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Effects of Channelization on Sediment Distribution and Aquatic Habitat at the Mouth of Redwood Creek, Northwestern California

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GEOMORPHIC PROCESSES AND AQUATIC HABITAT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

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EFFECTS OF CHANNELIZATION ON SEDIMENT DISTRIBUTION AND AQUATIC HABITAT AT THE MOUTH OF REDWOOD CREEK, NORTHWESTERN CALIFORNIA

By CYNTHIA L. RICKS[1]

ABSTRACT

Since the early 1950's, the distribution of sediment at the mouth of Redwood Creek has been altered by the effects of channel aggradation and channelization along the lower reach. Severe flooding in 1953, 1955, and 1964 caused bank erosion, landslides, and changes in channel geometry upstream along Redwood Creek. The increased sediment load also resulted in channel aggradation and widening along the lower flood plain. Flood-control levees constructed from 1966 to 1968 channelized the lower reach of Redwood Creek and cut off the last downstream meander. The distribution of erosional and depositional sites at the mouth has been more drastically altered by channelization than by aggradation. Channelization was accompanied by smoothing the roughness of the streambed, shaping a trapezoidal channel with an increased hydraulic radius, and steepening the channel gradient. These changes caused an increase in the mean velocity and frequency of mobilization of the bed material between the levees. With streamflow confined between the levees, sediments deposited in the last downstream meander (south slough) and north slough are no longer flushed from the mouth of Redwood Creek. Since 1966, 50 percent of the lower estuary (between 0 and 1.2 m above sea level) has filled with sediment or become isolated from the embayment. Data on heavy minerals and on sediment size distribution indicate that, during high to moderate streamflow, sand- and gravel-sized sediment is flushed through the embayment. Overwash across the storm berm and transport by tidal currents are the dominant processes delivering sediment from the nearshore zone to the sloughs. Sediment accumulation has altered the seasonal sequence of migration and closure of the outflow channel, which determines the substrate distribution, water quality, and embayed water volume during the low-flow period from spring to early fall. More frequent closure and flooding of backwater areas and adjacent pastures have historically led to artificial breaching of the berm. Recently, such premature breaching released 75 percent of the embayed water, which was inhabited by 20,000 juvenile salmonids.

INTRODUCTION

The mouth of Redwood Creek is located 4.0 river km west of Orick, Calif. (fig. 1). The lower Redwood Creek flood plain encompasses the Orick valley from Prairie Creek to the ocean. Prior to 1966, a series of damaging floods deposited sediment and debris across the lower Redwood Creek flood plain. Concern for flood protection prompted the U.S. Army Corps of Engineers to channelize Redwood Creek in the vicinity of Orick. Levees were constructed along 5.1 km from the confluence with Prairie Creek to the mouth, between April 1966 and October 1968. The narrow trapezoidal channel was designed to contain a peak discharge of 2,180 m^3/s, about 50 percent larger than the peak flow of record (U.S. Army Corps of Engineers, 1961, 1966).

The lowermost section of the levees diverted streamflow directly to the ocean, bypassing the last downstream meander (fig. 2). The mouth presently consists of the main channel of Redwood Creek between the levees, a north slough, a south slough (the cutoff meander), and an embayment. The embayment is the relatively deep, broad part of the mouth landward from the beach.

Estuarine habitat at the mouth of Redwood Creek is transitory and limited in extent. During favorable conditions, saltwater has been detected only 1.5 km upstream from the mouth (Gregory, 1982). By increasing the historically steep stream gradient along lower Redwood Creek, channelization reduced the maximum upstream intrusion of saltwater.

In recent years, changes in the distribution of sediment at the mouth have isolated the north and south sloughs, thereby reducing the quantity and quality of aquatic habitat. Accumulation of sediment has been attributed to processes resulting from channelization and to increased fluvial sediment input. To distinguish between the effects of flooding under natural and channelized conditions, morphological, dendrochronological, and historical evidences of flooding along lower

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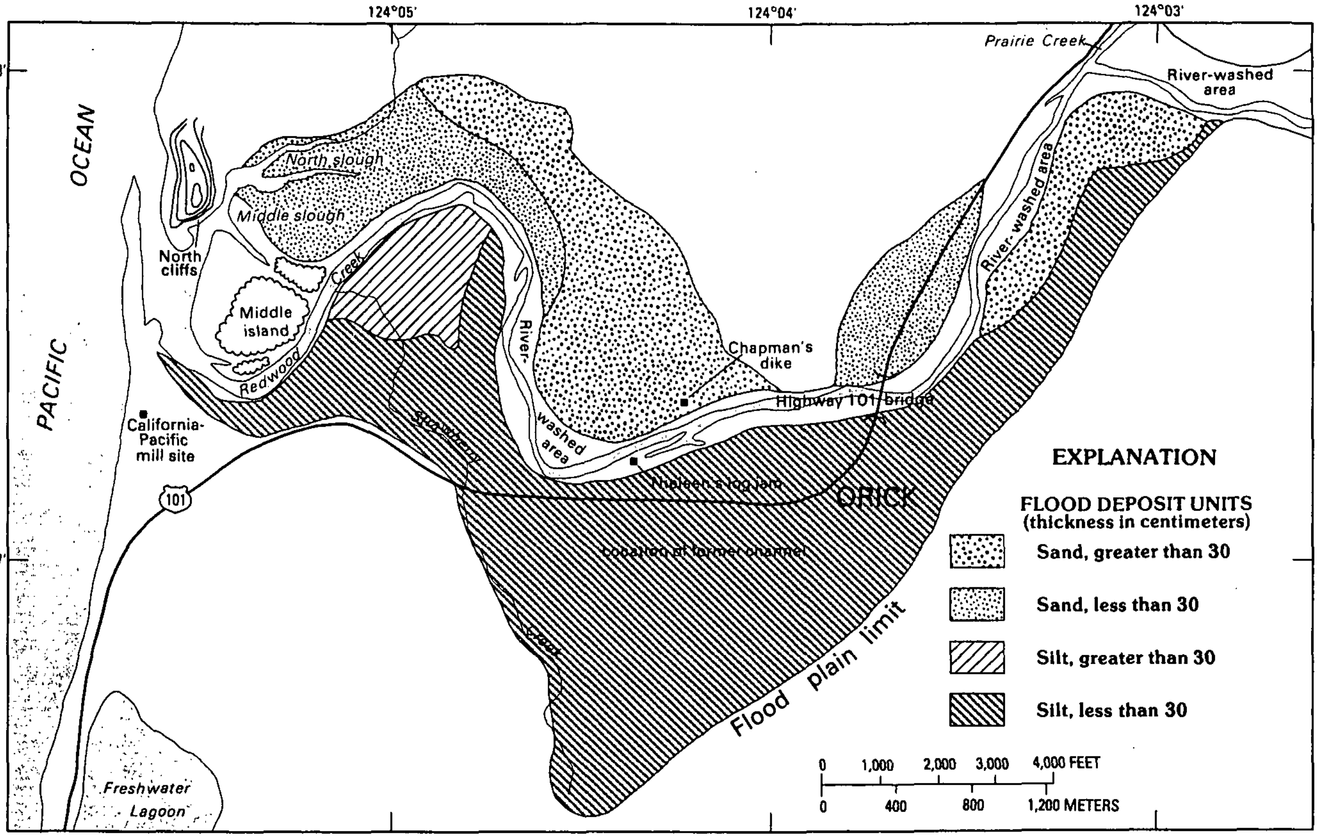

FIGURE 1.—Redwood Creek flood plain showing 1964 flood deposits and selected cultural features. This map shows the configuration of the mouth of Redwood Creek 2 weeks after the 1964 flood. Flood deposit units are from McLaughlin and Harradine (1965).

Redwood Creek are examined. The effects of channelization include direct alteration of stream configuration and habitat, as well as changes in the relative importance of fluvial and marine sediment input. Textural and mineralogical analyses, topographic surveys, and frequent field observations document sediment sources and transport processes. Typical seasonal variations in the configuration of the embayment are differentiated from sites and rates of net sediment accumulation. The outflow channel from the embayment to the ocean follows a seasonal progression that influences substrate distribution, water quality, and embayed water volume. Accumulation of sediment appears to have altered the seasonal progression of the outflow channel, thereby further restricting circulation and the volume of aquatic habitat.

ACKNOWLEDGMENTS

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DATA COLLECTION AND ANALYSIS

Long-term changes along the lower flood plain were documented by dendrochronological techniques and survey comparisons and by interpretation of aerial photographs. The stability of the last downstream meander prior to channelization was evaluated by mapping age relations in the spruce-alder forest located on the middle island (fig. 1). Live trees were dated from increment cores, and ring counts were taken on stumps of trees cut in 1978.

