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Physical and Chemical Parameters of Redwood Creek Estuary

by

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A Directed Study
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ABSTRACT

A one year study was made in the estuary of Redwood Creek to determine existing chemical water-quality conditions and nursery area available to out-migrating juvenile salmonids.

Overall, the quantity and quality of salmonid habitat along the lower reach was considered severely degraded. The draining of an embayment to prevent flooding of pastureland decreased juvenile salmonid habitat by half and isolated two sloughs. Poor circulation and a high oxygen demand has caused one of the sloughs to become anoxic along the bottom. The other slough had good water quality conditions but remained isolated through most of the summer.

Restoration of the estuary would require increasing the circulation between the embayment and sloughs throughout the summer and removal of woody debris from the north slough. The flooding and draining of local pastureland places a heavy respiratory requirement on the estuary. Any restoration plan will have to prevent flooding while maintaining the estuary's highest possible water level.

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INTRODUCTION

Over the past fifteen to twenty years, there has been a noticeable decline in the once productive salmonid fishery of Redwood Creek (California Division of Ecological Services, 1975). Researchers have pointed to timber harvesting and related road construction as responsible for degrading spawning and rearing areas (Janda 1978). Adverse conditions upstream are at least partially responsible for the decline of the salmonid fishery. Another reason is the poor condition of Redwood Creek's aquatic habitat within the lower reach and mouth.

The aquatic habitat of Redwood Creek within the lower reach and mouth has suffered from increased sediment deposition resulting from upstream land use practices and construction of flood control levees built on the coastal plain in 1968. The California Division of Ecological Services (1975) estimated that the levee project eliminated 50-75 percent of the wetland at the mouth (figure 1 and 2). The productivity of the lower reach is further degraded by channel aggradation and loss of riparian habitat.

Bradford and Iwatsubo (1978), following levee construction, found that estuarine conditions depend on stream discharge and the development of a sand sill at the mouth. High discharge during the winter and spring overwhelms the tide and prevents a salt wedge from entering past the mouth. Summer discharge allows creation of a sharply defined two layer system with freshwater overriding the denser saltwater.

Northcoast estuaries provide migrating juvenile salmonids with a more abundant food supply, space and cooler temperatures (Meyers 1980, Reimers 1973, Taniguchi 1970). Reimers (1973) and Taniguchi (1970) suggest that wild fall chinook smolts use the estuary for more than a rearing area and require an adaptation time to estuarine conditions before migrating into the ocean. Ninety percent of the successful spawners returning to Sixes River, Oregon, had spent at least three months rearing in the estuary before entering the ocean (Reimers 1973).

The objective of this study is to assist in determining the quantity and quality of estuarine habitat available to salmonids by monitoring physical and chemical parameters of lower Redwood Creek throughout 1980. Project monitoring included seasonal morphological changes of the sill at the mouth and water analysis within the lower reach. Analysis

