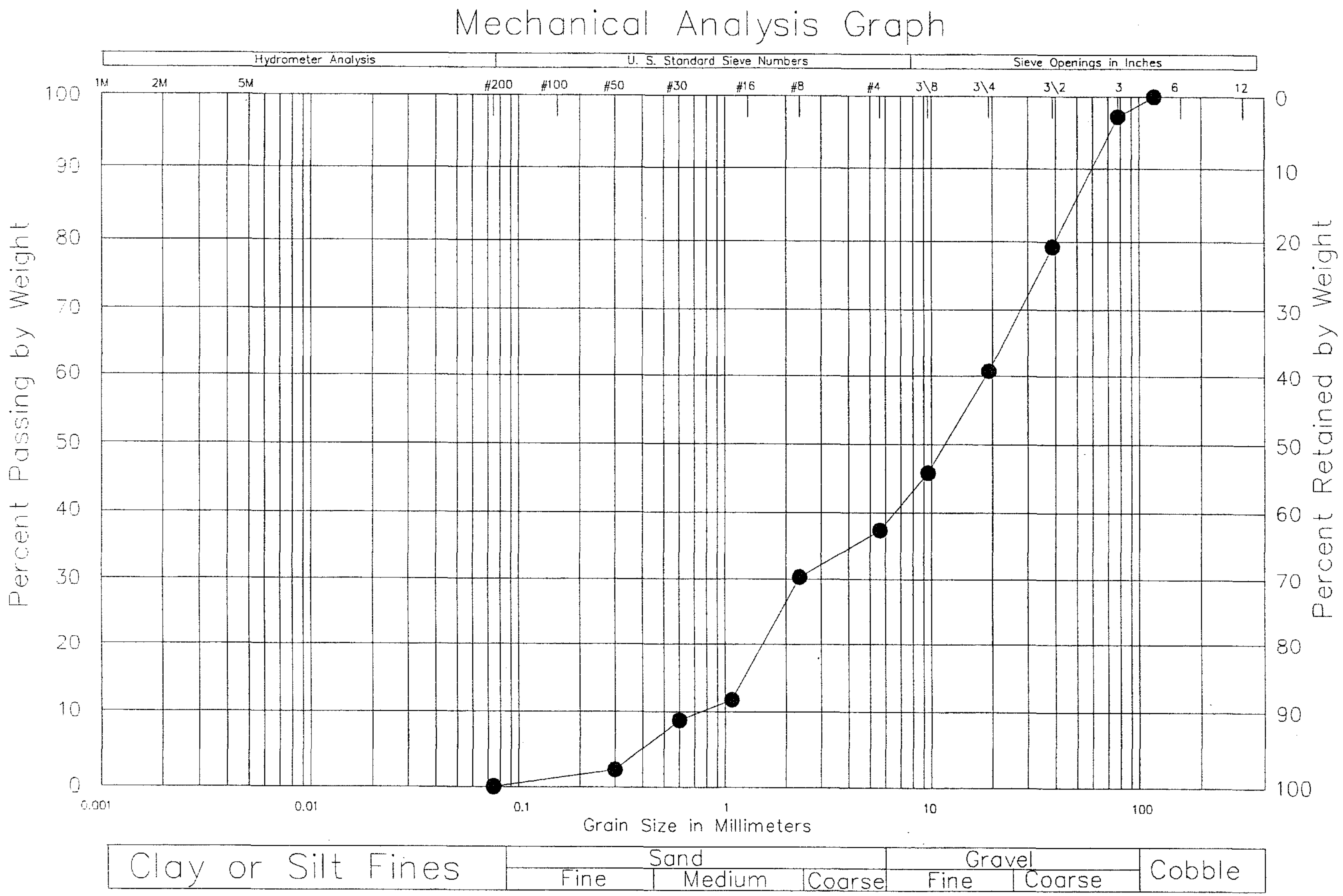
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT30



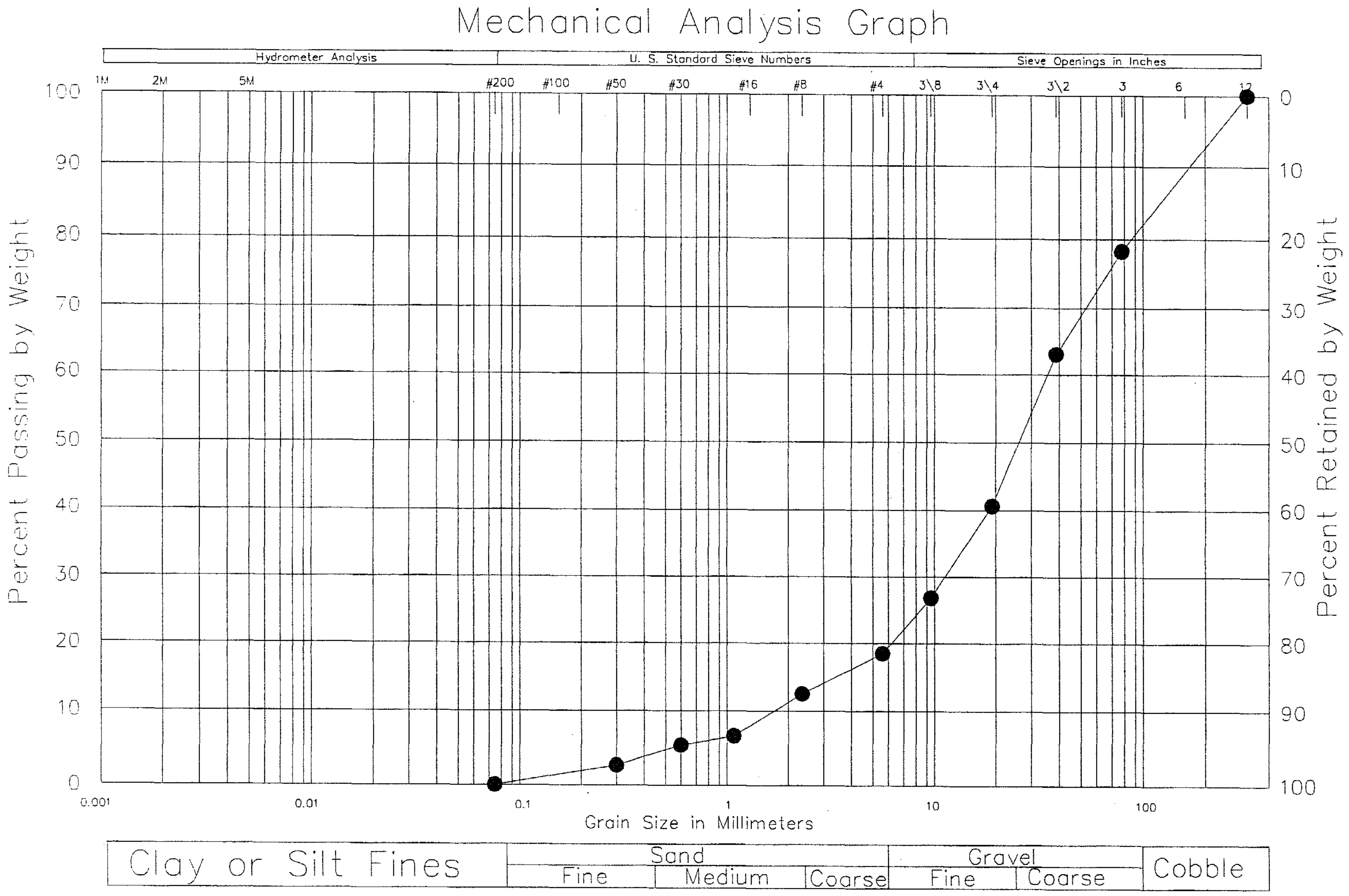
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT31