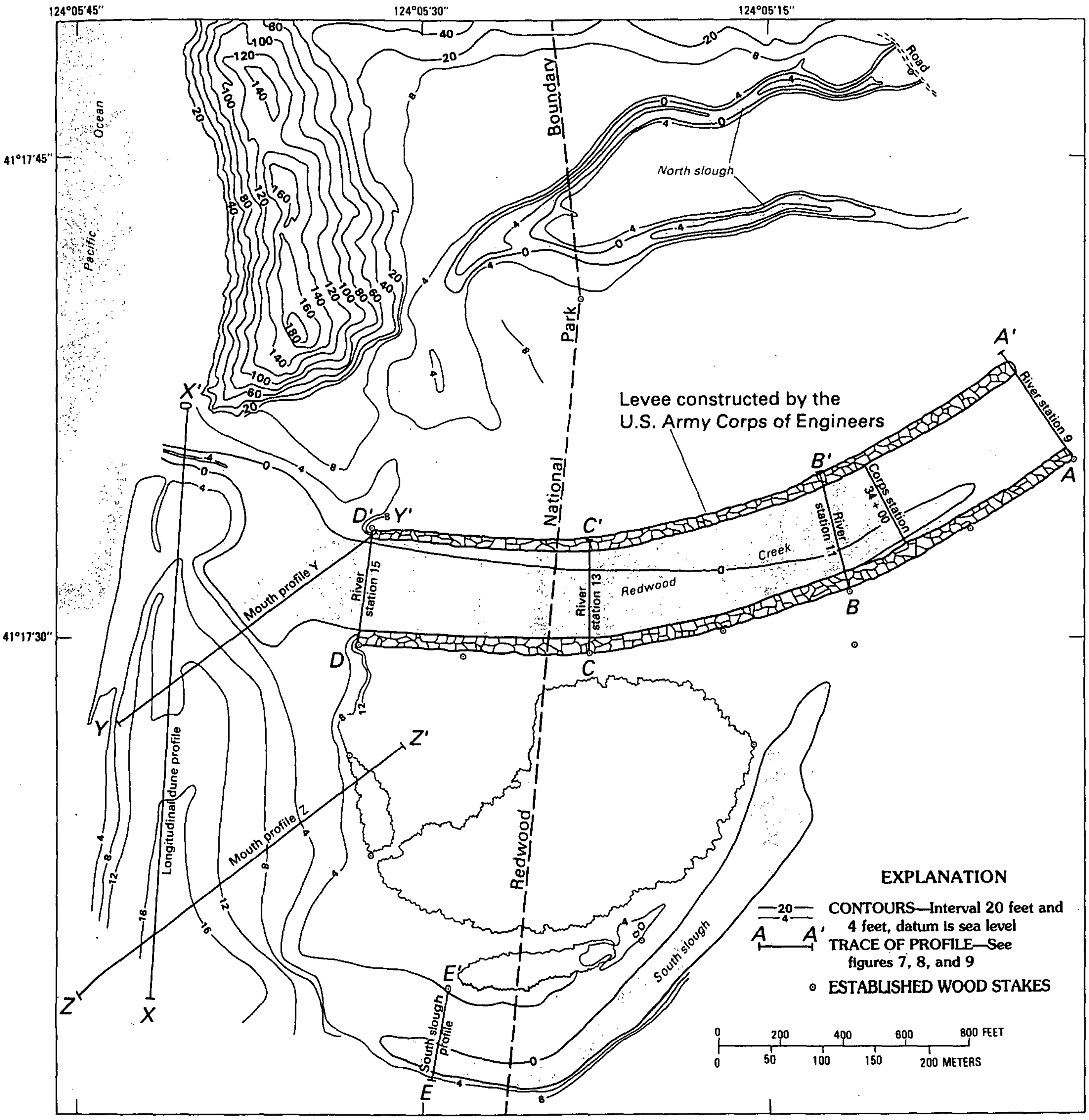

FIGURE 2.—Profile locations at the mouth of Redwood Creek.

Additional data came from historical photographs dating from 1931, interviews with local residents, streamflow gaging, and a flood deposit map compiled following the 1964 flood (McLaughlin and Harradine, 1965). The dates and magnitudes of pre-1949 floods on Redwood Creek have been inferred from regional precipitation and streamflow data as well as published accounts (chap. D, this volume; McGlashan and Briggs, 1939; Paulson, 1953; U.S. Army Corps of Engineers, 1961). After 1949, peak flood stages were measured by the Corps of Engineers on a staff gage at the Orick bridge, prior to establishment of the U.S. Geological Survey gaging station in October 1953.

Data on streambank erosion and migration of the last downstream meander, as well as on sedimentation adjacent to the embayment, were collected from vertical aerial photographs for the period 1936–68. Potential relations between high stream discharge and marine conditions were evaluated by plotting hydrographs for floods gaged at Orick against tide heights predicted for Humboldt Bay.

Sediment accumulation following levee construction was documented by comparing profiles surveyed by the Corps of Engineers in 1964 and 1966 with detailed topographic-bathymetric surveys conducted during summer 1980 and spring 1981.

Seasonal changes in mouth morphology and sedimentary structures of the mouth were documented repeatedly throughout the period of field observation from November 1979 to May 1982. The locations and approximate volumes of sediment mobilized during the 1980–81 winter season were obtained from successive topographic-bathymetric surveys. Fluvial sediment input was estimated from sediment transport, flow duration, and particle size plots for the U.S. Geological Survey gaging station at Orick, Calif.

Sieve analysis and heavy liquid separations of selected surface samples were used to delineate grain-size distribution and to distinguish among sediment sources by heavy-mineral variations. At the mouth, bottom material was sampled along profiles surveyed in summer 1980 and spring 1981. Where water depth prohibited scooping the upper 2 cm of sediment by hand, a gravity grab sampler was dropped from a row boat. Bottom material from streams and beaches adjacent to the mouth of Redwood Creek also was analyzed to identify lithologically distinct heavy-mineral sources.

The heavy-mineral fraction was separated from 56 samples of fine sand (0.250–0.125 mm) by gravity settling in tetrabromoethane (sp gr=2.96). Preliminary identification revealed that beach samples contained at least 20 percent strongly pleochroic blue-green hornblende, but the mineral was limited to only a few percent in Redwood Creek (Curt Peterson, School of Oceanography, Oregon State University, 1982, oral commun.). This indicator mineral and two other easily identifiable minerals, glaucophane and garnet, were used to facilitate rapid analysis of samples.

RESULTS

FLOOD-PLAIN MORPHOLOGY AND DENDROCHRONOLOGY

Below its confluence with Prairie Creek, Redwood Creek flows in a westerly direction through a widening valley to the ocean. Erosion scars on the lower flood plain indicate prehistoric flood overflow channels and stream channels (fig. 3). An arcuate patch of willows marks a former channel on the south side of the flood plain (fig. 1). Before channelization, several marshy areas and sloughs on the south flood plain drained into Strawberry Creek and the middle slough during overbank flows (fig. 1). On the north side of the flood plain, high flows occupied two channels that are now the fingers of the north slough.

Early photographs show that spruce (*Picea sitchensis*) once forested the Orick valley. The spruce grove near the mouth on the middle island (fig. 1) is relatively immature (fig. 4), suggesting that the trees became established following the floods in 1861–62 or 1890. The diversity in age distribution of the spruce may be the result of seedling establishment under conditions of periodic flooding. Spruce not located on higher elevation sites or not protected by accumulations of organic debris would have been destroyed by flooding. Although the maximum spruce age of 98 years suggests that the grove developed following the 1861–62 floods, it also could reflect an early unrecorded harvest or recovery from disease.

FLOOD HISTORY

Along the lower reaches of Redwood Creek, local residents recall severe flooding in the 1860's and in 1890 and 1927. At least as early as 1927, a short segment of the right bank downstream from Orick was protected by a low earthen structure called Chapman's dike (fig. 1). The 1927 flood breached the dike and flowed along the north side of the flood plain and into the north slough.

The late 1940's and early 1950's were prosperous years for the logging town of Orick. Many buildings were constructed along Redwood Creek in low marshy areas downstream from the Highway 101 bridge. This development led to local pressure for flood control after floods in 1953 and 1955. The California-Pacific Mill was established south of the last downstream meander in 1951 after Highway 101 was relocated in 1949 (fig. 1).

Since 1949, peak discharges for floods in Orick have been gaged at the Highway 101 bridge. Waananen and Crippen (1977) calculated a 16- to 17-year return period for the peak discharge of recent major floods (1,415 m^3/s; table 1). Coghlan (1984) discusses the effects of climatic patterns on flood frequencies, noting that it is not unreasonable to expect peaks on the order of 1,415 m^3/s

FIGURE 3.—Oblique aerial photograph of mouth of Redwood Creek, September 1948.

TABLE 1.—*Instantaneous peak discharge and storm runoff at Orick for recent major floods on Redwood Creek*

[Revised from Harden and others, 1978, p. 33. —, no data]

Storm dates	Instantaneous peak discharge (m^3/s)	Storm runoff (cm)
January 16–20, 1953 (peak, January 18)	1,415	—
December 15–23, 1955 (peak, December 22)	1,415	32.5
December 18–24, 1964 (peak, December 22)	1,430	[1]64.0
January 19–24, 1972 (peak, January 22)	1,285	28.7
March 1–4, 1972 (peak, March 3)	1,410	18.0
March 15–24, 1975 (peak, March 18)	1,420	28.2

[1] 64.0 cm is total runoff at Orick for the extended storm period December 18–30, 1964.

every 12 years. During more severe climatic periods such as that of 1953–75, a flood of this magnitude may occur every 3.5 years.