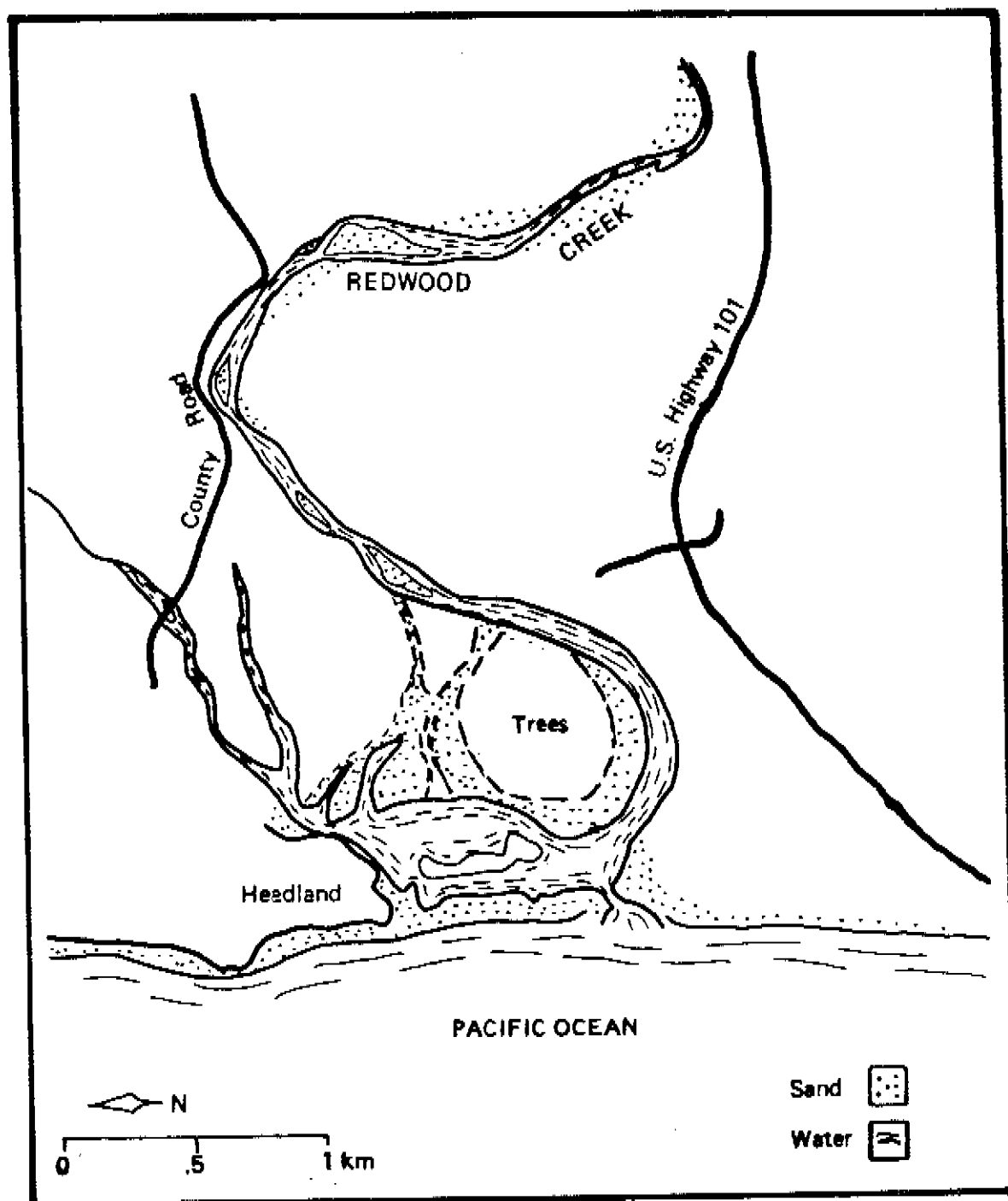


Figure 1. Configuration of Redwood Creek, prior to levee construction, in 1968, (aerial photograph overlay 4/8/68).