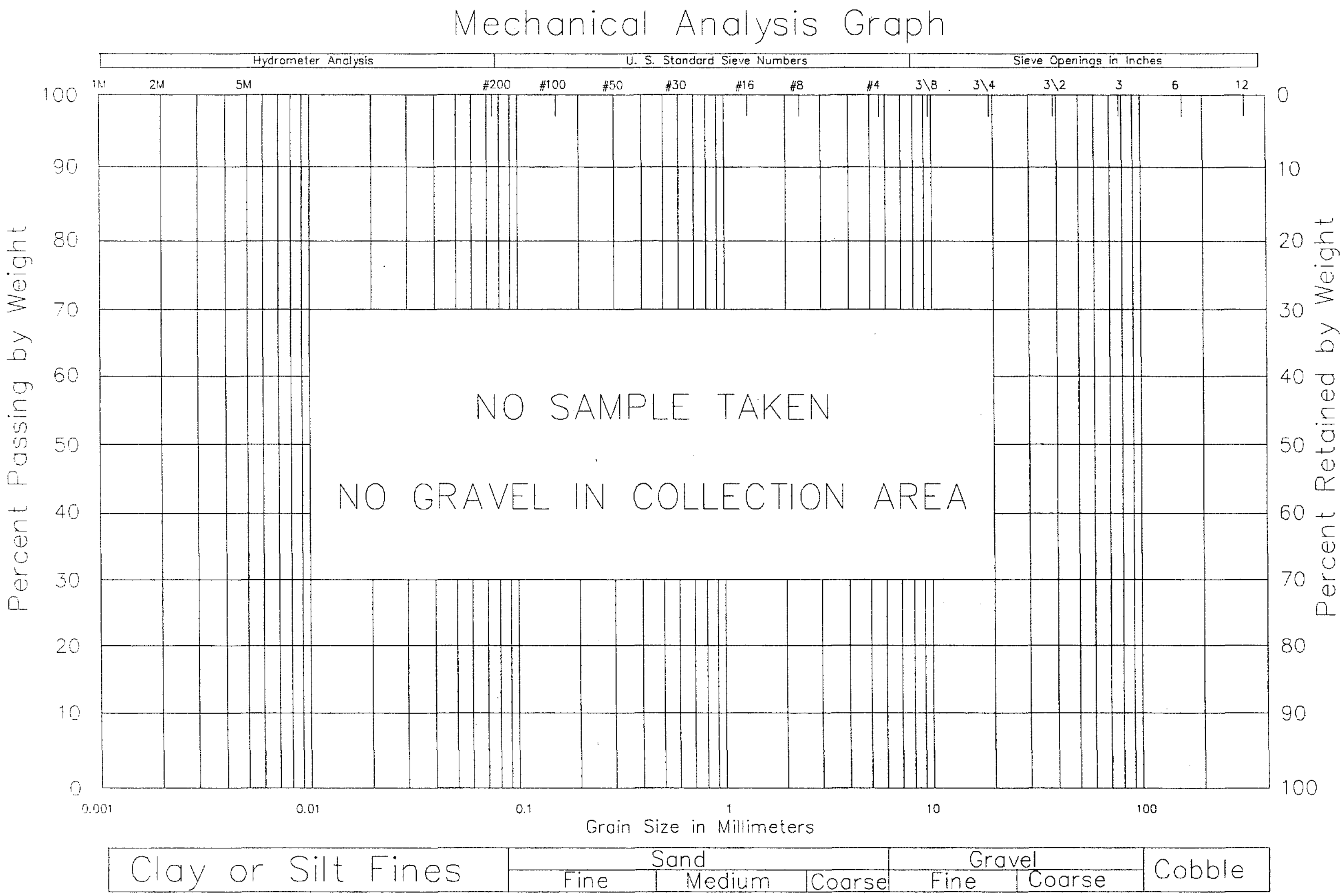
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT32



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT33



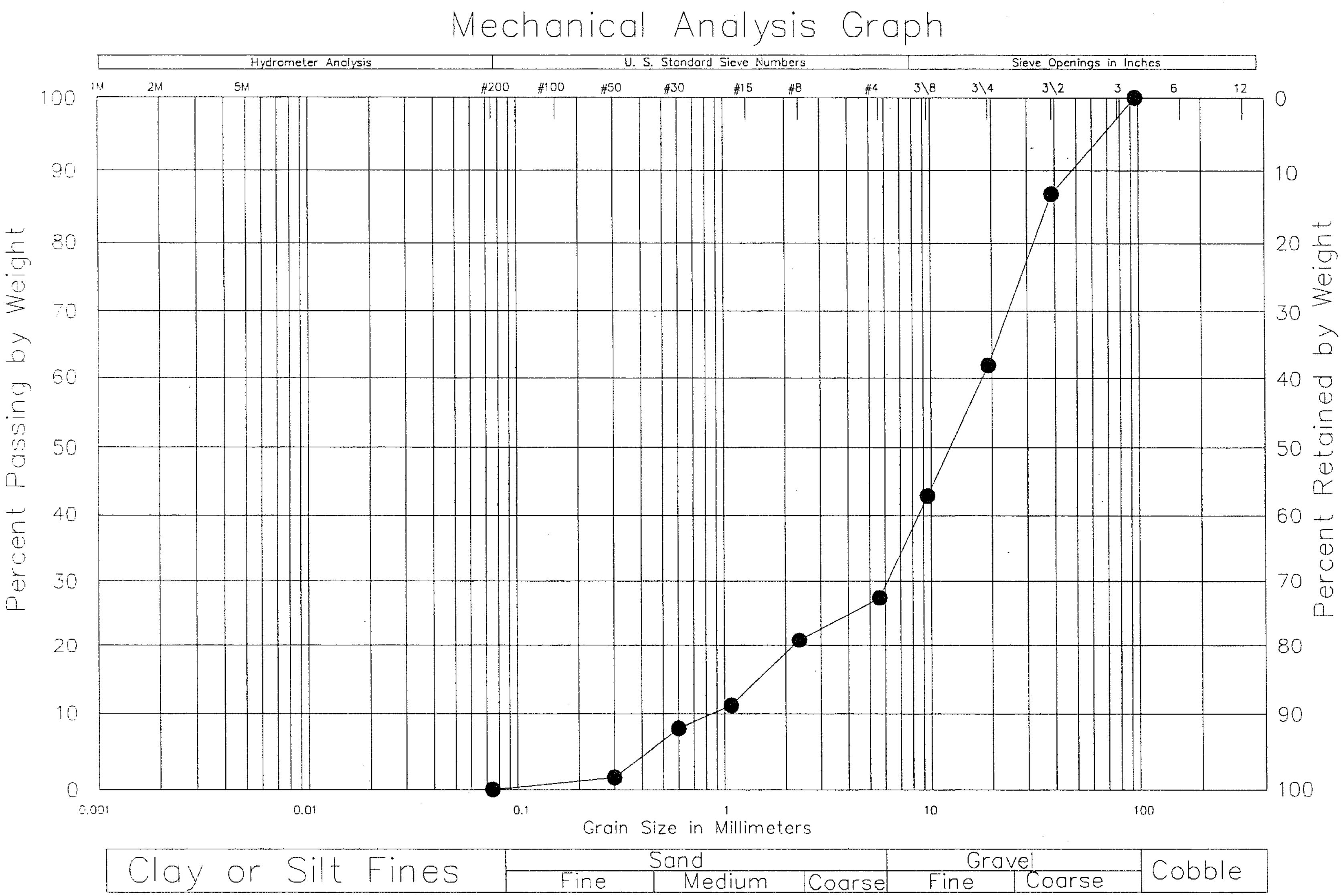
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT34



