# Flood History and Sedimentation at the Mouth of Redwood Creek, Humboldt County, California

by

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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, landsliding, and channel geometry changes along Redwood Creek. The increased sediment load resulted in channel aggradation and widening along the lower floodplain. Flood control levees constructed from 1966 to 1968 channelized the lower reach of Redwood Creek and extended beyond the last downstream meander. The distribution of erosional and depositional sites at the mouth has been more drastically altered by the effects of channelization than of aggradation.

Channelization was accompanied by removal of bed roughness elements, shaping a trapezoidal channel with an increased hydraulic radius, and steepening the channel gradient. This caused an increase in the mean velocity and frequency of mobilization of the substrate 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, 47-54 percent of the lower estuary (between 0 and 4 feet above MSL) has filled with sediment or become isolated from the embayment.

Sediment yield of Redwood Creek is among the highest for a basin of its size in North America, but under present conditions fluvial

Pg missing

ACKNOWLEDGEMENTS

When Redwood National Park became concerned about declining productivity at the mouth of Redwood Creek, interdisciplinary studies were initiated by Joe Yuska, Fisheries and Wildlife Department, Oregon State University. Valuable data from early storms would not have been collected without Joe's energy and enthusiasm in the field. Through the initial stages of the project, Dick Janda, U.S. Geological Survey; Fred Swanson and Curt Peterson, Oregon State University, provided discussions and guidance.

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Additional field observations and water quality data were provided by Russ Gregory, Humboldt State University. Flood and fishing history along Redwood Creek was documented with the help of Randy Feranna, Savina Barlow and Thelma Hufford. The residents of Orick warmly shared their past experiences and photographs.

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## INTRODUCTION

Sediment which has accumulated at the mouth of Redwood Creek in recent years has drastically reduced the volume of aquatic habitat. Increasing concern about the productivity of this habitat prompted the administrators of Redwood National Park to initiate interdisciplinary studies at the mouth of Redwood Creek. The objective of this phase of the project has been to identify the processes, sources and rates of sediment accumulation in order to recommend rehabilitation alternatives.

Coastal river mouths are historically and seasonally very dynamic. Nearshore and beach sediments shift in response to wind, wave, and tidal energy expended along the coastline. Marine processes interact with fluvial processes and both are highly variable. In northern California, climatic, tectonic and lithologic factors result in suspended sediment yields among the highest in North America for drainage basins of comparable size (Table 1). Large volumes of sediment supplied to northern California river mouths are subject to extreme seasonal variations in runoff and wave energy.

Redwood Creek drains a long, narrow basin with an area of 720 $km^2$ (280 $mi^2$) (Figure 1). It is one of several rivers oriented along north-northwest trending fault zones which have steep gradients due to rapid erosion in the region. The mouth of Redwood Creek is located 4.0 river kilometers (2.5 mi) west of Orick, California (Figures 1 and 2). Downstream from its confluence with Prairie Creek (Figure 2), Redwood Creek flows westerly through a widening valley to the ocean.

The mouth is sheltered on the north side by an unnamed point and several sea stacks. Presently, the mouth consists of the main channel of Redwood Creek, the north and south sloughs, and an embayment. The embayment is the relatively deep, broad part of a tidal inlet landward from the beach.

Figure 1: Northern California Location Map

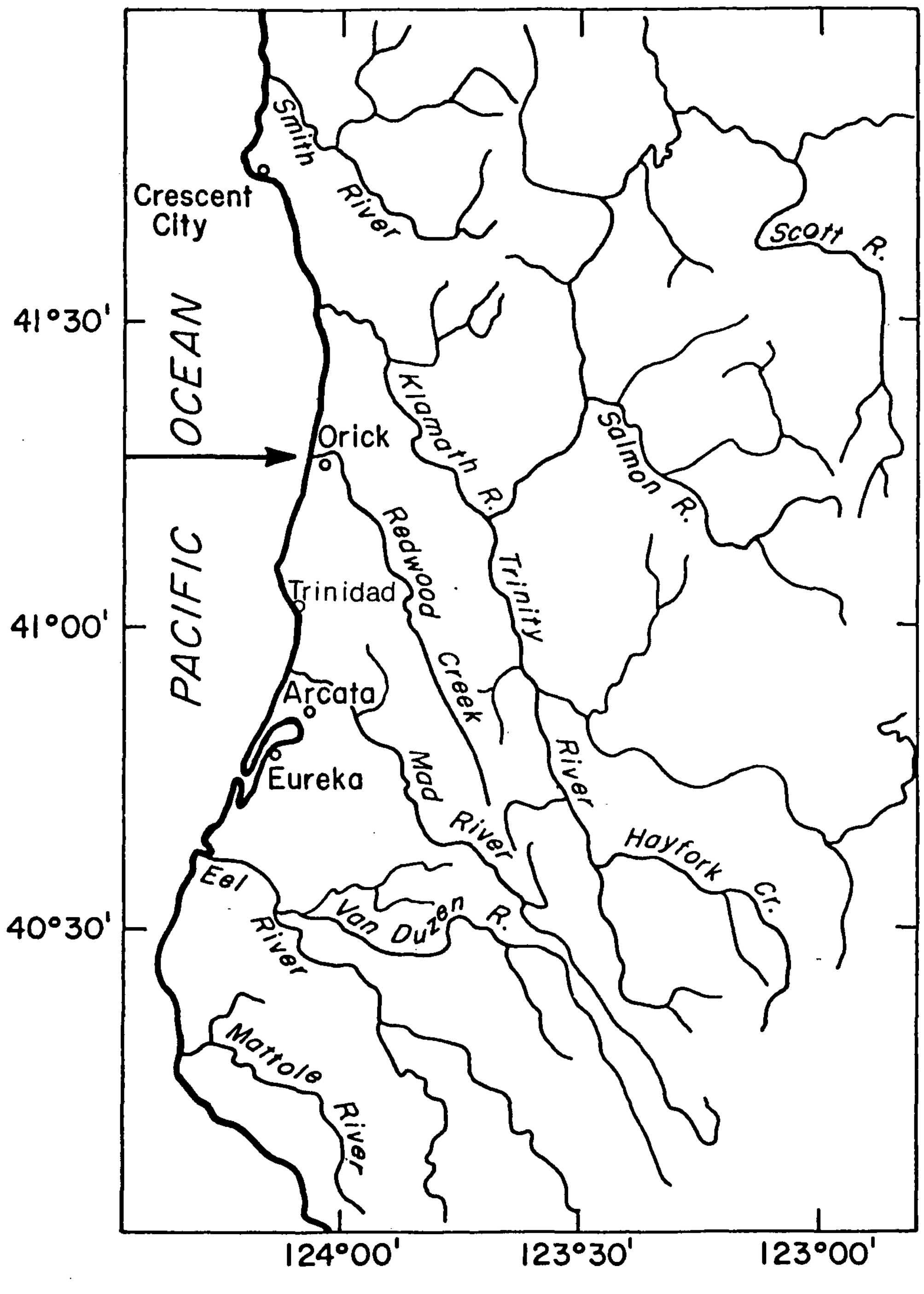


Figure 2: Topographic Map, Mouth of Redwood Creek (U.S. Geological Survey, 1966). Levees constructed from 1966 to 1968 ———

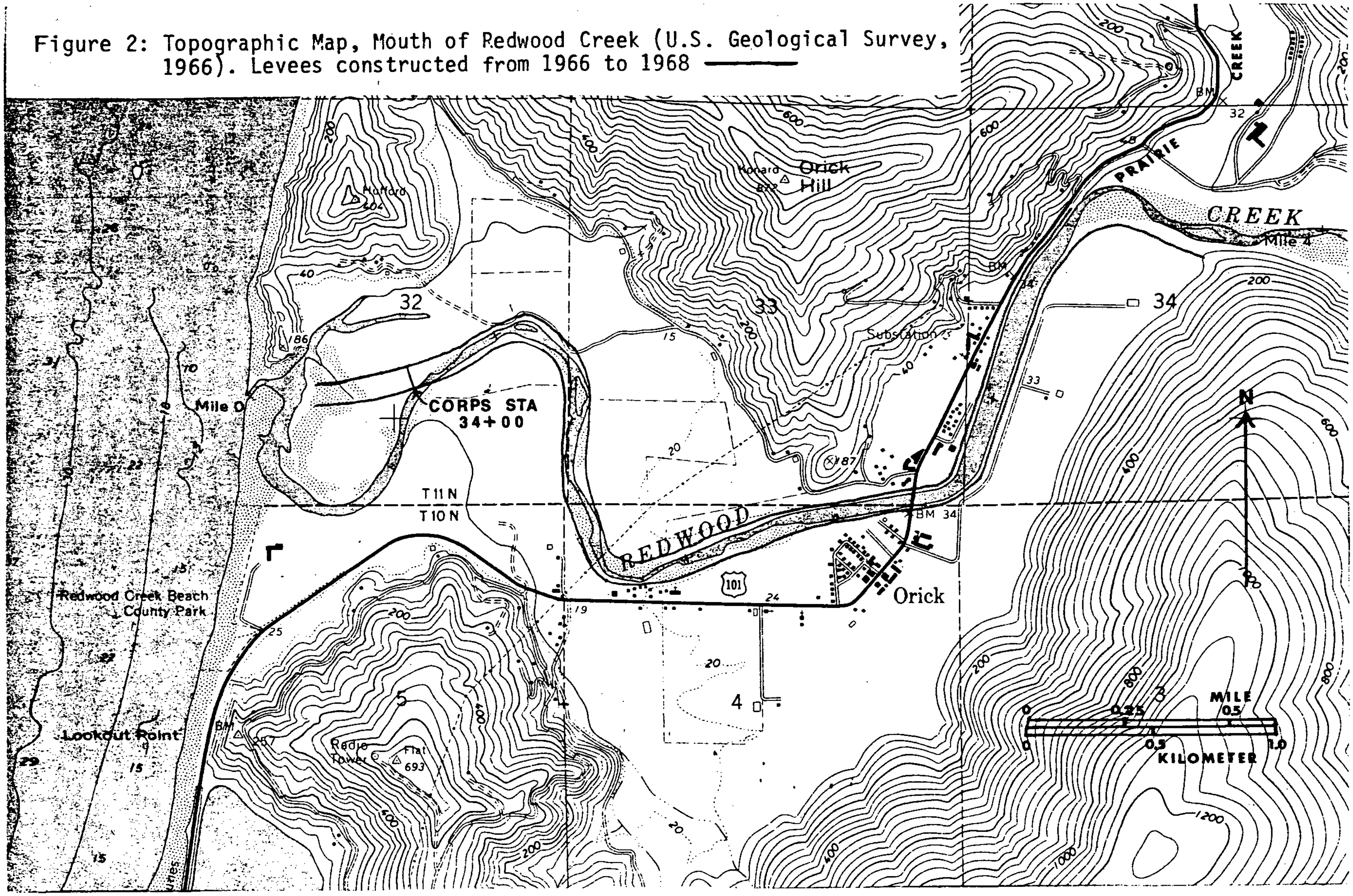


TABLE 1: Suspended Sediment Yield for Northern California and Other North American Rivers. Northern California Rivers Ranked by Average Annual Sediment Load (data from Janda and Nolan, 1979, Table 1; Griggs and Hein, 1980, Table 1; other North American rivers data from Holeman, 1968).

| STREAM/STATION | DRAINAGE AREA ($KM^2$) | PERIOD OF RECORD (WATER YEARS) | AVERAGE ANNUAL SEDIMENT YIELD TONNES/$KM^2$/YR |
|---|---|---|---|
| Eel River @ Scotia | 8,063 | 1958 - 1977 | 2,760 |
| Van Duzen River near Bridgeville (Tributary of Eel River) | 575 | 1956 - 1967<br>1975 | 3,000 |
| | 8,638 | | 2,776 |
| Klamath River @ Orleans | 21,950 | 1968 - 1977 | 162 |
| Trinity River @ Hoopa (Tributary of Klamath River) | 7,389 | 1957 - 1977 | 630 |
| | 29,339 | | 280 |
| Mad River @ Arcata | 1,256 | 1958 - 1974 | 2,000 |
| Sacramento River @ Sacramento | 60,943 | 1957 - 1969 | 40 |
| Russian River near Guerneville | 3,465 | 1965 - 1977 | 676 |
| Redwood Creek @ Orick[1] | 720 | 1971 - 1977 | 2,250 |
| Mattole River near Petrolia[2] | 622 | 1967 | 5,730 |

[1] Janda (1978, p. 3) reports that Redwood Creek at Orick transported 2,620 tonnes/$km^2$ (7,480 T/$mi^2$) during WY 1971-1976. This is 32 percent more than was transported past Eel River at Scotia for the same period. The suspended sediment discharge for Redwood Creek was increased by major storms which were more intense in the north during the period of concurrent record (Janda and Nolan, 1979, p. IV-11; Harden and others, 1978).

[2] Griggs and Hein (1980, Table 1) estimated sediment yield for the Mattole River near Petrolia by using values from gauged streams in the vicinity, sediment plumes on LANDSAT imagery and considering basin geology and relief. The estimated yield, 2,500 tonnes/$km^2$/yr, is less than half of the value measured for WY 1967. However, based on other nearby gauging stations, Janda and Nolan (1979, p. IV-11) indicated that WY 1967 did not have any unusually large storms and exceptionally high sediment yields could be expected from the Mattole River basin.

TABLE 1: (continued)

| STREAM/STATION | AREA(KM²) DRAINAGE | PERIOD OF RECORD (WATER YEARS) | AVERAGE ANNUAL SEDIMENT YIELD TONNES/KM²/YR |
|---|---|---|---|
| Colorado | 356,900 | 1926 - 1957 | 380 |
| Mississippi | 3,222,000 | 1952 - 1965 | 97 |
| Columbia | 265,700 | 1950 - 1952 | 35 |
| Saskatchewan | 323,900 | 1954 - 1960<br>1962 - 1964 | 13 |
| Rio San Juan | 31,080 | 1934 - 1941 | 156 |
| Average, North America | | | 86 |

The steep stream gradient along lower Redwood Creek limits the upstream extent of saltwater intrusion and tidal fluctuations. As strictly defined, it may be argued that the term "estuary" is inappropriate for the mouth of Redwood Creek. In terms of the classical drowned river valley or coastal plain estuary, the Redwood Creek Valley is almost completely filled. Sediment transported during floods is deposited across the lower Redwood Creek Valley floodplain and forms a submarine fan offshore. Pritchard (1967, p.3) defines an estuary as a "semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." Throughout much of the year, high freshwater discharge or the presence of a sill across the mouth of Redwood Creek prevents the entry of sea water. Also, displacement of the tidal prism by sediment accumulation has decreased the potential for saltwater intrusion.

Prior to recent changes in sedimentation patterns, the mouth of Redwood Creek functioned like other small estuarine systems in northern California and southern Oregon, such as the Sixes River mouth (Jones, 1972; Reimers, 1973; Boggs and Jones, 1976). Sediment trapped in the estuary during summer conditions of low streamflow was flushed during periods of high discharge.

Increased sediment input from the basin and artificial channelization of lower Redwood Creek have evidently changed the distribution of sediment at the mouth over the last 30 years. The texture and quantity of sediment delivered to the mouth have been altered by land use and floods in the basin. Floods in 1953, 1955 and 1964 prompted the U.S. Army Corps of Engineers to channelize Redwood Creek in the vicinity of Orick (Figure 2). The lowermost section of the levee extends beyond the last downstream meander and diverts the flow directly to the ocean.

Understanding the relative contributions of these two causes of long-term sediment accumulation is crucial for management and rehabilitation efforts. When proposing to alter segments of the levee to restore circulation in backwater areas, the potential effects of aggradation should be considered. Also, movement of anomalously large quantities of sediment stored in Redwood Creek basin is relevant to the timing of plans for such levee alterations. The feasibility of dredging alternatives may be assessed, based on locations and rates of sedimentation in the estuary.

In order to obtain a perspective on the magnitude of annual and seasonal sedimentation, the history of flooding is presented in the first half of the thesis. Techniques used to evaluate sedimentation processes, sources and rates are discussed in each of the Methods sections under Flood History and Sediment Sources and Transport Processes. Reviews of pertinent literature and the results and discussion have been organized by time scale, from long-term geologic setting to short-term changes in circulation and aquatic habitat.

# GEOLOGIC SETTING

## Regional Geology

In northern California (Figure 3), Upper Jurassic to Upper Cretaceous metasedimentary and metavolcanic rocks of the Franciscan assemblage are thrust beneath the Klamath Mountains geologic province (Irwin, 1966; Davis, 1966). The Klamath Mountains province consists of Paleozoic to Upper Jurassic ophiolites, metasedimentary and metavolcanic rocks and melange, intruded by plutons primarily of Late Jurassic age (Irwin, 1966; Davis, 1966). These rocks occur in a series of eastward dipping thrust sheets, all regionally metamorphosed to at least the greenschist facies. Schists of the Central Metamorphic belt (CM) were metamorphosed to the upper greenschist and alamandine-amphibolite facies (Davis, 1966, p. 41).

On the western boundary of the Klamath Mountains province, the Western Jurrassic belt is underthrust by the Franciscan assemblage along the South Fork fault (Davis, 1966; Harden and others, 1982) (see Figure 4).

The Franciscan assemblage occurs in north-northwest trending belts which differ in degree of metamorphism, shearing, and tectonic mixing (Janda, 1979, p. II-7). The assemblage consists of unbroken, coherent units; broken formations lacking exotic tectonic blocks; and melange (Jones and others, 1978). Blake, Irwin, and Coleman (1967) classify the degree of metamorphism of these units based on fabric and mineralogy. Sandstones and mudstones of their texture zone 1 are but slightly recrystallized and appear unmetamorphosed while texture zone 3 metasediments are fully segregated quartz-mica-feldspar and quartz-mica schists.

## Geology of Redwood Creek Drainage Basin

Franciscan units on the east and west sides of the Redwood Creek drainage basin (Figure 4) are separated by the Grogan fault along a wide zone of brecciation (Kelsey, Weaver, and Madej, 1979, p. XIII-9). A texture zone 1 sandstone and mudstone unit on the

Figure 3: Regional Geologic Map.

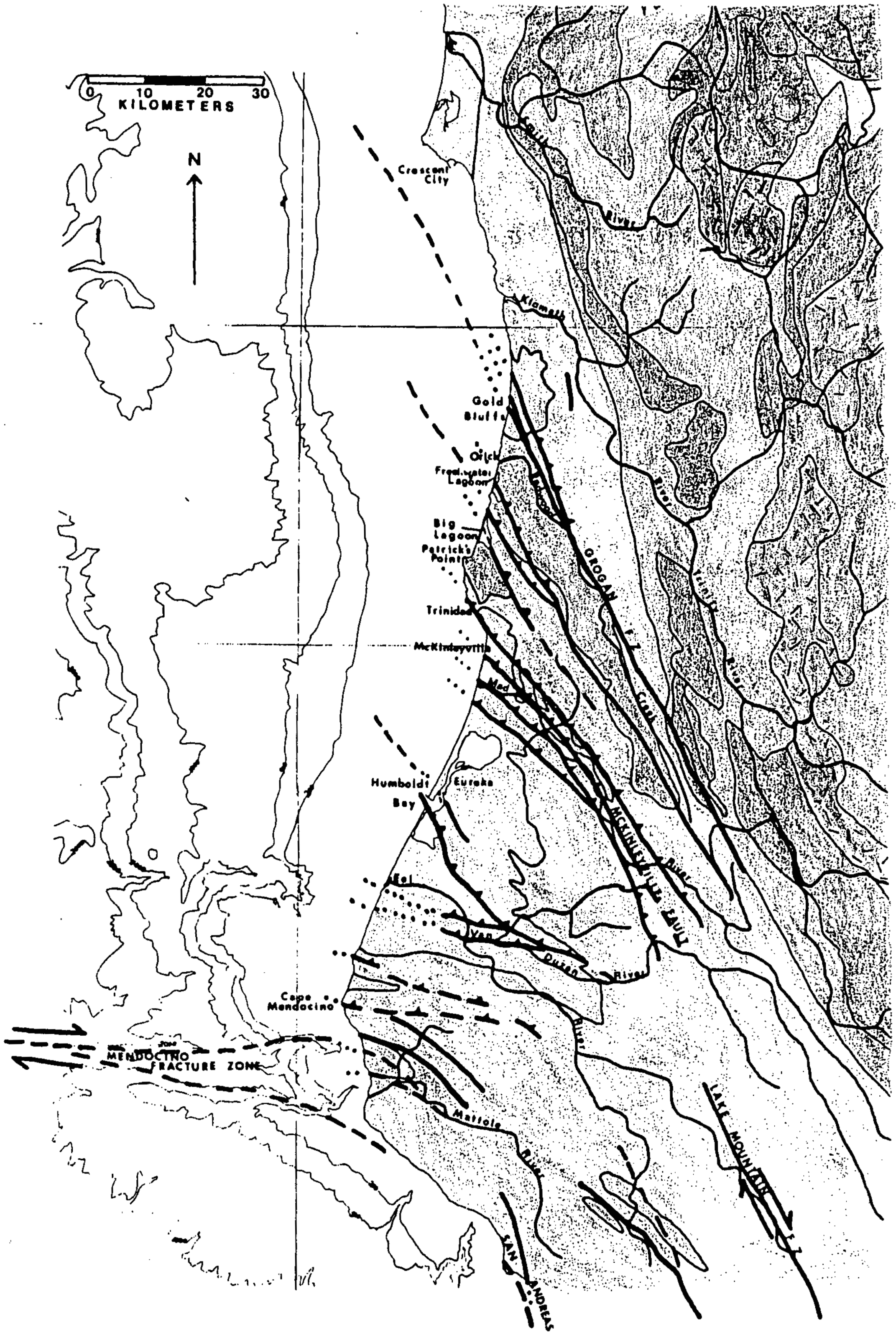


Figure 3: Regional Geologic Map
Bathymetry from U.S. Department of Commerce, 1969
Geology modified from Irwin, 1966, p.22
Quaternary faults from Carver, Stephens, and Young, 1982

EXPLANATION

| | |
|---|---|
| QT | Cenozoic deposits |
| JCR | Late Jurassic (Tithonian) to Late Cretaceous rocks |
| Ju | Western Jurassic belt |
| PT | Western Paleozoic and Triassic belt |
| CM | Central Metamorphic belt |
| EK | Eastern Klamath belt |
| gr | Granitic rocks |
| um | Ultramafic rocks |

Figure 4: Geologic Map of Redwood Creek Drainage Basin and Vicinity (from Harden, Kelsey, Morrison, and Stephens, 1982; and Kelsey, 1982).

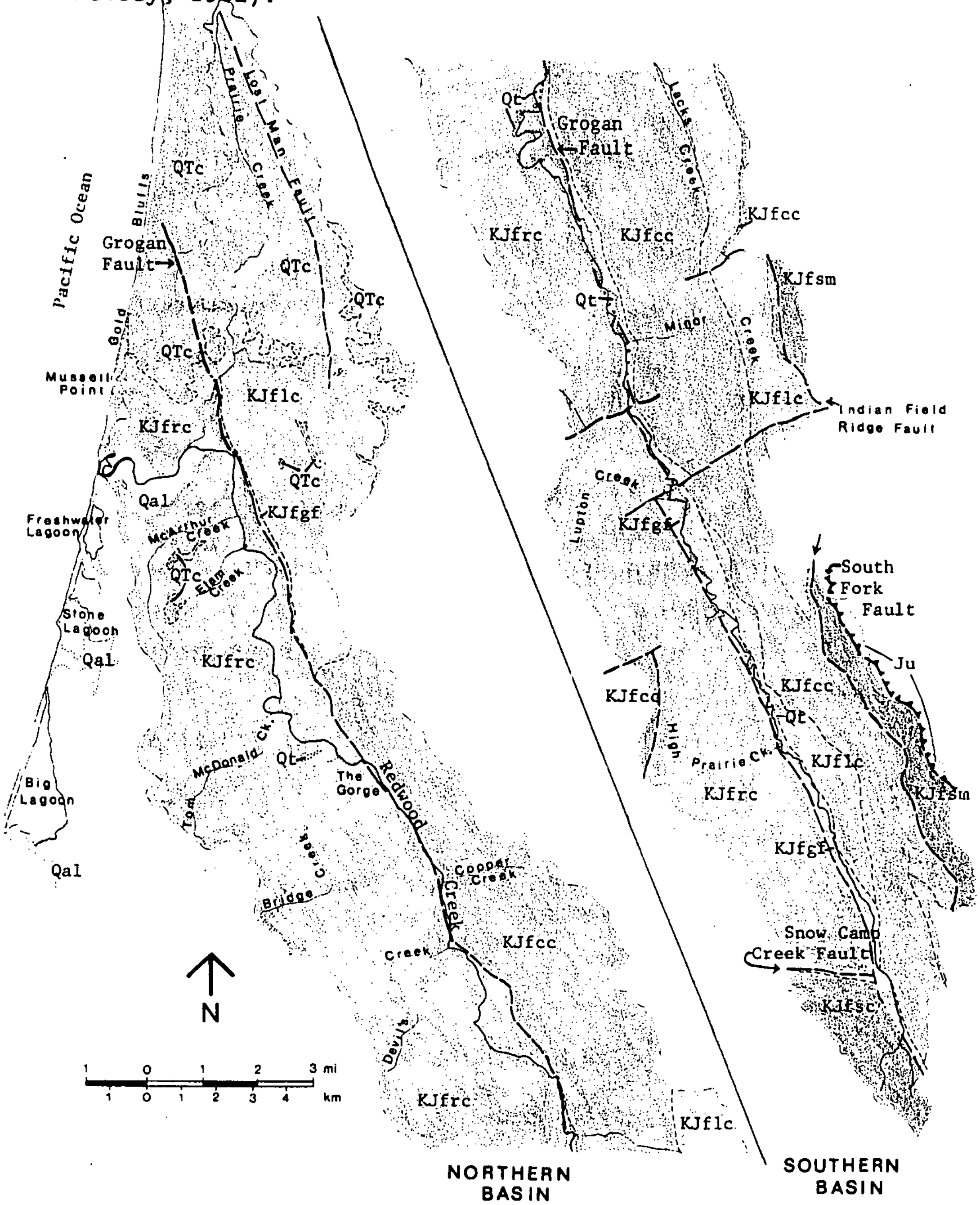


Figure 4: Geologic Map of Redwood Creek Drainage Basin and Vicinity (from Harden, Kelsey, Morrison, and Stephens, 1982; and Kelsey, 1982)(continued)

EXPLANATION

| | |
|---|---|
| Qal | Modern Alluvium and Beach Deposits |
| Qt | Stream Terrace Deposits |
| QTc | Coastal Plain Sediments (informally designated Prairie Creek Group) |
| --------- | unconformity |
| | Sandstones and Mudstones |
| KJflc | Coherent Unit of Lacks Creek |
| KJfcc | Incoherent Unit of Coyote Creek |
| | Schists |
| KJfrc | Schist of Redwood Creek |
| KJfsm | South Fork Mountain Schist |
| KJfgf | Metamorphosed Sandstones and Mudstones of the Grogan Fault Zone |
| KJfsc | Sandstone and Melange Unit of Snow Camp Mountain |

Symbols

- Divide of Redwood Creek Drainage Basin
- Redwood Creek
- Tributaries
- Faults, dotted beneath Qal and Qt
- Thrust Faults, barbs on upper plate
- Contacts, dotted beneath Qal and Qt
- Stream Terrace Deposits (Qt)
- Modern Alluvium (Qal) and Beach Deposits

east side is subdivided into coherent (KJflc) and incoherent (KJfcc) subunits (Harden and others, 1982). These subunits consist of lithic and quartzofeldspathic graywackes which resemble the sandstones of the central belt Franciscan described by Blake and Jones (1978). The incoherent subunit (KJfcc) contains fewer massive sandstone beds, a lower sandstone to mudstone ratio, and is more brecciated than the coherent subunit (KJflc) (Harden and others, 1982). The incoherent subunit also includes tectonic blocks of greenstone and chert (Harden and others, 1982).

The schist of Redwood Creek (KJfrc) underlies the west side of the drainage basin and is lithologically and texturally similar to the South Fork Mountain Schist (KJfsm) (Blake, Irwin, and Coleman, 1967; Harden and others, 1982). Both schists consist of metamorphosed mudstones with a quartz-albite-white mica-chlorite assemblage, and sandstones metamorphosed to quartzofeldspathic schists. Greenstones and meta-tuffs with quartz-albite-chlorite-epidote-actinolite assemblages also occur in the schist of Redwood Creek (Harden and others, 1982). The schist of Redwood Creek exposed in the sea stacks and cliffs at the mouth of Redwood Creek consists of dark gray fine-grained carbonaceous schist with abundant quartz veins and light green chloritic schist (S. Cashman, oral communication, 1982).

## Quaternary Geology

North-northwest trending thrust faults separate the Franciscan assemblage belts and commonly control the trend of ridges and valleys in northern California. The history of movement along these north-northwest trending faults, including the Grogan fault, is unclear. As the Mendocino Triple Junction migrated northward in late Tertiary time, stresses exerted by the northward-moving Pacific Plate may have reactivated strike-slip motion along these older thrust faults (Janda, 1979, p. II-4).

Herd (1978) postulates that right-lateral displacement along the San Andreas fault continues northward along a right-stepping en echelon fault system which includes the Maacama, Lake Mountain, and McKinleyville fault zones (Figure 3). According to Herd (1978), these fault zones define define the eastern boundary of a narrow "Humboldt Plate" which is being underthrusted by the Gorda Plate beneath the continential margin. However, recent explorations of late Pleistocene terraces in the Trinidad area show predominately dip-slip motion on northwest trending, northeast dipping reverse and thrust faults of the McKinleyville - Mad River fault zone (Carver, Stephens, and Young, 1982; Coppersmith and others, 1982).

Localized uplift and subsidence creates problems with interpreting deformation rates of dated marine terraces. Generally, deformation is more pronounced in higher terraces, indicating continuous deformation throughout the later Pleistocene (Wahrhaftig and Birman, 1965). Uplift rates of 2.5 meters/1000 years at Cape Mendocino (Figure 3) and 4.0 meters/1000 years at Spanish Flat (about 25 kilometers southeast of Cape Mendocino), are the highest rates reported for the region (Lajoie and others, 1982; Sarna-Wojcicki and others, 1982).

Between Trinidad and Patrick's Point (Figure 3), a well-preserved sequence of five marine terraces rise to an elevation of 244 meters (1,130 feet) (Stephens, 1982). Based on elevations of dated terraces developed on non-tectonic coastlines, comparisons of soil profile development, and paleomagnetic data, these terraces were probably uplifted at a rate of 1.2 meters/1000 years during Quaternary time (Page, Packer and Stephens, 1982). Tilting of the youngest terrace below sea level at Big Lagoon may be associated with downwarping on the lower plate of the Big Lagoon fault (Stephens, 1982).

Eustatic changes in sea level due to continential deglaciation as well as tectonic movements in the Holocene have influenced the present shoreline configuration. The most rapid phase of deglaciation, from 10,000-7,000 years B.P. (before present) was accompanied by a worldwide sea level rise of 8-10 millimeters/year (Komar, 1976, p. 155; Bloom, 1978, p. 407). Littoral deposits developed as the rate of rise slowed to 1.4 millimeters/year from 7,000-4,000 years B.P. (Komar, 1976, p. 155). The sea reached its present level about 4,000-2,000 years ago, although tide gauge records in "stable areas" show a eustatic rise in sea level of 1.2 millimeters/year over the past 50 years, with even higher rates recently (Komar, 1976, p. 156 c.f. Marmer, 1952). Sea level dropped between 1800 and 1850, followed by a climatic warming trend since 1850 (Komar, 1976, p. 157).