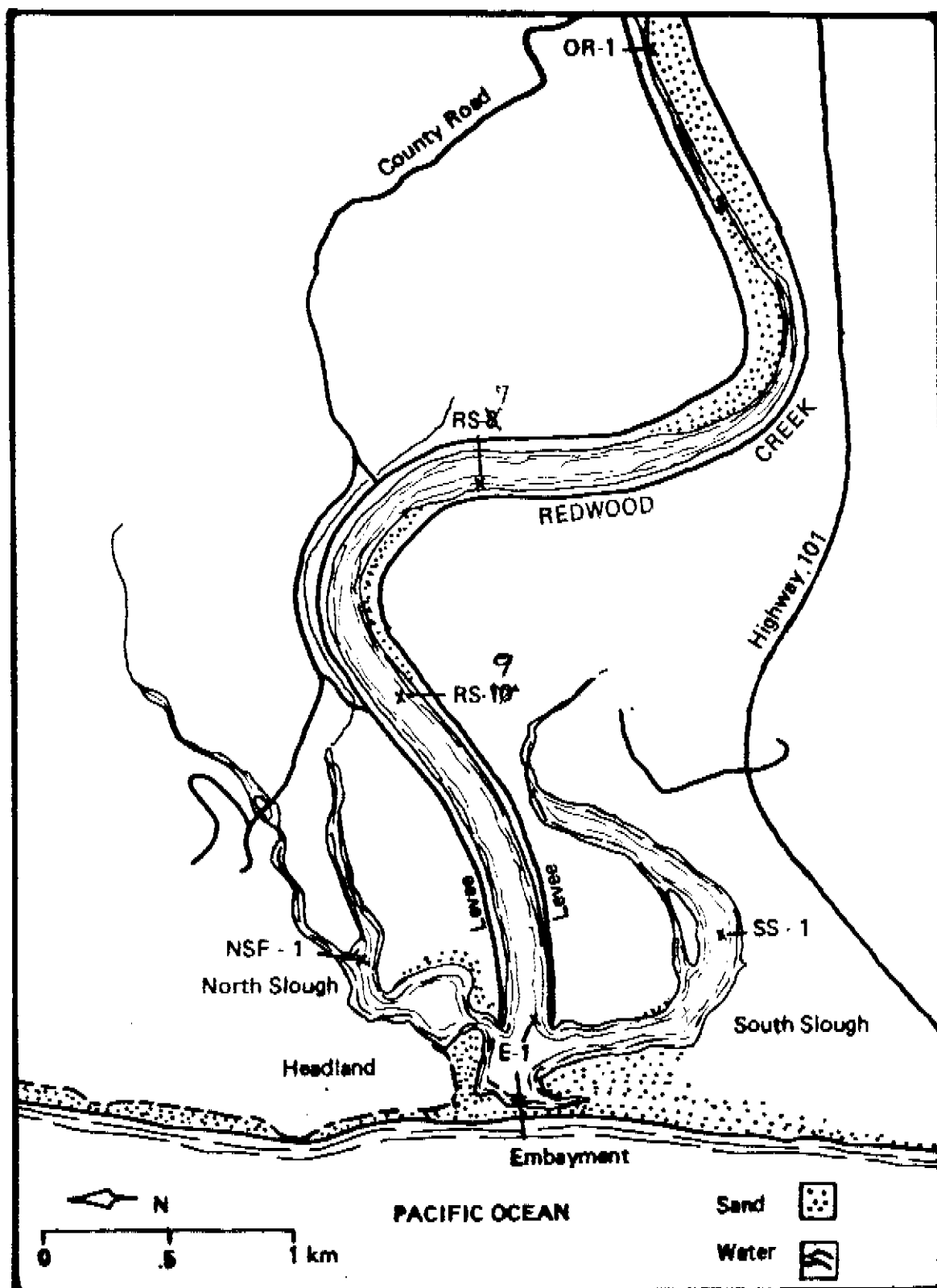


Figure 2. Redwood Creek, post levee construction, 1978. Map of study area showing station locations and compartments (aerial photograph overlay 8/16/78).

of the data provides a basis for programs that could increase salmonid nursery area and return lower Redwood Creek to a higher level of productivity.

PHYSIOGRAPHY AND HYDROLOGY

Redwood Creek is located on the northern coast of California, 60 km north of Eureka (figure 3). The stream flows northwest for 88 km from an elevation of 1600 meters to the Pacific Ocean. Flow in the stream is directly influenced by rainfall with discharge ranging from over $378 \text{ m}^3/\text{sec}$ during winter to lows of $0.15 \text{ m}^3/\text{sec}$ in summer (figure 4) (U.S. Geological Survey Water Data, 1981). Redwood Creek drains a 720 730 km^2 watershed. The overall basin is approximately 80 km in length and less than 16 km in width at the widest point. The lower reach of Redwood Creek extends 6.4 km across a small coastal plain before emptying into the Pacific Ocean.