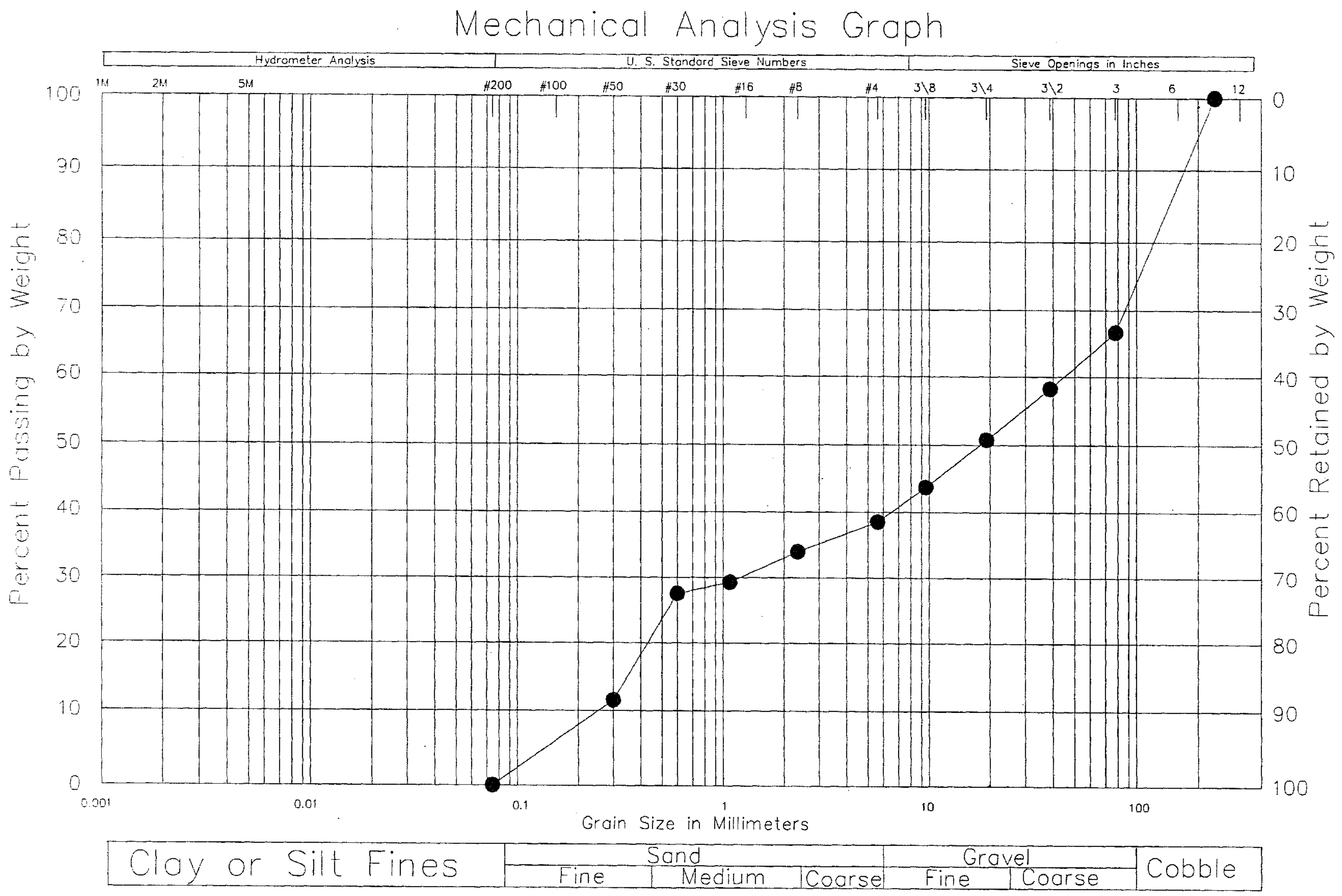
NO SAMPLE TAKEN

NO GRAVEL IN COLLECTION AREA

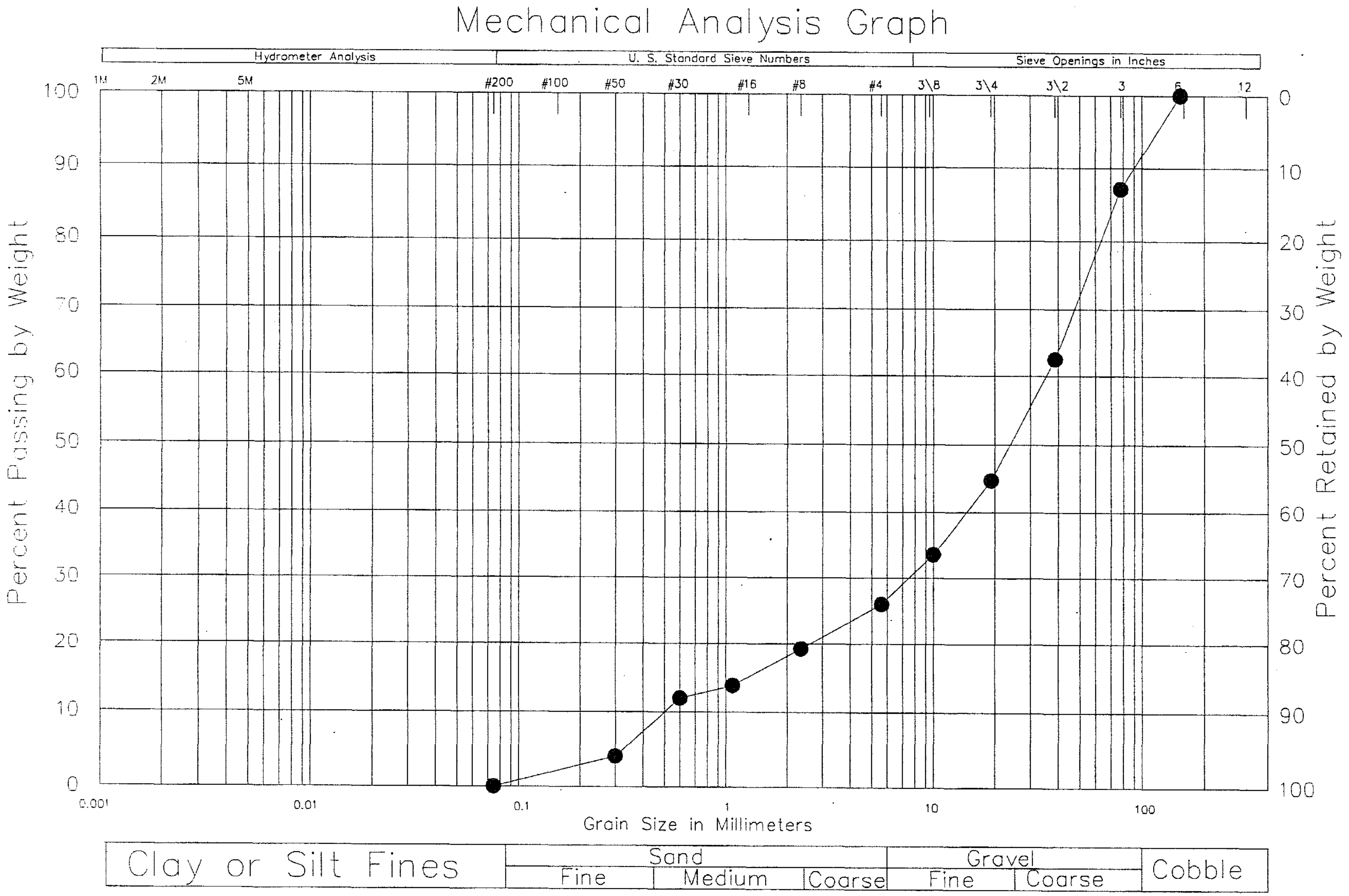
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT35