Local residents reported that the lower Redwood Creek channel was narrow and deep prior to the floods of 1953 and 1955. Aerial photographs of the lower flood plain show that the September 1954 channel appears wider and more aggraded than the June 1948 channel. The storm of January 16–20, 1953, was brief and intense and attained a peak discharge of 1,415 m^3/s (table 1). Downstream from the Highway 101 bridge (fig. 1), bank erosion removed sections of the county road. The Corps of Engineers placed emergency riprap along 600 m of the bank. Chapman's dike failed, leaving flood deposits in fields on the north side.

Precipitation during the storm of December 15–23, 1955, was more prolonged than in the 1953 storm. Following the 1955 flood, the Corps of Engineers provided bank protection along 460 m of the left bank downstream from Nielsen's log jam (fig. 1). On the north side, the Corps constructed a levee 1.5 m high at the site of the 550-m-long earthen dike, which had developed a 90-m breach.

The peak discharge of the December 18–24, 1964, flood was only slightly larger than for the floods of 1953 and 1955 (table 1), but the total flood volume and damage to streambanks and hillslopes was much greater (Janda and others, 1975). The thickness and texture of the 1964 flood deposits were mapped during a Humboldt County soil survey (McLaughlin and Harradine, 1965). Figure 1 depicts the mapped units and the configuration of the mouth 2 weeks after the 1964 flood. Flood deposits were thicker and coarser on the north side of the flood plain

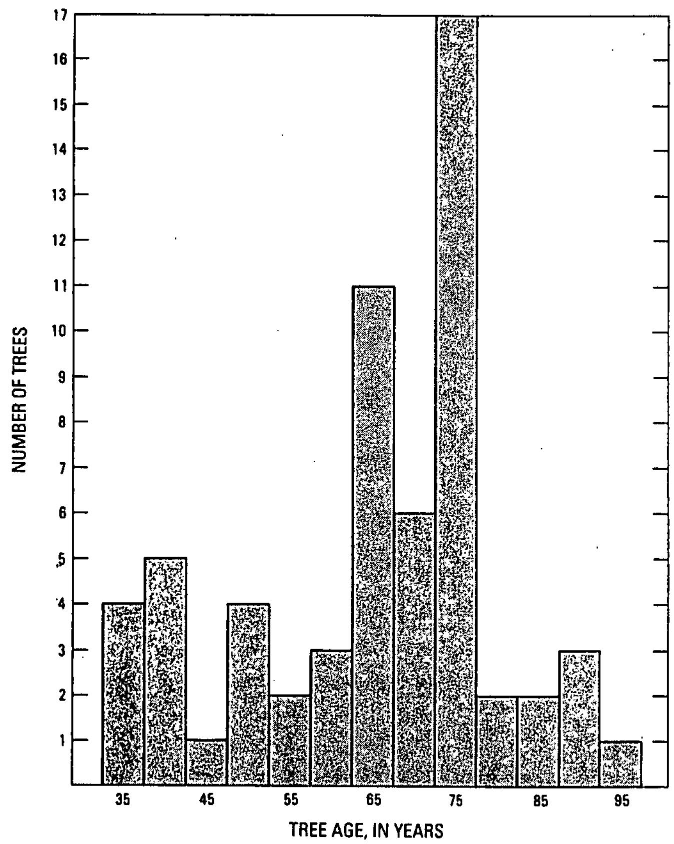

FIGURE 4.—Age distribution of *Picea sitchensis* (Sitka spruce) on the middle island, mouth of Redwood Creek.

than the south side. Catastrophic failure of the 1.5-m-high levee may have released higher velocity flows onto the north side.

Orick residents stated that the 1964 deposits were generally twice as thick as the 1955 deposits. Near the mouth, waves breaking against the middle island may have augmented deposition between the middle and north sloughs (fig. 1). Aerial photographs of the mouth taken between 1931 and 1967 show that the most extensive sediment storage site developed between the middle and north sloughs as a result of the 1964 flood. This event also eroded the beach berm from the north cliffs south to the California-Pacific Mill (fig. 1).

RATE OF STREAMBANK EROSION

The last downstream meander migrated progressively to the south from 1936 to 1967 at a rate of less than 2.1 m/yr (fig. 5). Significant episodes of streambank erosion were clearly associated with major floods (fig. 6) having peak discharges of at least 1,065 m^3/s.

However, the degree of migration of the last downstream meander differed during floods of similar magnitude in 1953, 1955, and 1964. Following a prolonged period of little or no streambank erosion (fig. 6), the concave bank had migrated considerably after the January 1953 flood (fig. 5). Although the December 1955 flood attained the same peak discharge as the 1953 flood (table 1), streambank erosion was not extensive (figs. 5, 6).

Nanson and Hicken (1983) proposed that differences in the degree of migration of stream meanders may be caused by processes that maintain an equilibrious channel width. When a convex bank is well defined and vegetated, migration occurs by erosion of the concave bank and is associated with channel widening. Successive floods of similar magnitude will not significantly erode the concave bank because velocity and boundary shear stress are reduced in a widened channel. The convex bank migrates by accretion and revegetation of a point bar until the equilibrious channel width is restored. The next major flood will again erode the concave bank of the confined channel.

In July 1957, the convex bank consisted of a wide point bar covered by organic debris that may have retarded erosion and aided revegetation of the bar. A well-vegetated insular bar had developed by August 1962, confining a narrower channel. Considerable concave bank erosion was again associated with the December 1964 flood.

The extent of streambank erosion also may depend on the duration and the rates of rise and recession of the major floods. Positive ground-water pore pressures in streambanks during flood recession may cause slumping of the bank (Keller, 1977). If this process was important along the last downstream meander, more extensive bank erosion probably would have occurred during the 1955 flood, when rapid recession coincided with ebbing tides.

EFFECTS OF CHANNELIZATION

During channelization and levee construction, the channel gradient was increased from 0.07 to 0.14 percent. This increase was due to removal of the last downstream meander and the excavation of the channel to a predetermined design slope. The combined effect of smoothing the roughness of the bed, increasing the hydraulic radius by shaping a trapezoidal channel, and increasing the slope increased the mean flow velocity. The resulting greater stream competence caused the bed material between the levees to be mobilized more frequently.

After channelization, sediment accumulated rapidly across the beach berm and in the downstream end of the abandoned meander, now the south slough (figs. 2, 7, 8). Along the north cliffs (fig. 1), water depths of at least 6 m apparently prevented the Corps of Engineers from surveying the neck of the north slough in 1964. By