The flood control project on Redwood Creek, in the form of levees, extends from the mouth of Prairie Creek downstream past Orick to within a few hundred yards of the stream opening to the ocean (figure 3). The ends of the levees open to a small embayment partly sheltered from the ocean by a sandbar. The embayment connects with the southern abandoned oxbow section of channel (south slough) and the northern marsh drainage (north slough) during winter flows (figure 2).

Bradford and Iwatsubo (1978) reported that, in the high discharge periods of winter and spring, the sandbar is broken through at one or more points, allowing connection to the ocean. Prevailing northwest winds and longshore currents form a sill of sand at the tidal inlet in summer, constricting or closing the tidal inlet. The tidal inlet may be closed for varying intervals of time during the late fall months, preventing surface discharge to the ocean and salt intrusion into the stream. Water may percolate into or out of the embayment through the bar, but tidal action is strongly damped. Fresh water addition from upstream backs up the embayment and floods into the north and south sloughs whenever the bar closes.

During the summer and fall, the sill creates a two layer system in the embayment at ebb tide (Bradford and Iwatsubo 1978). Salt water is retained on the bottom behind the sill while fresh water moves downstream above the saltwater and over the sill into the ocean. The interface between these two layers is sharply defined. On flood tide, the inlet is inundated by cold, full strength seawater, resulting in extensive vertical mixing and movement of a salt wedge upstream (Bradford and Iwatsubo 1978).