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT36

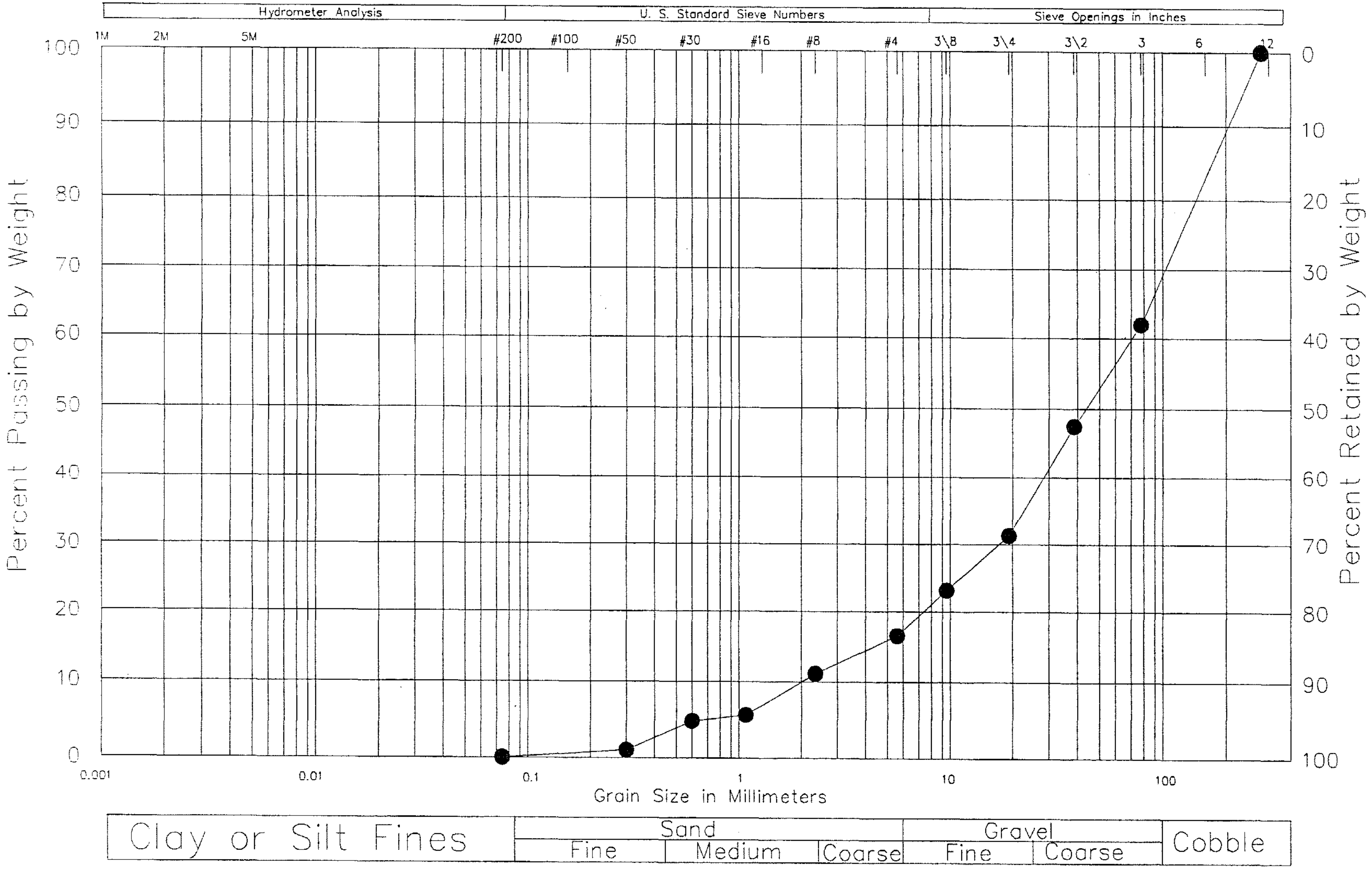


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT37

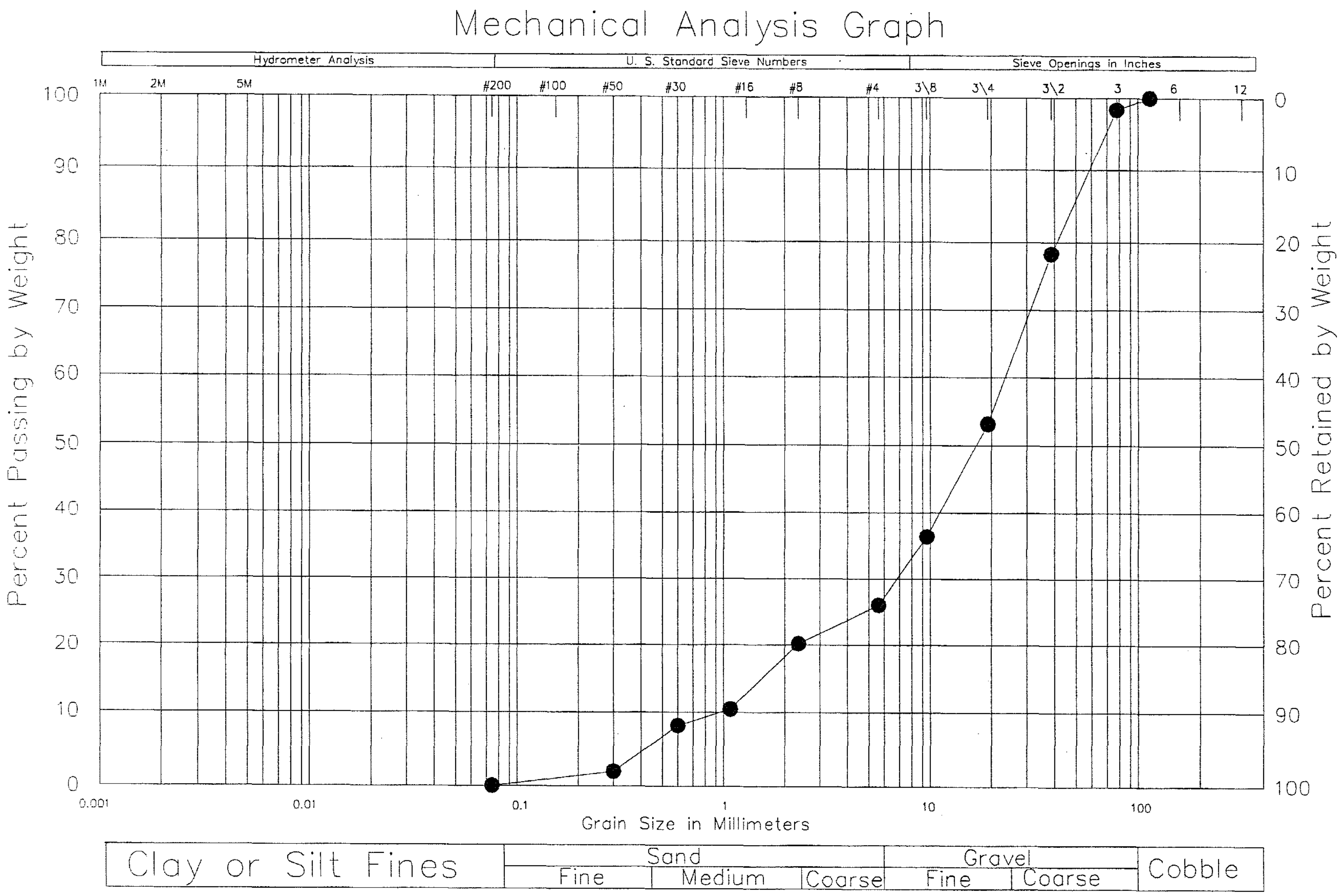