Recent submergence between Big Lagoon and Orick (Figure 4) is evident from lagoons and alluviated coastal valleys (Janda and others, 1975, p. 21). Geomorphic evidence at the mouth of Redwood Creek suggests tectonic emergence rather than submergence. The small size of the Redwood Creek estuary and limited tidal influence argue against downwarping at the mouth. Prior to levee construction, the channel appeared to be at grade, with a historically stable meander configuration. Dendrochronological data presented in the next section provide other evidence of relative channel stability for the past 98 years.

Recent aggradation of Redwood Creek is probably a normal phase in the evolution of a tectonically emergent basin as described by Bloom (1978, p. 247). However, it seems that aggradation, triggered by intense storms, has been compounded by severe ground disruption in the basin. Relations among land-use changes, flood magnitude and frequency, channel aggradation and long-term estuarine sedimentation are addressed in the next section.

# REDWOOD CREEK DRAINAGE BASIN

## Precipitation, Runoff and Sedimentation

The seasonal concentration and high annual values of precipitation are major factors in the high sediment yield from the Redwood Creek drainage basin. Mean annual precipitation is 200 centimeters (80 inches) for the basin, although local rainfall may vary by as much as 8.3 centimeters/100 meters of elevation (10 inches/1000 feet) due to orographic effects (Rantz, 1964). Rainfall associated with major storms is often distributed unevenly across the north to south elongated basin. Most of the precipitation occurs from November to March, the season of high soil moisture and low evapotranspiration rates (Figure 5). The mean annual runoff-precipitation ratio was 66 percent for water years (WY) 1954-1973 (Janda and others, 1975, p. 136 c.f. Rantz, 1964). For individual storms, runoff may approach much higher values due to shallow soils, impervious bedrock and steep tributaries. Floods are generally associated with warm storms of regional extent, producing prolonged rainfall of moderate intensity (Janda and others, 1975). High antecedent precipitation has also contributed to major floods of the past 30 years (Table 2).

Infrequent, high magnitude storms account for a disproportionate share of sediment transport relative to water discharge. For example, on the Eel River at Scotia, approximately 314 million tons of suspended sediment were transported during WY 1957-WY 1967. Of that amount, 145 million tons or 46 percent were measured in the 10-day period, December 21-30, 1964 (Brown and Ritter, 1971). For Redwood Creek at Orick during WY 1971-WY 1973, 80 percent of the total suspended sediment load was transported during high stream discharges that occurred only 5 percent of the time. During these major events, 37 percent of the total water discharge for WY 1971-WY 1973 was measured (Janda and others, 1975).

Observed changes in discharge and sediment transport characteristics may be caused by intensive land disturbance and/or flood damage. This is a controversial issue that need not be addressed here. Changes in rainfall-runoff relations are suggested by flow

Figure 5: Mean Monthly Precipitation and Temperature for Orick-Prairie Creek State Park and Mean Monthly Runoff for Redwood Creek at Orick for Water Years 1954-1972 (from Janda and others, 1975, p.21)

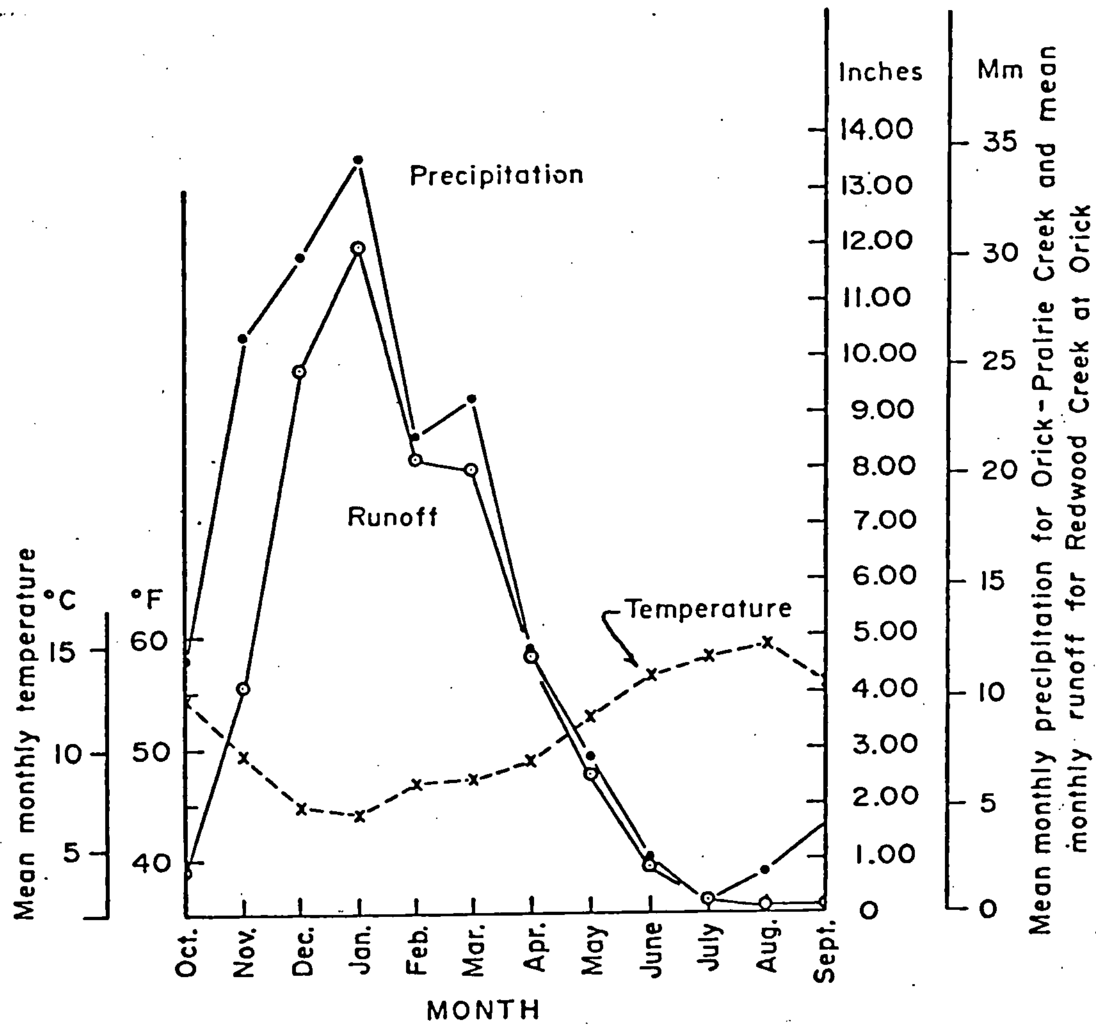


TABLE 2: Instantaneous Peak Discharge, Total Runoff and Antecedent Precipitation Index at Orick for Recent Major Floods on Redwood Creek (revised from Harden, Janda and Nolan, 1978, p. 33).

| Storm Dates | Instantaneous Peak Discharge $m^3$/sec (CFS) | Instantaneous Peak Discharge $m^3$/sec/$km^2$ (CFS/$mi^2$) | Storm Runoff cm (in) | Antecedent Precipitation Index[1] cm (in) |
|---|---|---|---|---|
| January 16-20, 1953 (peak January 18) | 1,415 (50,000) | 1.97 (180) | - - | 22.5 (8.85) |
| December 15-23, 1955 (peak @ 0600, December 22) | 1,415 (50,000) | 1.97 (180) | 32.5 (12.8) | 17.1 (6.74) |
| December 18-24, 1964 (peak @ 2100, December 22) | 1,430 (50,500) | 1.99 (182) | 41.4[2] (16.3) | 17.4 (6.86) |
| January 19-24, 1972 (peak @ 1430, January 22) | 1,285 (45,300) | 1.78 (163) | 28.7 (11.3) | 11.4 (4.48) |
| March 1-4, 1972 (peak @ 0045, March 3) | 1,410 (49,700) | 1.96 (179) | 18.0 (7.1) | 21.8 (8.60) |
| March 15-24, 1975 (peak @ 1300, March 18) | 1,420 (50,200) | 1.98 (181) | 28.2 (11.1) | 12.6 (4.94) |

1 API indicates the effect of previous rainfall in wetting the soil and of natural drainage and evapotranspiration in reducing the soil moisture.

2 Total runoff at Orick for the extended storm period December 18-30, 1964, was 64.0 cm (25.2 in).

duration curves constructed for two periods, WY 1954-WY 1963 and WY 1964-WY 1973 (Janda and others, 1975, p. 155). More frequent high peak discharges and lower summer flows observed in the latter period could result from increased runoff. Janda and others (1975, p. 155) also report a trend toward higher runoff and higher runoff-precipitation ratios during a period of decreased annual precipitation. The rainfall-runoff model for Redwood Creek computed by Lee, Kapple, and Dawdy (1975) indicates a 20 percent increase in storm season runoff between WY 1954-WY 1958 and WY 1968-WY 1972.

At the river mouth, the magnitude of peak discharge affects the degree of channel and bank erosion and overbank deposition. Lower summer flows influence the water volume of aquatic habitat by affecting closure and breaching of the mouth.

Associated with increases in the frequency and magnitude of peak discharges, changes in sediment transport relations have been observed following the 1964 flood on many northern California streams (Brown and Ritter, 1971). For a given discharge, suspended sediment loads increased two to five times over pre-flood values, but then decreased toward the pre-1964 flood loads (Janda, 1978, p. 51). Similar slight increases may have occurred on Redwood Creek in response to the January and March, 1972 floods (Janda and others, 1975).

Stream channel configuration changes along most reaches of Redwood Creek suggest that sediment available for bedload transport increased following major floods in 1953, 1955, and 1964. The bedload plus suspended sand load measured at the Orick gaging station has been estimated to be 37 percent less than the amount passing the South Park Boundary gaging station (Nolan and Janda, 1979, p. X-12). The majority of the surplus coarse sediment must be stored along the intervening 32-kilometer (20-mile) reach. Increased sediment storage along Redwood Creek has been documented by cross-sections established by the U.S. Geological Survey in 1973, and more recent surveys by Redwood National Park personnel (Nolan, Harden, and Janda, 1976; Nolan, 1979; Kelsey and others, 1981). Aggradation has been accompanied by increased streambed elevation, channel width and velocity, more braided channel patterns, and streambank erosion. Bank-cutting along reaches lacking an upper floodplain accelerates streamside landsliding and loss of riparian vegetation. Streamside landslides and aggrading channels are visible on aerial photos taken since the mid-fifties (Nolan and Janda, 1979, p. X-1). The December, 1964 flood initiated the most intense recent episode of aggradation. Later floods also delivered more sediment to the channel than could be effectively transported by Redwood Creek (Janda, 1978, p. 20, 50).

Localized scour has been observed in upstream reaches which aggraded following the 1964 flood. Janda (1978, p. 21) reported that the zone of greatest aggradation moved downstream to the reach between Elam Creek and the mouth of the gorge following the floods of 1972 and 1975 (Table 2, Figure 4). Considering estimated bedload transport rates and the volume of material in storage, Janda (1978, p. 56) speculated that Redwood Creek would not return to its pre-1964 flood configuration for considerably more than 15 years. Detailed inventories of sediment stored in the active channel of Redwood Creek above the 1947 thalweg yielded an estimate of 40 years of equivalent sediment discharge stored upstream of Orick (Kelsey and others, 1981, p. 64). This estimate was based on an annual bedload and coarse suspended load of 463,000 tonnes/year (510,000 tons/year).

On the Eel River at Scotia, higher percentages of sand were transported in suspension during flows greater than 1,130 $m^3$/second (40,000 cfs) following the 1964 flood (Brown and Ritter, 1971, p. 32-34). It would be reasonable to expect a similar shift in particle-size distribution in suspended loads along Redwood Creek.

# FLOOD HISTORY

## Methods

Each method used to examine the effects of flooding on the morphology of lower Redwood Creek covers a different time scale. Prehistoric and early historic flood features have been preserved on the floodplain (Figure 6). Here, the term floodplain refers only to the area inundated by streamflows greater than bankfull, downstream from the confluence of Redwood Creek and Prairie Creek (Figure 7). These morphological features are discussed with dendrochronological evidence of flood magnitudes from 1600 to 1964. From aerial photography for the period 1931-1981, details of erosion and deposition across the floodplain and mouth have been interpreted. Bathymetric profiles document the 1964-1981 period before and after channelization of Redwood Creek.

Dendrochronological techniques were applied to assess the relative stability of the natural channel configuration near the mouth. The spruce-alder forest located between the downstream meander and former overflow channels (Figure 6) was mapped using 1967 aerial photography. Annual growth rings were visible on many stumps left from spruce harvested in 1978. Counted ages were adjusted to account for the time since harvest (3 years) and time to attain stump height (assumed to be 2 years). Standing live spruce and selected alder were dated from increment cores taken at breast height (3 years added). Indistinct annual rings in the alder cores were counted with the aid of a dendrochronometer.

Interviews with local residents provided information on the historic fishery and effects of floods on Redwood Creek (Feranna and Ricks, unpublished report). Oral records describe flood magnitude, flood deposits, channel configuration changes, marine conditions, and water depth at the mouth of Redwood Creek (Appendix A).

The dates and magnitudes of early floods on Redwood Creek have been inferred from regional precipitation and streamflow data (McGlashan and Briggs, 1939; Paulsen, 1953; U. S. Army Corps of Engineers, 1961, Table A-2, A-4; Harden, Janda, and Nolan, 1978).

Figure 6: Oblique Aerial Photograph, Mouth of Redwood Creek, September, 1948.

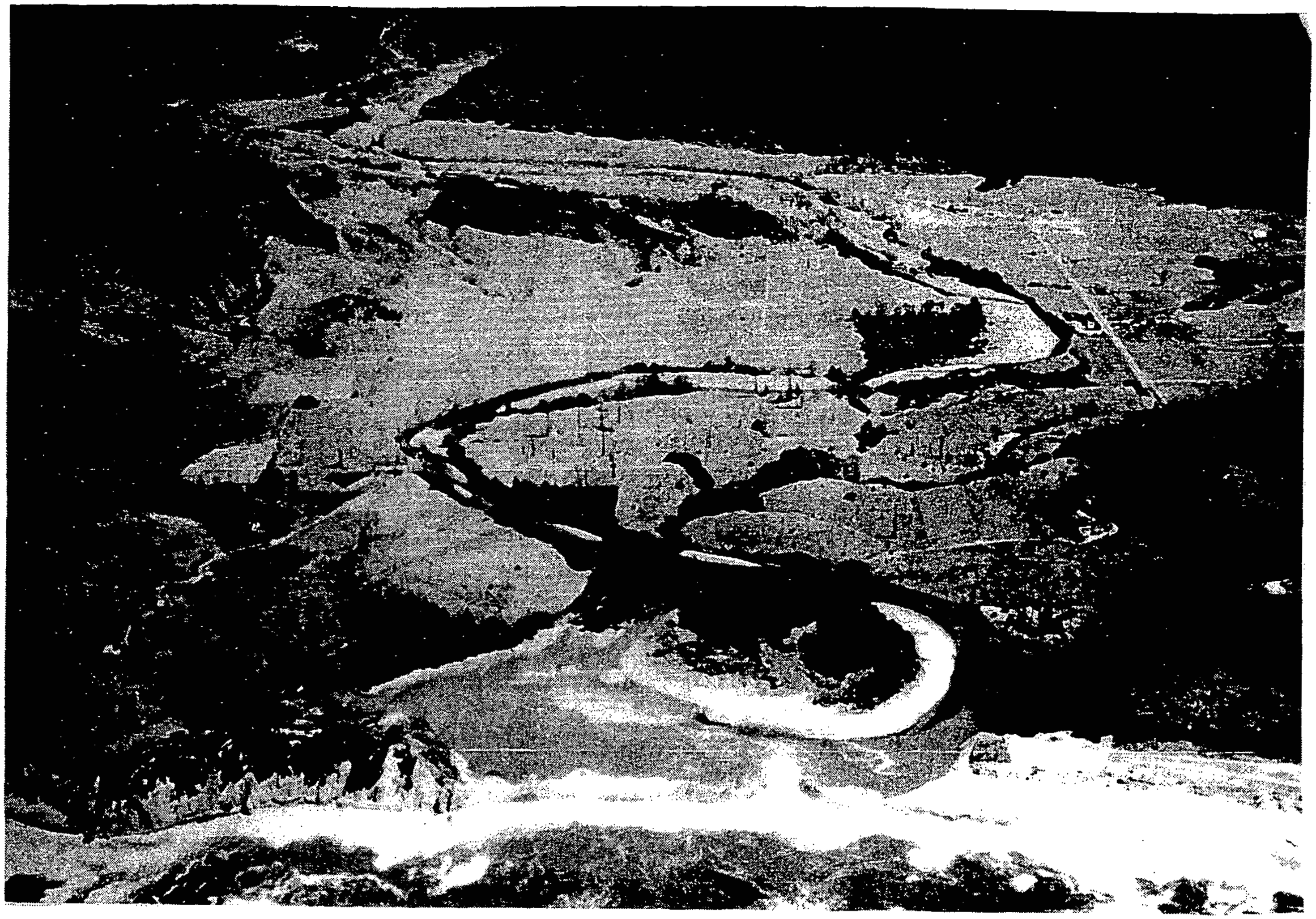


Figure 7: Redwood Creek Floodplain, 1964 Flood Deposits and Selected Cultural Features

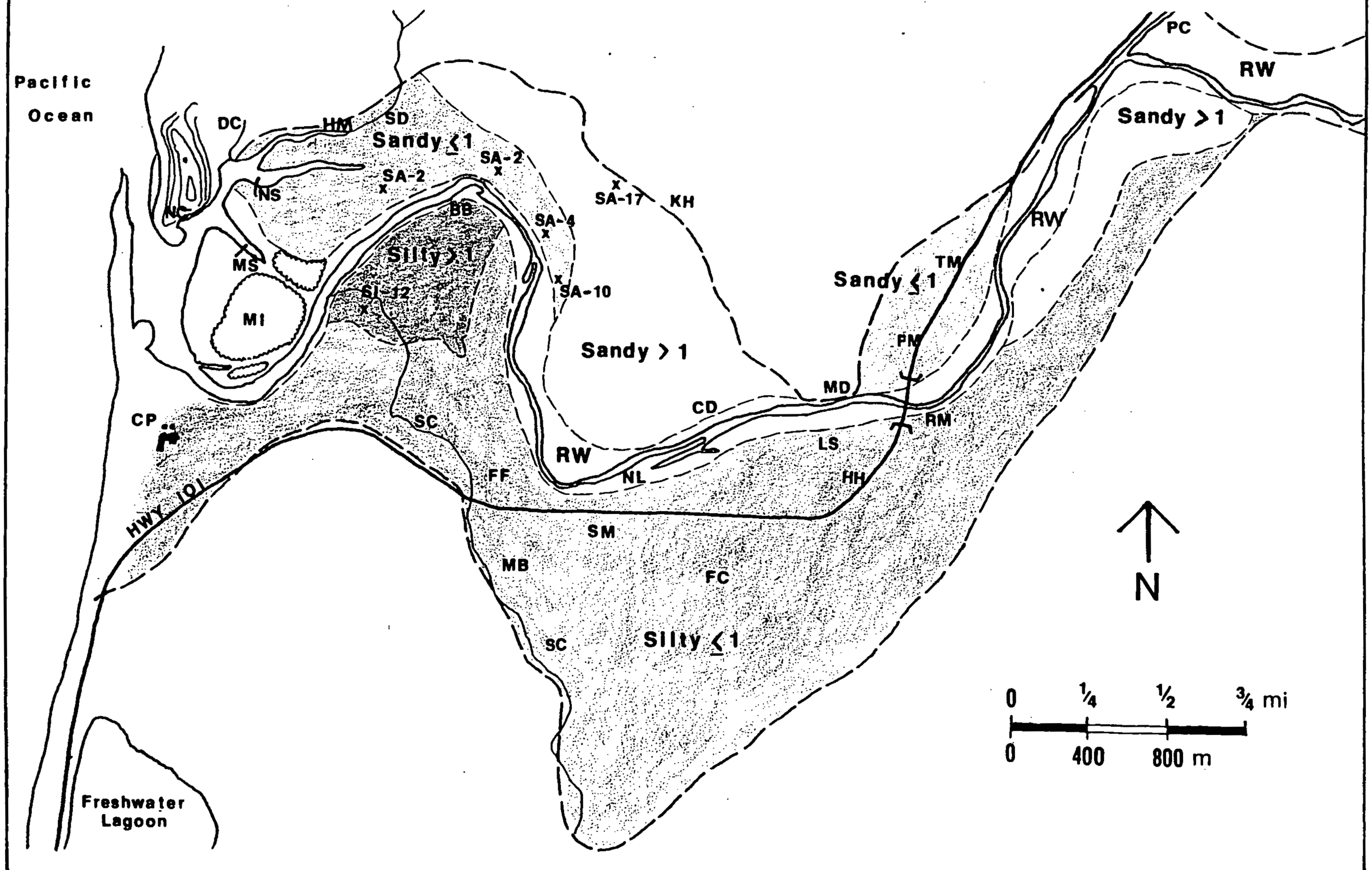


Figure 7: Redwood Creek Floodplain
1964 Flood Deposits and Selected Cultural Features
(continued)

1964 Flood Deposits - Mapped Units

(McLaughlin and Harradine, 1965, Map Sheet 1)

| | |
|---|---|
| — — — — | Floodplain |
| - - - - - | Mapped Units |
| Sandy $>1$ | Sandy deposits greater than one foot |
| Sandy $\leq 1$ | Sandy deposits of one foot or less |
| Silty $>1$ | Silty deposits greater than one foot |
| Silty $\leq 1$ | Silty deposits of one foot or less |
| RW | Riverwashed areas prior to recent flood, bankfull channel |
| x SA-4 | Core locations with depth of deposit (inches)<br>texture: SA =sand, SI =silt |

Other Features

| | |
|---|---|
| ——— | Highway 101 |
| —}—{— | Redwood Creek Bridge |
| BB | Baine's bend |
| CD | Chapman's dike |
| CP | California Pacific Mill site |
| DC | Dorrence Creek |
| FC | Former channel, marked by willows |
| FF | Foster's field |
| HH | Hagood's Hardware Store |
| HM | Hufford's mill |
| KH | Kring's house |
| LS | Lundblade subdivision |
| MB | Marvin Barlow's house |
| MD | McNamara's driveway |
| MI | Middle island |
| MS | Middle slough |
| NC | North cliffs |
| NL | Neilsen's log jam |
| NS | North slough |
| PC | Prairie Creek |
| PM | Palm Motel |
| RM | Rainbow Motel |
| SC | Strawberry Creek |
| SD | Sand Cache Creek |
| SM | Savina and Marvin Barlow's present house |
| TM | Tipton's Motel |

After 1949, peak flood stages were measured by the U. S. Army Corps of Engineers with a staff gauge at the Orick bridge, prior to establishment of the U. S. Geological Survey gauging station in October, 1953. Precipitation gauges in the Redwood Creek basin have provided details of storm intensity, duration, and distribution since the early 1950's.

Historical photos were obtained from a variety of sources (Appendix B). Photo interpretations were supplemented by interviews and streamflow gauging data. Floodplain and channel configuration changes have been referenced to selected cultural features (Figure 7), particularly those mentioned in Appendix A. Soil surveys following the December, 1964 flood included maps of the depth and texture of flood deposits in Humboldt County (McLaughlin and Harradine, 1965, Map Sheet 1). Mapped units and core sample locations obtained from the original field overlays have been plotted on the Redwood Creek floodplain map (Figure 7).

Vertical aerial photos taken from 1931 to 1968 were reduced or enlarged to a common scale in order to construct maps of streambank erosion and migration of the last downstream meander as well as sedimentation in the embayment. Potential interactions between high stream discharge and marine conditions were evaluated by plotting hydrographs for floods gauged at Orick with tide heights predicted for Humboldt Bay. Since high water levels obscure many of the critical features on the aerial photos, maps were not drawn for the post-channelization period.

Changes in sediment distribution following levee construction were documented by comparing surveys from summer, 1980, and spring, 1981, with U. S. Army Corps of Engineers maps (1964 and 1966 surveys, Drawing Number 85-33-6, Sheets 8 and 16, San Francisco District Corps of Engineers). Detailed topographic/bathymetric maps and profiles were surveyed using an engineer's automatic level (or occasionally a theodolite), Brunton compass and stadia rod (see Map Plate 1 for profile locations). The stadia rod was leveled from a small rowboat or canoe to obtain bathymetric contours in areas where deep water prohibited wading. The survey data were reduced and plotted by computer on MINITAB, a packaged statistical program. Seventeen profiles were drafted with the aid of a graphics plotter (Appendix C). In order to facilitate comparisons with Army Corps surveys, the topographic/bathymetric maps were plotted at a scale of one inch equals 100 feet. Contours were drafted at two-foot intervals, although only the four-foot contours appear on the reduced maps (Map Plates 1-3). The topographic/bathymetric maps were used to estimate changes in water volume and sediment distribution at the mouth. Areas were obtained either with a digital readout planimeter or an electronic digitizer.

## Flood Magnitude and Frequency

Upstream reaches of northern California streams are generally steep and narrow; therefore, evidence of older destructive floods is rarely preserved. Helley and LaMarche (1973) located gravel deposits in northern California supporting conifers established after 1600 A.D., providing evidence of an event that exceeded the December, 1964 flood. They also concluded that floods of the 1964 flood magnitude have occurred several times since 1600 A.D. Northern California experienced widespread flooding in 1852, 1861-62, 1879, 1881, 1888, and 1890 (McGlashan and Briggs, 1939, p. 471-476). The period from November 1861 through January 1862 was by far the wettest on record for the region (Harden, Janda, and Nolan, 1978, p. 61). Four flood peaks occurred, including record discharges on the lower Eel, Klamath, and Smith Rivers. Beaches near Crescent City were covered for miles with woody debris. One local resident spoke of the flood debris line from "1860" which remained in trees near Prairie Creek for many years (Davison, Appendix A).

Near the Tall Trees Grove along Redwood Creek, a bridge built 10 feet higher than the 1861-62 flood peak was destroyed in January, 1867 (Harden, Janda, and Nolan, 1978, p. 66). Unfortunately, no other records of flooding at that time were gathered by McGlashan and Briggs (1939).

Storm rainfall for January 31 - February 4, 1890 was higher at Crescent City, Eureka, and probably Arcata than for recent storms listed in Table 2 (Harden, Janda, and Nolan, 1978, p. 69). Runoff may have been augmented by snow melt, since warm rains fell after unusually heavy snows in the winter of 1889-1890. Local news reports suggest that coastal parts of Redwood Creek basin received more rain in 1890 than in 1964 (Harden, Janda, and Nolan, 1978, p. 71). Davison corroborated reports of a house on lower Redwood Creek that was washed away in the flood of 1890 (Appendix A; Harden, Janda, and Nolan, 1978, p. 71). Flood debris from the Klamath River was again deposited across large areas of Crescent City Beach.

Annual rainfall recorded at Crescent City and Eureka during the first 20 years of this century was considerably greater than the 1954-1973 mean (Janda and others, 1975, Figure 28). McGlashan and Briggs's (1939, Table 18) data for the Eel, Klamath and Smith Rivers indicate flooding on the lower Eel and lower Klamath in 1914 and 1915. The lower Klamath and Smith Rivers reached exceptionally high stages during February 19-20, 1927. Lower Redwood Creek residents recalled the 1927 flood (Zuber, Taggart; Appendix A).

Overbank flows generally left deposits across the floodplain which appear as white streaks on aerial photographs. Flood deposits on pastures downstream from the Orick bridge (Figure 7) in 1931 probably resulted from the 1927 flood. This event breached a low earthen dike (CD, Figure 7), allowing flood waters to rush along the north side of the floodplain into the north slough (Taggart, S. Barlow; Appendix A). Flood deposits were not apparent along the western half of the floodplain where natural drainage channels existed adjacent to forest margins (e.g. Strawberry Creek).

Several north coast discharge records were set by the damaging flood of December 9-12, 1937, but most stations reported peak flows lower than the 1927 levels (McGlashan and Briggs, 1939). On Redwood Creek, the 1941 photo revealed new flood deposits on the north and south sides of the floodplain.

The late 1940's and early 1950's were prosperous years for the logging town of Orick. Many buildings were constructed along Redwood Creek downstream from the bridge, including the Lundblade subdivision (LS, Figure 7). One resident suggested that most of these structures were located in low marshy areas and sloughs, subject to flooding

(S. Barlow, Appendix A). This led to pressure for flood control after several storms in the 1950's. The California-Pacific Mill site was established south of the last downstream meander in 1951 after Highway 101 was relocated in 1949.

Flood magnitudes and frequencies could be compared after the U.S. Army Corps of Engineers established a peak flow staff gauge at the Orick bridge in 1949 and the U.S. Geological Survey installed a gauging station in 1953 (Table 3). The U.S. Army Corps of Engineers (1961) reported that bankfull stage occurred at a discharge of 480 $m^3$/sec (17,000 cfs). This stage was expected once every two years. Flooding of low-lying areas near Orick occurred when discharge reached 710 - 850 $m^2$/sec (25,000 - 30,000 cfs). Janda and others (1975, p. 147) data showed the two-year return period flood having a peak discharge of 650 $m^3$/sec (23,000 cfs). Flood frequency calculations by Waananen and Crippen (1977, p. 54-55) yielded a 720 $m^3$/sec (25,500 cfs) two-year flood.

The recurrence frequency for a peak discharge of 1,415 $m^3$/sec (50,000 cfs) was cited as 15 or 20 years (U.S. Army Corps of Engineers, 1961, p. 15). For the same flood, later estimates gave a 16-17 year return period (Waananean and Crippen, 1977, p. 54-55). Coghlan (in preparation) discusses the effects of changing climatic patterns on flood frequencies, noting that it is not unreasonable to expect peaks on the order of 1,415 $m^3$/sec (50,000 cfs) every 13 years. During more severe climatic periods such as 1953 - 1975, this flood occurred every 3.5 years.

Although the estimated peak discharge of the October, 1950 flood was only 650 $m^3$/sec (23,000 cfs) (Table 3), the associated rainstorm was exceptionally intense in the coastal area (Janda and others, 1975, p. 147). The Orick-Prairie Creek State Park station measured an unprecedented calendar day precipitation of 29.2 cm (11.50 in) (Paulson, 1953). Residents along Prairie Creek referred to the storm as a "typhoon" (Davison, Appendix A). Flooding in the region ranked with that of 1890 and 1927. The confluence of Prairie Creek and Redwood Creek expanded into a large ponded area. During major floods Prairie Creek appears to flow backwards from the force of Redwood Creek where it bends to the west (Figure 7).