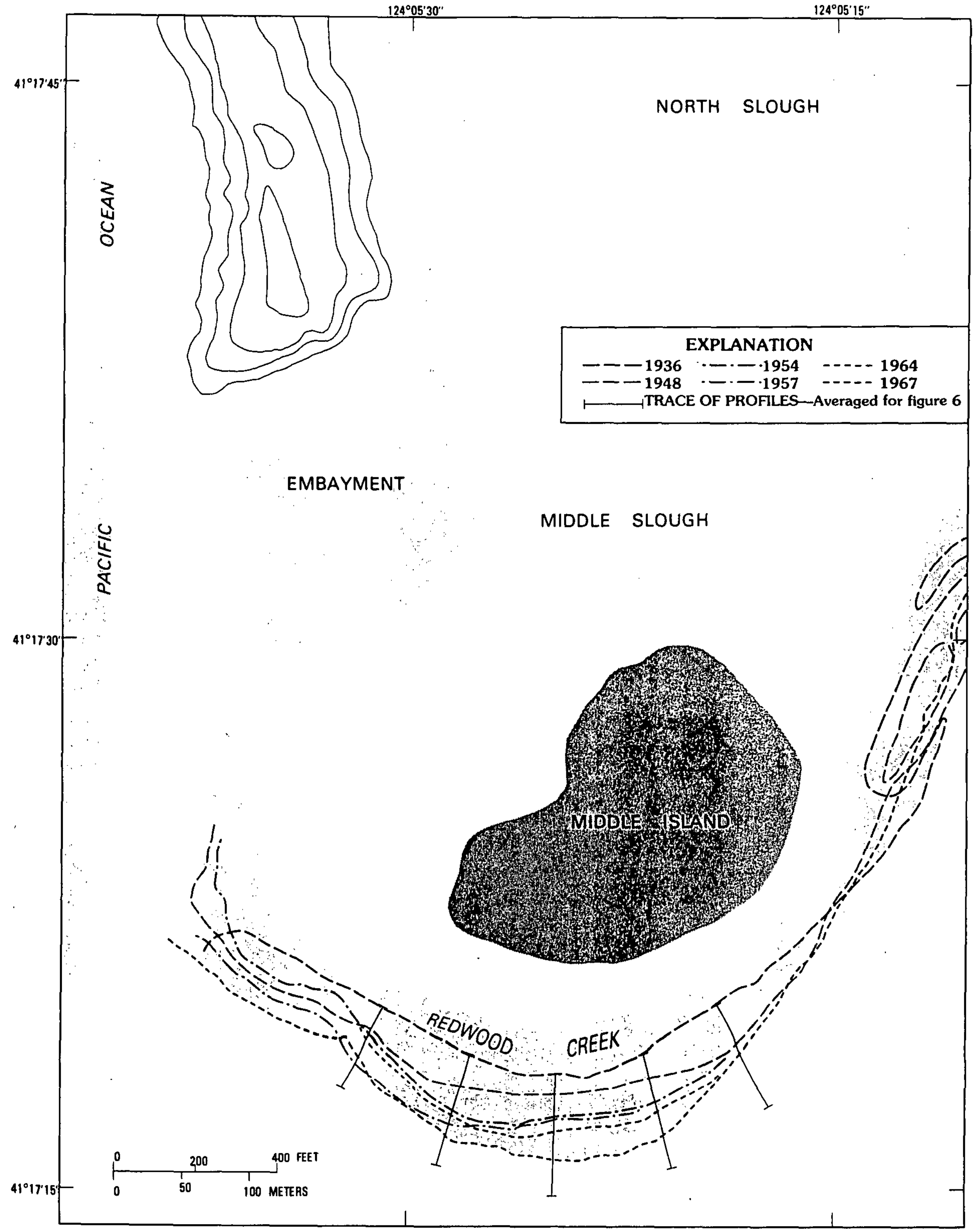

FIGURE 5.—Bank positions along the last downstream meander at the mouth of Redwood Creek, 1936 to 1967. The five cross-section lines through the streambank provided the bank erosion data for figure 6.

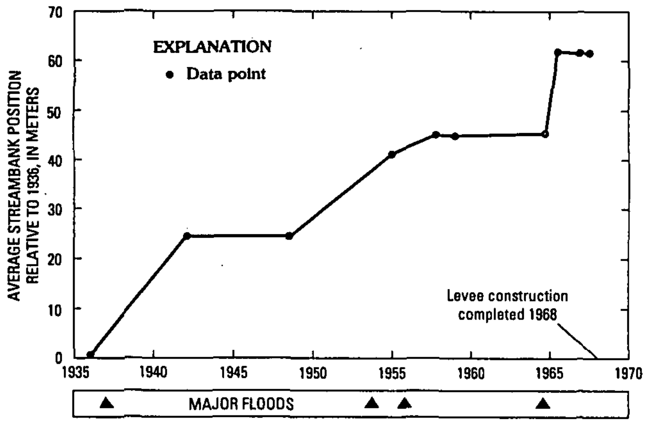

FIGURE 6.—Cumulative southward migration of the last downstream meander at the mouth of Redwood Creek, based on average erosion for the five cross-section lines shown in figure 5. Major floods have peak discharges of at least 1,065 m^3/s.

TABLE 2.—*Annual discharge of coarse-size fraction for Redwood Creek at Orick*

Size fraction[1]	Annual discharge (Mg)	Data base	Source
Suspended sediment	1,340,000	1954–80	J.R. Crippen, written commun., 1981.
....Do....	1,330,000–2,790,000	1978–80	USGS gaging station at Orick, Calif.
Bedload sediment	173,000	1954–80	J.R. Crippen, written commun. 1981.
....Do....	43,000–646,000	1974–76, 1978	USGS gaging station at Orick, Calif.
Suspended sand	860,000–1,130,000	1974–80	....Do....
Sand in bedload	62,000–96,000	1975–76, 1978, 1980	....Do....
Total sand	930,000–1,220,000	1974–80	....Do....
Sand and gravel	1,040,000–1,310,000	1974–80	....Do....

[1] Sand size=0.062–2.0 mm.

September 1974, a subaerial deposit had isolated the north slough from the main channel. Profiles at river stations 9, 11, 13, and 15 (fig. 9) illustrate the degree of aggradation between the levees since the design channel was excavated. Griggs and Paris (1982) observed that similar aggradation along the channelized lower portion of the San Lorenzo River, Calif., lowered the stream gradient toward the prechannelization equilibrium value. Aggradation also reduced the discharge capacity of the channelized reach. Along the lower reach of Redwood Creek, a stream gradient survey from approximately 2.3 km upstream of the mouth to the Highway 101 bridge showed a decrease from the 1966 design gradient (0.14 percent) to 0.11 percent in 1980 (M.A. Madej, written commun., 1982).

Since the Corps of Engineers surveys of 1964–66, 50 percent of the lower estuary (between 0 and 1.2 m above sea level) has filled with sediment or become isolated from the main channel. By confining the flow of Redwood Creek between levees, a trap for sediment was created in the sloughs. Minor flows from Strawberry and Sand Cache Creeks (fig. 1) provide the only circulation and flushing of sediment from the south slough and the north slough. The levees constrict the streamflow so efficiently that a very limited section of the beach berm is scoured by floods. The peak discharges for the December 1964 and March 1972 floods were very similar (table 1), but the extent of berm scour in 1972 was about 70 percent less with the channelized flow (fig. 10).

SEDIMENT SOURCES AND TRANSPORT PROCESSES

Redwood Creek transports 1,340,000 Mg of sediment as suspended load and 173,000 Mg as bedload past the Orick gaging station annually (table 2). The sand-sized fraction (0.062–2.0 mm) of the total load ranges from 62 to 81 percent. The sand plus gravel fractions compose 69 to 86 percent of the total load. Assuming a sediment density of 1.92 g/cm^3, 544,000 to 680,000 m^3 of sand and gravel are supplied to the mouth of Redwood Creek annually. Most of this sediment is transported through the mouth to the nearshore environment. Gravelly sand and sandy gravel remain in the channel between the levees and throughout the embayment following winter flows.

The overwash slope is primarily composed of slightly gravelly, very coarse to medium-grained sand. Waves deposit sands of similar texture to the south of the north cliffs. In the necks of the sloughs, the limit of tidal current tractive transport is marked by an abrupt increase in water depth (fig. 2) and a change in bed material from muddy sand to sandy mud.

During summer months, thick deposits of mud and muddy sand may accumulate in the embayment at Redwood Creek. Boggs and Jones (1976) suggest a predominantly marine origin for sand and muddy sand layers deposited at the mouth of the Sixes River, Oreg., during summer months. Their suggestion is based on the presence of marine detritus in the deposit and the low suspended sediment load of the river. To evaluate the potential fluvial contribution, the volume of suspended sediment from Redwood Creek at the Orick gaging station was calculated for the period from early July to mid-October 1980. The summer fluvial input could not account for a major part of mud in the embayment, but