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT38

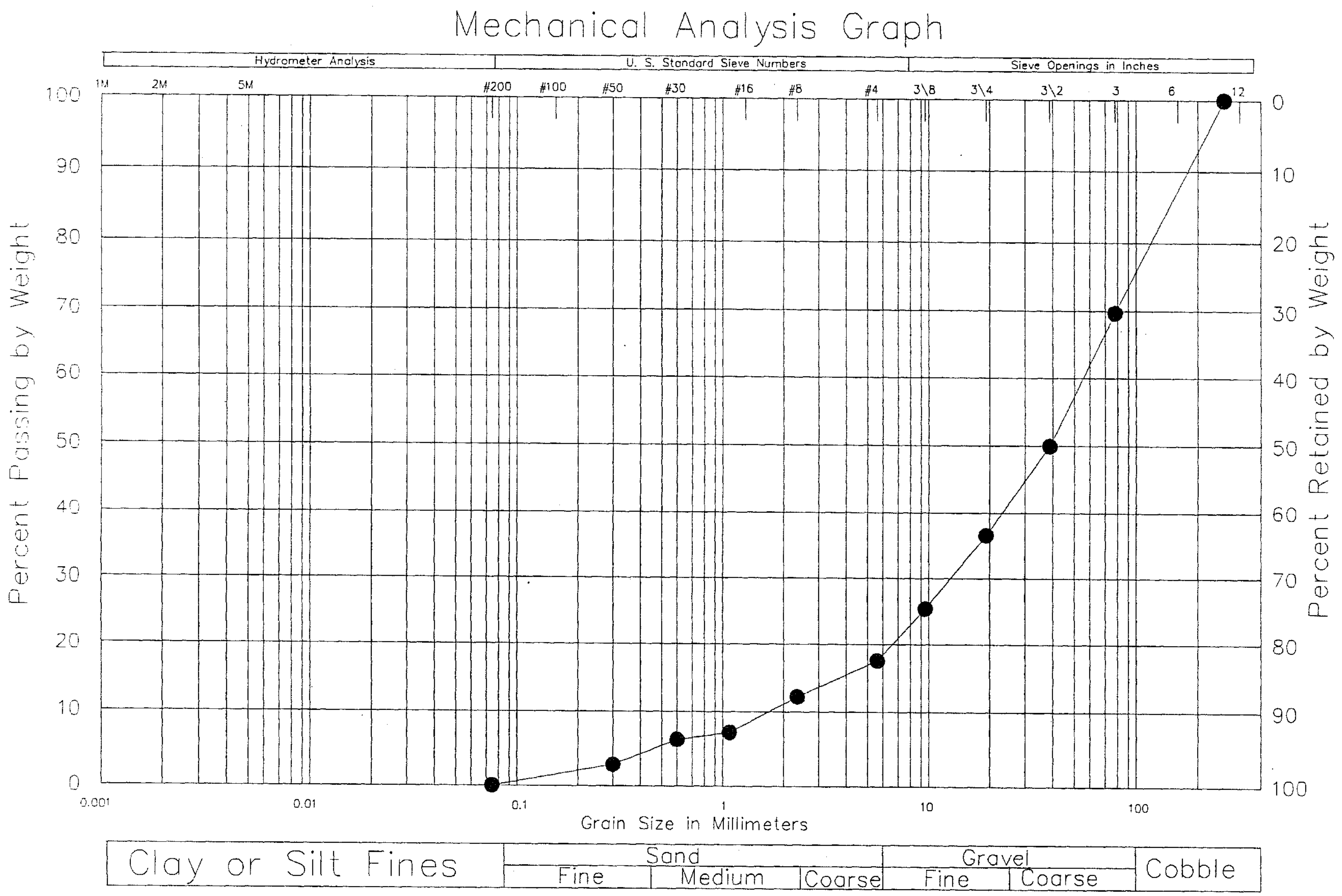
Mechanical Analysis Graph



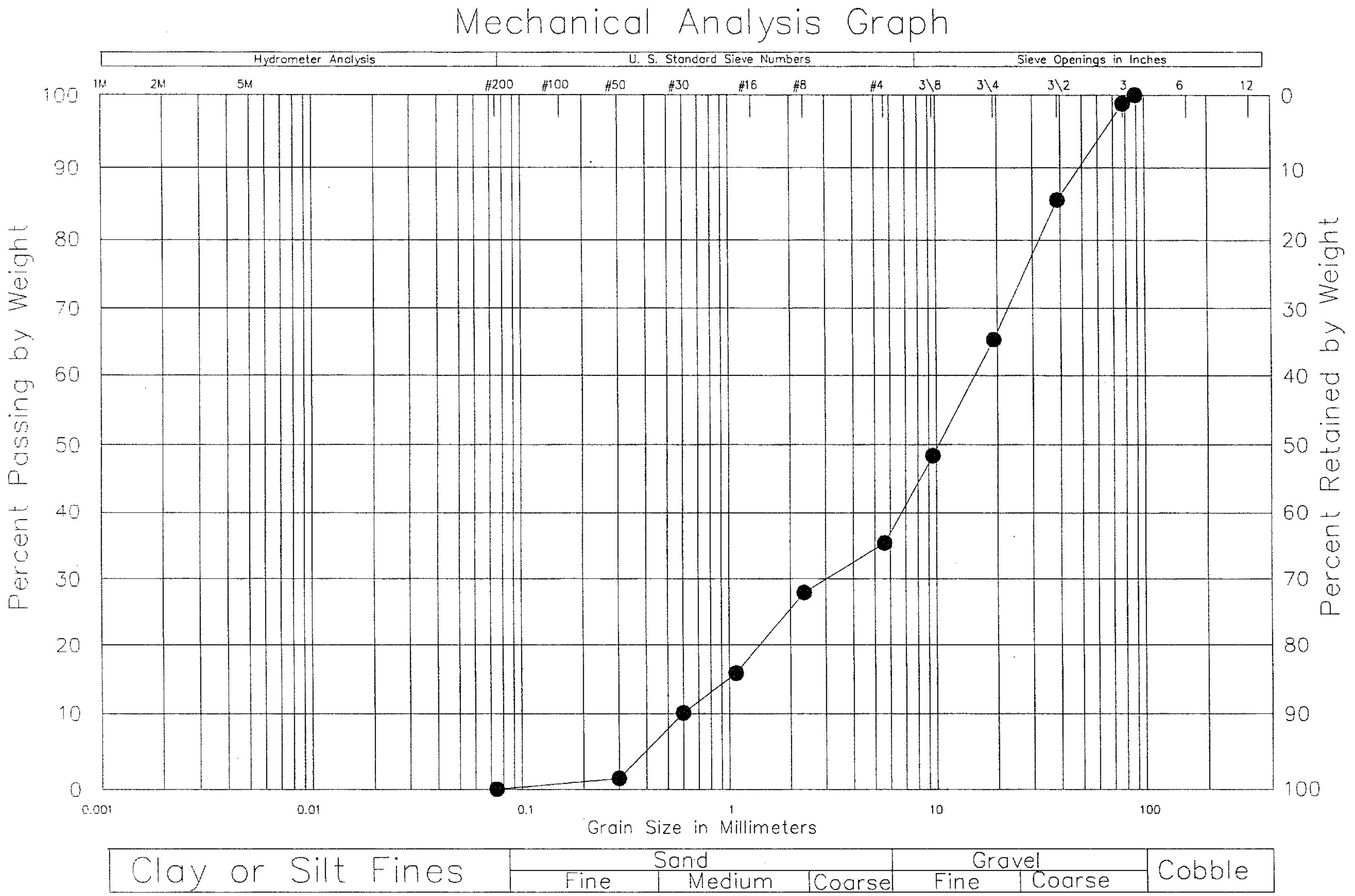
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT39