TABLE 3: Annual Peak Discharge and Other Peak Discharges Above 480 $m^3$/sec (17,000 cfs) for Redwood Creek @ Orick, Water Years 1948 - 1982.

| Date | Peak Discharge $m^3$/sec | cfs | Source of Data (listed below) | |
|---|---|---|---|---|
| January 7, 1948 | 850 | 30,000 | High water mark | (1) |
| 1949 | No data available | | - | |
| January 18, 1950 | 1,050 | 37,000 | Staff gauge | (1) |
| October 29 - 30, 1950 | 650 | 23,000 | | (2) |
| January 17, 1951 | 790 | 28,000 | Staff gauge | (1) |
| February 1, 1952 | 380 | 13,500 | Staff gauge | (1) |
| January 18, 1953 | 1,415 | 50,000 | Staff gauge | (1) |
| November 24, 1953 | 770 | 27,200 | | (3) |
| December 31, 1954 | 795 | 28,100 | | (3) |
| December 22, 1955 | 1,415 | 50,000 | | (3) |
| March 12, 1957 | 680 | 24,100 | | (3) |
| November 13, 1957 | 630 | 22,200 | | (3) |
| January 12, 1959 | 495 | 17,500 | | (3) |
| February 8, 1960 | 705 | 24,900 | | (3) |
| November 25, 1960 | 415 | 14,700 | | (4) |
| December 19, 1961 | 615 | 21,800 | | (4) |
| December 2, 1962 | 740 | 26,100 | | (4) |
| November 8, 1963 | 755 | 26,600 | | (4) |
| January 20, 1964 | 1,065 | 37,700 | | (4) |
| December 10, 1964 | 560 | 19,800 | | (4) |
| December 22, 1964 | 1,430 | 50,500 | High water mark | (4) |
| January 4, 1966 | 1,120 | 39,600 | | (5) |
| December 5, 1966 | 695 | 24,500 | | (5) |
| January 15, 1968 | 420 | 14,900 | | (5) |
| January 13, 1969 | 480 | 17,000 | | (5) |
| January 21, 1969 | 485 | 17,200 | | (5) |
| January 22, 1970 | 695 | 24,500 | | (5) |
| January 27, 1970 | 795 | 28,000 | | (5) |
| November 24, 1970 | 865 | 30,500 | | (6) |
| December 3, 1970 | 720 | 25,400 | | (6) |
| January 18, 1971 | 580 | 20,400 | | (6) |

TABLE 3: (continued)

| Date | Peak Discharge m³/sec | cfs | Source of Data (listed below) |
|---|---|---|---|
| December 6, 1971 | 570 | 20,100 | (6) |
| January 22, 1972 | 1,285 | 45,300 | (6) |
| March 3, 1972 | 1,405 | 49,700 | (6) |
| December 17, 1972 | 285 | 10,000 | (6) |
| April 1, 1974 | 700 | 24,800 | (6) |
| February 19, 1975 | 560 | 19,700 | (6) |
| March 18, 1975 | 1,420 | 50,200 | (6) |
| March 25, 1975 | 570 | 20,100 | (6) |
| February 28, 1976 | 343 | 12,100 | (6) |
| March 9, 1977 | 94 | 3,310 | (6) |
| December 14, 1977 | 600 | 21,200 | (6) |
| January 11, 1979 | 399 | 14,100 | (6) |
| March 14, 1980 | 549 | 19,400 | (6) |
| December 2, 1980 | 256 | 9,030 | (7) |
| December 20, 1981 | 750 | 26,500 | (7) |

Source of Data

(1) U.S. Army Corps of Engineers, 1961.

(2) Janda and others, 1975, p. 147.

(3) U.S. Geological Survey Water Supply Paper 1735, 1964.

(4) U.S. Geological Survey Water Supply Paper 1929, 1970.

(5) U.S. Geological Survey Water Supply Paper 2129, 1976.

(6) U.S. Geological Survey Water Resources Data for California 1971 - 1981.

(7) U.S. Geological Survey Water Resources Division, Eureka, provisional data.

The storm of January 16-20, 1953, was also brief, intense and concentrated along the coast. High antecedent moisture probably contributed to the record peak discharge of 1415 $m^3$/sec (50,000 cfs) (Table 2). This storm apparently did not damage stream channels and hillslopes as much as later storms. Redwood Creek was narrow and deep prior to the floods of 1953 and 1955, which widened the streambed in the vicinity of Orick, according to a local resident (Hagood, Appendix A). Sections of the county road were completely removed by bank erosion adjacent to the Rainbow Motel (RM, Figure 7). Emergency rip rap was placed along 600 meters (2,000 ft) of the bank by the U.S. Army Corps of Engineers (1956, p. 22; S. Barlow, Appendix A).

From aerial photographs, the September, 1954 channel appears wider and more aggraded than the June, 1948 channel. It is difficult to quantify this change due to lack of reference points and differences in water levels. Streamflow gauging had not yet begun in 1948. When the 1954 photo was taken, discharge was 3.6 $m^3$/sec (129 cfs), somewhat high for September. Thus the apparent aggradation is probably not due to low water levels in September, 1954. Flood deposits are present in the 1954 photo in fields on the north side suggesting the Chapman dike failed in 1953 (CD, Figure 7). Some of the riparian vegetation near this site was harvested and/or eroded between 1948 and 1954.

Precipitation during the December 15-23, 1955 storm was more prolonged and uniformly distributed over the Redwood Creek basin than during the 1953 storm. The peak discharge was calculated as 1,415 $m^3$/sec (50,000 cfs). The 1957 photographs show evidence of flow through sloughs across the south side of the floodplain and into Strawberry Creek. At the fork in Strawberry Creek a small mill pond was washed out. Residents along Strawberry Creek reported water up to the rafters of at least one house, and a garage was washed across Highway 101 (M. Barlow, Appendix A). The Army Corps provided bank protection along 460 meters (1,500 ft) of the south bank downstream from Nielsen's log jam (NL, Figure 7) following the 1955 flood (U.S. Army Corps of Engineers, 1961, p. 19). On the north side, the Army Corps repaired a 90 meter (300 ft) breach in the 550 meter (1,800 ft) long Chapman dike. A 1.5 meter high levee was to be constructed at the site using materials borrowed from the floodplain. Evidence of that activity is visible on the 1957 photo.

The flood of December 18-24, 1964 was the most damaging event of the century in the north coast region (Harden, Janda, and Nolan, 1978, p. 31). The peak discharge of this flood was only slightly larger than those of 1953 and 1955 (Table 2) but the total flood volume and damage to streambanks and hillslopes was much greater (Janda and others, 1975, p. 147). The 1964 flood may have been augmented by precipitation on saturated hillslopes while rivers were still high following the flood peak (Harden, Janda, and Nolan, 1978, p. 45). This storm was concentrated on the higher inland portions of the basin.

Orick was completely inundated under 1.5 meters (5 ft) of water and thick flood deposits, logs and debris covered pastures in the valley (California Department of Water Resources, 1966). The thickness and texture of the 1964 deposits were mapped during a Humboldt County soil survey (McLaughlin and Harradine, 1965, Map Sheet 1). These map units and core locations are shown with the January 13, 1965 mouth configuration in Figure 7. Sediment of 0.9 meters (3.0 ft) in thickness was deposited near Tipton's Motel (TM, Figure 7) and the water was "half mud" during the 1964 flood (Tipton, Appendix A). McNamara (Appendix A) noted that the water remained high much longer in 1964 than 1955, contributing to the greater depth of the deposit near the Palm Motel in 1964 (PM, Figure 7). He measured 53 centimeters (21 inches) of silt in 1964, and only half of that amount in 1955. The water was 3 meters (10 ft) deep at the base of McNamara's driveway (MD, Figure 7). At flood stage Redwood Creek flowed through the constricted area where the base of the McNamara's steep driveway is located and onto the open floodplain. The 1.5 meter (5 ft) earthen levee again developed a 50 meter (160 ft) wide breach during this flood. Failure of the levee may have been catastrophic, releasing high velocity flood waters which deposited thicker, coarser sediment on the north side than on the south side of the floodplain (Figure 7).

## Floodplain Morphology and Dendrochronology

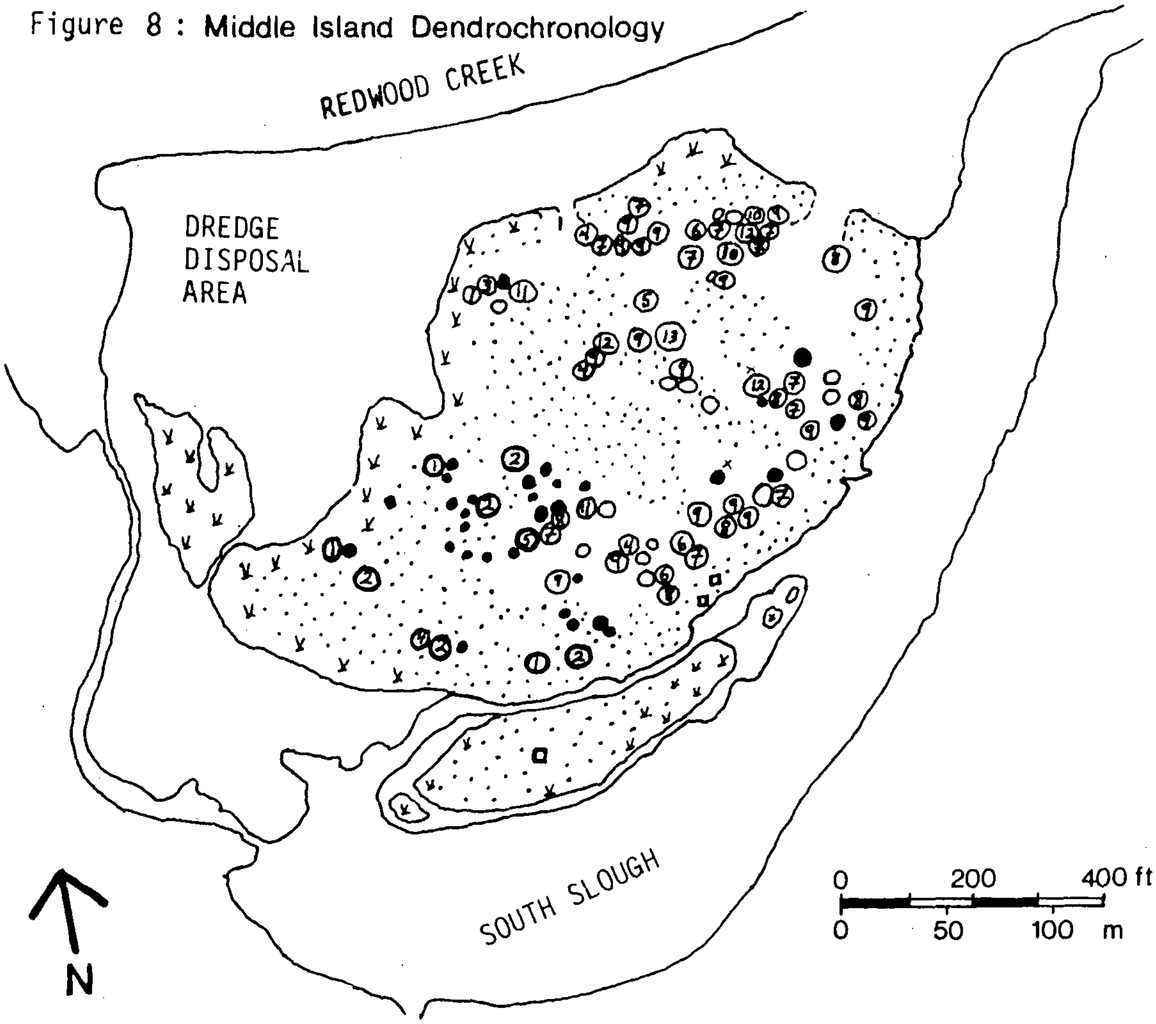
Prehistoric overflow features and possibly former stream channels are evident on the Redwood Creek floodplain. The two fingers of the north slough appear to have been scoured by high flows. On the south side of the floodplain, an arcuate patch of willows (FC, Figure 7) is visible on a 1948 oblique aerial photo (Figure 6). Several "swampy" places and sloughs in this area drained into Strawberry Creek and the middle slough during overbank flows (Barlow, Appendix A).

The presence of numerous stumps in early photographs (e.g., Figure 6) indicates that spruce forest was once more extensive in the Orick Valley. At the mouth of Redwood Creek, spruce were removed from the north side of the middle island prior to levee construction. In 1978, some trees also were completely removed from the middle island when roads were bulldozed to harvest the spruce. Tree age distribution shows that the grove on the middle island was not established after a single flood (Figure 8). Older Sitka spruce (_Picea sitchensis_) are clustered together, but the distribution is generally all-aged. This distribution is unlike that of floodplains near laterally migrating channels having even-aged meander scrolls (Everitt, 1968). The characteristic ridge and swale topography (Hicken, 1974, p. 414) is also absent on the middle island.

The all-aged distribution of spruce may be the result of seedling establishment under conditions of periodic flooding. Spruce seedlings do not germinate well on alluvium due to poor moisture retention and extremes of temperatures and sunlight (Fowells, 1965). Other species such as red alder (_Alnus rubra_), can invade flood deposits and prepare the moist, organic seedbed required for spruce establishment (Fowells, 1965).

If flooding is responsible for destroying older spruce and forming sites for future establishment, the maximum spruce age of 98 years suggests that the forest may have developed following the 1861-62 floods. The two peak times of establishment in the early 1900's do not reflect a uniform lag time after the 1861-62 and 1890 floods, however (Figure 9). Spruce not located on higher elevation

Figure 8 : Middle Island Dendrochronology



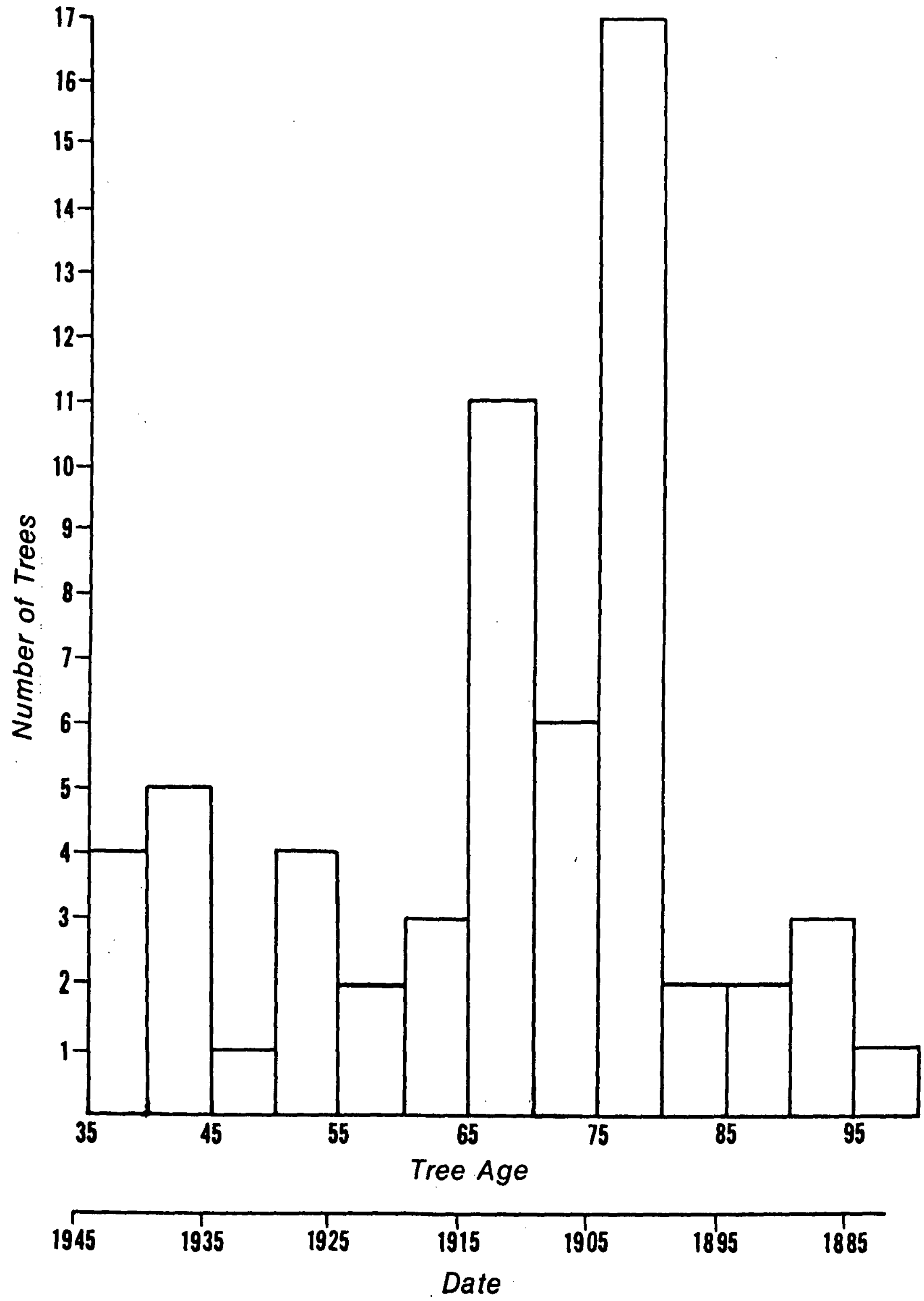

Symbols

- shrubs
- *Alnus rubra* and shrubs
- *Alnus rubra*, core locations
- *Picea sitchensis*, standing live
- *Picea sitchensis*, stump

*Picea* Age Classes

| Class | Age Range (years) |
|---|---|
| 1 | 35-39 |
| 2 | 40-44 |
| 3 | 45-49 |
| 4 | 50-54 |
| 5 | 55-59 |
| 6 | 60-64 |
| 7 | 65-69 |
| 8 | 70-74 |
| 9 | 75-79 |
| 10 | 80-84 |
| 11 | 85-89 |
| 12 | 90-94 |
| 13 | 95-99 |

Figure 9: Age Distribution of Picea sitchensis on the Middle Island, Mouth of Redwood Creek.



sites or protected by accumulations of large organic debris may have been destroyed by flooding and/or storm waves. Recurrent scouring of flood channels across the middle island would alter the tree age distribution shown in Figure 9.

On the Hoh River floodplain in Washington, this species of spruce has a 300-400 year lifespan (Swanson and Lienkaemper, 1979). The relative immaturity of the middle island stand could reflect an early unrecorded harvest or recovery from disease rather than flood damage.

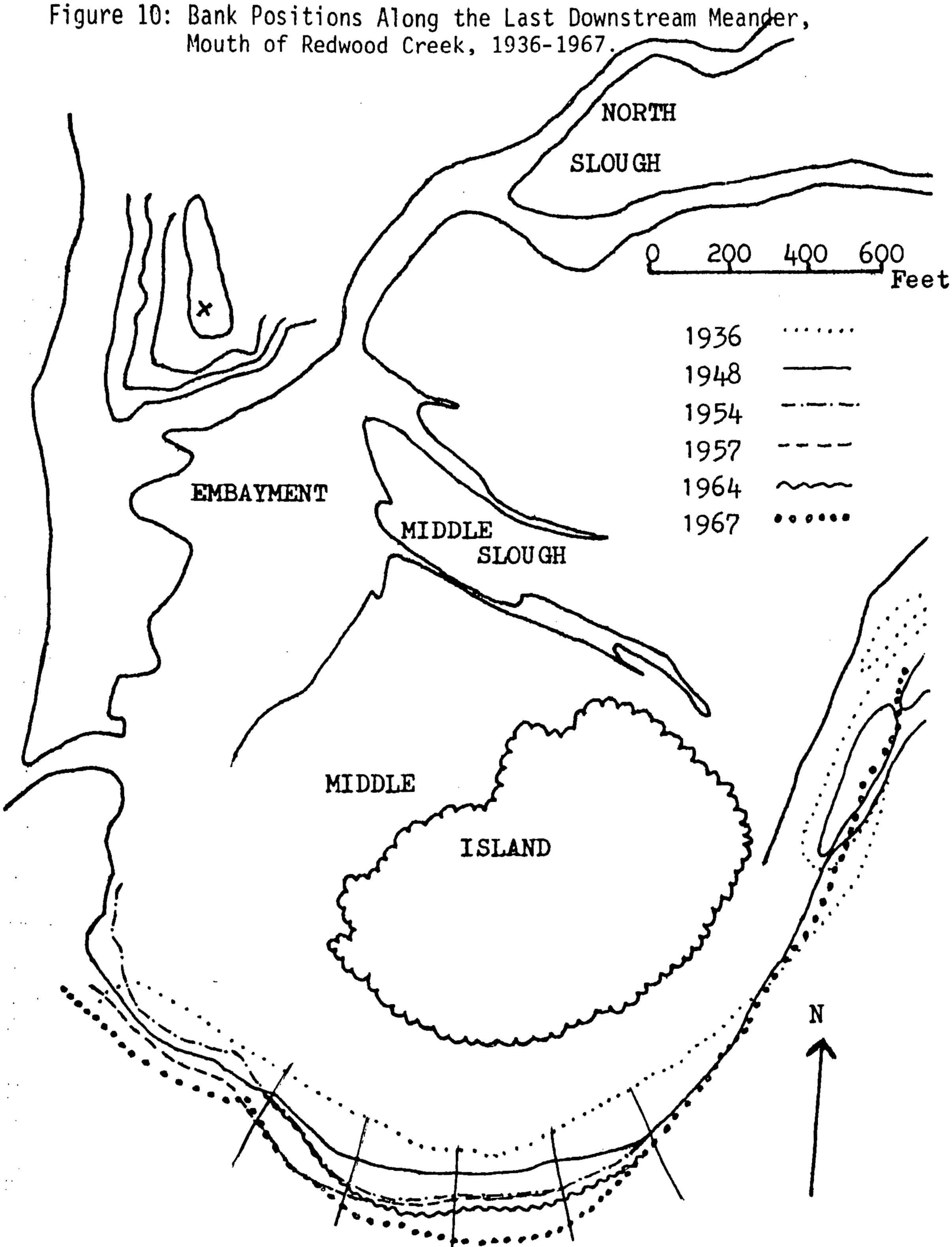
Younger spruce and red alder occur on the southwest side of the middle island adjacent to the channel. Alder has also invaded a crescent-shaped patch in the center of the island. Red alder was not cored extensively since it is a hardwood with rather indistinct growth rings. Red alder has a maximum age of about 100 years and the aerial photograph record covers about half of this time period. Photos from 1931 to 1948 (Figure 6) show that the bare crescent-shaped patch may have been an overflow channel for floods in 1927 or earlier.

## Streambank Erosion and Migration of the Last Downstream Meander

Streambank positions along the last downstream meander migrated progressively to the south from 1936 to 1967 at a rate of 2.1 m/yr (6.9 ft/yr) (Figure 10). Significant episodes of streambank erosion were clearly associated with low frequency, high magnitude floods having peak discharges of at least 1,065 $m^3$/sec (37,700 cfs) (Figure 11). Due to the small scale of the 1936 photo and overhanging riparian vegetation, the 1936 bank position is the least accurately represented.

Dendrochronology of floodplain vegetation yielded channel migration rates of 1.4 m/yr (4.6 ft/yr) and 1.8 m/yr (5.9 ft/yr) over a 120 year period for two bends along the Chinchaga River in northern Alberta (Nanson and Hickin, 1983, p. 332). Although these two bends were simlar in planform, bank height, and sediment composition, migration rates from 1955 to 1975 averaged 5 m/yr (16.4 ft/yr) and 0m/yr (0 ft/yr), respectively. Nanson and Hicken (1983, p. 332-334)

Figure 10: Bank Positions Along the Last Downstream Meander, Mouth of Redwood Creek, 1936-1967.




Average bank positions obtained from these lines. See Figure 11.

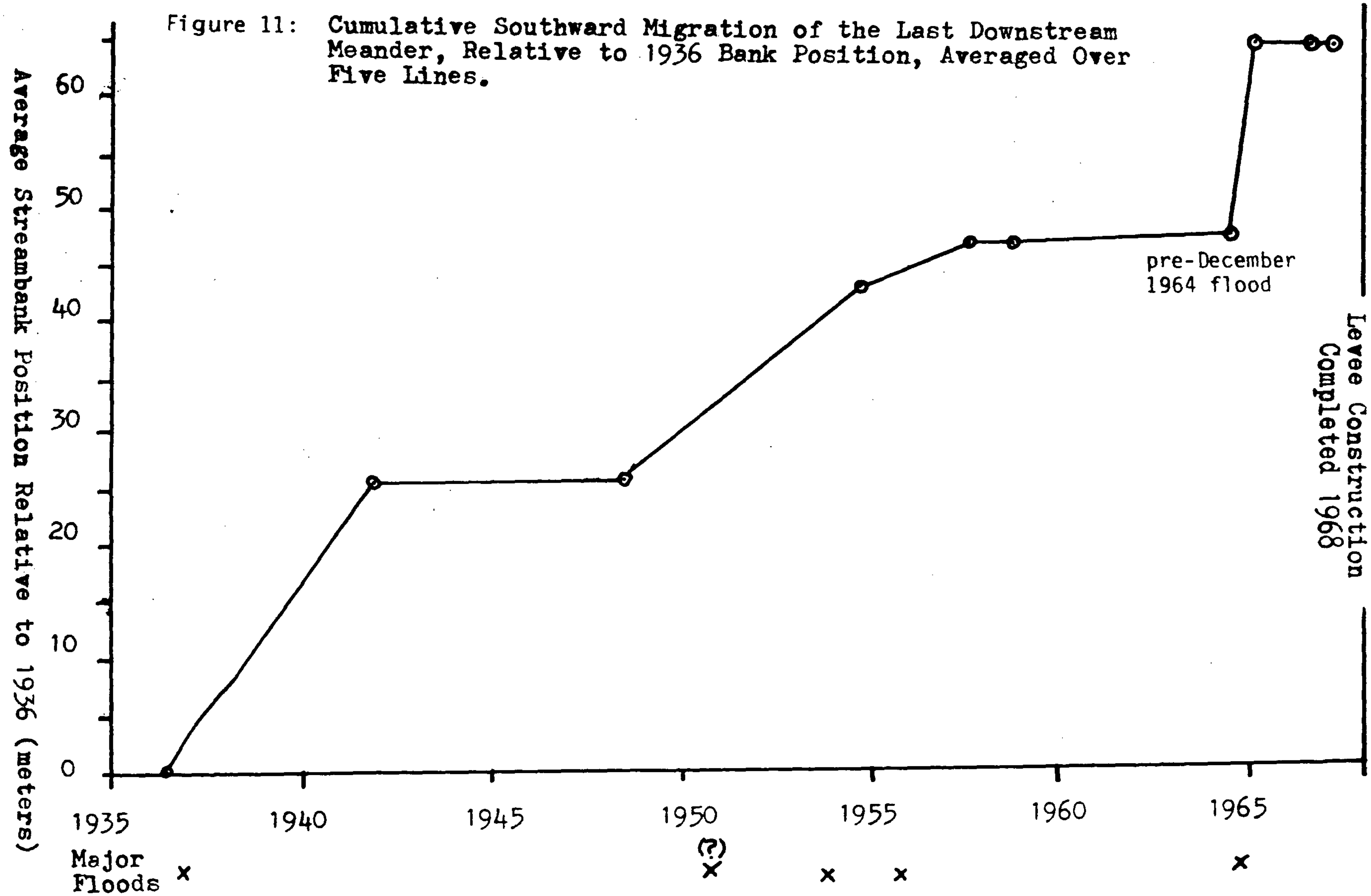



Figure 11: **Cumulative Southward Migration of the Last Downstream Meander, Relative to 1936 Bank Position, Averaged Over Five Lines.**

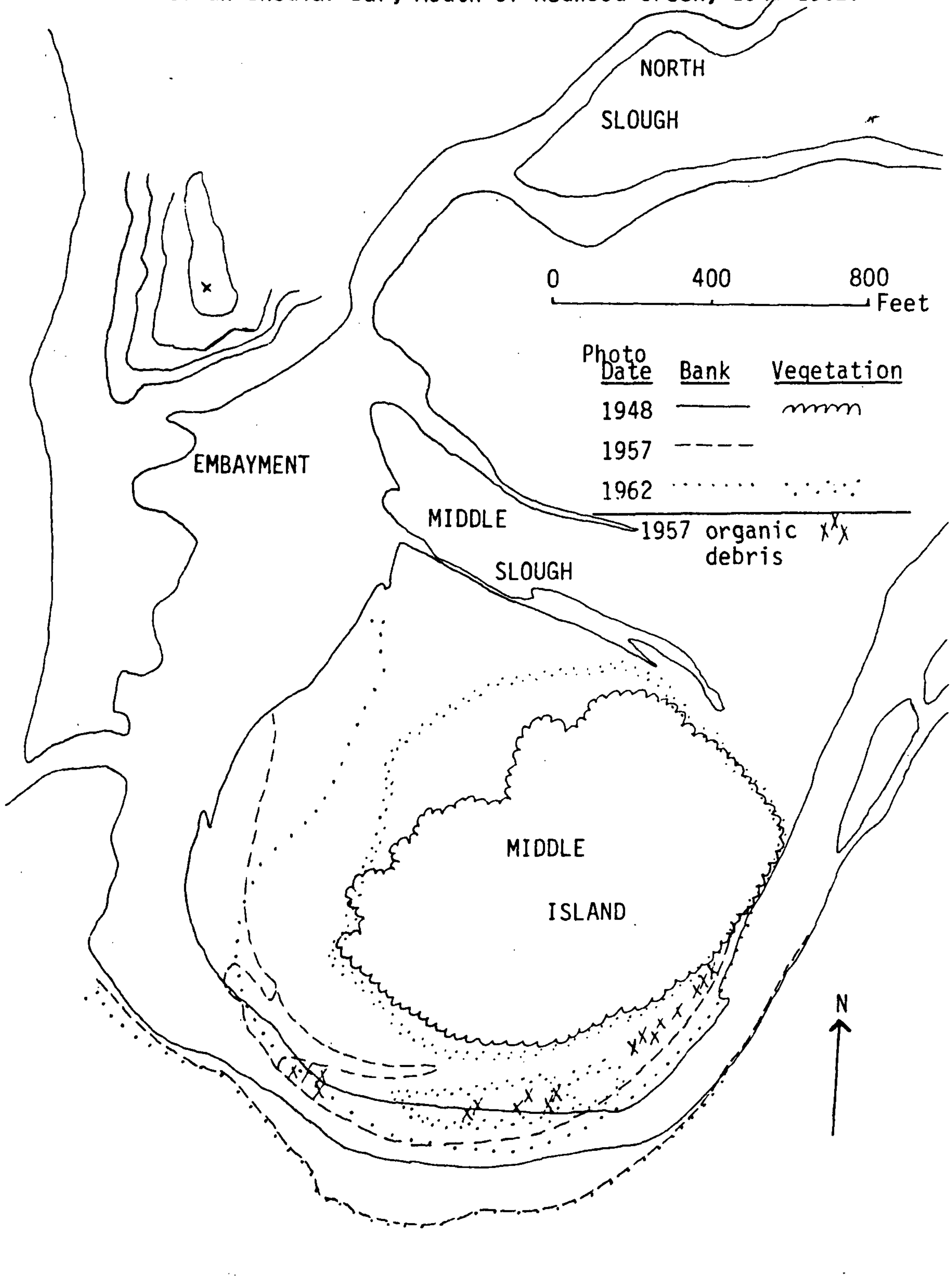
found that differences in the degree of migration may be caused by processes which maintain an equilibrium channel width. When a convex bank is well-defined and vegetated, migration occurs by erosion of the concave bank and is associated with channel widening. Successive floods of similar magnitude will not significantly erode the concave bank since 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 equilibrium channel width is restored. The next major flood will again erode the concave bank of the confined channel.

The discontinuous pattern of migration along the last downstream meander during floods in 1953, 1955, and 1964 is consistent with the sequence described above (Nanson and Hickin, 1983, p. 332-334). Following a prolonged period of little or no streambank erosion (Figure 11), the concave bank migrated considerably during the January 1953 flood (Figure 10). Although the December 1955 flood attained the same peak discharge (Table 2), streambank erosion was not extensive (Figures 10 and 11). The 1955 flood may have exceeded bankfull level at a lower discharge due to the wider and more aggraded channel.

In July 1957, the convex bank consisted of a wide point bar covered by organic debris which may have retarded erosion and aided revegetation of the bar (Figure 12). A well-vegetated insular bar had developed by August 1962, confining the channel to a smaller width. Apparently, the minor flood of January 1964 (Table 3) eroded the concave bank slightly. Considerable concave bank erosion was again associated with the December 1964 flood.

The extent of streambank erosion may also depend on the duration and the rates of rise and recession of the major floods. Keller (1977, p. 40) observes that erosion generally follows floods when discharge drops rapidly, leaving "unsupported" groundwater in the bank. The groundwater positive pore pressure causes slumping of the stream bank into the channel, where it is removed by later flows. The slope of the falling limb of the hydrograph gives the rate of recession of the flood. Unfortunately, of the four or five floods associated with erosion of the south bank, only the 1955 and 1964

Figure 12: Migration of the Last Downstream Meander and Formation of an Insular Bar, Mouth of Redwood Creek, 1948-1962.



floods were gauged at Orick (Figure 13). If slumping were an important mechanism, rapid recession of the 1955 flood coupled with ebbing tides should have caused extensive streambank erosion.