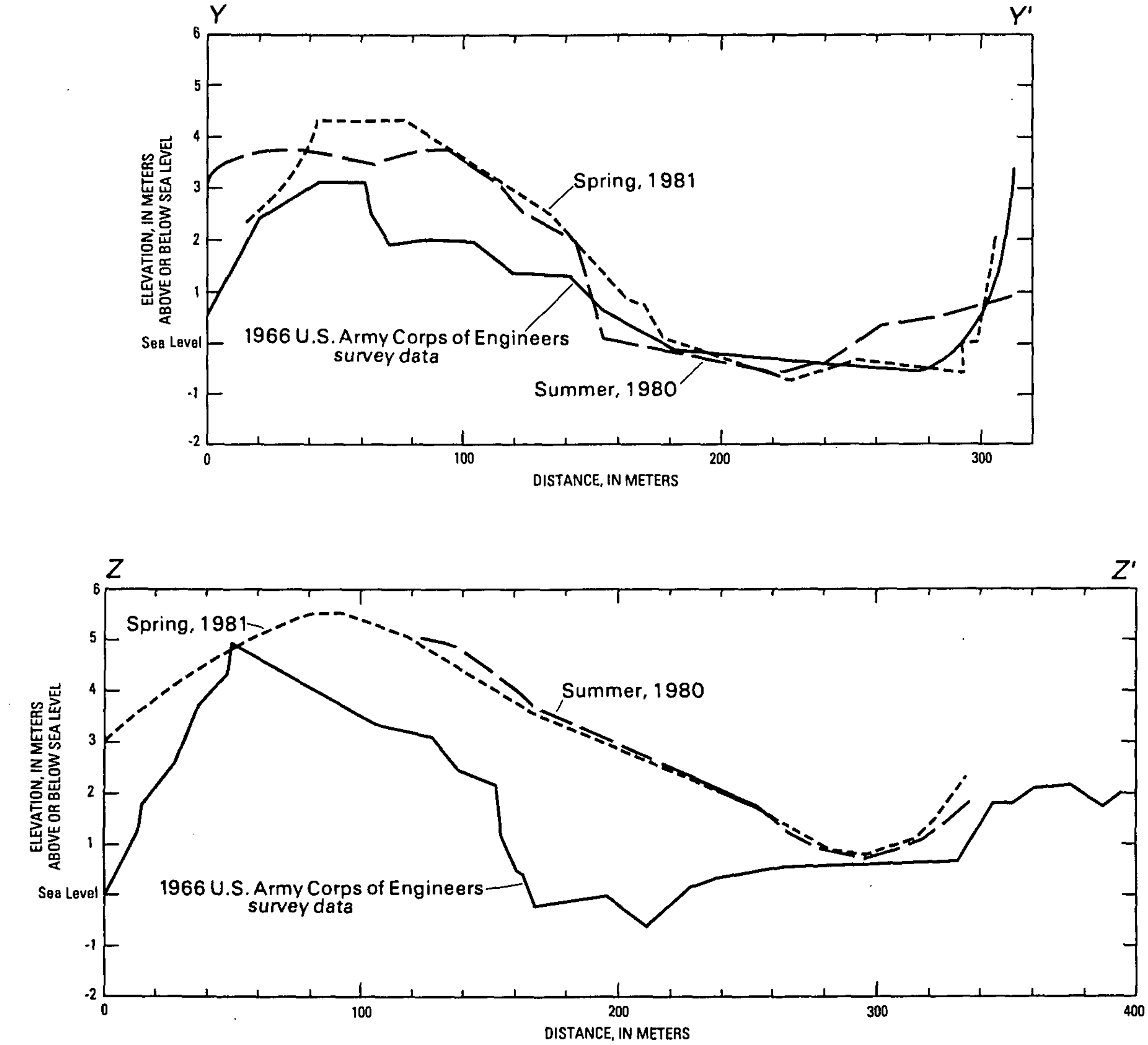

FIGURE 7.—Topographic profiles *Y–Y'* and *Z–Z'* across the mouth of Redwood Creek. Profile locations are shown in figure 2.

the volume data were not complete enough to allow evaluation of the actual contribution, if any.

Analyses of heavy minerals provide more substantial evidence of the relative contributions of marine and fluvial sediment to the Redwood Creek embayment and sloughs. Mineralogical analyses show that Redwood Creek sediment can be distinguished from marine contributions from northern and southern sources by the presence and (or) relative abundances of glaucophane and blue-green hornblende in the bottom sediment (fig. 11). The Klamath River to the north carries a large component of blue-green hornblende, whereas the Mad and Eel Rivers to the south are an abundant source of glaucophane (fig. 11). Samples of beach sand from 0.3 km south of the Klamath River to the mouth of Redwood Creek have 11 to 26 percent blue-green hornblende,

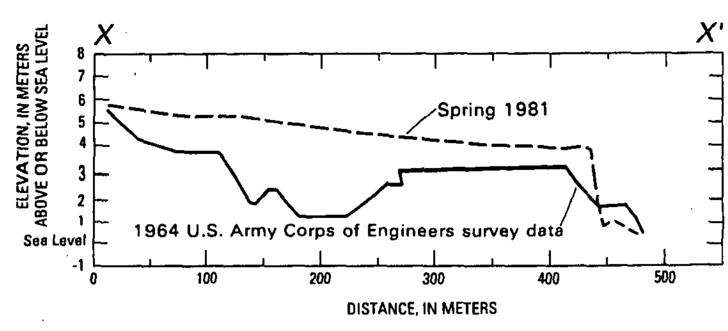

FIGURE 8.—Longitudinal dune profile *X–X'*, mouth of Redwood Creek. Dune profile location is shown in figure 2.

indicating southward longshore drift of Klamath-derived sands. Although Bodin (1982) postulated northward longshore drift between the Eel River mouth and Trini-

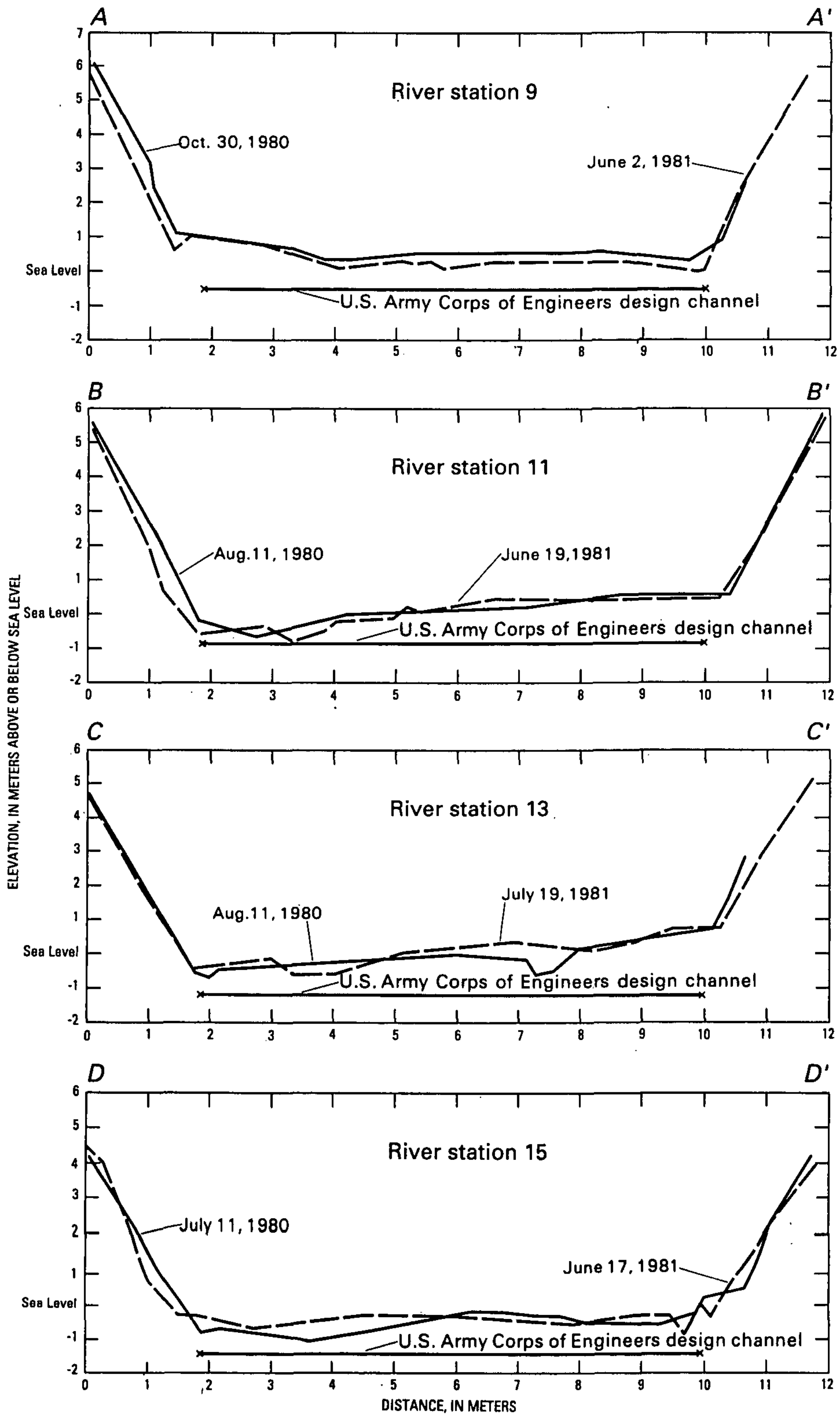

FIGURE 9.—River profiles *A–A'*, *B–B'*, *C–C'*, and *D–D'* along lower Redwood Creek. River station locations are shown in figure 2.

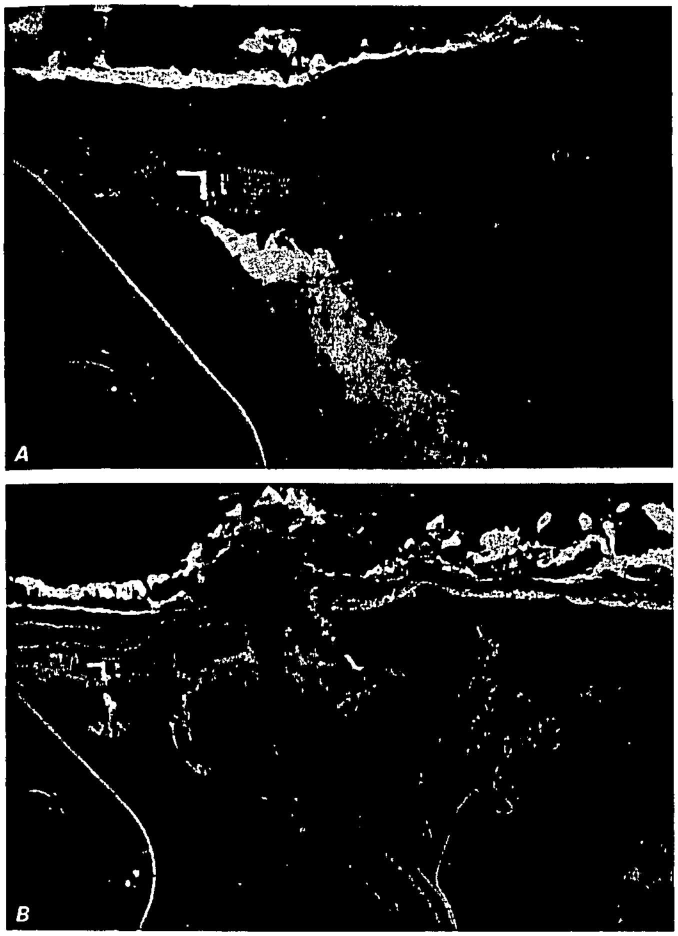

FIGURE 10.—Aerial photographs showing extent of scour of beach berm during major floods. *A*, January 13, 1965, following flood of December 18–24, 1964. *B*, March 7, 1972, following flood of March 1–4, 1972.

dad, no glaucophane-bearing sediment is found as far north as the mouth of Redwood Creek.