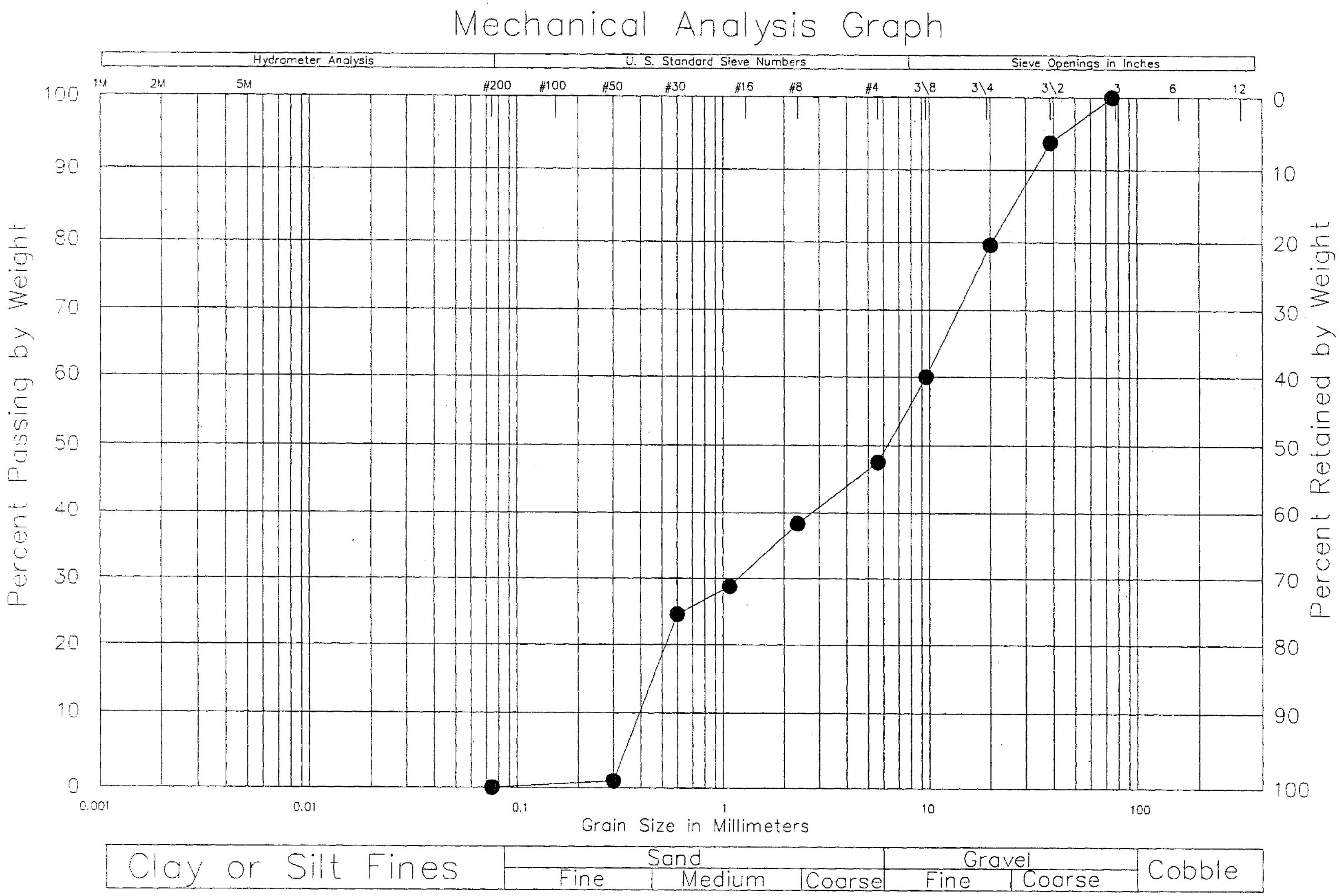
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT40