Streambank erosion along the outer bend of a meander is a natural process in channel pattern evolution. Erosion of the last downstream meander in 1964 was not unusual, either in location or magnitude. Rip rap in the form of old car bodies was placed along the south bank in 1965 in an effort to protect the California-Pacific Mill and pastures from further erosion. The last downstream meander was cut off from the main channel by levees constructed in 1968.

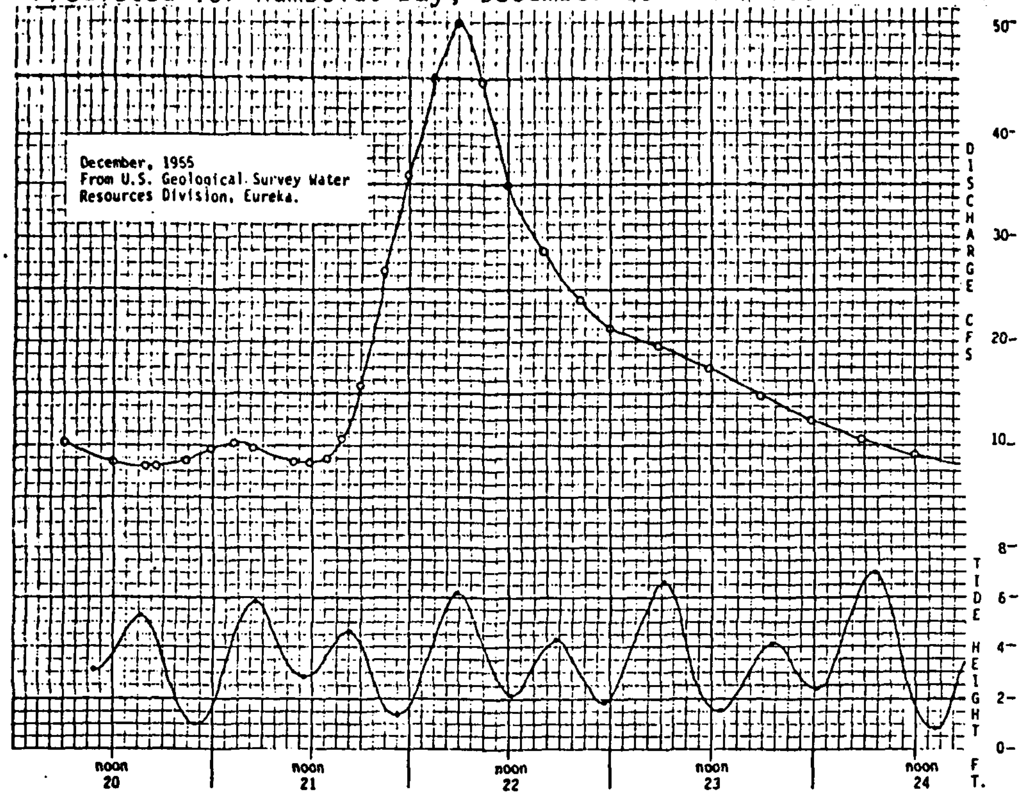
Many upstream reaches of Redwood Creek have aggraded and developed braided rather than meandering channel patterns. Channel widening and braiding will accompany the zone of maximum aggradation as it moves downstream. If rehabilitation measures lead to restoration of circulation through the last downstream meander, aggradation should be anticipated (Figure 14).

## Sedimentation in the Embayment

The embayment is the relatively deep, broad part of the estuary landward from the beach (e.g., Figure 10). In the embayment, water levels fluctuate with discharge, tides and the configuration of the outflow channel. The submerged area varies considerably with the water level, especially across gently sloping surfaces. In order to compare changes in sediment stored adjacent to the embayment, photographs with similar water levels were selected. Configurations of relatively stable features such as the fork in the north slough were compared to eliminate photos taken during high discharge or when the mouth was closed. However, long-term changes in stored sediment may not be quantified based on aerial photos measurements alone, since the water depths are unknown.

Sediment deposits along the west side of the embayment vary seasonally with wave transport and outlet configuration. For example, the unusually large emergent lobe of sand in the embayment following the 1931 summer season was probably deposited by tidal currents moving directly through a straight outlet (Figure 15). A

Figure 13: Peak Flows Gauged for Redwood Creek at Orick and Tides Predicted for Humboldt Bay; December 1955 and December 1964.



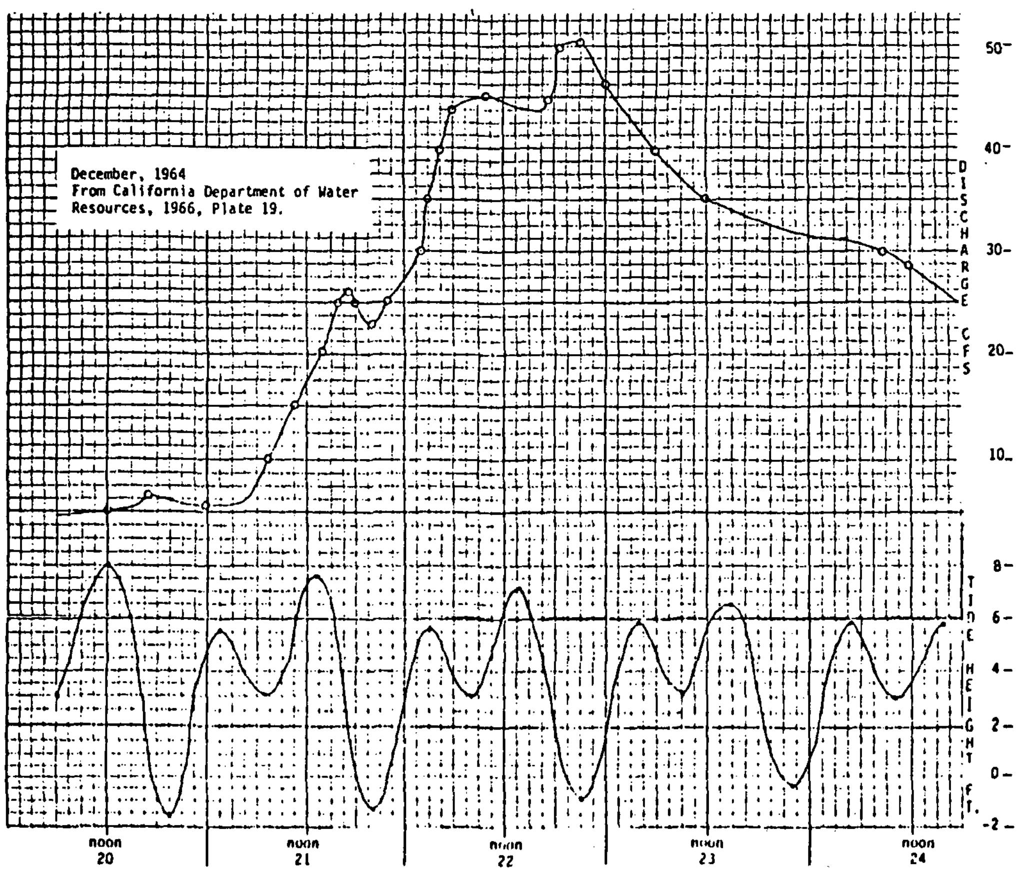
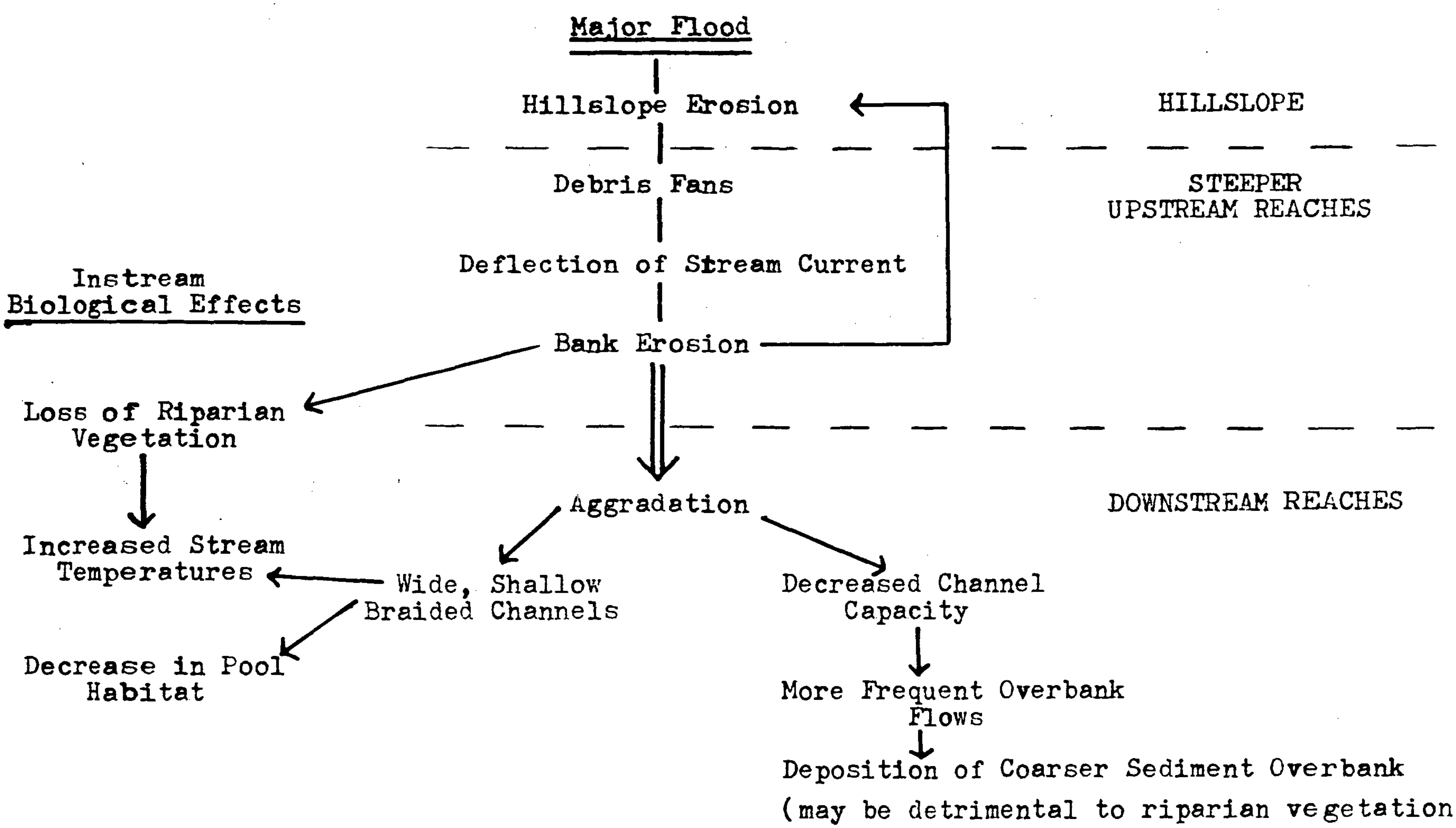



Figure 14: Effects of Aggradation (modified from Janda and others, 1975, Figure 56).



smaller deposit of this type was present in July, 1957 (Figure 16). Seasonal sedimentation processes, structures and morphology are documented in more detail in the following section.

Sediment accumulations along the east side of the embayment adjacent to the middle island, middle slough and north slouth (see Figure 10) persist through the seasons. The deposits have been modified by the complex interaction of river current eddies against the north cliffs, currents in the mainstem and middle slough as well as tidal height and wave energy. Despite the variability introduced by these interactions, there has been a noticeable trend toward accretion of sediment in the area between the middle and north sloughs (Figures 15-17). This trend probably results from flood transport of sediment from the basin.

Significant deposition between the middle and north sloughs was observed in aerial photos from January 13, 1965 (Figure 18). The slow recession of the 1964 flood contributed to extensive deposition across the entire floodplain (Figures 7 and 13). At the point of overbank flow, slight increases in the height or stage of a stream produce large increases in the inundated area. During flood recession, if high waves and/or storm tides back up the flow and increase the inundated area, velocity decreases. When the competence of sediment-laden flood waters declines, material is deposited in the embayment.

Several northern California stream gauging stations located near the coast are affected by tidally induced backwater (B. Hensel, 1982, personal communication). Although this effect has not been observed at the Orick Station, Wooldridge (1977, p. 16) suggests that marine storms induce enough backwater to "buffer" stages of major floods on Redwood Creek at a common peak level (Table 2). Wave and storm tide data are insufficient to evaluate this possibility.

Prior to channelization, floods scoured the channel adjacent to the north cliffs and removed beach deposits at the mouth. Along the north cliffs from Dorrence Creek to the west (DC, Figure 7) the water was at least 6 meters (20 ft) deep (White, Appendix A). The December, 1964 flood removed the beach berm from the north cliffs almost to the California-Pacific Mill site (Figure 18). The open

Figure 15: Embayment Shorelines, 1931-1948.

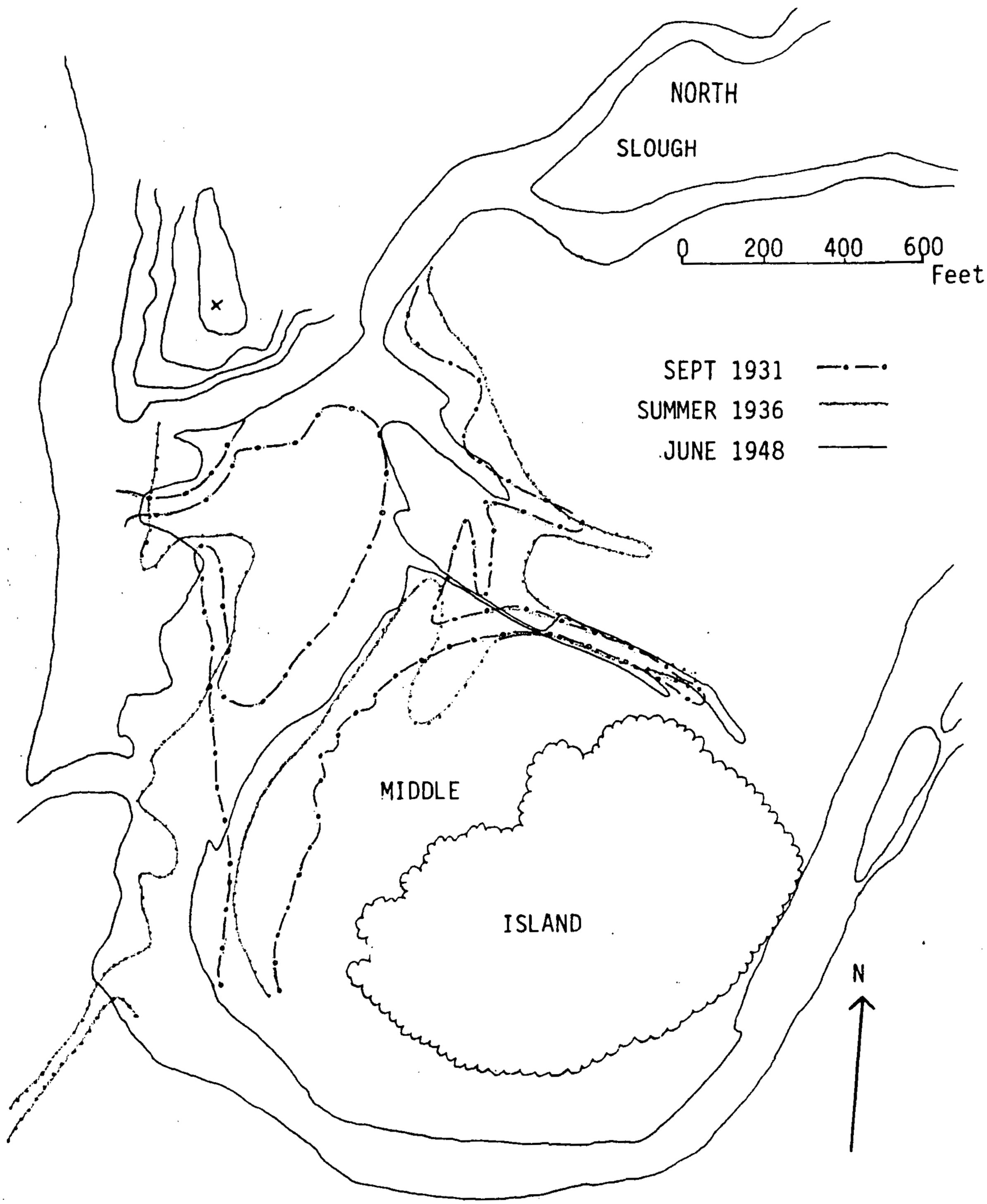


Figure 16: Embayment Shorelines, 1954-1958.

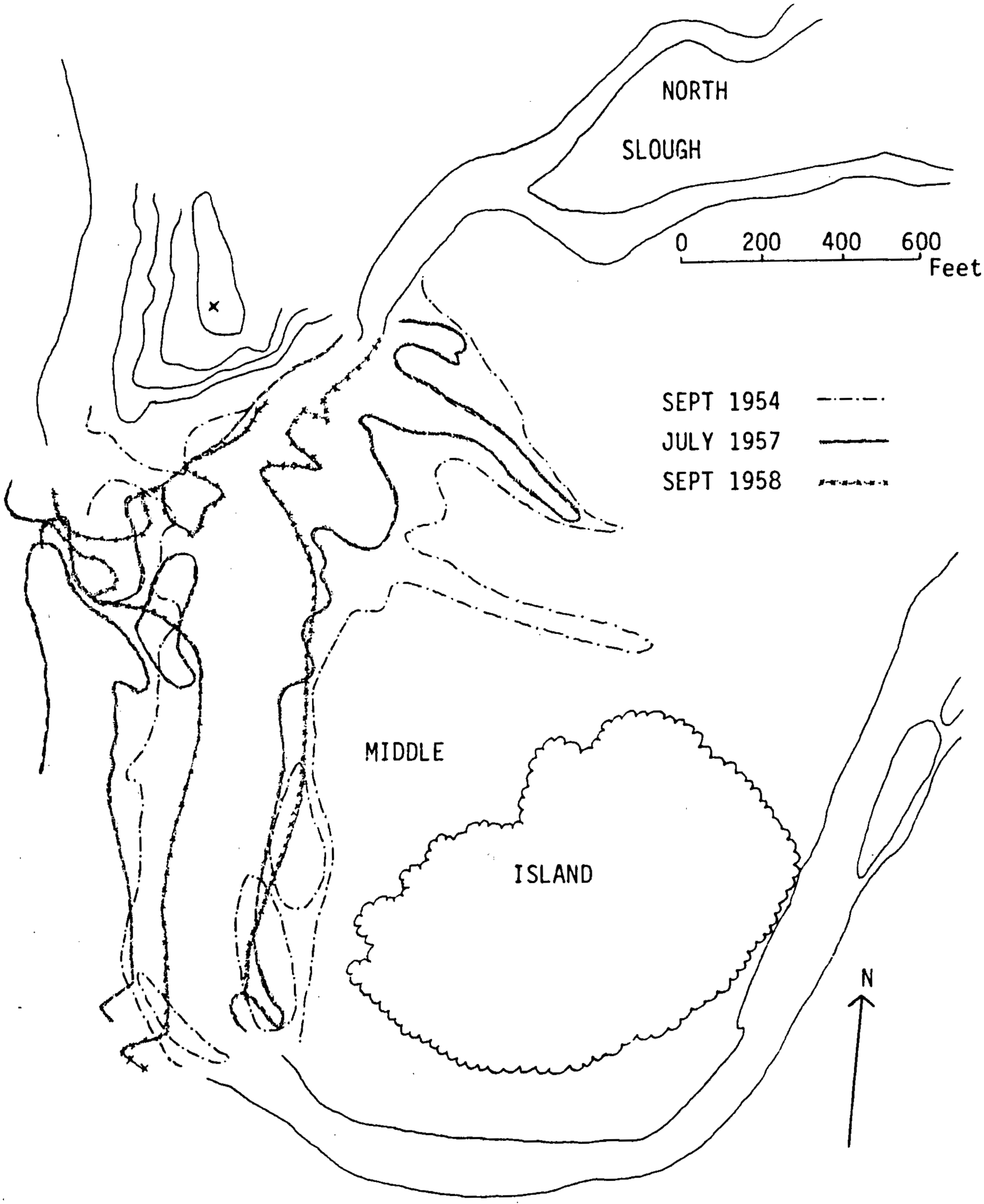


Figure 17: Embayment Shorelines, 1962-1967.

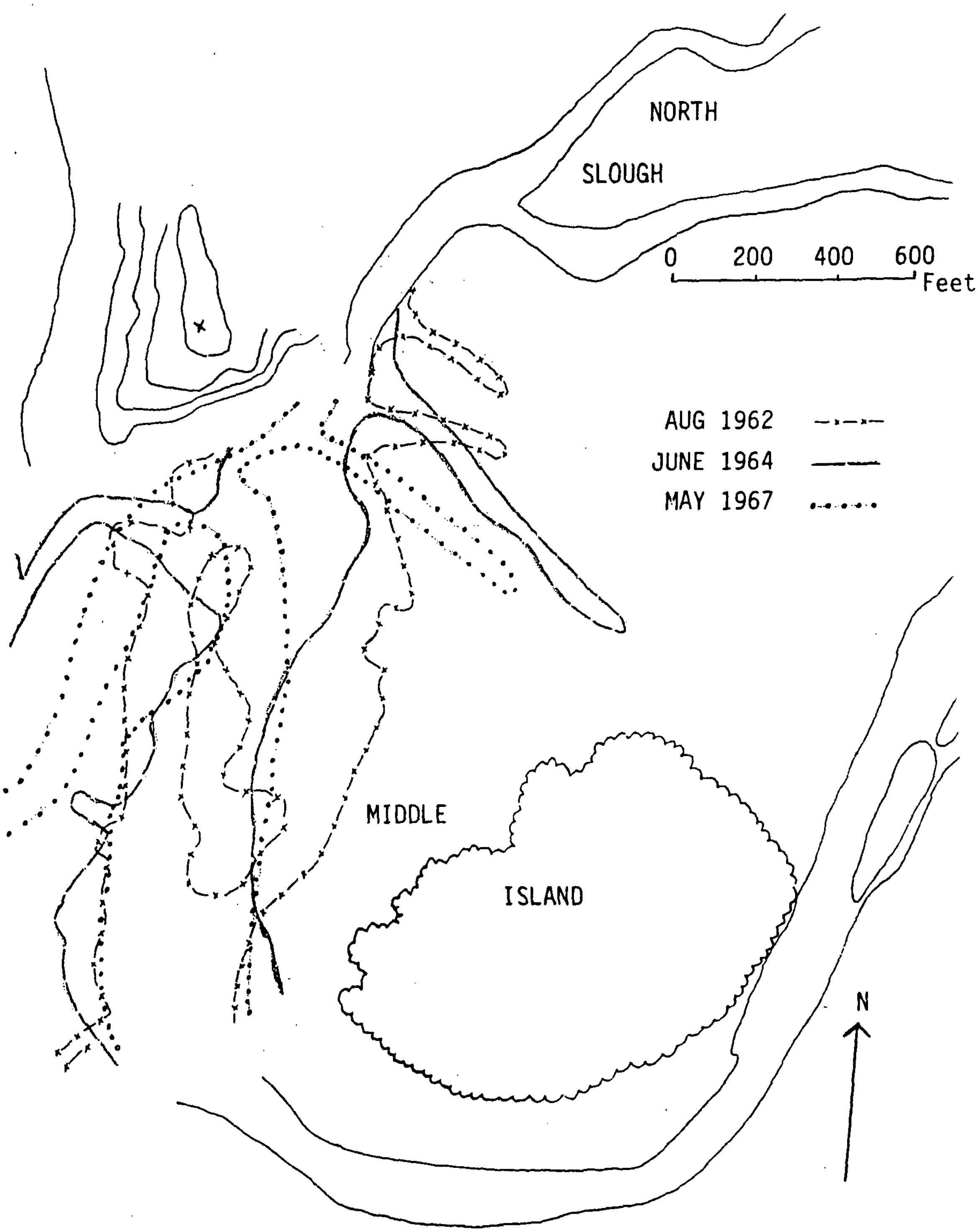
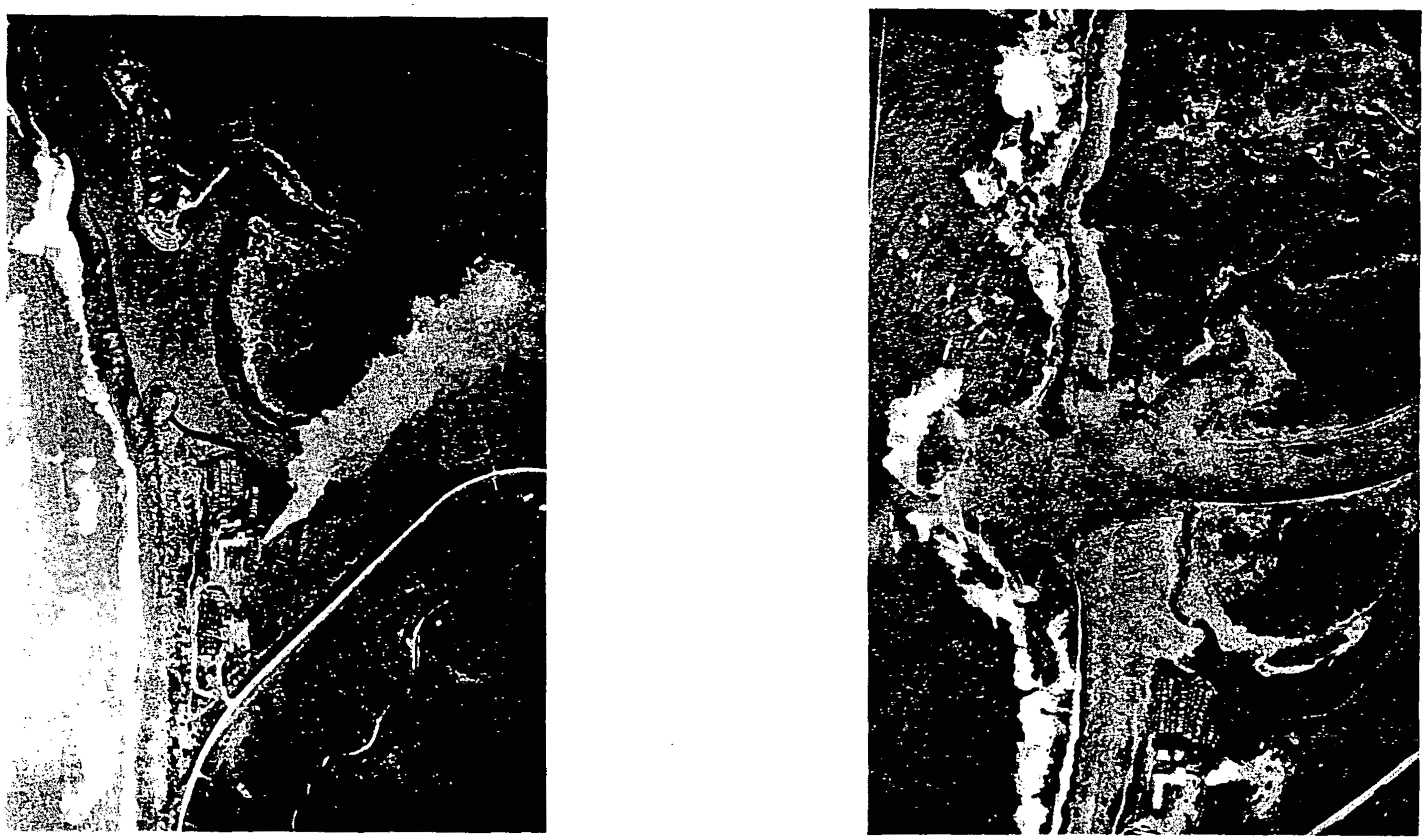


Figure 18: Aerial Photographs Showing Extent of Scour of Beach Berm Following Major Floods

a) January 13, 1965
following flood of December 15-23, 1964

b) March 7, 1972
following flood of March 1-4, 1972



mouth allowed waves to enter and break against the middle island (White, Appendix A). Waves were also observed propagating up past Baines' bend (BB, Figure 7) during other floods (S. Barlow, Appendix A). Wave diffraction created lobate deposits at the north and south extremities of the open mouth (Figure 18). Within two weeks after the 1964 flood, a new bar emerged offshore from south to north. Embayment deposits were subject to direct reworking by waves until the new bar formed across the mouth.

Long-term sediment accumulation adjacent to the embayment may result from fluvial transport in a more indirect sense. Sediment deposited in the nearshore zone during floods is available for onshore transport. Sediment redeposited by waves between the middle and north sloughs would be less likely to be eroded from the embayment during winter flows.

## Effects of Channelization

### Direct and Immediate Impacts

Local pressure 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 kilometers (3.2 mi), from the confluence with Prairie Creek to the mouth, between April, 1966 and October, 1968 (Figure 2). The narrow trapezoidal channel was designed to contain a peak discharge of 2,180 $m^3$/sec (77,000 cfs), about 50 percent larger than the peak flow of record (U. S. Army Corps of Engineers, 1961, 1966). Bulldozers were used to remove riparian vegetation, destabilize gravel bars and excavate a trapezoidal channel. Dredge spoils were deposited adjacent to the levees. Levee construction resulted in the loss of diverse habitats associated with pool and riffle structure and the riparian zone.

The lowermost section of the levee extended beyond the last downstream meander, leaving a south slough with little circulation. The channel gradient was increased from 0.07 percent to 0.14 percent by removing the meander and excavating the channel to the design slope. The change in mean flow velocity is given by the Manning equation (Blatt, Middleton, and Murray, 1972; p. 87):

$$V = \frac{R^{2/3} \; S^{1/2}}{n} \text{ (metric units)}$$

The hydraulic radius R, equals A/P, the cross-sectional area divided by the wetted perimeter. Increases in slope(S) are not directly transferred to an increase in flow velocity, since the bed roughness factor n, will also adjust. Bed roughness is a function of median grain size, bedforms, and other roughness elements such as streambank vegetation. The combined effect of removing roughness elements, increasing the hydraulic radius by shaping a trapezoidal channel, and increasing the slope, is to increase the mean flow velocity. The resultant increase in the stream's competence to transport sediment causes the substrate between the levees to be mobilized more frequently.

Indirect and Cumulative Impacts

Sediment accumulated rapidly in the abandoned meander, now the neck of the south slough. By March 1972 (Figure 18) wave overwash had filled the old channel east of the beach berm. Mouth Profiles Y and Z (Map Plate 1, Figure 19) illustrate the amount of accumulation across the berm and in the south slough neck since the 1966 Army Corps survey. The small outlet from the south slough established its present position between June 1976 and May 1978 (Figure 20). Aerial photos from May 1978 and September 1981 show recent deposition at the south end of the neck of the south slough. Continued filling in this area is evident from South Slough Profile A (Figure 21), and from field observations of sedimentary structures following a minor 740 $m^3$/sec (26,000 cfs) flood in December, 1981.