The heavy-mineral composition of fine sands at the mouth of Redwood Creek indicates that sediment is being transported from the beach environment into the embayment and the sloughs. The Redwood Creek basin does not contain blue-green hornblende, but at the mouth of Redwood Creek, mean values for blue-green hornblende from the north slough, south slough, and embayment are 23, 24, and 25 percent, respectively, slightly enriched relative to the beaches and extremely high relative to Redwood Creek. Upstream from the mouth of Redwood Creek, as far as the confluence with Prairie Creek (fig. 1), the blue-green hornblende content ranges from 2.2 to 9.0 percent. Prairie Creek contributes a minor amount of blue-green hornblende because it drains Plio-Pleistocene sediments deposited by the ancestral Klamath River (Kelsey, 1982). Upstream from Prairie Creek, sediment of the Redwood Creek channel contains

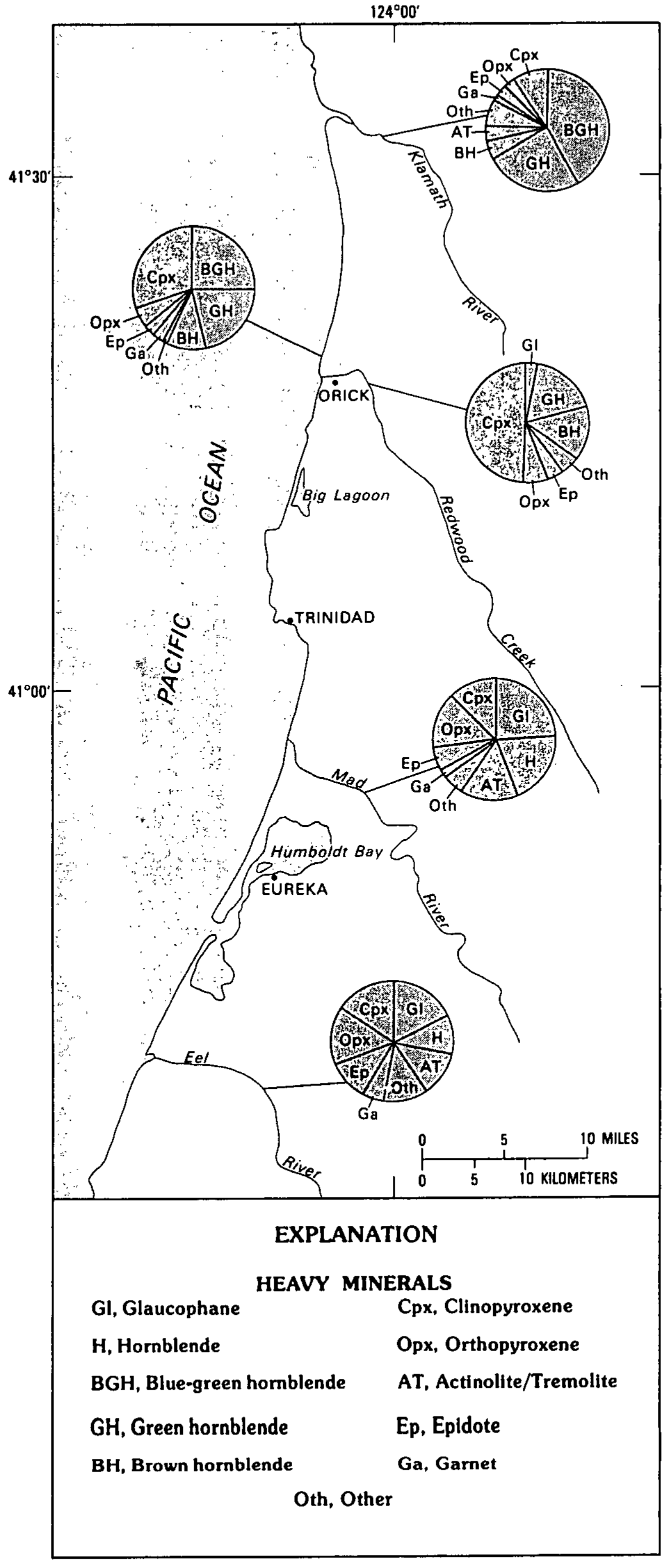

FIGURE 11.—Heavy-mineral analyses of northern California river sands and of the beach sand near the mouth of Redwood Creek. Klamath River data from Kulm and others (1968); Mad and Eel River data from Bodin (1982); and Redwood Creek and beach data from Curt Peterson (written commun., 1982).

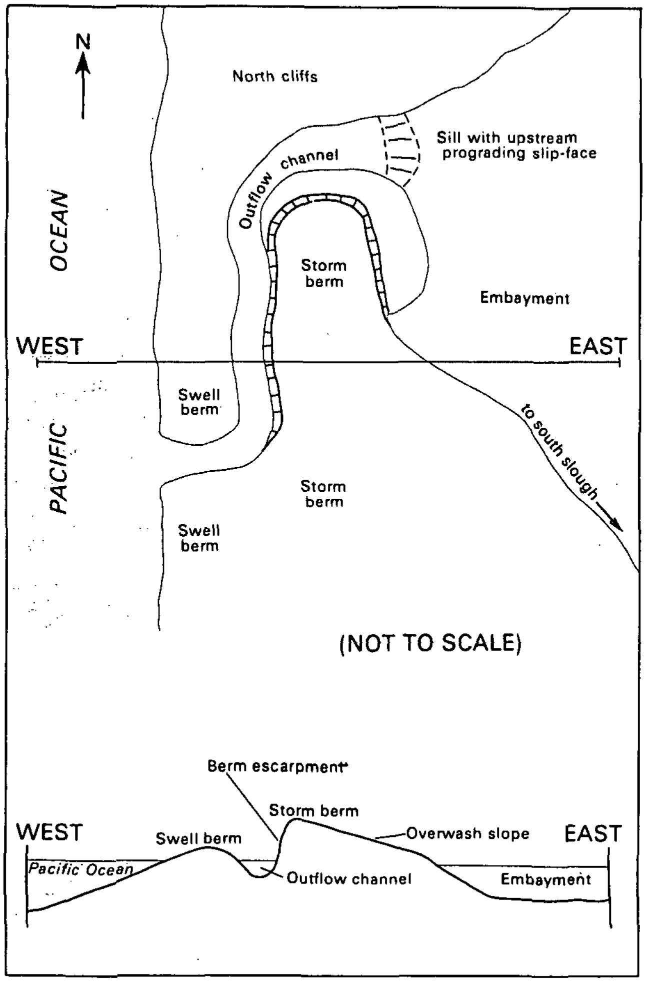

FIGURE 12.—Schematic diagram of typical summer morphological features at the mouth of Redwood Creek.

no blue-green hornblende. Heavy-mineral analyses therefore provide substantial evidence for an important contribution of marine sediment to lowermost Redwood Creek.

Overwash and tidal currents presently deposit most of the sediment in the sloughs and the embayment, with minor contributions from eolian transport and from landslides along sea cliffs. During winter storms in the years after channelization, wave overwash deposited a wide storm berm in the south slough (figs. 7, 8, 12). Overwash deposition rates were calculated for the overwash slope (fig. 12) for the area between mouth profiles *Y–Y′* and *Z–Z′* and between the storm berm crest and the middle of the south slough (figs. 2, 7). During the 1980–81 winter season, 4,200 m^3 of sediment were deposited by overwash. Between 1966, when levee construction began, and 1980, the average rate of overwash deposits was 3,400 m^3/yr. Deposition in the estuary during a winter storm bringing both high tides and high waves would be much greater than volumes cited for 1980 to 1982.

The subaerial deposit south of the north cliffs (fig. 1) is directly exposed to wave attack during storms arriving from the southwest to west-southwest. Sediment and organic debris are mobilized by tidal currents and redistributed in the north slough neck.

The neck of the south slough is protected from direct wave attack by the storm berm (fig. 12). Tidal currents deposited sand waves in the south slough near profile *E–E′* (fig. 2) at least twice from 1980 to 1982. The deposition by tidal currents was most extensive following peak discharges that scoured a wide mouth. Following a peak discharge, tidal currents deposited 63 m^3 of material as sand waves in the neck of the south slough (assuming deposition across an initially flat surface).

Prior to channelization, fluvial sediment probably did not accumulate in the embayment but was periodically flushed from the mouth. Fluvial sediment deposited in the nearshore environment is subject to resuspension and onshore transport during winter storms. Less than 1 percent of the annual sand and gravel load of Redwood Creek is washed back over the storm berm crest into the area between mouth profiles *Y–Y′* and *Z–Z′* (fig. 2).