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT41



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT42

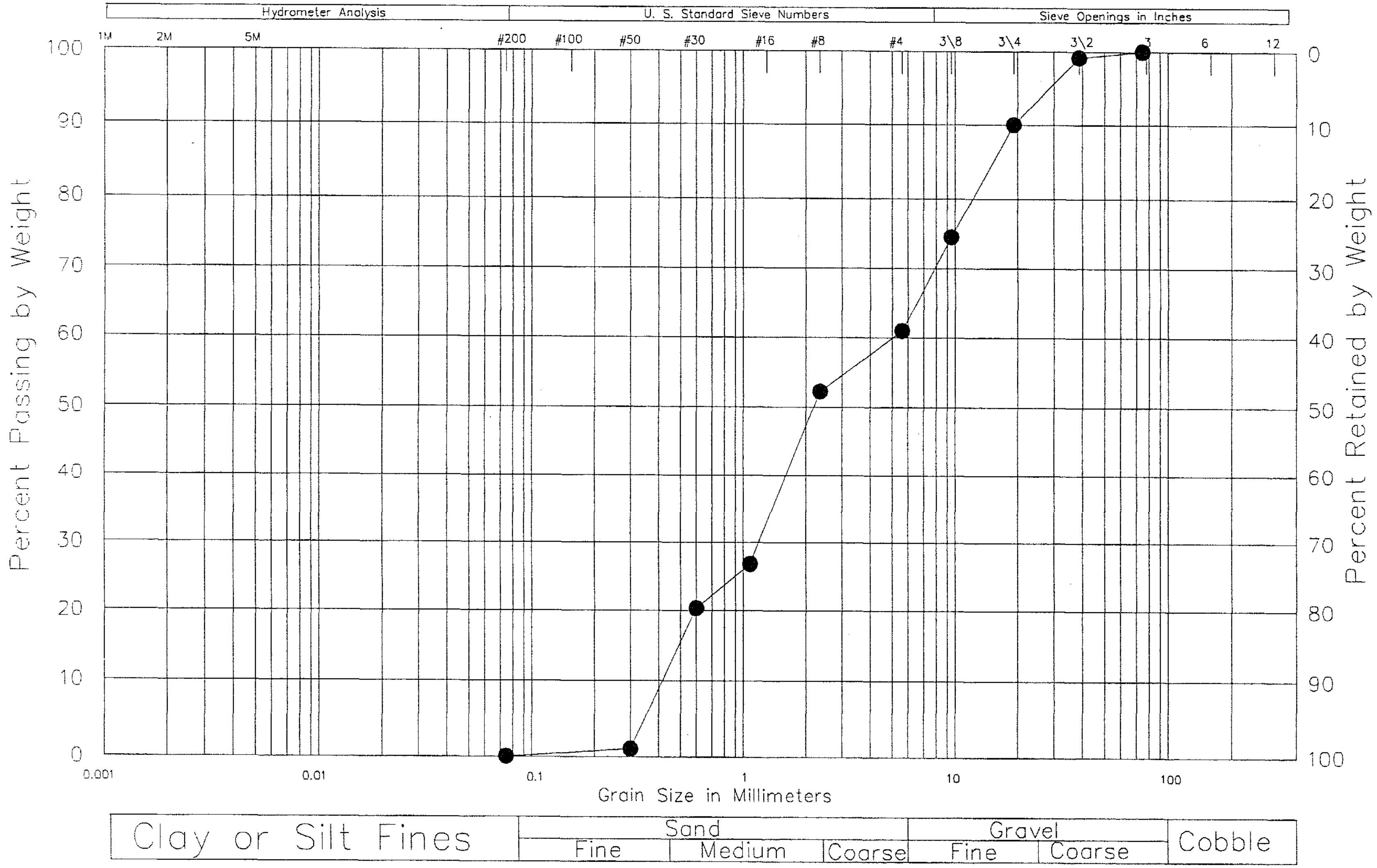


Mechanical Analysis Graph

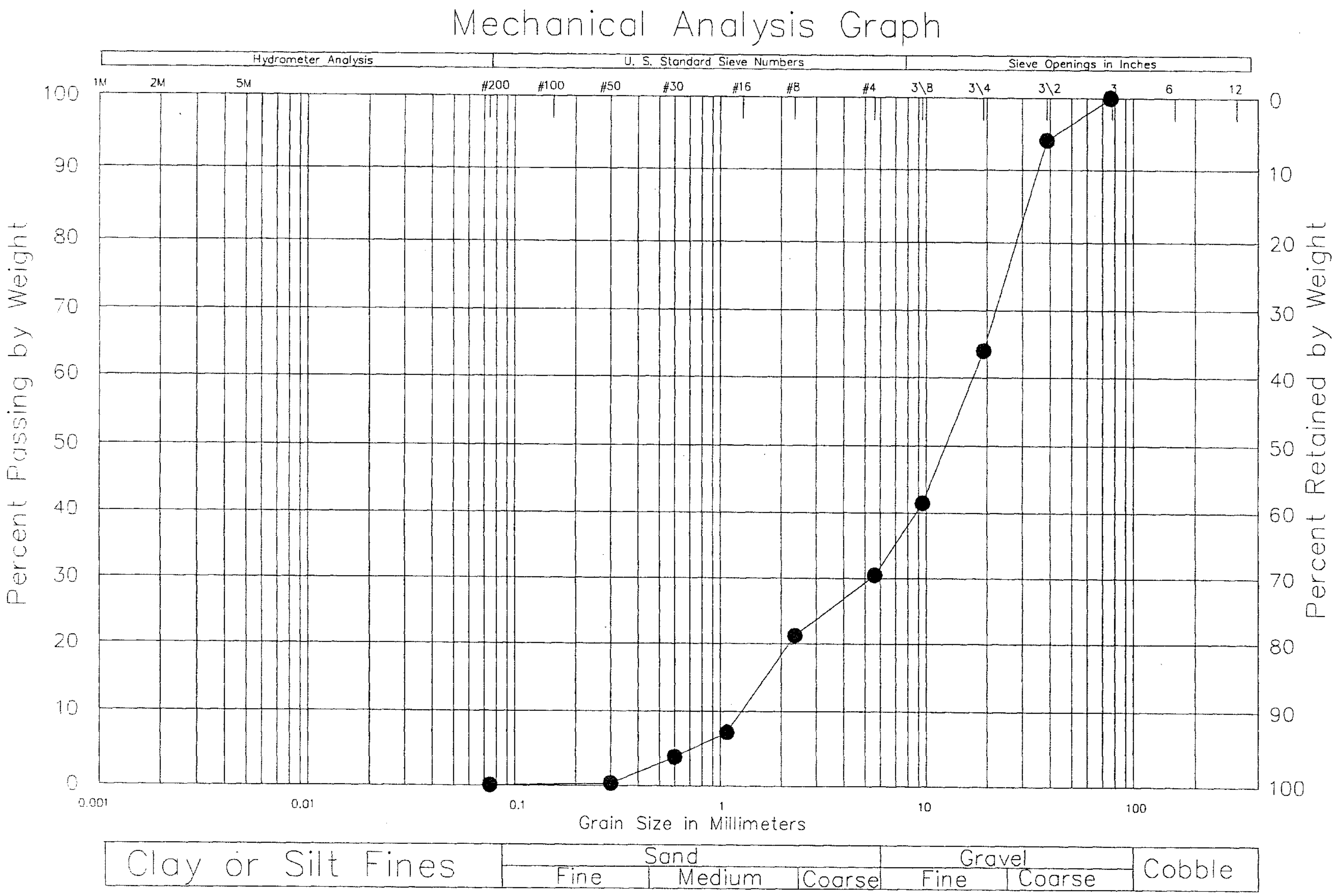
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER