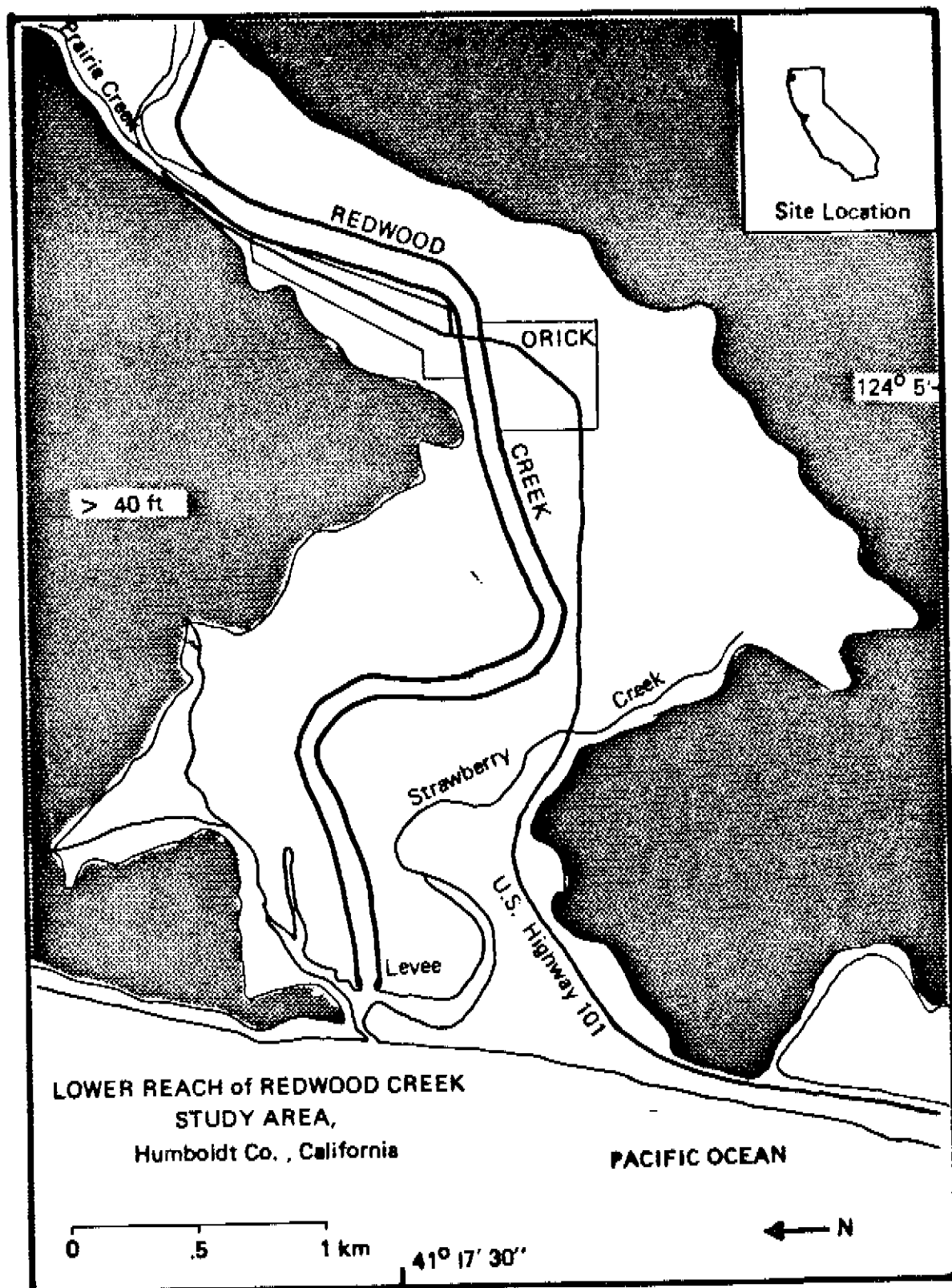


Figure 3. Index map showing location of the lower reach of Redwood Creek on the northern California coast.