Prior to channelization, water depths of at least 6 meters (20 ft) along the north cliffs (White, Appendix A) apparently prevented the Army Corps from surveying the neck of the north slough. Most of the sediment accumulated in the north slough neck between March 1972 and September 1974. Between September 1974 and May 1978, the outlet channel across the neck migrated to its present (1981)

Figure 19: MOUTH PROFILE Y

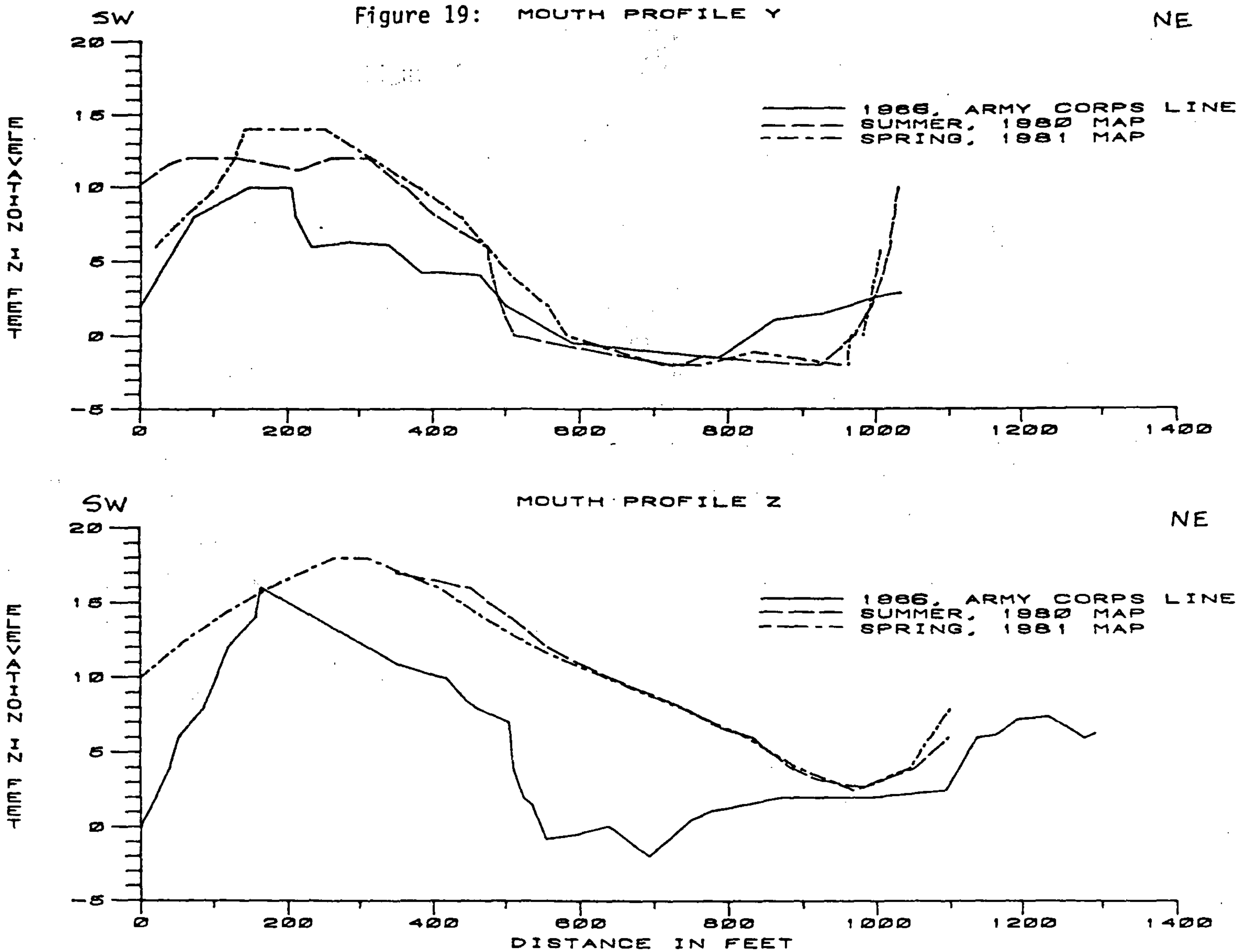


Figure 20: Vertical Aerial Photograph, Mouth of Redwood Creek, May 3, 1978.

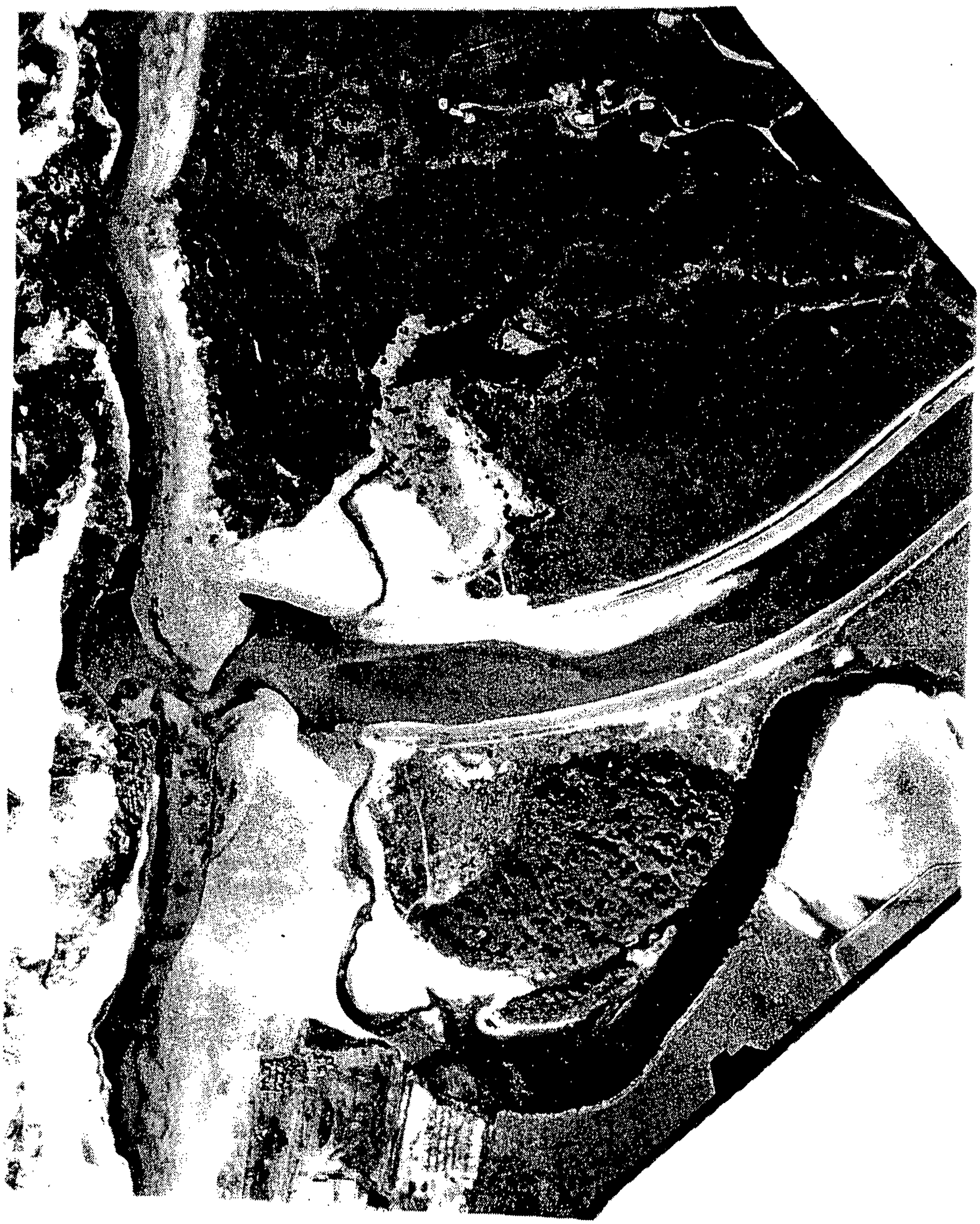
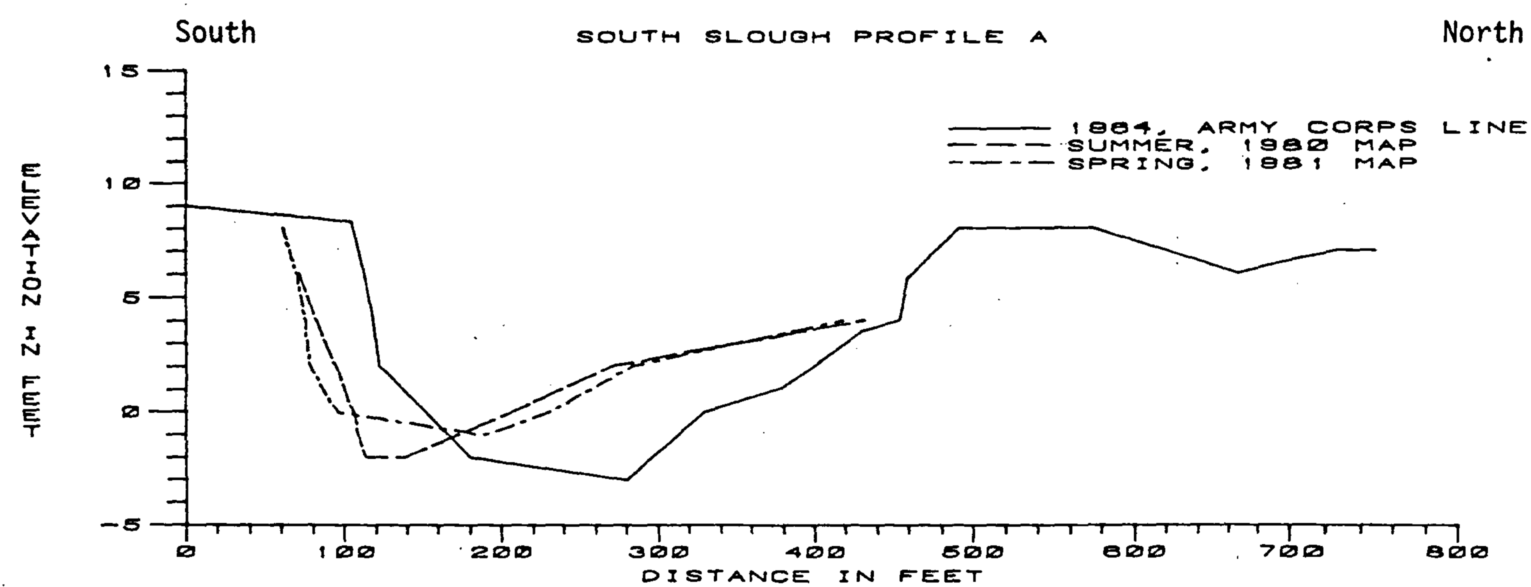


Figure 21: South Slough Profile A.



position. Across Mouth Profile X (Figure 22), 0.6-1.8 meters (2-6 ft) of sediment accumulated between 1964 and 1979, although the elevation of the subaerial deposit varies from year to year due to its direct exposure to waves.

River Station Profiles 9 through 15 (Figures 23 and 24) illustrate the amount of aggradation between the levees since the design channel was excavated. Griggs and Paris (1982) found that aggradation along the lower San Lorenzo River lowered the stream gradient toward the pre-channelization equilibrium value. This process also reduced the theoretical capacity of the flood control project. The stream gradient along Redwood Creek between each of the River Station Profiles is quite variable, and a more detailed longitudinal survey is needed between the levees. Channel surveys from approximately 2.3 kilometers (1.4 mi.) upstream of the mouth to the Highway 101 bridge (M.A. Madej, 1981, written communication) showed a decrease from the design gradient, 0.14 percent, to 0.11 percent in 1980.

Since the Corps of Engineers' 1964-66 surveys, 47-54 percent of the estuary below Corps Station 34+00 (Figure 2), between 0 and 4 feet above MSL, has filled with sediment or become isolated from the embayment (Appendix I). Presently, the volume of the lower estuary at the end of each rainy season varies with the peak flow for the year. By confining the flow of Redwood Creek between levees, a trap for sediment was created in the backwater areas. Minor flows from Strawberry and Sand Cache Creeks (SC, SD, Figure 7) provide the only circulation and flushing of sediment from the sloughs.

The levees constrict the streamflow so efficiently that a very limited section of the beach berm is scoured by floods. Steep escarpments in the berm mark the limits of scour, particularly on the south side. Aerial photos show the maximum extent of scour along the berm from the December 22, 1964 flood (1,430 $m^3$/sec) and the March 3, 1972 flood (1,410 $m^3$/sec) (Figure 18).

Channelization may also have altered the configuration of nearshore deposits. Prior to levee construction, Redwood Creek flowed around the last downstream meander and exited to the north during high discharge. The 1964 flood scoured down to previously unexposed rocks immediately offshore to the north of the mouth.

Figure 22: Mouth Profile X.

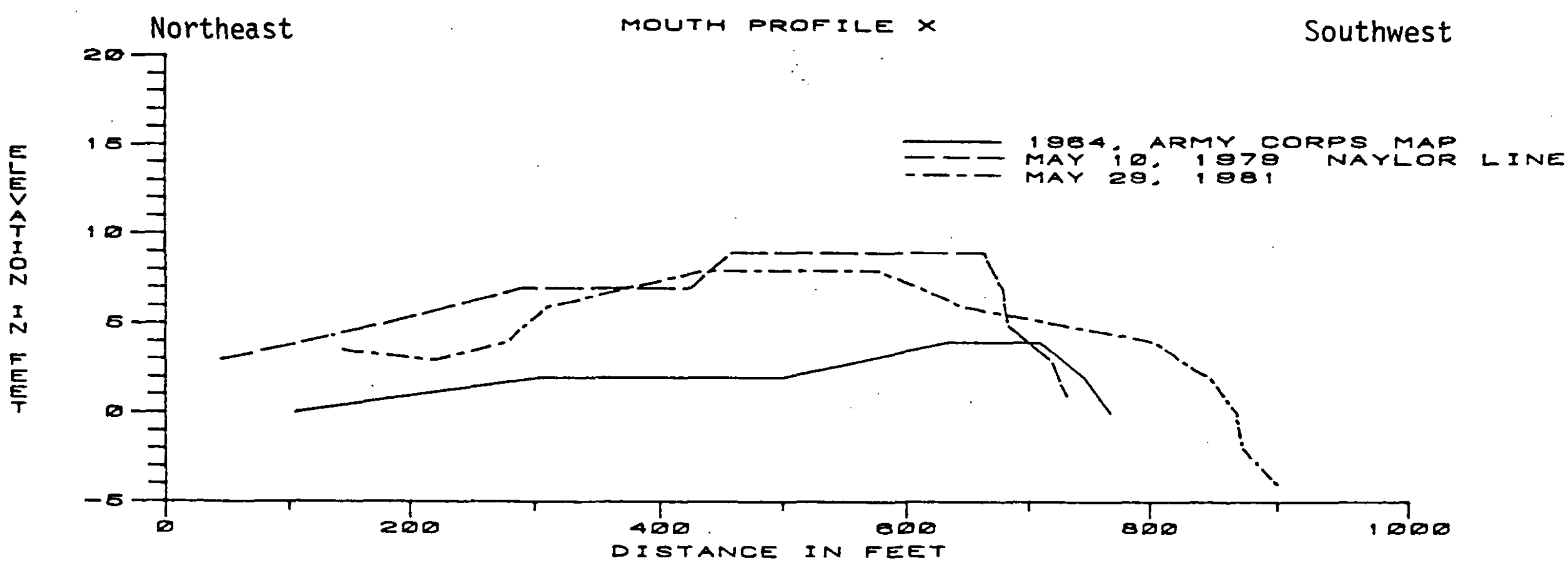
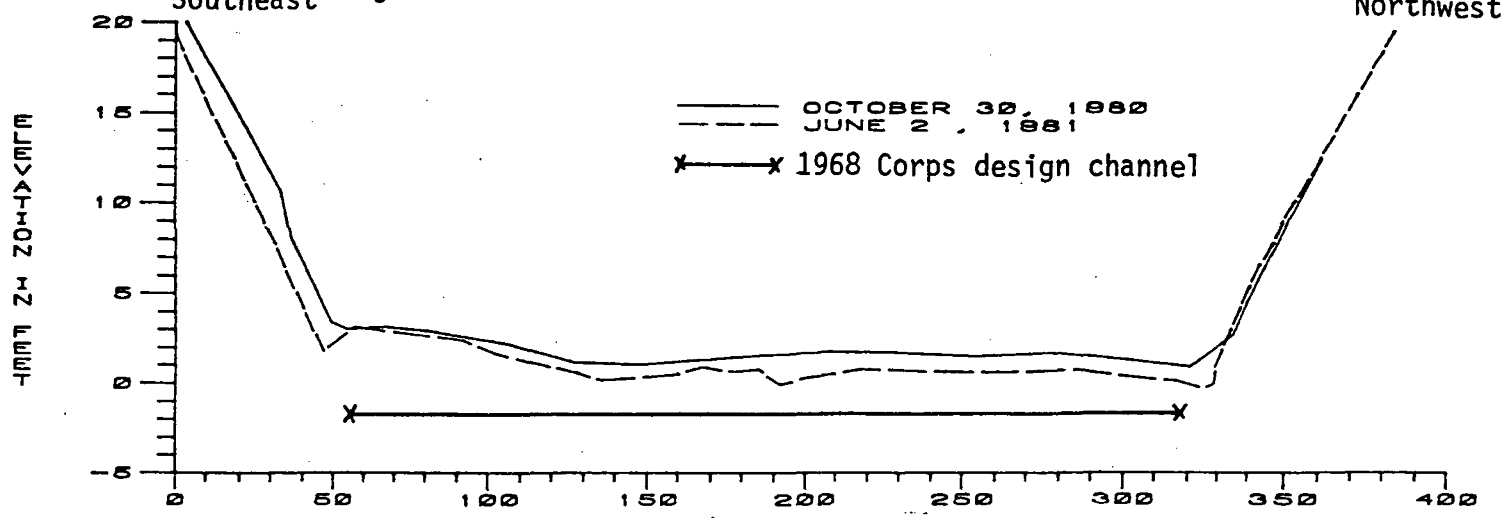


Figure 23: RIVER PROFILE STATION NINE




RIVER PROFILE STATION ELEVEN

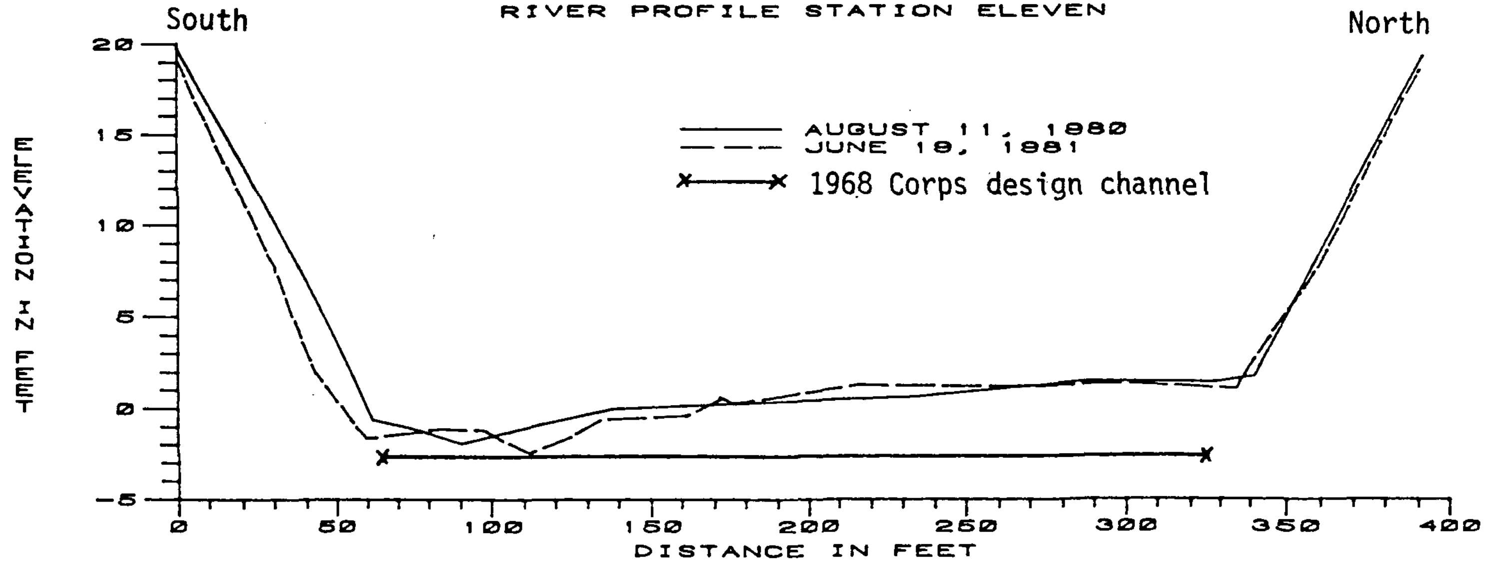
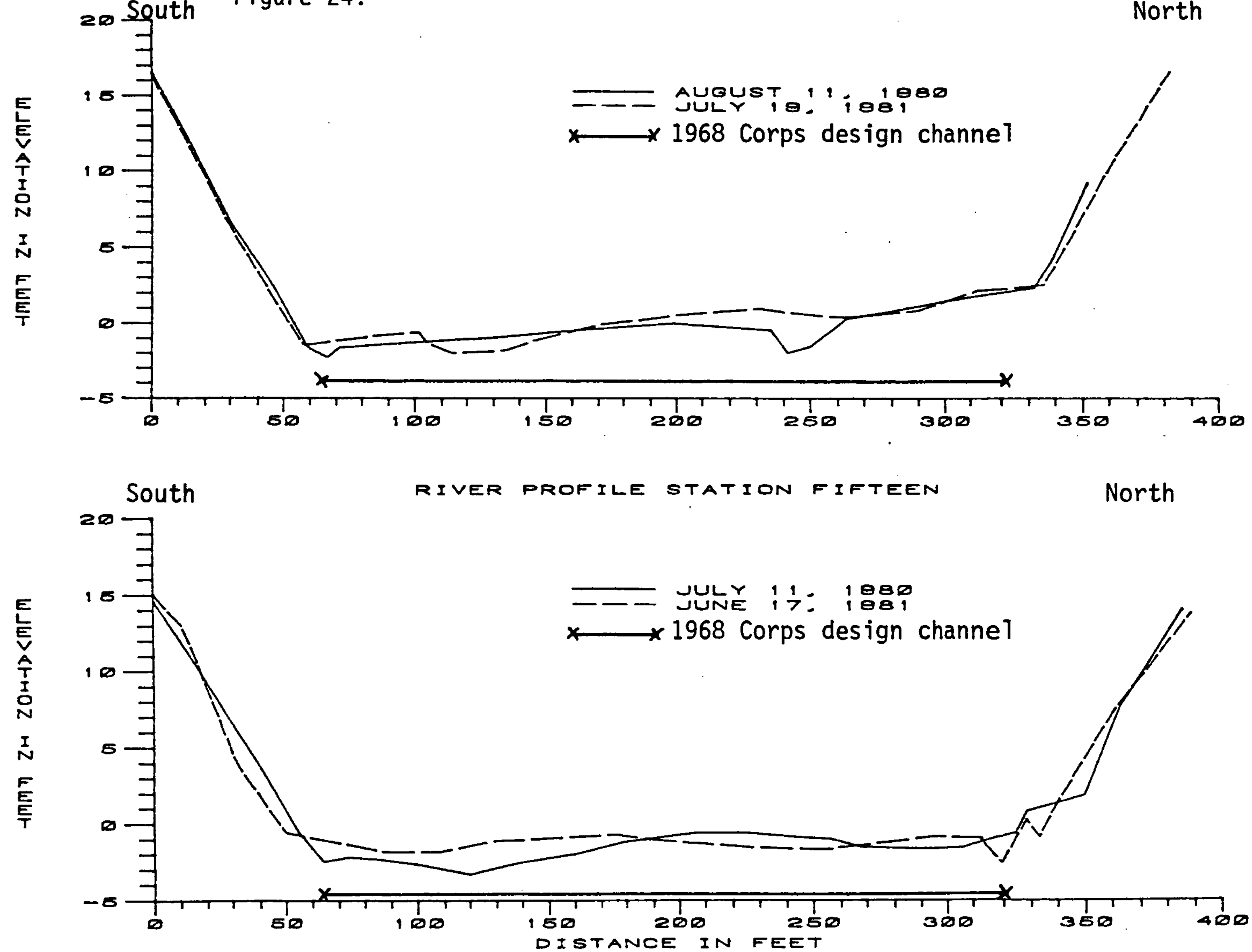


Figure 24: RIVER PROFILE STATION THIRTEEN



Channelized peak flows presently deposit more sediment directly to the west of the mouth. Winter storm waves approaching from the southwest resuspend the nearshore deposits. Westward movement of the bulk of the nearshore deposits due to channelization could consequently affect the amount of Redwood Creek sand mobilized by longshore drift.

## Summary

### Flood Magnitude and Frequency

1. Historic records and local accounts of rainfall and flood magnitudes indicate that the floods of 1861-62 and 1890 had peak flows which were comparable to or greater than the 1953 to 1975 series of damaging floods.

2. In the vicinity of Orick, the Redwood Creek channel was narrow and deep prior to 1953, according to local residents. The Corps of Engineers initiated several bank protection projects along this reach following the 1953 and 1955 floods. Channel widening and aggradation is also evident from aerial photos taken during this period.

3. The December 1964 flood was the most damaging event of the century, particularly in the upper basin. Along the lower floodplain, the 1964 flood deposited twice as much sand and silt as the 1955 flood due to its greater volume of runoff, longer duration and slower recession rate. Failure of the Chapman/Army Corps dike during the 1964 flood may have been responsible for thicker and coarser sediments being deposited on the north side as compared with the south side of the floodplain.

### Floodplain Morphology and Dendrochronology

1. The maximum spruce age of 98 years suggests that the grove began to develop on the middle island following the 1861-62 floods.

However, the immaturity of the stand could also reflect an early unrecorded harvest or recovery from disease.

2. The all-aged distribution of spruce on the middle island probably results from recurrent scouring of flood channels and progressive migration of the last downstream meander. Recent overflow channels on the middle island have been invaded by red alder.

Streambank Erosion and Migration of the Last Downstream Meander

1. From 1936 to 1967, the south bank of the last downstream meander eroded at a rate of less than 2.1 meters/year (6.9 ft/yr).

2. Streambank erosion was associated with floods having peak discharges of 1,065 $m^3$/sec (37,700 cfs) or greater.

3. Discontinuous rates of concave streambank erosion and accretion and revegetation of the convex bank suggest that the meander tended to maintain an equilibrium channel width from 1953 to 1964.

4. The potential for aggradation and streambank erosion should be considered in designing rehabilitation alternatives which include restoration of circulation in the last downstream meander.

Sedimentation in the Embayment

1. Aerial photos 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.

2. The 1964 flood scoured the embayment and the beach berm from the north cliffs almost to the California-Pacific Mill site.

3. The open mouth allowed waves to break against the middle island, which may have augmented deposition between the middle and north sloughs.

Effects of Channelization - Direct and Immediate Impacts

1. Riparian vegetation, which supplies nutrients and streamside protection for fish and which reduces instream temperatures, was removed.

2. Levees were extended beyond the last downstream meander, leaving a south slough with little circulation.

3. Increasing the stream gradient, removing bed roughness elements, and shaping a trapezoidal channel increased the mean flow velocity between the levees. Sediment is therefore transported more efficiently through the mouth and the substrate is less stable.

Effects of Channelization - Indirect and Cumulative Impacts

1. Aggradation between the levees has lowered the stream gradient toward the pre-channelization equilibrium value, possibly reducing the theoretical capacity of the flood control project.

2. Since the Corps of Engineers 1964-66 surveys, 47 to 54 percent of the lower estuary (below Corps Station 34+00 and betwee 0 and 4 feet above MSL) has filled with sediment or become isolated from the embayment.

3. Channelization may have also altered the distribution of sediment in the narshore environment, which could affect the amount of Redwood Creek sediment mobilized by longshore drift.

# SEDIMENT SOURCES AND TRANSPORT PROCESSES

## Methods

Periodic observations of storm conditions, sedimentary structures, distribution of large organic debris and changes in morphology were collected at the mouth of Redwood Creek from November, 1979 to January, 1982. Frequent field observations were necessary to document morphological changes which often occurred during short-lived, high energy storms. Graphs of daily discharge, maximum daily tide height and wave power were constructed for each month from January, 1980 through January, 1982 (Appendix E). These graphs provide the means to examine differences between the two years of field observation, identify extreme events during this period and evaluate conclusions based on these years with respect to the effects of future storm events.

Data on daily discharge of Redwood Creek at the Orick gauging station are available from published annual reports (U. S. Geological Survey Water Resources Division, 1980, 1981, 1982) and unpublished values from the U.S. Geological Survey Water Resources Division, Eureka. Shift adjustments and rating curves were applied to gauge heights to obtain hourly discharge values for storms of interest. Maximum daily tides predicted for Humboldt Bay were plotted without corrections for height or time (U.S. Department of Commerce, 1980, 1981, 1982).

The Nearshore Research Group at Scripps Institute of Oceanography installed a WAVERIDER accelerometer buoy to record deep water wave energy offshore from Humboldt Bay in March, 1980. The buoy data were polled at 6-hour intervals, analyzed for wave height and period distribution, and published monthly (Seymour and others, 1980, 1981, 1982). Wave power was calculated from these data using the equations described in Appendix F. Wave power was calculated for the monthly graphs since wave energy during a storm is a function of both wave height and period.

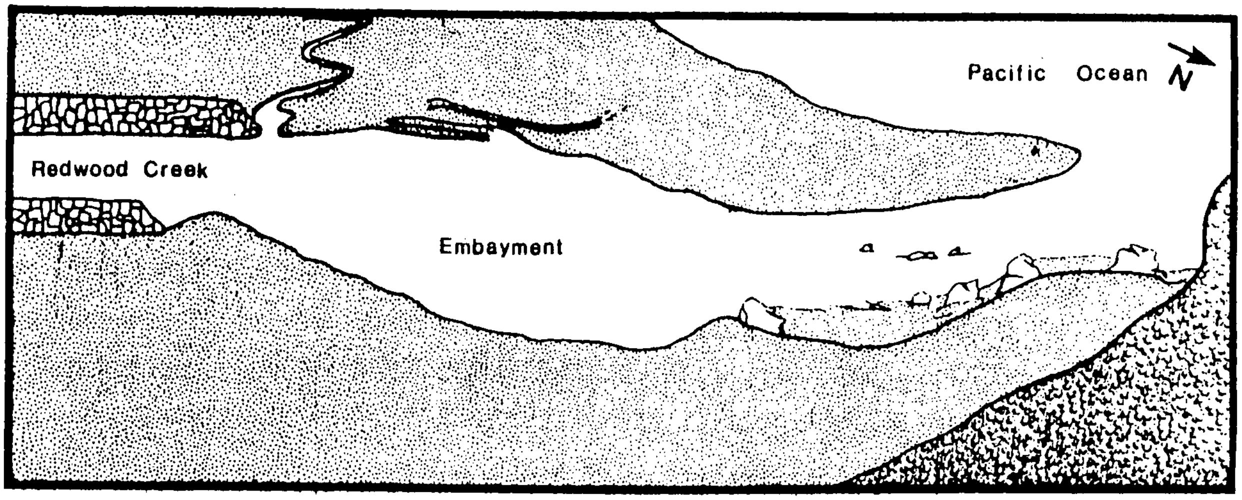
Marine storms at the mouth of Redwood Creek may be compared in a relative sense using the wave power values. However, the actual wave power is affected by the distance of the WAVERIDER station from the mouth of Redwood Creek, the lack of directionality in the data, and diffraction and refraction during shoaling. Wave energy also varies with the velocity of onshore winds which pile up waves against the shoreline, creating a storm surge.

Oblique views of the mouth of Redwood Creek were periodically photographed from the top of the north cliffs (location labelled with an X on Figure 10) between November 1979 and January 1982. Three of these photo sequences which illustrate seasonal changes in configuration were sketched (Figure 25). Morphological comparisons were also facilitated by vertical and oblique aerial photographs.