SITE: SACT43

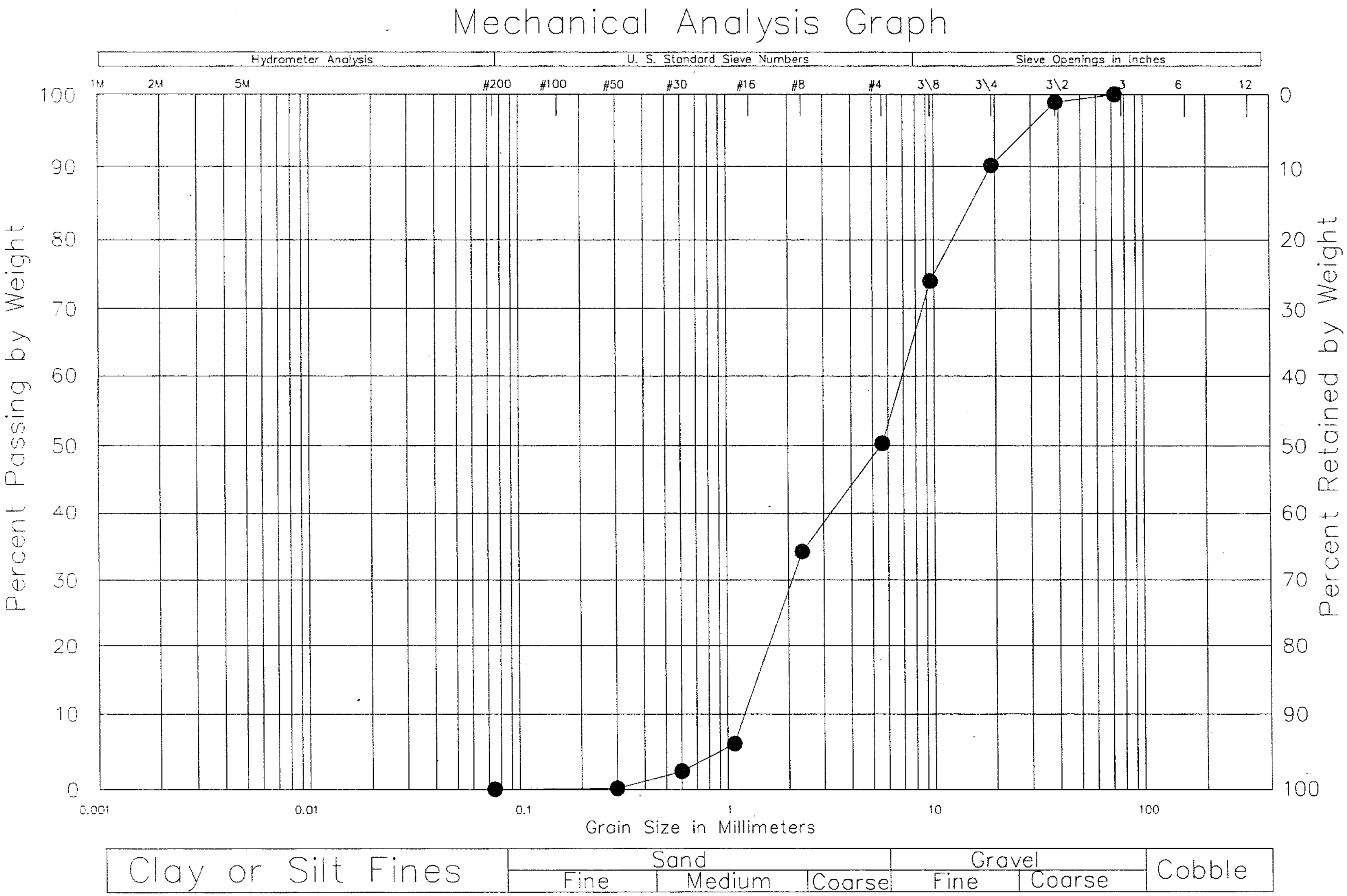
Mechanical Analysis Graph



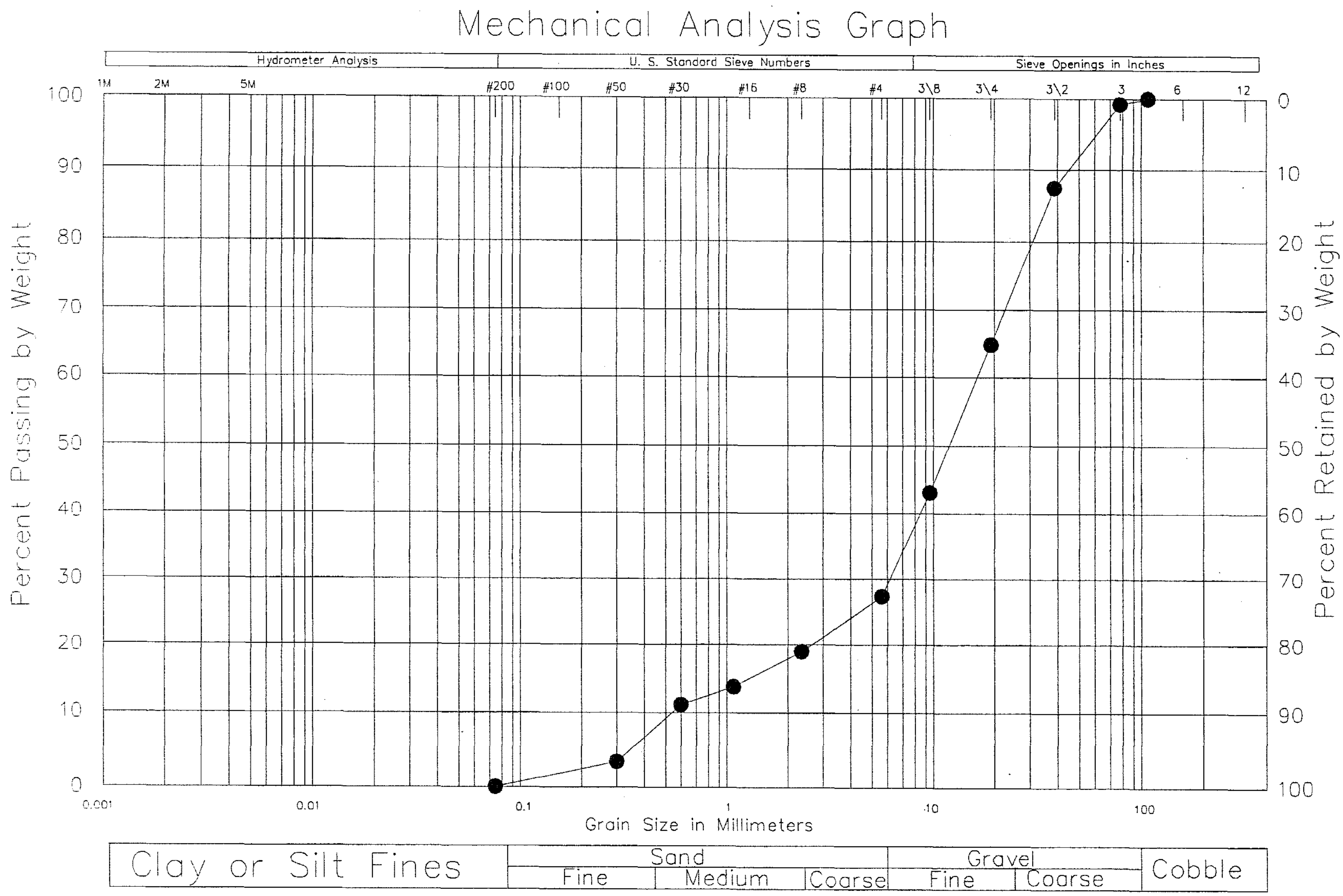
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT44



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT45



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT46



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER
SITE: SACT47

CONVERSION FACTORS

Quantity	To Convert from Metric Unit	To Customary Unit	Multiply Metric Unit By	To Convert to Metric Unit Multiply Customary Unit By
Length	millimetres (mm)	inches (in)	0.03937	25.4
	centimetres (cm) for snow depth	inches (in)	0.3937	2.54
	metres (m)	feet (ft)	3.2808	0.3048
	kilometres (km)	miles (mi)	0.62139	1.6093
Area	square millimetres (mm^2)	square inches (in^2)	0.00155	645.16
	square metres (m^2)	square feet (ft^2)	10.764	0.092903
	hectares (ha)	acres (ac)	2.4710	0.40469
	square kilometres (km^2)	square miles (mi^2)	0.3861	2.590
Volume	litres (L)	gallons (gal)	0.26417	3.7854
	megalitres	million gallons (10^6 gal)	0.26417	3.7854
	cubic metres (m^3)	cubic feet (ft^3)	35.315	0.028317
	cubic metres (m^3)	cubic yards (yd^3)	1.308	0.76455
	cubic dekametres (dam^3)	acre-feet (ac-ft)	0.8107	1.2335
Flow	cubic metres per second (m^3/s)	cubic feet per second (ft^3/s)	35.315	0.028317
	litres per minute (L/min)	gallons per minute (gal/min)	0.26417	3.7854
	litres per day (L/day)	gallons per day (gal/day)	0.26417	3.7854
	megalitres per day (ML/day)	million gallons per day (mgd)	0.26417	3.7854
	cubic dekametres per day (dam^3/day)	acre-feet per day (ac-ft/day)	0.8107	1.2335
Mass	kilograms (kg)	pounds (lb)	2.2046	0.45359
	megagrams (Mg)	tons (short, 2,000 lb)	1.1023	0.90718
Velocity	metres per second (m/s)	feet per second (ft/s)	3.2808	0.3048
Power	kilowatts (kW)	horsepower (hp)	1.3405	0.746
Pressure	kilopascals (kPa)	pounds per square inch (psi)	0.14505	6.8948
	kilopascals (kPa)	feet head of water	0.33456	2.989
Specific Capacity	litres per minute per metre drawdown	gallons per minute per foot drawdown	0.08052	12.419
Concentration	milligrams per litre (mg/L)	parts per million (ppm)	1.0	1.0
Electrical Conductivity	microsiemens per centimetre (uS/cm)	micromhos per centimetre	1.0	1.0
Temperature	degrees Celsius (°C)	degrees Fahrenheit (°F)	(1.8 × °C)+32	(°F−32)/1.8