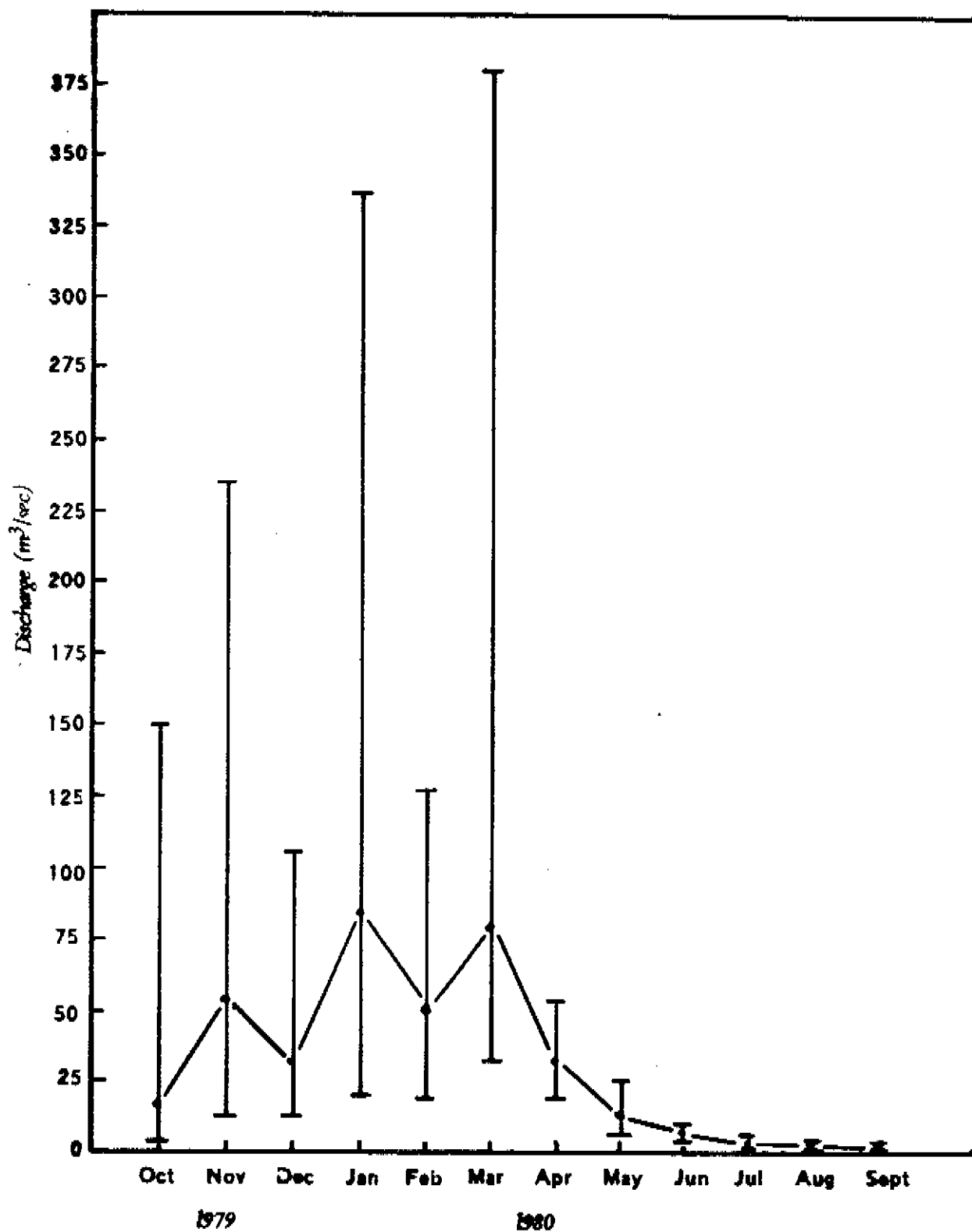


Figure 4. The range and mean monthly discharge of Redwood Creek, California, for water year Oct. 1979 to Sept. 1980 (U.S.G.S. water data report, 1980).

METHODS AND MATERIALS

The levee construction on Redwood Creek created a physical barrier to circulation between the stream and the two sloughs. This barrier allowed the compartments to be isolated during part of the year. The methods were designed to show the change in water quality parameters as the stream and sloughs mixed in spring, became isolated in summer, and became united again in the fall.

Four stations were monitored in the lower reach of Redwood Creek. The stations were at the mouth of Redwood Creek (E-1), south slough (SS-1), north slough fork (NSF-1), and Orick Bridge (OR-1), (figure 2). The sampling schedule from March to November, 1980, was at least once a month and twice if time and weather permitted.

FIELD SAMPLING

Water quality parameters monitored in this study include dissolved oxygen, pH, salinity, conductivity, temperatures, alkalinity, turbidity, ammonia, phosphate, nitrate and nitrite. Water samples were collected from a quarter meter below the surface with an alpha bottle. Water was siphoned into a brown dissolved oxygen bottle and fixed with manganous sulphate and alkaline iodide. The remainder of the sample was distributed to three one-liter plastic sample bottles and placed on ice until return to the laboratory. Temperature, salinity, and conductivity were determined in situ with a YSI salinometer.

Morphology of the embayment changed during the summer with the development of a berm at the stream's mouth. This process was recorded on photographic slides taken from a hill overlooking the lower reach of Redwood Creek as well as aerial photographs. Aerial photographs from 1962 through 1981 were used for a historical perspective of seasonal change of inlet morphology.

location?
Continuous temperature recordings were made for the north and south sloughs with Ryan Thermographs. The thermographs were secured with light line to concrete blocks and allowed to float approximately one meter below surface. The depth of the thermograph varied with changes in water level.

LABORATORY METHODS

Dissolved oxygen, pH, alkalinity and turbidity analyses were undertaken at the Telonicher Marine Laboratory in Trinidad immediately after all water samples had been collected.