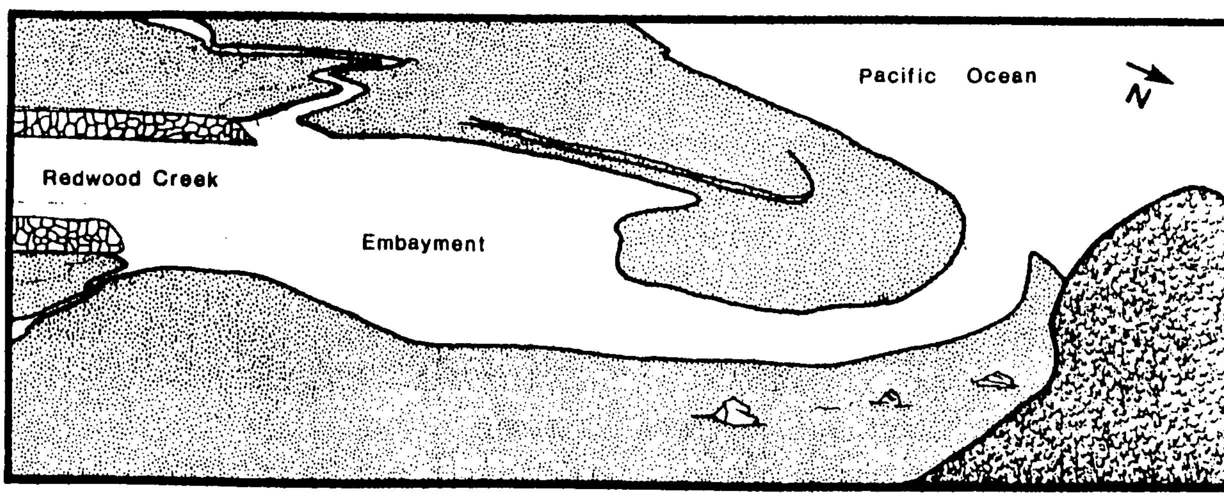
Sediment transport, flow duration and particle size plots for Redwood Creek at Orick were employed to determine the proportion of the annual suspended sediment load and bedload with potential for storage in the estuarine and beach environments. Suspended sediment transport curves constructed by J. R. Crippen (U.S. Geological Survey, 1981, written communication) for WY 1978-80 were used to obtain ranges of daily suspended sediment discharge for corresponding water discharge intervals. The percentage of time that each water discharge interval occurred was obtained from recent streamflow duration curves provided by M. Weston (U.S. Geological Survey Water Resources Divison, Eureka). Hydrographs from five major floods gave estimates of duration of streamflow for discharges greater than 710 $m^3$/sec (25,000 cfs). Daily suspended sediment discharge (SSD) ranges corresponding to each water discharge interval were multiplied by the number of days of occurrence to yield ranges of annual SSD. Table 4 includes the results of these computations.

Bedload transport curves were not available due to the broad range of bedload discharge for a given water discharge, reflecting the difficulty of sampling bedload. Sediment in transit within 0.08 meters (0.25 ft) of the bed surface (U.S. Geological Survey Water Resources Division, 1974, 1975, 1976, 1978) was plotted against instantaneous discharge, producing a very crude sediment transport curve. A broad range of annual bedload discharge was calculated, again using the flow duration curve.

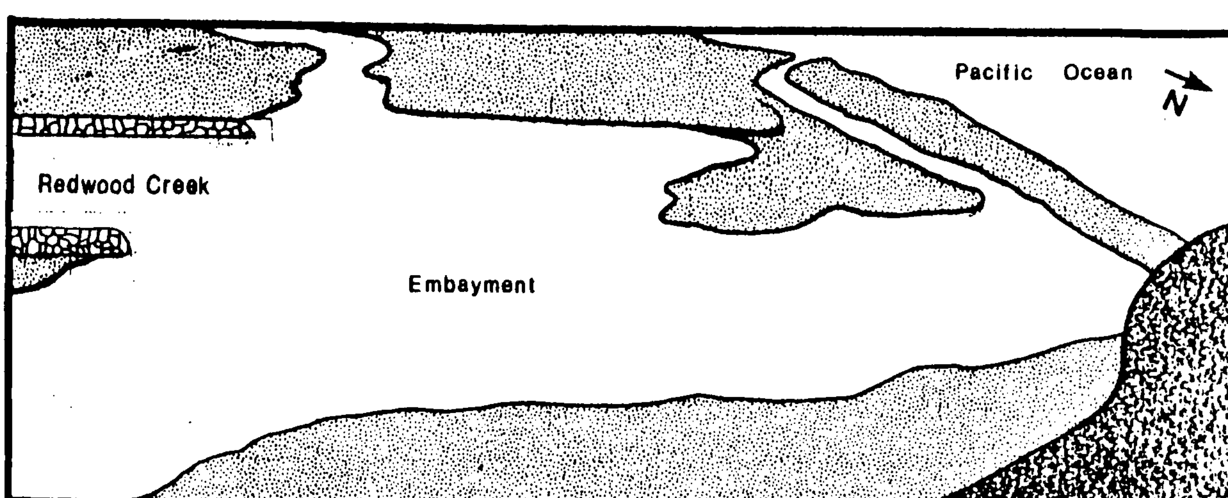
Figure 25: Mouth of Redwood Creek, Oblique Views From Top of North Cliffs to the South




(a) January 12, 1980




(b) April 19, 1980




(c) June 14, 1980

The proportion of sand in the suspended sediment and in the bedload was found by graphing particle size versus water discharge in the format used by Brown and Ritter for the Eel River at Scotia, California (1971, p. 35). For suspended sediment samples, the percentages of particles finer than 0.062 mm (sand-silt break) and 0.0004 mm (silt-clay break) were plotted against instantaneous discharges (U. S. Geological Survey Water Resources Division, 1974-1980). Only the 2.0 mm gravel-sand break was plotted for bedload samples (U. S. Geological Survey Water Resource Division, 1975, 1976, 1978, 1980 and M. A. Madej, 1980, unpublished data). Because these graphs show high variability in relations between sediment and water discharge, the maximum and minimum percentages of sand were used for each water discharge interval.

The lower values of the annual suspended sediment load and bedload calculations agree with J. R. Crippen's 1981 estimates (Table 4). Therefore, for each water discharge interval, the annual suspended sediment and bedload values were adjusted to the lower end of the range before computing the percentage of sand. Table 4 shows the total amount of suspended sand transported at all of the water discharge intervals for suspended sediment and for bedload. The total bedload was added to the suspended sand load to compute the proportion of sand and gravel in the sediment.

During the period of field observation, the symmetry, orientation, crest length, width, and form of ripples, megaripples, and sand waves were noted whenever encountered. Internal structures of some surface features were box cored and x-rayed using techniques developed by Clifton, Hunter, and Phillips (1971, p. 654-5). However, x-raying was discontinued due to the poor definition of structure in the coarse-textured sediment. Trenches were excavated to depths of 0.6-0.9 meters (2-3 ft) to examine internal structures of interest.

Two experiments designed to measure rates of sedimentation by berm overwash and tidal currents were unsuccessful. Overwash occurred at high tide on several occasions in late September, 1980. During this period, the crest and slope of the overwash surface was carefully surveyed prior to one of the highest tides. Unfortunately,

TABLE 4: Proportions of Sand and Gravel in Suspended Sediment and Bedload from Redwood Creek @ Orick

Sediment loads in Tonnes/yr
(Tons/yr)

| | |
|---|---|
| Annual suspended sediment discharge<br>Range from flow duration curve, 1982, and sediment transport curve, 1978 - 1980 1978 | Annual bedload<br>Range from flow duration curve, 1982, and instantaneous sampling 1974 - 1976, |
| 1,330,000 - 2,790,000 | 43,000 - 646,000 |
| (1,470,000 - 3,070,000) | (47,000 - 712,000) |
| From J. R. Crippen, 1981, written communication, for Water Years 1954 to 1980 | |
| 1,340,000 | 173,000 |
| (1,480,000) | (191,000) |
| Annual suspended sand discharge<br>Particle size data, 1974 - 1980 | Annual discharge of sand in bedload<br>Particle size data, 1975, 1976, 1978, 1980 |
| 860,000 - 1,130,000 | 62,000 - 96,000 |
| (950,000 - 1,240,000) | (68,000 - 106,000) |
| 65% - 84% of total suspended load | 36% - 55% of total bedload |

Annual sand discharge

930,000 - 1,220,000

(1,020,000 - 1,340,000)

62% - 81% of total suspended and bedload

Annual sand and gravel discharge

1,040,000 - 1,310,000

(1,150,000 - 1,440,000)

69% - 86% of total suspended and bedload the wave height at the time of the tide was insufficient to wash over the crest.

A plexiglass sheet was buried beneath 22 centimeters (8.5 in) of sand at an upper intertidal site in the north slough where tidal ripples were present. Holes were drilled in the sheet to allow water penetration and a float was attached to relocate the site. The experiment was vandalized before any significant scour or fill could be measured.

Organic debris located south of the north cliffs was photographed to document movement resulting from marine storms. All debris exceeding 0.3 meters (1.0 ft) in diameter along North Slough Profile A (Map Plate 1) was mapped, tagged, and described. Later, the tagged debris was relocated to evaluate the extent and direction of movement.

Sieve analysis and heavy liquid separations of selected surface samples were used to delineate substrate grain size distribution and to distinguish among sediment sources by heavy mineral variations. The Klamath River, Prairie Creek, Gold Bluffs unit, Redwood Creek, and beaches to the north and south were also sampled to characterize lithologically distinct heavy mineral sources.

River sands were sampled along point bars and beach samples were generally obtained from the middle of the swash or intertidal zone. In the estuary, samples were spaced at approximately equidistant sites along the surveyed profiles. Due to changing water levels and availability of sampling equipment during summer, 1980, 60 samples were taken from the estuary at different times (Map Plate 2). In spring, 1981, when streamflow and tidal conditions were favorable, 26 estuarine samples were obtained. Subaerial samples were scooped to a depth of 2 centimeters (1 in) into a plastic bag. Four underwater sampling methods included scooping carefully into one side of a box corer, free-diving scoops into a plastic bag, an Eckman dredge used in conjunction with invertebrate sampling, and a clam-shell type gravity sampler. In retrospect, a sampling box similar to the one designed by Boggs (Jones, 1972) would have standardized and reduced the loss of fines under deep water sampling conditions. Gravel or debris was often caught in the jaws of the clam-shell grab, releasing some of the sample (samples designated *, Appendix G).

Muddy samples were air dried, weighed, and wet sieved to remove the less than 0.0625 mm fraction. The samples were redried and weighed to obtain a rough percentage of mud by subtraction. Salts were removed from beach sediment by rinsing several times in tap water.

After drying, samples were split into 30-90 gram subsamples and weighed to 0.01 gram. The subsamples were dry sieved at one phi ($\phi$) intervals for 15 minutes in a Ro-Tap mechanical sieve shaker and reweighed. Aggregates were noted when present and the weight percentage of each size class calculated (Appendices G, H and I).

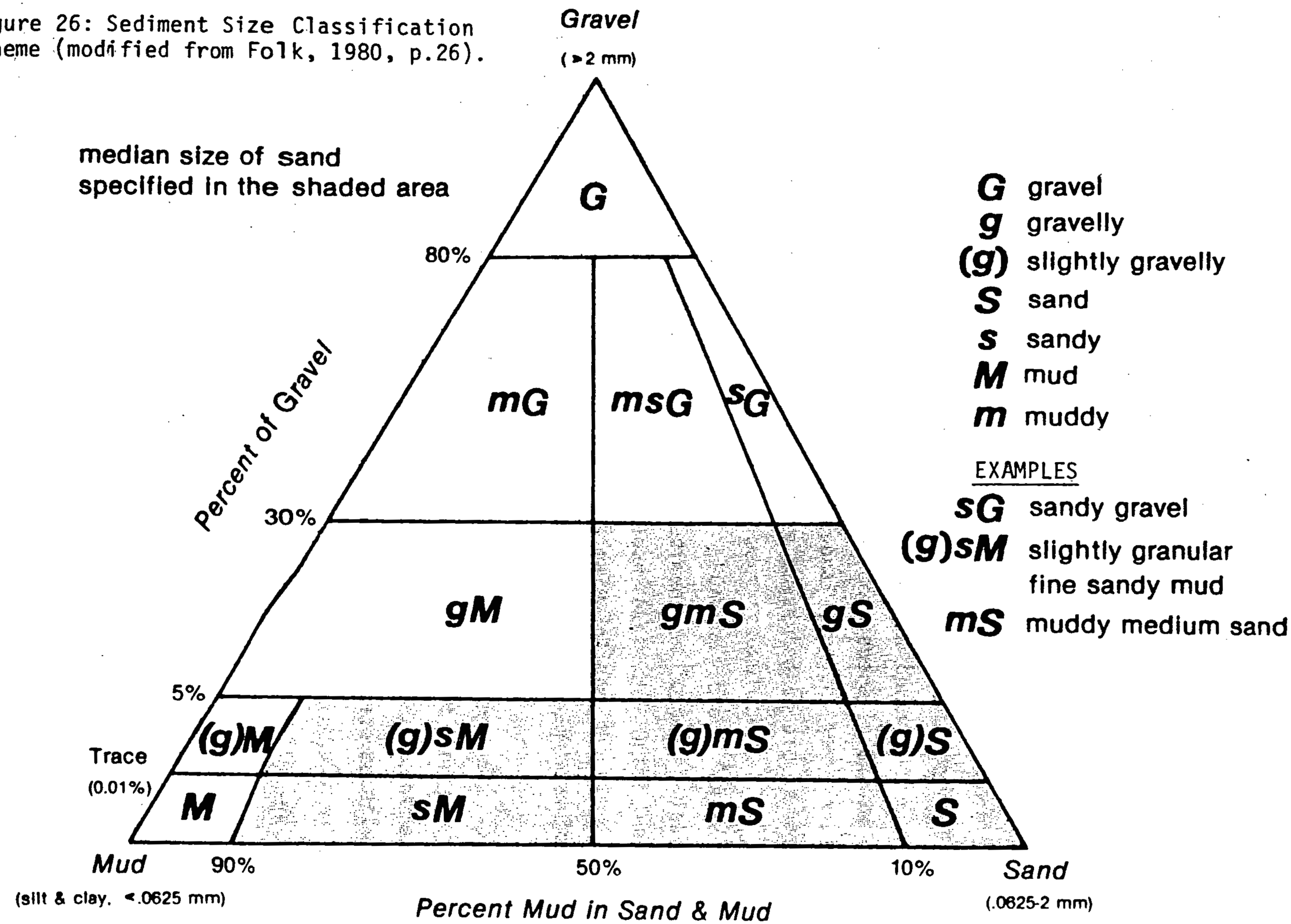
Sediment size distribution maps were constructed by Folk's (1980, p. 30-31) method of contouring the percent mud of the total sand plus mud (equivalent to Folk's sand:mud ratio) and the percent gravel. The size classification scheme is shown on the triangular diagram modified from Folk (1980)(Figure 26). The size patterns on Map Plates 2 and 3 depict different fields from the triangular diagram.

The heavy mineral fraction of the 0.250-0.125 mm size interval was separated by gravity settling in tetrabromoethane (specific gravity = 2.96). The percentage of heavy minerals in two to three grams was determined for 56 samples. Several samples which may have spilled during transport from the lab are designated * in Appendix J. Microsplits of the heavy fraction were mounted in Canada balsam on glass slides and cured in a 60°C oven for three days.

Preliminary identification of heavy minerals from Redwood Creek and a nearby beach revealed that strongly pleochroic blue-green hornblende is abundant in the beach sample but comprises only a few percent in the Redwood Creek samples (C. Peterson, 1982, personal communication). Using this indicator mineral rather than identifying all minerals facilitated rapid analysis of many samples. Two other easily identified minerals, glaucophane and garnet, were also noted when present.

In preparation for counting, the microscope slides were renumbered to eliminate investigator bias. At least 200 non-micaceous grains were counted on each slide. In most samples, when the opaque and micaceous grains were excluded from the count, the blue-green

Figure 26: Sediment Size Classification Scheme (modified from Folk, 1980, p.26).



hornblende content changed by less than two percent. However, the non-opaque, non-micaceous count was tabulated for the opaque-rich Klamath River Beach sample (0-01, Appendix J). Blue-green hornblende percentages for several slides were recounted to check for reproducibility, and all varied by less than three percent.

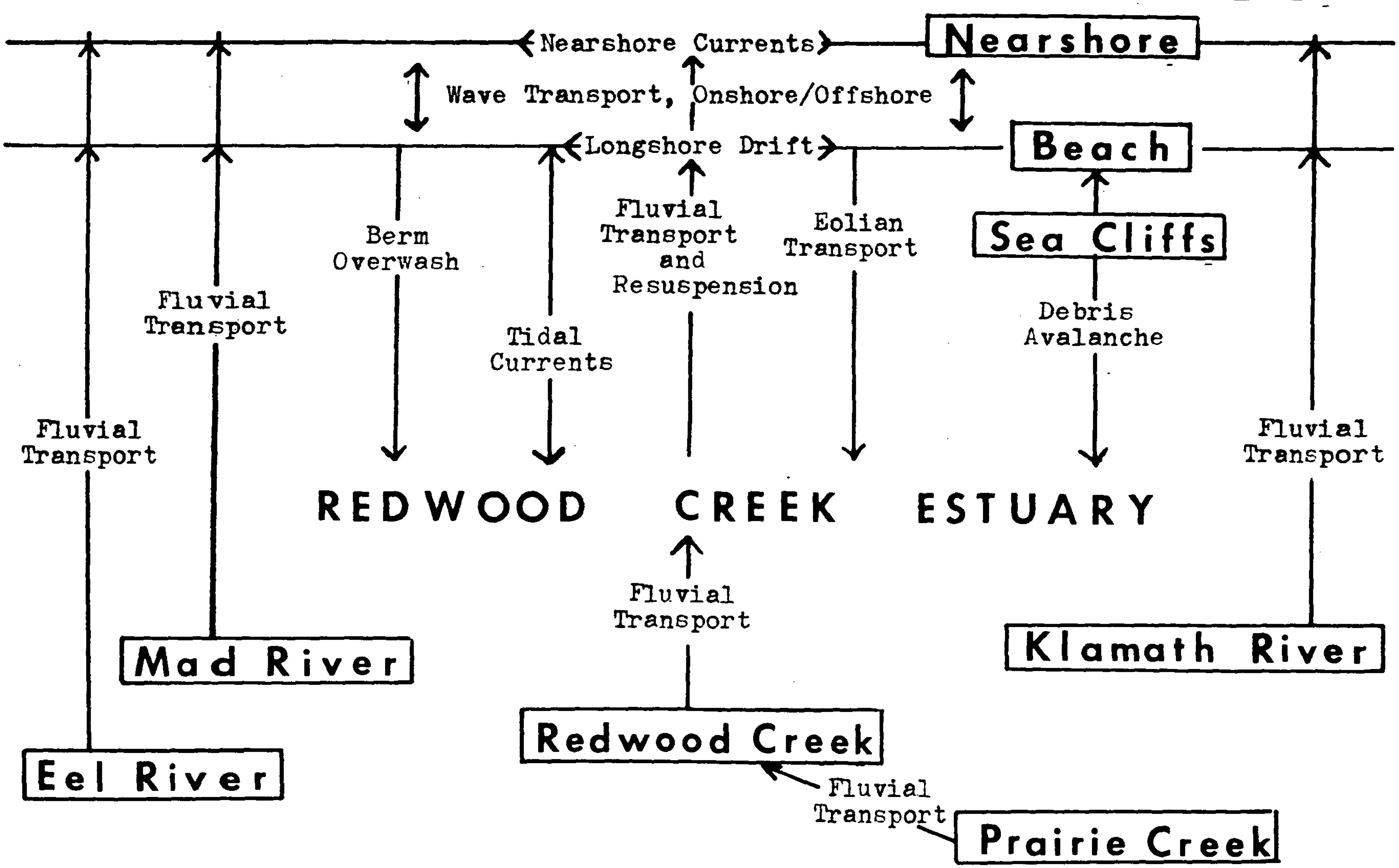
Redwood Creek

Changes in the configuration of the mouth of Redwood Creek resulting from major floods and channelization of the lower reach were examined in the previous section. Figure 27 outlines sediment sources and transport processes with potential to contribute sediment to the estuary. Transport from these sources generally occurs on an annual or seasonal basis. The seasonal progression of mouth morphology and sedimentary structures is presented to aid in differentiating seasonal changes from net sediment accumulation.

According to recent estimates, Redwood Creek transports 1,340,000 tonnes (1,480,000 tons) of sediment as suspended load and 173,000 tonnes (191,000 tons) as bedload past the Orick gauging station annually (Table 4). From the calculations described previously, the sand size fraction (0.062-2.0 mm) comprises 62 to 81 percent of the total load. These values are considerably greater than the 25 percent obtained for the Eel River (Ritter, 1972, p. 7). The gravel and sand fractions which have potential for storage in the estuary or transport to the beach comprise 69 to 86 percent of the total load. Assuming the specific weight of bed material is 1.92 g/cm$^3$ (120 lb/ft$^3$), a volume of 544,000 m$^3$ (416,000 yd$^3$) to 680,000 m$^3$ (520,000 yd$^3$) of sand and gravel is supplied to the mouth of Redwood Creek annually.

High flows which mobilize most of the annual sediment load, transport gravel and finer sediment through the mouth. For example, during WY 1980, flows with instantaneous peak discharges (Q peak) of 357 and 405 m$^3$/sec (12,600 and 14,300 cfs) scoured the channel down to bedrock in places, leaving gravel in the channel bed. From the channel bed outward, gravel, sandy gravel, gravelly coarse sand and

Figure 27: Diagram Showing Sediment Sources and Transport Processes to the Redwood Creek Estuary.



slightly gravelly coarse sand remained following a more moderate flow on March 26, 1981, with a Q peak of 178 $m^3/sec$ (6,270 cfs) (M samples, Map Plate 3).

## Sea Cliff Erosion

Although sea cliff landslides are abundant and often active along the northcoast (Figure 3), the total contribution of sediment relative to fluvial inputs is only locally significant (Griggs and Hein, 1980). The mechanisms and rates of landslides have been characterized for sea cliffs from Crescent City to Orick by Smith (1978) and from Big Lagoon to Little River by G. Carver (1982, oral communication). Locally, the unnamed point north of the mouth of Redwood Creek has contributed sediment to the beach and directly into the embayment. Comparison of historical sketches and photos of this point by Tuttle (1981, p. 134) yielded approximate retreat rates of 24 meters (80 ft) in 130 yrs and 9 meters (30 ft) in 50 yrs. This point and nearby sea stacks are composed of unweathered, finely crystalline Redwood Creek schist with numerous quartz veins injected along fractures.

The hillslope above the point is actively eroding below a 3 meter (10 ft) high headwall. Upslope, abundant tension cracks delineate glide blocks which transform into debris avalanches on the downslope toes of the south and west sides of the hillslope. The lower part of the south debris avalanche was reactivated during winter 1981-82. Approximately 60 $m^3$ (45 $yd^3$) of poorly sorted rock debris including angular schist and quartz cobbles was deposited as a debris fan over the beach sands at the base of the cliff. The base of the west debris avalanche is exposed directly to wave attack and has been active throughout the field observation period.

A larger debris avalanche on the southeast side of the hill is presently stable. Aerial photos show that this feature became active between 1954 and 1957 and reactivated slightly during the 1964 flood, in response to erosion along the base of the cliff. The lower part of the debris avalanche last failed during winter 1966-67.

## Nearshore Currents

Nearshore ocean circulation directions during December-March, the period of peak fluvial sediment discharge, influence the nearshore distribution of sandy deposits as well as offshore dispersal of finer-grained sediment plumes.

Sediment supplied to the beach and estuary from the nearshore marine environment is potentially derived from the Klamath, Mad, and Eel Rivers as well as from Redwood Creek (Table 1). ERTS imagery of sediment plumes and drift card data indicate seasonal reversals of nearshore circulation which affect sediment deposition patterns (Carlson and Harden, 1975). In October or November, when north winds are weak or absent (Figure 28), the northward-flowing Davidson current develops and persists through February (Carlson and Harden 1975; Griggs and Hein, 1980). Griggs and Hein (1980) found similar results using LANDSAT imagery but noted a 15-25 kilometer (10-15 mi) wide nearshore band of southward flow. The Klamath River plume has been discernable as far as 50 kilometers (30 mi) offshore and 50 kilometers (30 mi) south of the mouth of the river. The mouth of Redwood Creek is located approximately 28 kilometers (17.5 mi) south of the Klamath River mouth. However, Carlson and Harden (1975, p. 120) also reported that the most rapid currents of the year in October and December flowed at a rate of 25 km/day (15 mi/day) from Redwood Creek north to the Smith River (Figure 3).

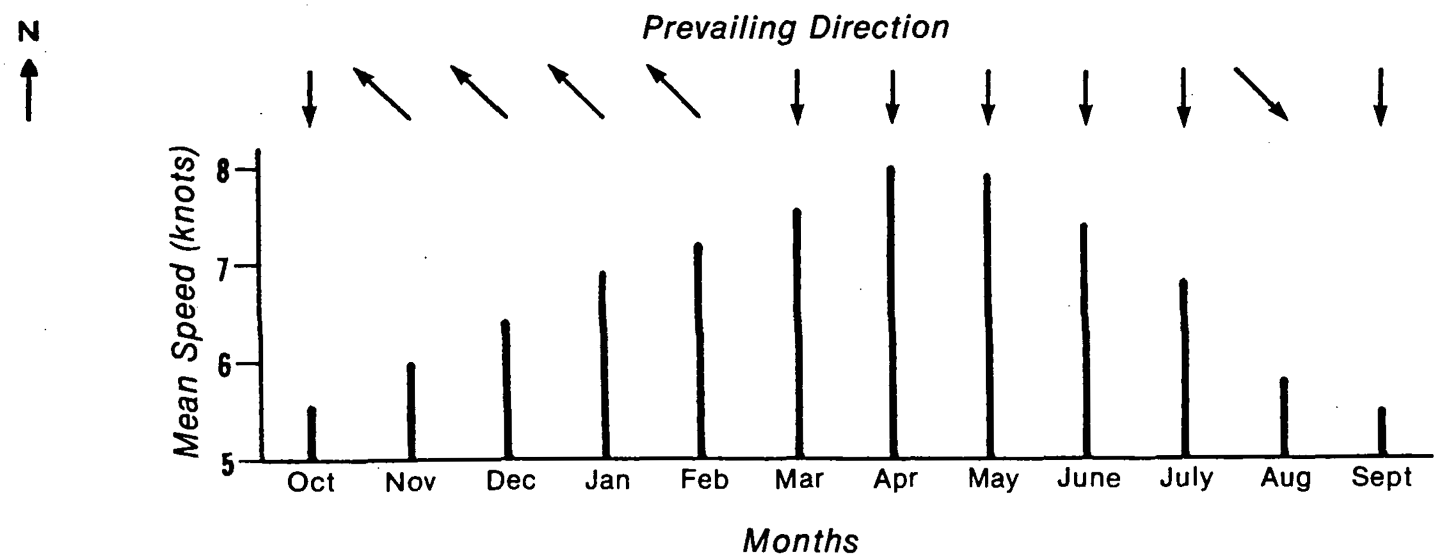
Strong north winds move surface water to the south and offshore and create an Eckman spiral which generates upwelling from March through July or August (Figure 28). The southward flowing California current dominates nearshore and offshore circulation from July through November. Because fluvial sediment discharge from April through November is much reduced, most of the sediment transported along the coast during these months has been resuspended by waves.

## Waves

Waves generated by storms become sorted according to their wave periods by wave dispersion and arrive at the shoreline as uniform

Figure 28:

Monthly Average Wind Velocities at Eureka, California (54-year record) (published by U.S. Dept. of Commerce, modified from Carlson and Harden, 1975, table 4)



swells. Locally generated wind waves, termed seas, generally have shorter wave periods. Although seas may have wave periods up to 15-20 sec (Komar, 1976, p. 76), waves with periods of 10 sec or less are generally classified as seas (Fox and Davis, 1978, p. 1544; Seymour and others, 1980, p. 3).

Wave stations from Crescent City, California to Grays Harbor, Washington, are similar with respect to predominant wave direction, height, period, origin, and season of occurrence (Table 5). Seas tend to be larger than swells and the highest waves of both occur during the winter months. The highest swells arrive from the NW-W direction and the highest seas from the SW-SSE. Significant sediment transport results from the highest waves, since they occur during the season of maximum sediment suspension and dissipate energy across the widest surf zone.

With changing wave conditions from winter to summer, sediment from offshore bars is transported onshore and the storm-dominated beach profile is replaced by a swell beach profile (Figure 29). Offshore bars form where sediment-laden onshore currents created by storm waves converge with offshore currents carrying sediment from the beachface (Bascom, 1954, p. 166; Komar, 1976, p. 293).

Storm waves have high steepness values, defined as the ratio of deep water wave height to length, $H_\infty/L_\infty$, ($L = gT^2/2\pi$), T = wave period). The steeper, unstable wave crests break more frequently, transport more water onshore and saturate the swash zone. At the upper end of the swash zone, sediment is deposited as the swash transforms from turbulent to laminar flow (Duncan, 1964, p. 187). During high tides or periods of exceptional storm waves, the swash rushes over and percolates into the storm berm, leaving the entire sediment load as an overwash deposit (Figure 30).

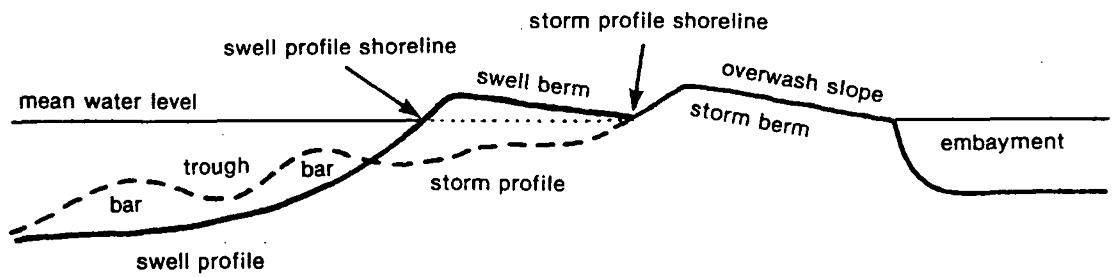
The berm on the south side of the mouth of Redwood Creek (Appendix C, Beach Profile E, 1981 survey) consists of a wide, well developed storm berm with a higher crest than the swell berm. On the north side of the mouth, storm waves may remove the beach up to the base of the sea cliff, destabilizing debris avalanches and preventing development of a storm berm. The swell berm becomes well developed in the summer when low steepness swells transport the offshore bars

TABLE 5: Wave Climate During 1956 - 1958, from Hindcasted Wave Data for Stations from Crescent City, California, to Grays Harbor, Washington (National Marine Consultants, 1960; Summarized from Bourke, 1971, p. 91, 94).

| Origin | Predominant Direction for Season | Height | Period |
|---|---|---|---|
| seas-local | fall, winter SW-SSE<br>spring, summer N-NW | winter highest<br>SW-SSE highest | winter longest<br>SW-SSE longest<br>summer shortest |
| swells-distant | all seasons NW-W | winter highest | autumn longest<br>NW-W longest<br>summer shortest |

Figure 29:

Beach Profiles for Storm (winter) Conditions and Swell (summer) Conditions (modified from Bascom, 1954 and Komar, 1976, p. 289)




Berm: The nearly horizontal portion of the beach or backshore
Storm profile: Almost no berm, sand shifted into offshore bars, gentle slope
Swell profile: Wide berm, smooth offshore, steeper slope

onshore.

Aerial photographs show that landward migration of offshore bars was a mechanism for building new beaches at the mouth of Redwood Creek following the December, 1964 and March, 1975 floods. After the 1964 flood, the bar became land-tied on the south side of the mouth where the discharge was low (Figure 18). Southwesterly winds driving longshore drift to the north were probably also a factor in the growth of the new beach.