The proportion of sediment in the beach and nearshore environments contributed by Redwood Creek is difficult to estimate. Intermediate values of blue-green hornblende, clinopyroxene, and brown hornblende in a sample from a beach near the mouth of Redwood Creek indicate mixing of Klamath River and Redwood Creek sources (fig. 11). Diverting streamflow directly to the ocean may have reduced the amount of Redwood Creek sediment in the beach and nearshore environments because the channelized stream may transport sediment beyond the nearshore zone, which is subject to wave resuspension.

SEASONAL PROGRESSION OF THE OUTFLOW CHANNEL

Generally, seasonal changes in the configuration of the outflow channel and in tidal current transport do not contribute to net sediment accumulation in the sloughs and the embayment. However, these seasonal features strongly influence the character of aquatic habitat by determining the distribution of substrate, quality of water, and volume of embayed water.

High discharge during the winter season typically erodes an escarpment in the storm berm and establishes a straight outflow channel (fig. 13*A*). As discharge decreases through the spring months, the straight outflow channel may be modified by incoming high waves and tidal currents. When the outflow channel is straight, diffraction of waves around the berm escarpment deposits a lobe (fig. 13*B*). During late spring and summer, the

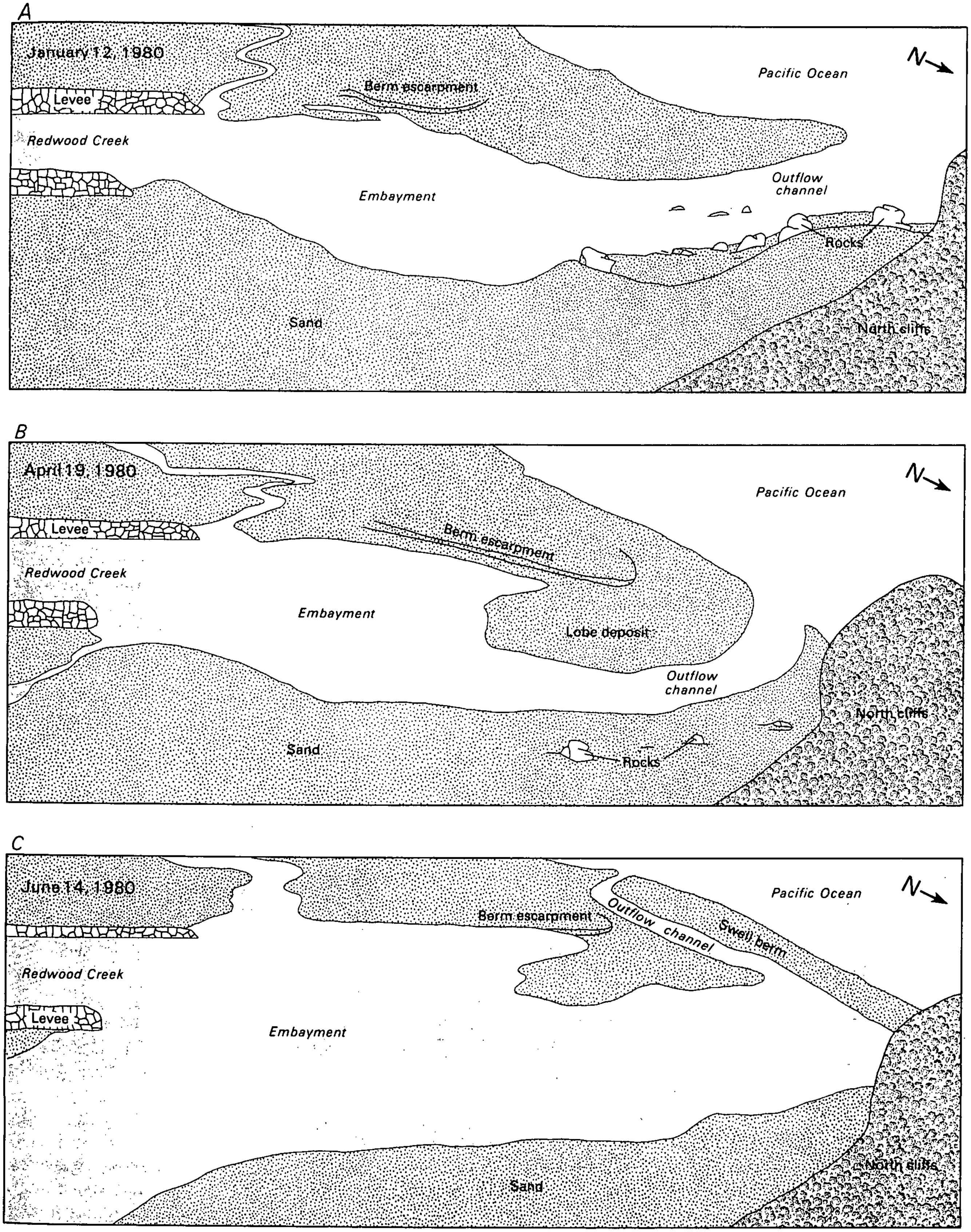

FIGURE 13.—Mouth of Redwood Creek—oblique views from the top of the north cliffs looking to the south.

outflow channel becomes narrower as discharge decreases and tidal currents transport sediment into the mouth. Incoming tidal currents slow upon reaching the wide embayment and deposit a sill at the upstream end of the outflow channel (Jones, 1972).

The sill builds above the low-tide level in the outflow channel and progrades upstream by accretion onto a steep slipface (Boggs and Jones, 1976). Clifton and others (1973) observed that sills alter the timing of the tides relative to the ocean and dampen the effective tidal range in small estuaries along the southern Oregon coast. In the upstream part of the outflow channel of the Sixes River mouth, Boggs and Jones (1976) measured bottom-current velocities that were commonly twice as fast on the floodtide as on the ebb. With the sill present, the highest velocity flood currents developed prior to the high tide in the ocean and moved through the deepest channel of the estuary (Boggs and Jones, 1976). This time-velocity asymmetry between flood and ebb currents is responsible for the net transport of marine sediment into the Sixes River estuary as well as into the Redwood Creek estuary.

The outflow channels of streams like Redwood Creek that have summer discharges ranging from 0.1 to 10 m^3/s commonly migrate alongshore (Clifton and others, 1973). During the period of field observation, the mouth of Redwood Creek migrated south when the discharge was as high as 6 m^3/s. The outflow channel migrates rapidly and episodically when prevailing north-northwest winds and high seas coincide with high tides. Waves deflect streamflow against the shoreward channel bank, eroding the bank while depositing a berm on the seaward side (swell berm on fig 13*C*). The outflow channel is located shoreward of the incipient swell berm and erodes into the storm berm (fig. 12).

When any part of the cross-sectional area of a tidal inlet is below sea level, the mouth is "functionally" open (Rice, 1974; see also Johnson, 1974). The ratio of wave energy to tidal energy per tidal cycle determines whether the mouth will close (O'Brien, 1971). Tidal energy depends on both the amplitude of the tide and the tidal prism. With a large tidal prism, the velocity of the ebb current is sufficient to erode the tidal inlet, preventing functional closure. At the mouth of Redwood Creek, stream discharge increases the velocity of the ebb current in the outflow channel. With decreasing discharge in the spring, a sill may build above sea level, thereby functionally closing the mouth. This process may presently occur more rapidly or earlier in the year than was the case prior to 1968. Due to the increased stream gradient of Redwood Creek from channelization and accumulation of sediment in the sloughs, the tidal prism has decreased by 50 percent below U.S. Army Corps of Engineers station 34+00 (fig. 2). Also, flow duration curves indicate a slight decrease in stream discharge during the summer months due to increased storm runoff (Janda and others, 1975).

As the sill builds above sea level, the effective tidal range is dampened. The velocity of the ebb current decreases, allowing the sill and outflow channel to build higher. The rate of outflow decreases, causing expansion of the water volume in the embayment because stream discharge is greater than the combined rates of outflow, seepage, and evaporation. Seepage rates through the sill and berm from the embayment to the ocean depend on the relative water levels, grain size, sorting, and area of the embayment in contact with the sill and berm (Clifton and others, 1973). Prior to deposition of the wide storm berm, water could seep along a steeper gradient through the swell berm from the embayment to the ocean (fig. 3). Presently, seepage is probably concentrated along a small part of the berm that is scoured during high discharge. Lower rates of seepage that result from the effects of channelization also could contribute to more rapid or earlier expansion of the embayment.

From 1980 to 1982, the natural sequence of longshore migration, functional closure, and total closure of the outflow channel was frequently interrupted by man-induced breaching of the berm. However, the outflow channel invariably closed completely as early as mid-July. Waves washing over the swell berm filled the migrated outflow channel in 1980 and 1982 and the straight perpendicular channel in 1981.

The configuration of the outflow channel determines both the degree of saltwater intrusion and the texture and distribution of sediments transported by flood tidal currents. Boggs and Jones (1976) show that flood currents do not dissipate as rapidly through a straight outflow channel as through a channel that has migrated alongshore. Through the straight outflow channel, sediment is transported farther up the estuary. Thus, breaching of longshore migration of the outflow channel, or lack of such migration, causes reworking of the embayment substrate. This reworking may be detrimental to benthic invertebrates.