Dissolved oxygen was determined by the Winkler method (Strickland and Parsons 1972) and pH was determined with a Sargent-Welch Model PAX pH/activity meter after calibration with 4.01 and 9.01 standard. Carbonate alkalinity was determined by potentiometric titration to an end point pH of 4.5 and reported as milliequivalents CaCO_3 /liter. Turbidity samples were determined with a Hach 2100A Turbidity Meter.

Ammonia, phosphate, nitrate and nitrite samples were frozen upon arrival at the Marine Station. These samples were analyzed within 6 weeks or else discarded owing to degradation. All of the nutrient samples were determined by spectrophotometric procedures described in Strickland and Parsons (1972). Capability of nutrient test were 6-0.03 ug-at PO_4 /l, 10-0.1 ug-at NH_3 /l, 45-0.05 ug-at NO_3 /l, and 2.5-0.01 ug-at NO_2 /l (Strickland and Parsons 1972). A Perkin-Elmer Spectrophotometer with Hitachi 200 readout determined absorbances with a 10 cm sample cell for ammonia, phosphate and nitrite. Spectrophotometry of nitrate was done with 1 cm sample cell.

RESULTS

Construction of flood control levees on the lower reach of Redwood Creek created a four compartment system. One compartment is from Orick bridge station, where the stream flows along a narrow bed between the levees, to the embayment at the end of the levees. The next two compartments are each of the sloughs, which connect with the stream only during periods of high discharge or when impoundment of water occurs from development of a berm at the mouth. The fourth compartment is the embayment, where water from Redwood Creek, the sloughs, and the ocean mix. The results of this study are presented to show the different conditions existing in each of the compartments.

ORICK BRIDGE

Discharge

Redwood Creek is fed by numerous tributaries. The steepness of the slopes in the watershed allows the streams and the main channel to rise rapidly in response to rainfall. At low flow the stream is very shallow.

Temperature and Oxygen

Temperature ranged from a low of 11.5°C in February to a high of 20.5°C in August. Oxygen concentrations were

close to saturation throughout the study (figure 5). Bradford-Iwatsubo (1978) reported oxygen concentrations averaging 96% saturation throughout the year at upstream stations. They attributed this to physical turbulence along the stream bed.

pH and Alkalinity

The water analyzed from the Orick bridge station had a relatively small range of pH (figure 6). A peak value of 8.4 occurred on October 1, possibly caused by the first rains in fall leaching the soil in the watershed. Prior to this, pH ranged from 7.9 to 7.8. Alkalinity values ranged from a high of 0.62 milliequiv./l CaCO_3 on November 11 to a low of 0.38 milliequiv./l CaCO_3 on October 12 (figure 7).

Nutrients

The increase in ammonia, phosphate, and nitrate during October and November could also be attributed to the first storms of fall leaching nutrients from the watershed (figure 8). Nitrate had the greatest increase in mid-October but possibly this is the result of a point source entering from the Orick area rather than from the watershed. The decrease to below the limit of detection of nitrate and the decrease of nitrite was probably caused by dilution as runoff increased.

Turbidities

Turbidities during the late summer and fall were very low, probably due to the small amount of discharge from the watershed (figure 9). Turbidity increased in mid-October when water velocity increased and soil eroded with the first rains of the season.

EMBAYMENT

Changes in water quality parameters throughout the year in the embayment reflect the mixture of fluvial and coastal processes. Salt intrusion, circulation with the sloughs, and volume of water in the embayment depend on discharge from Redwood Creek and the morphology of the berm at the mouth. Water levels in the embayment often rose high enough during winter storm events to reach both the sloughs. Additionally, high tides would often block the stream flow and force water into the sloughs.