## Overwash

Recent deposition across the storm berm has been limited to a narrow strip shoreward of the berm crest (Appendix C). Several factors account for this depositional pattern: water percolates rapidly into the coarse overwash slope; and large organic debris which is abundant shoreward of the berm crest, slows the progress of the overwash. In the past, this debris was carried onto the overwash slope by storm waves. However, storm waves did not perceptibly alter the distribution of the debris south of Beach Profile C between aerial photograph dates of June, 1978, and September, 1981. The magnitude of storms required to overwash the storm berm is discussed further in the section on Net Sediment Accumulation.

The storm berm probably grew to its present extent by swash and overwash deposition across a swell berm. Planar laminations are exposed in berm escarpments to the north and east of the storm berm and in cut banks of swell berms following breaching. Clifton (1969) attributed the origin of beach laminations to grain segregation within bed flow during wave backwash. He observed reverse size grading and upward-decreasing density gradation in laminae affected by backwash. However, Clifton examined layering only in the part of the swash zone subject to both swash and backwash. Duncan's (1964) measurements show that swash deposition predominates during high tide when the beach water table is still low. The sediment lens deposited on the shoreward side of the swash zone is not subject to sorting by backwash. Also sediment deposited by swash as it flows over the berm crest is not reworked since there is rapid percolation of the swash into the overwash slope. The genesis of planar lamination in coarse overwash deposits appears to be poorly understood. Most overwash descriptions apply to hurricane wash-overs in finer sediment along the Gulf and East coasts. The textural and density gradations in overwash laminations should be examined in the detail applied to beach laminations by Clifton (1969).

## Eolian Transport

On April 10, 1981, small scale ripples formed on the dry sub-aerial sand deposit south of the north cliffs following several days of 30-40 km/hr (20-25 mph) winds. The ripples had wavelengths of 3-4 centimeters (1.5-2.0 in) and amplitudes of 1 centimeter (0.5 in) with extremely long crests becoming discontinuous near obstacles. The direction normal to the ripples, N80E, was different from the prevailing winds recorded at Trinidad, California, that day, NNW, and on the previous day, WNW. This discrepancy is probably due to the influence of the headland on the wind pattern on the north side of the mouth. Larger lithic fragments accumulated on the stoss side of the ripples while smaller grains of quartz accumulated on the leeward side. These were the only wind-associated structures noted during the field observation period.

The wide storm berm is well exposed to north winds which attain maximum velocities in the spring (Figure 28). However, eolian structures are absent from the surface of the storm berm. Several factors are probably responsible for reducing the bed shear velocity below that which is required to overcome grain inertia. The presence of organic debris may interrupt the fetch across the berm. The lack of debris movement over the last few years allowed perennial vegetation to become established and stabilize berm sands. Eolian transportable fine sands are not abundant on the overwash slope. Transport may not occur during wind storms accompanied by rainfall which moistens the sand. Eolian structures may be disrupted by vehicle traffic on the berm. The lack of wind-formed structures suggest that eolian transport is not a major contributor of sand to the north and south sloughs.

Tidal Currents

The mouth of Redwood Creek experiences mixed semidiurnal tides of moderate range. The diurnal and mean ranges reported for Humboldt Bay are 2.0 and 1.4 meters (6.4 and 4.5 ft), respectively (U. S. Department of Commerce, 1980). The maximum and minimum tides predicted during 1980-82 were 2.5 and -0.7 meters (8.2 and -2.2 ft). Due to the steep stream gradient, the tidal prism (volume of water subject to tidal fluctuations) at the mouth of Redwood Creek is only 70,800 $m^3$ (93,000 $yd^3$) (see Appendix D). The limit of the estuary is at River Station 7, 1.5 kilometers (0.9 mi) upstream, as defined by the maximum extent of saltwater intrusion measured November 29, 1980 (R. Gregory, 1980, unpublished data). Tidal bores have also been observed shoaling upstream at least as far as River Station 7 (located between BB and NL, Figure 7).

When a high tide coincides with high discharge (e.g. February 15-24, 1980, see Appendix E), water may back up into the sloughs over the bankful level. The backwater effect allows transport of sediment into supratidal areas during flood tides. Tidal current deposition is most effective when the mouth is wide, scoured by a previous high discharge. During high flows, suspended sediments originating from Redwood Creek and the south slough are visible as a green and brown color contrast on the water surface. At high tide, incoming waves create small gyres on the surface, mixing the visible sediments in the south slough neck adjacent to the south levee.

Net transport of sediment into the estuary by flood tide currents can be partially explained by the dissimilar nature of flood and ebb tidal currents. The flood tide is propagated by small waves or bores with a surging flow (Clifton, Phillips, and Hunter, 1973, p. 120, 123). Unfortunately, the surging flood current velocity cannot be accurately measured with standard current meters that yield an average value over several seconds. This problem was encountered by Jones (1972, p. 51) in measuring surging flood current velocities at the mouth of the Sixes River, Oregon. In contrast, the ebb current is confined to tidal channels and flows like a stream. The velocity of the ebb current in the outflow channel is increased by the stream discharge. Sediment deposited in the embayment and sloughs by flood currents is eroded by the ebb flow only along the channels.

## Resuspension

Sediment previously deposited in the embayment and slough necks is subject to erosion by fluvial discharge. The extent of erosion of the embayment and adjacent berm during high flows depends on the peak fluvial discharge and, to a lesser degree, the timing of the tides. High fluvial discharge also erodes into the berm along the channel margins. The erosional escarpment is generally poorly developed along the rocky north side of the channel. The berm escarpment on the south side remains until it is re-eroded by a higher flow or obliterated by overwash (Figure 30). The position of the berm escarpment along the berm in a north-south direction is established by the preceeding peak flow. Berm escarpments which persisted through the summer months in WY 1980, 1981, and 1982 were formed by peak flows during the preceeding winter of 549, 178, and 735 $m^3$/sec (19,400, 6,270, and 26,000 cfs) respectively. The WY 1982 position would plot approximately at 1,050 ft with the two other berm escarpments shown on Longitudinal Dune Profile Two (Figure 31).

Discharge from Sand Cache and Strawberry Creeks (Figure 7) through the north and sough sloughs is tidally dependent. When backwater develops, the sloughs function as ebb flow channels, remaining stagnant until the tide and/or discharge recede. Sediment stored in the slough necks is then eroded to a degree, depending on the recession rate.

## Seasonal Progression of Mouth Morphology and Sedimentary Structures

Seasonal changes in the configuration of the outflow channel and tidal current transport generally do not contribute to net sediment accumulation at the mouth of Redwood Creek. However, these seasonal features strongly influence the character of aquatic habitat by determining the embayment volume, substrate size distribution and water quality.

Figure 30: Typical Summer Morphological Features, Mouth of Redwood Creek.

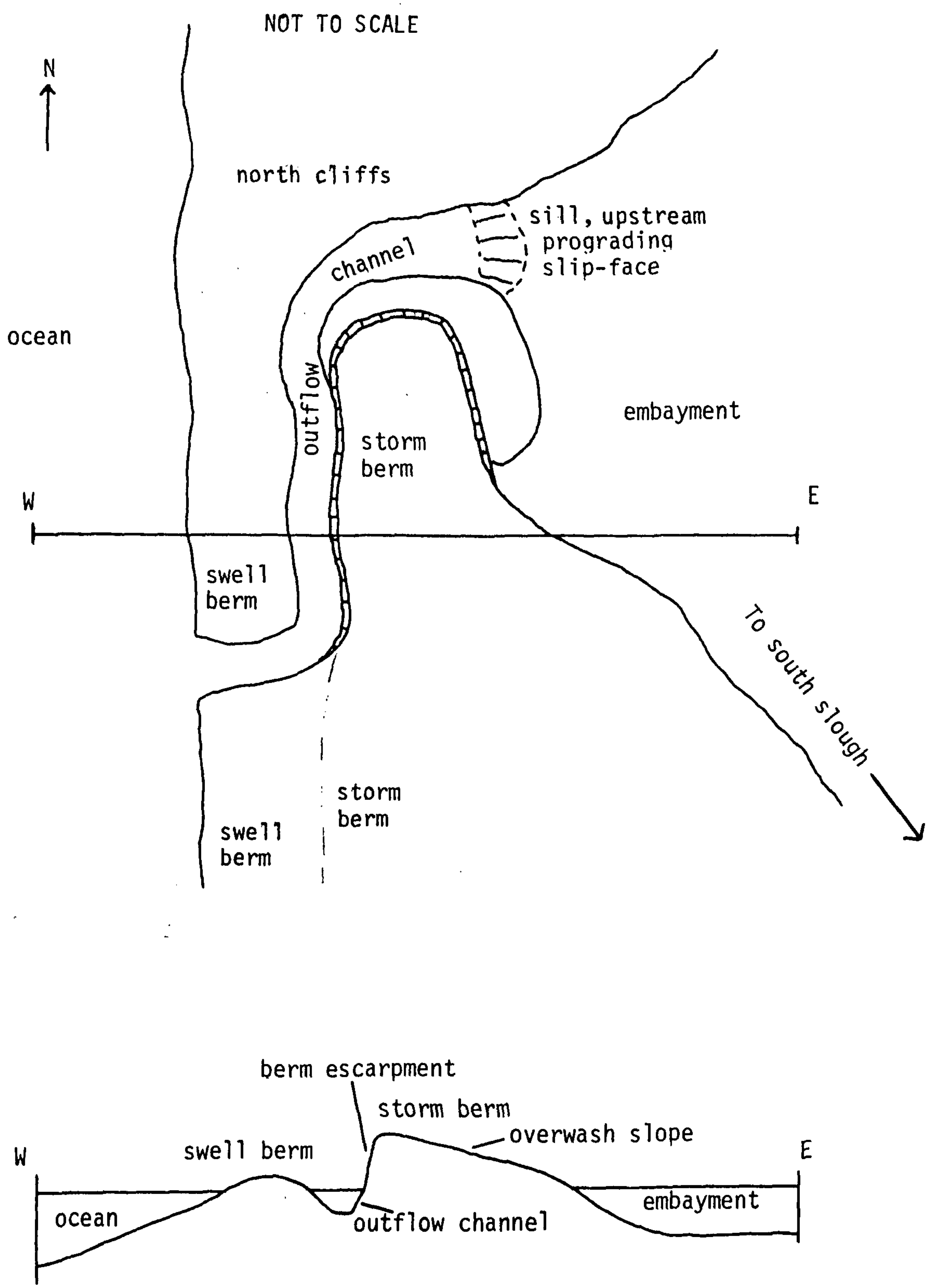
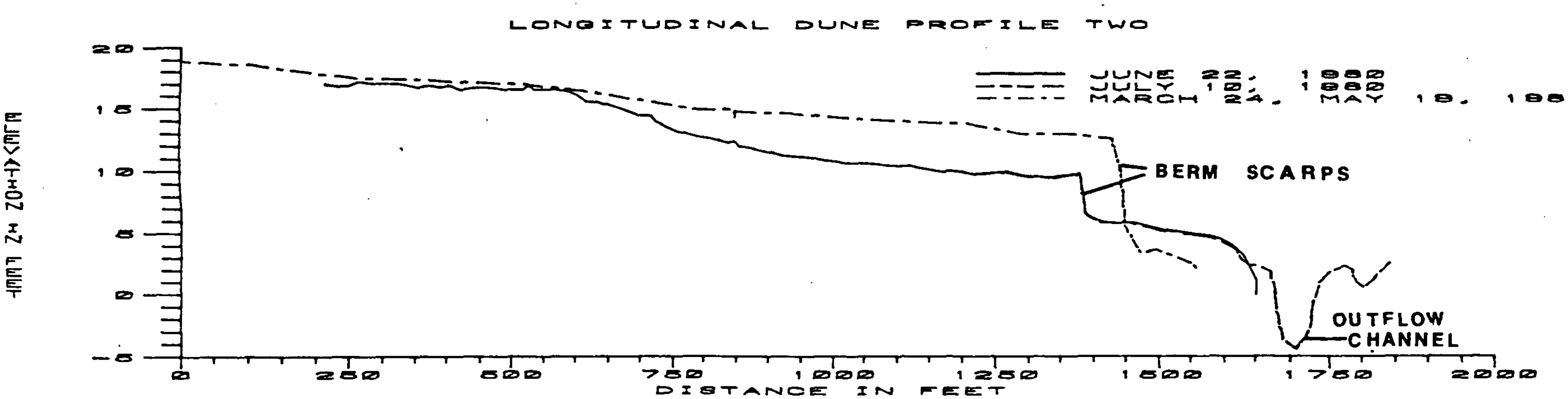


Figure 31: Longitudinal Dune Profile Two.



Following the water year convention, the season begins in October with increasing discharge in a "normal" year. High discharge typically establishes a straight outflow channel as illustrated in Figure 25a, following a peak flow of 405 $m^3$/sec (14,300 cfs). All discharges cited in this section were gauged at Orick, 4.0 kilometers (2.5 mi) upstream from the mouth.

As discharge decreases through the spring months, the straight outflow channel may be modified by incoming high waves and tidal currents. In the spring, high waves are generally associated with high winds, as reflected in the larger component of sea than swell. Sediments transported by flood tide currents along the margins of the outflow channel are deposited within the embayment. When the outflow channel is straight, waves diffracting around the berm escarpment deposit a lobe.

During April, 1980, a diffraction lobe was deposited by a series of waves characterized by high seas. Waves of this magnitude and frequency were recorded on only five occasions between April and September of 1980 and 1981 (Appendix E). Onshore winds at Trinidad, California, on April 10, 1980 were normal to the shoreline (WNW) with velocity of 15-40 km/hr (10-25 mph). The oblique view in Figure 25b was sketched from photographs taken on April 19, 1980 and illustrates the diffraction lobe morphology.

In the past, when the outflow channel was straight, the lobe developed into a large emergent deposit which reduced the volume of the embayment (Figure 15, September, 1931, and Figure 16, July, 1957). Lobes were also deposited on either side of the scoured flood channel as waves diffracted around the margins following the December, 1964 storm (Figure 18).

The diffraction lobe which developed in spring, 1980, appears in Beach Profile A (Appendix C) and Map Plate 1. A box core in this lobe taken in August 1980 revealed alternating gravel and coarse sand layers typical of swash-backwash laminae. The layering is attributed to flood current bores of different energies which deposit and rework the sediment on the lobe.

Numerous ridges adjacent to a diffraction lobe are visible in photos taken from the top of the north cliffs in August, 1979.

Upstream from the outflow channel, the ridges appear normal to the expected flood current direction, but deeper in the embayment, they become concentric with the diffraction lobe. Perhaps these concentric features are small-scale tidal sand ridges, parallel to the principal tidal current direction, as described by Blatt, Middleton and Murray (1972, p. 135).

The magnitude and frequency of incoming tidal bores depend on the tide height, size, and orientation of waves, stream discharge and the configuration of the outflow channel. Flood tide currents dissipate across the intertidal sand flats, forming small scale sedimentary structures. Ripples are commonly exposed in the slough necks between 0 and 1.2 meters (0 and 4 ft) above MSL (see Map Plates 2 and 3).

During late spring and summer, the outflow channel becomes narrower as fluvial discharge decreases and as tidal currents transport sediment onshore and into the mouth (Figure 25b, c). 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 slip-face (Boggs and Jones, 1976, p. 420). The sill resembles flood-dominated tidal deltas found shoreward of larger tidal inlets. Since the outflow channels present in summer, 1980, and spring, 1981, were both surveyed soon after being eroded during a breach, the sill does not appear on Map Plates 2 and 3.

Clifton, Phillips, and Hunter (1973, p. 126) observed that sills alter the timing of the tides relative to the ocean and damp 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, p. 423) measured bottom currrent velocities that were commonly at least twice those on the flood tide 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, p. 422). This time-velocity asymmetry between flood and ebb currents is clearly responsible for the net transport of marine sediment into the Sixes River estuary as well as the Redwood Creek estuary when a sill is present.

Clifton, Phillips, and Hunter (1973, p. 120) observed that the outflow channels of streams with summer discharges ranging from 0.1 to 10 $m^3$/sec (3.5-350 cfs) commonly migrate alongshore (Figure 30). During the period of field observation, the mouth of Redwood Creek migrated when the discharge was as high as 6 $m^3$/sec (200 cfs). The outflow channel generally migrates south during May through August. Occasionally the outflow channel migrates to the north or recurves upon itself after migrating to the south.

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 (Figures 25 c and 30). Two outflow channels may be present following a high tide before one captures the flow. The outflow channel is located shoreward of the incipient swell berm and erodes into the storm berm (Appendix C, Beach Profile B, July, 1980 Survey and Figure 30). Migration reduces the channel gradient and velocity.

In the outflow channel, sedimentary structures respond to changing tidal currents and stream discharge. Megaripples migrating downstream were observed in June, 1980 with a discharge of 4.4 $m^3$/sec (156 cfs). The megaripples were lunate in the upstream reach of the channel, transforming into cuspate or linguoid shapes downstream. Further downstream, smooth flow across the megaripples breaks down and becomes turbulent. The location of this transition from the lower to the upper flow regime corresponds to a nick point in the water surface gradient. The nick point moves upstream and downstream in response to the ebb and flood currents.

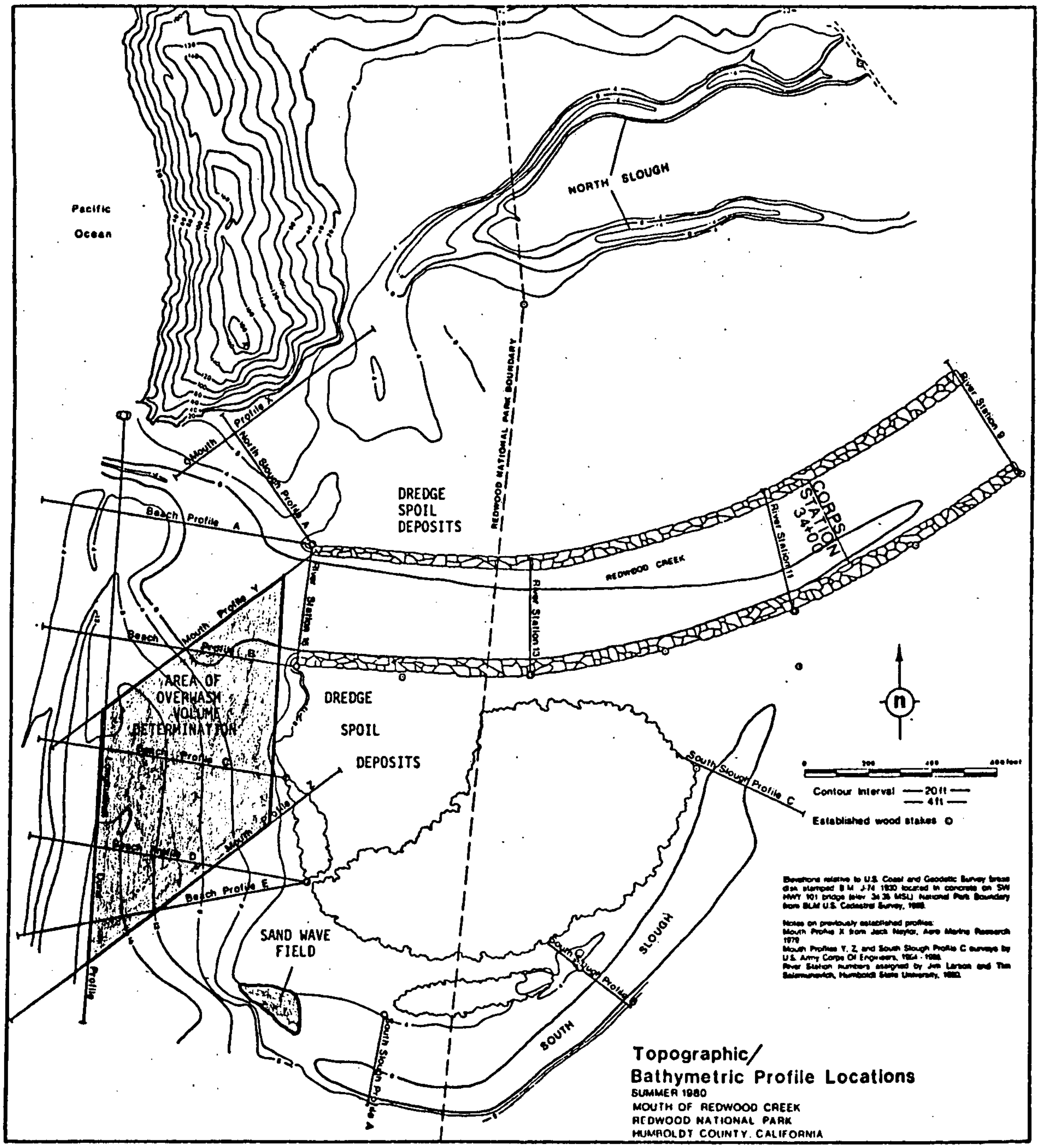
According to coastal engineering criteria, when a cross-sectional area of a tidal inlet exists below mean sea level, the mouth is "functionally" open (Rice, 1974, p. 17 c.f. Johnson, 1974). The ratio of wave energy to tidal energy per tidal cycle determines whether the mouth will close (O'Brien, 1971). Tidal energy depends on both the amplitude of the tide and the tidal prism. With a large tidal prism, the ebb current velocity is effective in eroding the tidal inlet and preventing functional closure.

At the mouth of Redwood Creek, stream discharge increases the ebb current velocity in the outflow channel. With decreasing discharge in the spring, a sill may build above mean sea level, thereby functionally closing the mouth. This process may presently occur more rapidly or earlier in the year than in the past. Due to the increase in the stream gradient of Redwood Creek from channelization and accumulation of sediment in the sloughs, the tidal prism below Corps Station 34+00 (Figure 32) has decreased by 47-54 percent since 1966 (Appendix D). Additionally, flow duration curves indicate a slight long-term decrease in stream discharge during the summer months (Janda and others, 1975, p. 155).

As the sill builds above mean sea level, the effective tidal range is damped. The ebb current velocity decreases, allowing the sill and outflow channel to build higher. The rate of outflow decreases, causing expansion of the embayment when stream discharge is greater than rates of outflow, seepage and evaporation. Seepage rates of water through the sill from the embayment to the ocean depend on the relative water levels, grain size, sorting and area of embayment contact with the sill and berm (Clifton, Phillips, and Hunter, 1973, p. 130). Presently, water may seep more slowly across the gentle gradient through the wide storm berm. The narrow, steeper gradient part of the swell berm, where seepage would be more rapid, is limited in length.

The configuration of the outflow channel determines the degree of saltwater intrusion and distance of sediment transport by flood tide currents. Boggs and Jones (1976) examined tidal current transport by releasing dyed grains in the lower part of the outflow channel of the Sixes River, southwestern Oregon. During a single flood tide, sediment was transported 0.8 kilometers (0.5 mi) up the estuary through a straight outflow channel. Flood currents were dissipated more rapidly through an outflow channel which had migrated alongshore, transporting sediment of the same size and density only 0.3 kilometers (0.2 mi) up the estuary. The two experiments were conducted during flood tides of similar velocity and duration and comparable stream discharge.

Figure 32: Mouth of Redwood Location Map.



Sediment is transported further into the embayment if the outflow channel is straight due to a recent breach and/or lack of migration. The sheltering effect of the headland may prevent alongshore migration if the outflow channel develops at the north end of the beach.

Although the natural sequence of alongshore migration and closure was frequently interrupted by artificial breaching during the period of field observation, the outflow channel 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. According to Jones (1972) the mouth of the Sixes River closes completely only once or twice in ten years. The Sixes River estuary, with its lower stream gradient, probably has a larger tidal prism than the Redwood Creek estuary.

## Distribution of Fluvial and Marine Sediment - Grain Size Analysis

The primary purpose of analyzing grain size was to delineate substrate textures available for invertebrate colonization rather than to indicate contrasting sediment sources and transport processes. Although samples were sieved at broad size intervals of one phi ($\phi$), the patterns of sediment size units for summer 1980 (Map Plate 2) and spring 1981 (Map Plate 3) do reflect sources and processes.

Flood tidal currents have been observed mixing green suspended sediment from Redwood Creek with brown suspended sediment from the south slough during periods of high fluvial discharge. At moderate discharges, fine sediment suspended by waves may also enter the sloughs. Fine sands and mud settle out of suspension in the low-energy environment which develops when the sloughs become isolated from the embayment during the spring (Map Plate 2).

Gravelly sand and sandy gravel remain in the channel between the levees and through the embayment following winter flows. The gravel deposit shown in Map Plate 3 was sampled approximately two weeks after a peak discharge of 178 $m^3$/sec (6,270 cfs). Current velocities were sufficient to transport gravel of one centimeter (0.4 in) in size at sample locality M-03.

The overwash slope is primarily composed of slightly gravelly, very coarse to medium-grained sand. Waves deposit similar-textured sands to the south of the north cliffs. In the necks of the sloughs, the change from slightly gravelly muddy sand to slightly gravelly sandy mud is marked by an abrupt increase in water depth (Map Plate 2). This textural and morphological change corresponds to the limit of tidal current tractive transport into the sloughs.

During summer months, thick deposits of mud and muddy sand may accumulate in the embayment at Redwood Creek. Boggs and Jones (1976, p. 424) suggest a predominately marine origin for sand and muddy sand layers deposited at the mouth of the Sixes River during summer months. Their premise 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 gauging station was calculated for early July to mid-October, 1980. Graphs of particle size distribution with discharge show that the mud fraction comprises 90-100 percent of the suspended sediment load transported during low summer discharges. If the entire load transported past the Highway 101 bridge during this period reached the embayment, it would cover only 1,510 $m^2$ (16,200 $ft^2$) with 1 centimeter (0.4 in) of mud.

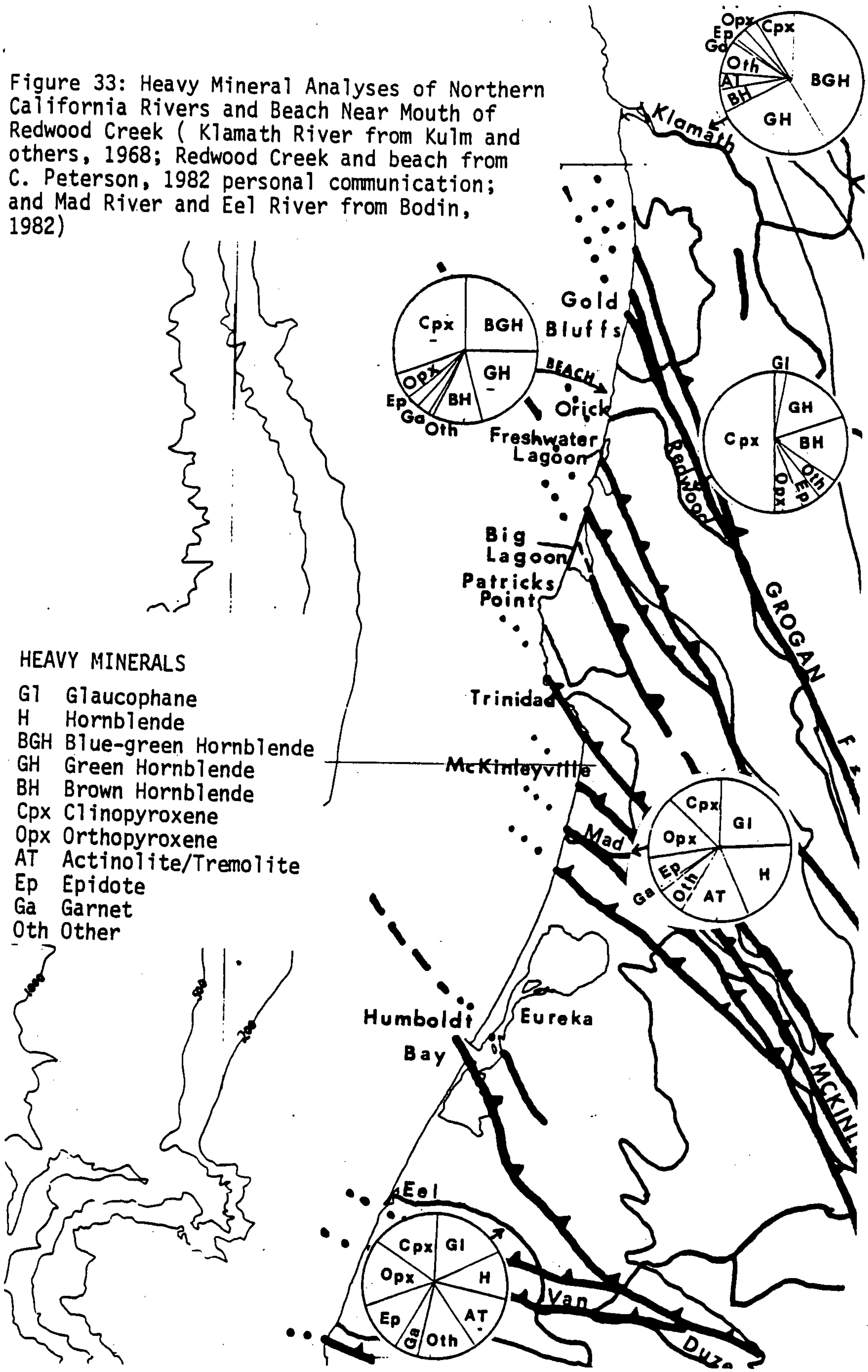
Samples taken from the embayment in mid-August and mid-September, 1980, delineate the area containing greater than 10 percent mud in the upper 5 centimeters (2 in) of sediment (Map Plate 2). One Eckman dredge sample containing over 70 percent mud attests to the variable thickness and concentration of fines in the embayment. Though not depicted by the Summer 1980 Sediment Size Distribution Map, 2-5 centimeter (1-2 in) thick layers containing mostly mud have also been observed in the slough necks. While the summer fluvial input could not account for a major part of mud in the embayment, the volume data are insufficient to evaluate the actual contribution, if any. Heavy mineral analyses provide more substantial evidence of the relative contributions of marine and fluvial sediment.

Distribution of Fluvial and Marine Sediment - Heavy Mineral Analysis

Sediments originating from Redwood Creek and from the beach environment may be distinguished by their heavy mineral compositions (Figure 33). The abundances of glaucophane, hornblende and clinopyroxene appear to be useful criteria for segregating Redwood Creek sediment from northern and southern sources. The distribution of marine sediment at the mouth of Redwood Creek is clearly delineated by the blue-green hornblende content of samples tabulated in Appendix J. Mean percentages of blue-green hornblende in the fine sand fraction of samples from the north slough, south slough and embayment are 23, 24 and 25 percent, respectively. These values are similar to the amount of blue-green hornblende in the beach samples and unlike the much lower percentage of this mineral in Redwood Creek samples. These results support the conclusion that sand is transported into the embayment and sloughs by storm berm overwash and flood tidal currents from the beach environment. The large fluvial sediment load is routed directly through the estuary by the channelized configuration of the lower reach.

The upstream limit of flood tidal current transport of sand was determined from samples collected from the lower channel and embayment during September 1980 and June 1981 (Figures 34 and 35). In June 1981, a distinct transition from gravelly sediment (sample locality N-01, Map Plate 3) to finer sediment (sample locality N-03) was mapped along River Station Profile 15. The topographic contour at 2 feet below MSL delineated a bar composed of finer sediment, which was emergent during a -0.2 meter (-0.8 ft) tide. This emergent bar resembled the deposits depicted in Figures 15 and 16. The finer sediment of the bar contained 27 percent blue-green hornblende, typical of beach sediments; whereas the coarse sediment at locality N-01 contained only 4 percent blue-green hornblende, typical of lower Redwood Creek. Thus, the mineralogy and texture of the samples show that flood tidal currents deposited the finer-grained bar over the gravelly river sediment. At the mouth of Redwood Creek, surficial deposits of marine and fluvial origin are distinct, unlike the transition zones in other estuaries where heavy minerals from both

Figure 33: Heavy Mineral Analyses of Northern California Rivers and Beach Near Mouth of Redwood Creek ( Klamath River from Kulm and others, 1968; Redwood Creek and beach from C. Peterson, 1982 personal communication; and Mad River and Eel River from Bodin, 1982)




HEAVY MINERALS

- Gl Glaucophane
- H Hornblende
- BGH Blue-green Hornblende
- GH Green Hornblende
- BH Brown Hornblende
- Cpx Clinopyroxene
- Opx Orthopyroxene
- AT Actinolite/Tremolite
- Ep Epidote
- Ga Garnet
- Oth Other

Figure 34: Lower Redwood Creek, Blue-Green Hornblende Content and Sediment Size Distribution, Summer 1980. See Figure 26 for Sediment Size Classification Symbols.