CIRCULATION AND AQUATIC HABITAT

The immediate effects of channelization, as well as net accumulation of sediment over the last 30 years, have drastically changed circulation, water quality, substrate distribution, and the volume of aquatic habitat at the mouth of Redwood Creek.

Riparian vegetation, which supplies nutrients and streamside protection for fish and reduces water temperatures, was removed during levee construction. The pool-and-riffle structure that was destroyed during excavation of the trapezoidal channel has since reestablished itself. However, in the interest of flood control, the U.S. Army Corps of Engineers requires Humboldt County to periodically remove willows and other riparian species invading gravel bars between the levees. Since the high-gradient channel was constructed in 1968, the stream gradient in the lower reach has declined, although not to its former level. The stream gradient and lack of roughness result in higher mean velocities and more frequent mobilization of bed material. Seasonal colonization by benthic invertebrates and the species diversity among the invertebrates may still be affected by the instability of the substrate.

Circulation through the north and south sloughs is now more restricted because of overwash and tidal current deposition in the slough necks. During most of the year, the sloughs are isolated from the embayment. The embayment and sloughs may become connected during high stream discharge, during periods of high waves, floodtides, or when the outflow channel is functionally closed. Discharge from Sand Cache and Strawberry Creeks through the north and south sloughs is tidally dependent (fig. 1). When backwater develops, the sloughs function as ebb-flow channels, remaining stagnant until the floodtide and (or) high discharge recede.

Circulation from Sand Cache Creek into the north slough is further restricted at a road crossing. In the north slough, a chemocline 1.5 to 2.0 m below the water surface persists throughout the year (R. Gregory and J. Yuska, unpub. data, 1981). The bottom consists of mud, fine organic debris, and abundant pieces of woody debris. Floating woody debris covered most of the north slough until recently when the debris were removed after they floated onto adjacent pastures; at that time, a log boom was installed. Although woody debris accumulated in the north slough prior to channelization, larger deposits of debris may now be stored without being flushed from the slough during periods of high stream discharge. Except at the surface, the north slough is anoxic due to restricted circulation, decomposition of organic debris, and, until recently, floating debris that inhibited light penetration and macrophyte establishment (Gregory, 1982).

Unrestricted flow from Strawberry Creek, and the lower elevations at the slough neck, provides better circulation through the south slough than through the north slough. Winter flows from Strawberry Creek flush saltwater from the south slough. In the spring, when the south slough is isolated from Redwood Creek, oxygen concentrations decrease and temperatures increase. Macrophyte production during the summer generally increases the dissolved oxygen concentrations (Gregory, 1982).

Although there is no permanent saline layer in the embayment, when saltwater intrudes, it generally forms a stratified, salt-wedge estuary. During November 1980, saltwater was detected in the main channel of Redwood Creek 1.5 km upstream from the mouth (Gregory, 1982). The well-defined saltwater wedge intruded against a 2.8-m^3/s discharge on a 2.0-m tide with 5.9-m waves (Seymour and others, 1980). These waves caused mixing above and slightly below the north slough halocline and pushed woody debris and saltwater into the south slough as far as Strawberry Creek (Gregory, 1982). Later in the month, 3.3-m waves on a 2.3-m tide entered the mouth against a 1.2-m^3/s discharge and again carried saltwater 1.5 km upstream.

Saltwater intrusion into the embayment and sloughs occurs most frequently during high tides in the late spring and early summer months before the outflow channel becomes functionally closed. After the tide recedes, saltwater is left in small pockets that are much shallower than the 3- to 4.5-m depressions found at the Sixes River estuary (Boggs and Jones, 1976). As the outflow channel becomes functionally closed, tidal action is dampened, and stratification of the water column breaks down, as observed by Boggs and Jones (1976).

Unless the outflow channel functionally closes early in the summer, allowing the embayment to expand, the volume of aquatic habitat will be extremely limited. Due to sediment accumulation following channelization, the embayment fills more rapidly, and water rises over adjacent pastures more frequently than in the past. In January 1981, water was backed up by a berm 3.6 m above sea level, the highest backwater in the memory of local landowners. The encroachment of rushes (*Juncus* spp.) in pastures and of dead spruce adjacent to the north slough are signs of more frequent inundation.

Historically, the mouth of Redwood Creek has been breached by man almost every year for two purposes. First, eager fishermen open the mouth late in the season to provide access to the creek for upmigrating anadromous fish. This practice is now regulated by the California Department of Fish and Game due to incidents of illegal fishing methods and the lack of suitable spawning habitat upstream prior to the first winter rains. Second, the berm is breached to drain flooded pastures and, more recently, to prevent woody debris from floating into the fields. The trench through the berm is dug by shovel immediately following high tide. Water flows at a steep gradient through the new outflow channel during ebbtide and results in considerable lowering of the embayment water level. This type of catastrophic breach lowered the water level by 2.0 m in July 1980, isolating both sloughs and reducing by 75 percent the available aquatic habitat for 20,000 juvenile salmonids.

Following a breach, a partially mixed estuary may develop when saltwater intrudes against lower summer discharge. Breaching also changes the embayment substrate through erosion of mud layers and deposition of sand by tidal currents. Nutrients washed from adjacent pastures during a breach produce a heavy respiration demand for oxygen in the sloughs (Gregory, 1982).

Changes in substrate and water quality caused by the timing of embayment expansion and breaching influence the distribution and abundance of the dominant benthic invertebrate *Corophium* (Larson and others, 1981, 1982). The *Corophium* population and the volume of aquatic habitat also affect utilization of the embayment rearing habitat by juvenile steelhead trout (*Salmo gairdneri*) and chinook salmon (*Oncorhynchun tshawytsch*) (Larson and others, 1981, 1982) during the critical period of spring through the early fall months.

DISCUSSION AND CONCLUSIONS

Sites of sediment accumulation at the mouth of Redwood Creek have become more extensive since the early 1950's. Although an increase in the quantity of sediment transported from the drainage basin resulted in channel aggradation along the lower reach, the distribution of erosional and depositional sites at the mouth was altered more drastically by the effects of the channelization of Redwood Creek that took place from 1966 to 1968.

Channel widening, aggradation, and extensive overbank deposition along the lower flood plain resulted from floods in 1953, 1955, and 1964. Bank erosion associated with these major floods was not unusual along the last downstream meander. Prior to channelization, the last downstream meander migrated laterally southward from 1936 to 1967 at a rate of 2.1 m/yr. Considering the naturally high sediment load of Redwood Creek, this short-term migration rate reflects a relatively stable meander configuration.

Between 1936 and 1967, sediment accreted in the embayment mainly between the middle and north sloughs. Most of the material was deposited during the slow recession of the 1964 flood. Fluvial sediment deposited in the nearshore zone during the 1964 flood may have been transported onshore, accumulating in the embayment. During major floods, scour occurred in overflow channels and at the mouth, where the beach berm was eroded from the north cliffs south nearly to the California-Pacific Mill (fig. 10*A*).

After high flows were confined by the levees, only a limited part of the beach berm was scoured, and a high storm berm developed to the south. Since channelization, 50 percent of the lower estuary (between 0 and 1.2 m above sea level) has become filled with sediment or isolated from the embayment. The total sediment load of Redwood Creek is composed of 69 to 86 percent sand and gravel. However, during high to moderate streamflow, most of the sand and some gravel are flushed out of the mouth, leaving gravel in the channel. Presently, overwash and tidal current transport are the dominant processes of deposition in the embayment and sloughs.

Analyses of heavy minerals in fluvial and beach sands verify the presence of marine sediment in the embayment and sloughs. Blue-green hornblende, abundant in the Klamath River, is found along beaches at least as far south as Freshwater Lagoon (fig. 1). In the embayment, tidal currents deposit sands containing 20 to 31 percent blue-green hornblende on top of coarser stream sediment containing trace amounts of blue-green hornblende.

Overwash during periods of high waves and high tides builds the storm berm. Flood tidal currents deposit sediment in supratidal areas under similar conditions, particularly when discharge is low and the mouth is wide from recent scour during high discharge. As the berm builds and the sloughs fill, the rates of sediment deposition by overwash and tidal currents decrease. Overwash and tidal current deposition recorded during the study period probably represents a typical winter. During a winter storm with record waves and tides following a record stream discharge, deposition in the estuary would be much greater than volumes cited for water years 1980 to 1982.

The water volume subject to tidal fluctuations (tidal prism) has decreased due to sediment deposition in the necks of the sloughs and the steep stream gradient constructed during channelization. Freshwater and potential estuarine habitats are shallow, and circulation between the embayment and sloughs is restricted. With a smaller tidal prism, the outflow channel functionally closes earlier in the season, and the embayment fills more rapidly, allowing water to rise over adjacent pastures. To drain the pastures, local landowners historically have breached the beach berm, thereby reducing the volume of available aquatic habitat by as much as 75 percent. Thus, channelization has directly and indirectly altered the distribution of sediment and the quantity and quality of aquatic habitat at the mouth of Redwood Creek.

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