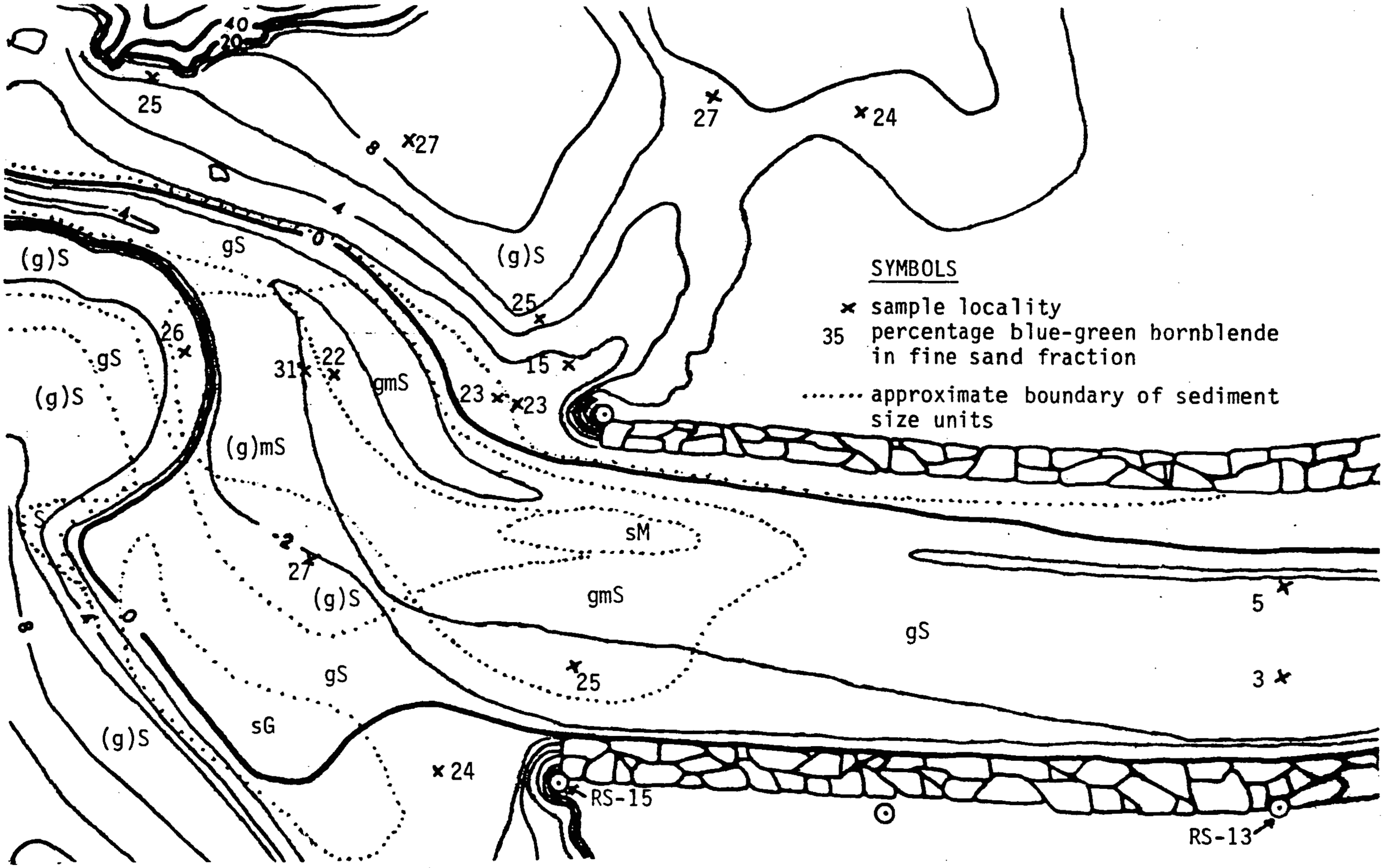
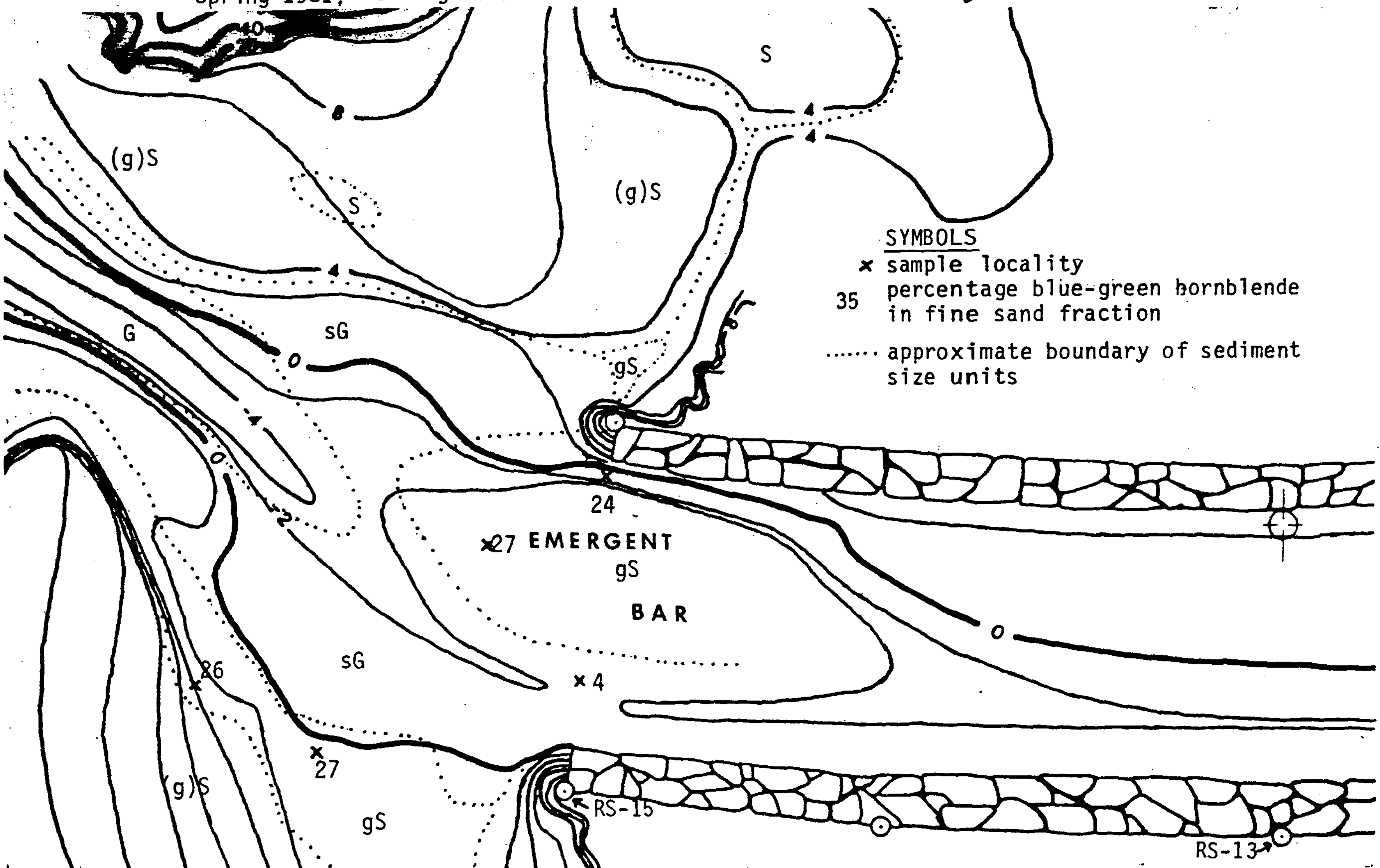


Figure 35: Lower Redwood Creek, Blue-Green Hornblende Content and Sediment Size Distribution, Spring 1981, See Figure 26 for Sediment Size Classification Symbols.



sources are mixed.

The suite of heavy minerals in beach samples near the mouth of Redwood Creek indicates that sediment from the Klamath River is present at least as far south as Freshwater Lagoon (Figure 33). Blue-green hornblende in Klamath River sands probably originates from amphibolite facies metamorphism, particularly in the central metamorphic belt of the Klamath Mountains province (Davis, 1966). Sediment from the Klamath River and a beach 0.3 kilometers (0.05 mi) south of the Klamath River mouth contained 18 and 11 percent blue-green hornblende, respectively (Appendix J). The mean percentage of blue-green hornblende in five beach samples located as far as 1.6 kilometers (1.0 mi) north of Redwood Creek was 22 percent. The mean for five beach samples located up to 2.8 kilometers (1.7 mi) to the south was 21 percent. Further analyses of beach samples south to the headland at Patrick's Point (Figure 33) would confirm a net southward longshore drift in this area.

Grain size analyses and heavy to light mineral ratios suggest a northward longshore drift between the Eel River mouth and Trinidad (Ritter, 1972; Bodin, 1982). The Mad and Eel Rivers drain Franciscan terrain which is lithologically similar to the sandstone and melange unit of Snow Camp Mountain in the Redwood Creek drainage basin (Figure 4, KJfgf). This unit contains exotic tectonic blocks of blueschist in the melange and is the source for glaucophane, abundant in the Mad and Eel Rivers and adjacent beaches (Figure 33). However, no glaucophane was detected in any of the beach samples near the mouth of Redwood Creek. Traces of glaucophane were present in all of the river samples above Prairie Creek (Appendix J).

The Gold Bluffs unit (informal designation) is exposed in sea cliffs adjacent to a wide beach north of the mouth of Redwood Creek (Figure 4). This unit does not appear to be a major source of sediment to the beach at present. The abundance of blue-green hornblende in sample H-10 from this unit (Appendix J) substantiates other evidence of deposition by ancestral Klamath and Trinity Rivers (Kelsey, 1982, p. 131). The Gold Bluffs and other Plio-Pleistocene units in the Prairie Creek drainage basin contribute blue-green hornblende to lower Redwood Creek. The blue-green hornblende content varies from 0 to 1.3 percent in samples above Prairie Creek and increases below Prairie Creek to 2.2 to 9.0 percent (Appendix J).

The mineralogy and abundance of the heavy mineral fraction in sands depend on the distance from the source rocks, resistance to abrasion, and other sorting processes during transport in addition to the lithology of the source rocks. During the summer, the abundance of heavy minerals in fine sand from the embayment depends on the degree of sorting of the overall sample. Fine sand from sediment sampled above mean sea level contained an average of 24 percent heavy minerals, while fine sand below mean sea level averaged 3 percent heavy minerals. The mean sea level datum corresponds to a 1.23 meter (4.02 ft) tide in the ocean (Appendix D). Apparently, the winnowing action of recurrent tidal fluctuations sorts and concentrates the heavy minerals above mean sea level.

The abundance of blue-green hornblende in the estuary generally does not depend on the heavy mineral concentration; it does depend on the sediment source. However, the sample with the highest concentration of heavy minerals in the estuary (H-01, Appendix J) also contained the highest percentage of the denser mineral, garnet, and had a relatively low percentage of blue-green hornblende. Sample H-01 was collected from the outlet (ebb flow channel) of the north slough.

The process of selective sorting of heavy minerals according to their hydraulic equivalence is probably of greater importance for fluvial sediments than for estuarine sediments. Sample G-13, from a coarse lag deposit on a point bar, contained the highest concentration of garnet measured, but only a trace of heavy minerals (Appendix J). Most of the heavy minerals were probably winnowed out along with the finer sediments. This example from Redwood Creek illustrates the problems inherent in obtaining a representative sample for heavy mineral analysis of fluvial sediment. Selective sorting may be responsible for some of the discrepancy between blue-green hornblende values for the Klamath River found by Kulm and others (1968) (Figure 33) and by this report (sample P-01, Appendix J).

Net Sediment Accumulation - Distribution, Processes and Rates

Aerial photograph interpretations and survey data presented in the section on Effects of Channelization documented the sites of net sediment accumulation since levee construction. These sites included the storm berm overwash slope and parts of the slough necks not subject to erosion by the slough neck channels. Recent sites and processes of sediment transport were observed in the field under known discharge, wave, wind and tidal conditions. Significant storm berm overwash and tidal current transport occurred during periods of high waves coincident with high tides. The extent of tidal current transport of sediment also depended on the opposing force of stream discharge and the width of the mouth (scoured by previous high stream discharge).

Graphs of monthly field conditions (Appendix E) combined with repeated surveys yielded estimates of the magnitude of events associated with observed rates of sediment deposition. Storm periods between field observations responsible for sediment transport and morphological change were also identified on these graphs.

Because the Humboldt Bay Inner WAVERIDER Buoy was inoperative during periods of high energy waves (Appendix F), it was not possible to quantify the occurrence frequencies for conditions which cause overwash, tidal current transport, and saltwater intrusion. Daily wave observations from the Humboldt State University Fred Telonicher Marine Lab at Trinidad, California, which are concurrent with WAVERIDER data, were used to estimate wave heights expected at the WAVERIDER Buoy (Appendix F).

Deposition on the Storm Berm Overwash Slope

The pattern of overwash deposition during the 1980-81 season is illustrated by Beach Profiles B, C. D and E (Appendix C) and Longitudinal Dune Profile Two (Figure 31). Waves washed into the neck of the south slough along Beach Profile B, but only washed over the storm berm crest along Beach Profiles C and D. Some variability between successive profile surveys of the overwash slope is caused by depressions around organic debris, off-road vehicle tracks and the large vertical exaggeration of the profiles.

Overwash across the slope as far south as Beach Profile C (see Map Plate 1) was observed during a 2.1 meter (6.9 ft) tide on January 9, 1981 (see Appendix E for 1981 conditions). Swells of 2.1-2.7 meters (7-9 ft) recorded at Trinidad, California, that day, were probably equivalent to a 5 meter (16 ft) WAVERIDER reading. On March 7, 1981, 4.4 meter (14 ft) WAVERIDER waves during a 2.0 meter (6.5 ft) tide reached the south slough only along the northern, lower parts of the storm berm. The building of the storm berm during the winter as well as the lower waves and tides may have limited the extent of overwash.

Following the 7.1 meter (23 ft) waves measured by WAVERIDER on November 14, 1981 (Appendix E), evidence of overwash across the storm berm crest was found from the berm escarpment to the California-Pacific Mill site. Waves reached the south slough in several places. Although this magnitude of overwash may have been unusual in terms of the large waves, deposition would have been greater if higher tides had also occurred.

Rates of overwash deposition were calculated for an area on the overwash slope from Mouth Profile Y to Mouth Profile Z and from the storm berm crest to the middle of the neck of the south slough (Figure 32). For the 1980-81 winter season, 4,200 $m^3$ (3,200 $yd^3$) of sediment were deposited by overwash. Between 1966, when the Army Corps surveyed the area, and 1980, 47,600 $m^3$ (36,400 $yd^3$) accumulated, yielding an average rate of deposition of 3,400 $m^3$/year (2,600 $yd^3$).

Overwash deposition across the storm berm probably was most rapid in the storm seasons immediately following channelization. Therefore, the average rate of deposition for the period 1966 to 1980 gives a minimum volume of material that would have to be removed each year to maintain the lower, pre-channelization berm. As of 1981, the volume of material to be removed from the specified area to restore it to the 1966 surface was 51,800 $m^3$ (39,600 $yd^3$).

Deposition in the Necks of the Sloughs

The intertidal area south of the north cliffs is exposed directly to wave attack during storms arriving from the southwest to west-southwest. Sediment is mobilized and redistributed around the large accumulation of organic debris in this area. Along North Slough Profile A (Appendix C), a 0.9 meter (2.9 ft) diameter stump remained in place during the winter 1980-81 storms, creating a large scoured area.

The neck of the south slough is protected from direct wave attack by the storm berm. Tidal currents deposited sand waves in the neck of the south slough west of South Slough Profile A (Figure 32) at least twice following peak flows which scoured a wide mouth. The peak flow for WY 1982 was 740 $m^3$/sec (26,000 cfs). After the peak flow, waves travelled into the neck of the south slough past Beach Profile C, eroding dredge spoil deposits along the bank. These waves were observed on January 12, 1982 (Appendix E) on a 2.2 meter (7.3 ft) tide with moderate waves against a 30 $m^3$/sec (1100 cfs) discharge. Three days earlier the waves and discharge were similar but the highest tide predicted in at least three years occurred, 2.5 meters (8.2 ft). Sand waves found west of South Slough Profile A on January 12 apparently formed during this high tide (Figure 32).

The volume of sediment mobilized was roughly estimated by assuming that the sand waves were deposited on an initially flat surface. Because each sand wave was asymmetrical with an amplitude of 20-30 centimeters (8-12 in), its volume was approximated as a wedge with a vertical upstream-facing slope. The sand wave field covered an irregular area of 530 $m^2$ (5700 $ft^2$). The length of individual crests varied from 6 to 18 meters (20 to 60 ft); wavelength ranged from 1.5 to 7.5 meters (5 to 25 ft) in width. The volume of material mobilized by tidal currents in the neck of the south slough was 63 $m^3$ (82 $yd^3$).

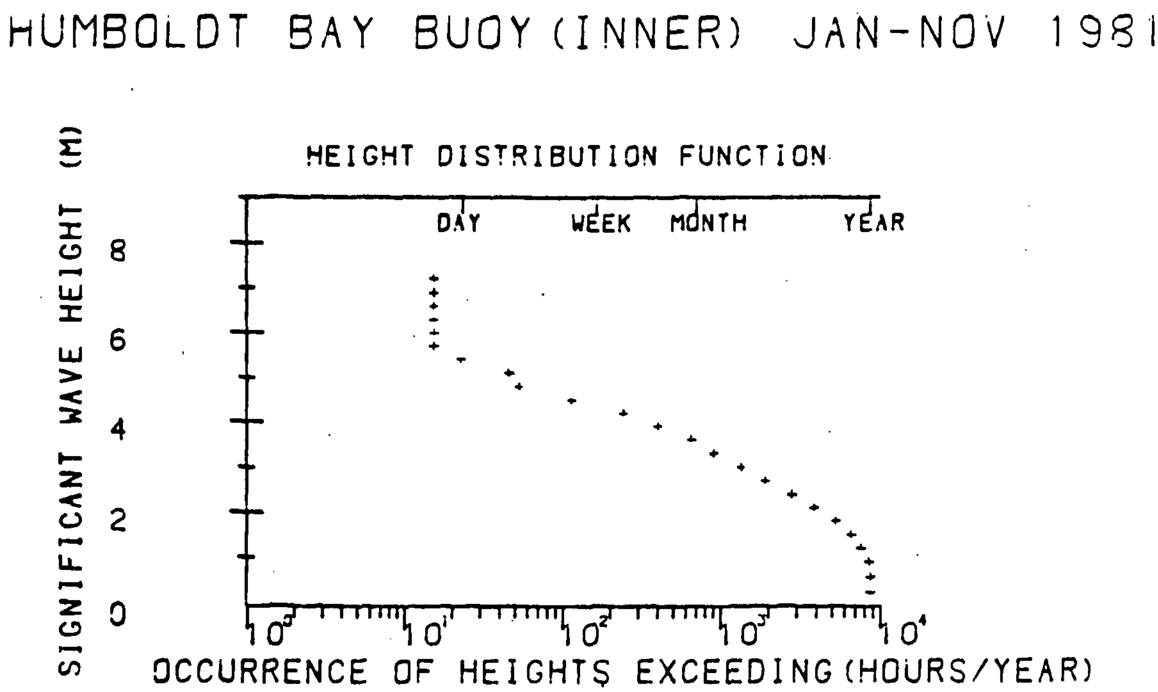
Dredge spoils excavated from the channel during channelization were placed adjacent to both levees (Figure 32). Cutbanks in the actively eroding dredge spoils occur as cliffs which average 2 meters (6 ft) high south of the south levee. From 1968 to 1981, the cutbanks receded as little as 9 meters and as much as 24 meters (30 and 80 ft). Over this period an average volume of 150 $m^3$/yr (115 $yd^3$/yr) of sediment was removed. However, erosion is not an annual event; it depends on the tides, wave height, and width of the mouth.

## Prediction of Conditions Conducive to Deposition

From the wave heights measured by the Humboldt Bay Inner WAVERIDER Buoy for 1981 (Figure 36), it seems reasonable to expect 5.0 meter (16 ft) waves for at least 50 hours per year. During November 1981, waves exceeding 7.0 meters (23 ft) occurred for approximately 12 hours.

Considering the maximum events of record, potential exists for 7 meter (23 ft) WAVERIDER waves to coincide with high tides of 2.5 meters (8.2 ft) following a peak flow of Redwood Creek on the order of 1,420 $m^3$/sec (50,000 cfs). Such an event would cause overwash and tidal current deposition in the slough necks, erosion of dredge spoils, and saltwater intrusion far exceeding that observed during this study.

Figure 36: Significant Wave Heights Recorded by the Humboldt Bay Inner WAVERIDER Buoy, January Through November, 1981 (from Seymour and others, 1981, p. 57).



# CIRCULATION AND AQUATIC HABITAT

The direct and 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 which reduces instream temperatures, was removed during levee construction. The pool and riffle structure which was destroyed during excavation of the trapezoidal channel has since reestablished within the constraints of the levees. However, in the interest of flood control, the Army Corps of Engineers requires Humboldt County to periodically remove willows and other 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 species diversity among the invertebrates may still be affected by the instability of the substrate.

Circulation through the north and south sloughs has become more restricted as overwash and tidal currents deposit sediment in the slough necks. The sloughs are isolated from the embayment except during high stream discharge, high waves and/or flood tides or when the outflow channel is functionally closed. Discharge from Sand Cache and Strawberry Creeks through the north and south sloughs is tidally dependent (SD, SC, Figure 7). When backwater develops, the sloughs function as ebb flow channels, remaining stagnant until the flood tide 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 halocline 1.5-2.0 meters (5-6.5 ft) below the water surface persists throughout the year (R. Gregory, J. Yuska, unpublished data). The bottom consists of mud, fine organics, and abundant pieces of organic debris (sample G-07, Appendix G). Floating organic debris covered most of the north slough until recently when the debris was removed after it floated onto adjacent pastures and a log boom was installed. Although organic debris resided in the north slough prior to channelization (Appendix A), larger accumulations 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 which inhibited light penetration and macrophyte establishment (Gregory, 1982).

Unrestricted flow from Strawberry Creek and lower elevations at the slough neck provide better circulation through the south slough than through the north slough. Winter flows from Strawberry Creek flush salt water from the slough 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).

Salt water has been detected in the main channel of Redwood Creek 1.5 kilometers (0.9 mi) upstream (Gregory, 1982). A well-defined saltwater wedge intruded against a 1.2 $m^3$/sec (42 cfs) discharge on a 2.3 meter (7.4 ft) tide with 3.3 meter (10.8 ft) WAVERIDER waves (Appendix E, November 1980). Earlier in the month, 5.9 meter (19.4 ft) WAVERIDER waves on a 2.0 meter (6.5 ft) tide entered the mouth against a 2.8 $m^3$/sec (98 cfs) discharge. These waves caused mixing above and slightly below the north slough halocline, pushed woody debris and salt water into the south slough as far as Strawberry Creek, and again carried salt water 1.5 kilometers (0.9 mi) upstream (Gregory, 1982). Although there is no permanent saline layer in the embayment, when salt water intrudes, it generally forms a stratified salt wedge.

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, salt water is left in small pockets which are much shallower than the 3-4.5 meter (10-15 ft) depressions found at the Sixes River estuary (Boggs and Jones, 1976, p. 420). As the outflow channel becomes functionally closed, tidal action is damped and the embayment may expand. Stratification of the water column breaks down and marine detritus and mud accumulate in the embayment and sloughs.

Since 1966, the available volume of the lower estuary between 0 and 4 feet above MSL has declined by 47 to 54 percent (Appendix D). Unless the outflow channel functionally closes early in the summer, allowing the embayment to expand, the volume of aquatic habitat will be extremely limied. With the smaller volume, the embayment fills more rapidly and water rises over adjacent pastures more frequently than in the past. In January 1981, a high berm backed water up to 11.9 feet above MSL, the highest backwater in the memory of local land owners. The encroachment of rushes (Juncus spp.) in pastures and dead spruce adjacent to the north slough may be signs of more frequent inundation.

When backwater pastures become inundated, local residents dig a trench through the berm. Historically, the mouth of Redwood Creek has been breached almost every year for two purposes (Appendix A, Tipton, S. Barlow). First, eager fishermen open the mouth late in the season in order 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 drift logs 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 ebb tide and results in considerable lowering of the embayment water level. This type of catastrophic breach lowered the water level by 2.0 meters (6.4 ft) in July 1980, isolated both sloughs and reduced the available aquatic habitat being used by 20,000 juvenile salmonids by 75 percent.

Following a breach, a partially mixed estuary may develop when salt water intrudes against lower summer discharge. Breaching also changes the embayment substrate by eroding mud layers and depositing sand with renewed 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. The Corophium population and the volume of aquatic habitat also affects utilizaton of the embayment rearing habitat by juvenile steelhead trout (Salmo gairdneri) and chinook salmon (Oncorhynchus tshawytscha). Interrelations among invertebrate populations, downstream migration of juvenile fish, feeding habits and growth rates have been studied for the Redwood Creek estuary project by Larson, Ricks, and Salamunovich (1981) and by Larson, McKeon, Salamunovich, and Hofstra (1982).

# CONCLUSION

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 1966-68 channelization of Redwood Creek.

Early aerial photographs show that the lower floodplain of Redwood Creek was forested. Along the last downstream meander, dendrochronological data indicate that a grove of spruce began to develop on the middle island over 98 years ago, presumably following flood disturbance. The last downstream meander migrated laterally southward from 1936 to 1967 at a rate of less than 2.1 m/yr. Considering the naturally high sediment load of Redwood Creek, the meander configuration of the mouth was comparatively stable. Bank erosion associated with severe flooding in 1953, 1955, and 1964 was not unusual, either in location or magnitude along the last downstream meander. However, channel widening, aggradation and extensive overbank deposition along the lower floodplain resulted from this series of floods.

Between 1936 and 1967, prior to levee construction, 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 removed from the north cliffs south almost to the California-Pacific Mill site.

Levee construction during 1966-1968 resulted in removal of riparian vegetation, destabilization of gravel bars, and excavation of a trapezoidal channel. Extending the levees beyond the last downstream meander increased the stream gradient in this reach by a factor of 2.0, increasing the current velocity and frequency of mobilization of the substrate.

From 1968 through 1978, the slough necks adjacent to the levees aggraded rapidly. Since high flows were confined by the levees, only a limited part of the berm was scoured and a high storm berm developed to the south. After channelization, 47-54 percent of the lower estuary between zero and four feet above MSL was filled with sediment or isolated from the embayment. As a result, circulation between Redwood Creek and the sloughs became restricted.

Considering that the sediment yield of Redwood Creek is among the highest for a drainage basin of its size in North America, it might be expected that fluvial sediment would accumulate in the embayment and sloughs. The total sediment load of Redwood Creek is composed of 62-81 percent sand, significantly greater than the 25 percent transported by the Eel River. However, during high to moderate streamflow, most of the sand and some gravel are flushed out of the mouth, leaving a gravelly substrate in the channel. Presently, overwash and tidal current transport are the dominant processes of deposition in the embayment and sloughs. Landslides on the north cliffs and eolian transport constitute very minor sediment sources.

Heavy mineral analyses of fluvial and beach sands verify the presence of beach 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. In the embayment, tidal currents deposit sands containing 20 to 31 percent blue-green hornblende over coarser river sediment with less than 5 percent blue-green hornblende.

Overwash during periods of high waves and high tides continues to build 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. Also, it should be noted that the volume of sediment deposited by overwash and tidal currents during a hypothetical marine storm, with record waves and tides following a record stream discharge, would be much greater than volumes cited for WY 1980-1982.

The quantity and quality of aquatic habitat available during the spring through early fall months affects the survival of juvenile salmonids rearing in the embayment. Sediment accumulating in the necks of the sloughs displaces the water volume subject to tidal fluctuations (tidal prism). 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. In order to drain the pastures, local land owners may breach the berm, thereby rducing the volume of available aquatic habitat by as much as 75 percent.

# IMPLICATIONS FOR REHABILITATION OF AQUATIC HABITAT

The quality and quantity of aquatic habitat at the mouth of Redwood Creek could be improved by reestablishing circulation and access between the sloughs and embayment. Alternatives which merit serious consideration include restoring circulation through one or both of the sloughs, dredging the slough necks, and controlling the embayment water level.

Sediment could be scoured from the slough necks by diverting Redwood Creek through spillways or flood gates in the levees to the sloughs. The discharge and sediment load delivered to the sloughs would depend on the height and width of the spillway or timing of opening of the flood gate. The peak discharge and recession rate of flows diverted into the south slough would also determine the rate of lateral migration of the last downstream meander. Diverting a slowly receding flood with a large sediment load might cause aggradation and accelerated migration due to channel widening.

Properly designed improvements would not result in loss of flood control since the levees would continue to contain high flows within the channel. However, sediment stored within the channel may have already diminished the flood protection afforded by the levees. Restoring instream vegetation would create new bed roughness elements and also require reconsideration of the channel design.

Hydraulic engineering designs for the lower reach of the flood control project should allow for the recently estimated equivalent of 40 years of sediment stored in the active channel upstream from Orick. Heavy mineral and textural data show that this fluvial sediment is transported efficiently through the estuary by the present channelized configuration.

Dredging the slough necks and/or berm would be a continuing maintenance effort since the sediment is deposited annually by overwash and tidal currents. Overwash deposition into the south slough neck (Figure 32) was calculated from the volume of sediment accumulated since the Corps of Engineers' 1964-1966 surveys. The 3,400 $m^3/yr$ (2,600 $yd^3/yr$) rate is probably conservative because deposition would have been greatest during storm seasons immediately following 1968 levee construction when the storm berm was lower. Since overwash and tidal currents depend on the timing of waves, winds, tides, and discharge, deposition across the berm and in the slough necks will vary from year to year. The conditions recorded during the period of field observation are presented in Appendix E and should be compared with future events and associated volumes of deposition.

As a temporary means of maintaining an adequate volume of aquatic habitat with connection to the sloughs, the administrators of Redwood National Park manipulated the outflow channel from May through August 1982. In response to local land owners' concerns about flooding fields, park managers agreed to attempt a controlled breach of the mouth. The objective was to prevent a catastrophic breach of the type that reduced the volume of available aquatic habitat by 75 percent in July 1980. When the outflow channel migrated to the south in the spring, the low channel gradient allowed water to back up in the embayment. The outflow channel was shortened by about one-third of its length by digging a channel through the swell berm to capture the flow. The small increase in channel gradient and flow lowered the water level in the embayment. The controlled breach was executed on numerous occasions throughout the summer. Later in the summer, when the mouth closed completely, digging a new long, narrow outflow channel to the south also drained the embayment in a controlled manner.

Another method for maintaining a suitable water level would be to install a temporary outlet culvert in the swell berm early in the summer. Outflow from the embayment might prevent deposition in the culvert if the gradient, length, diameter, and embayment elevation could be adjusted to accommodate decreasing summer discharge.

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