Inlet and Berm Morphology

Redwood Creek has a fully exposed beach to swells

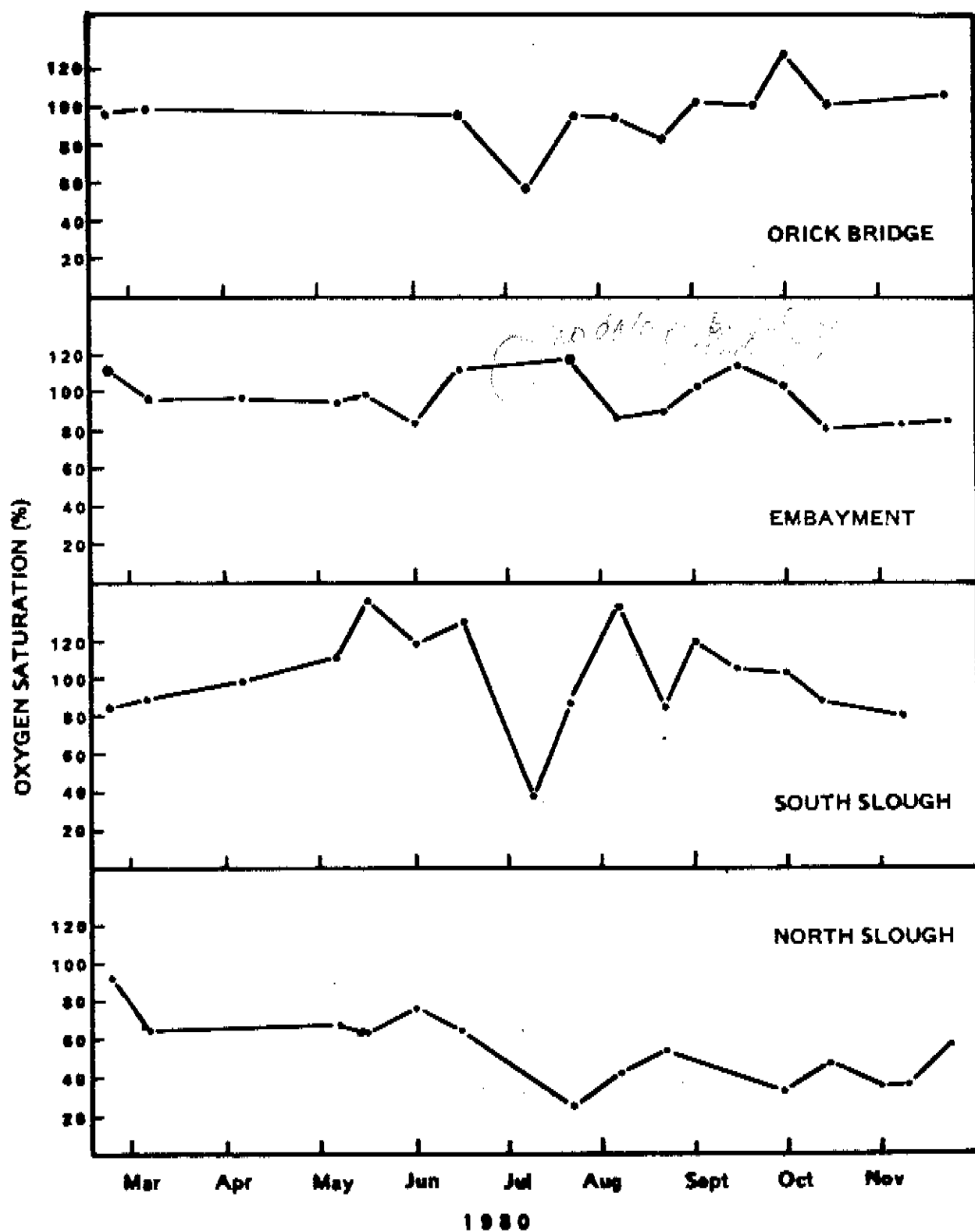


Figure 5. Monthly change of percent oxygen saturation for Orick bridge, embayment, south slough and north slough.

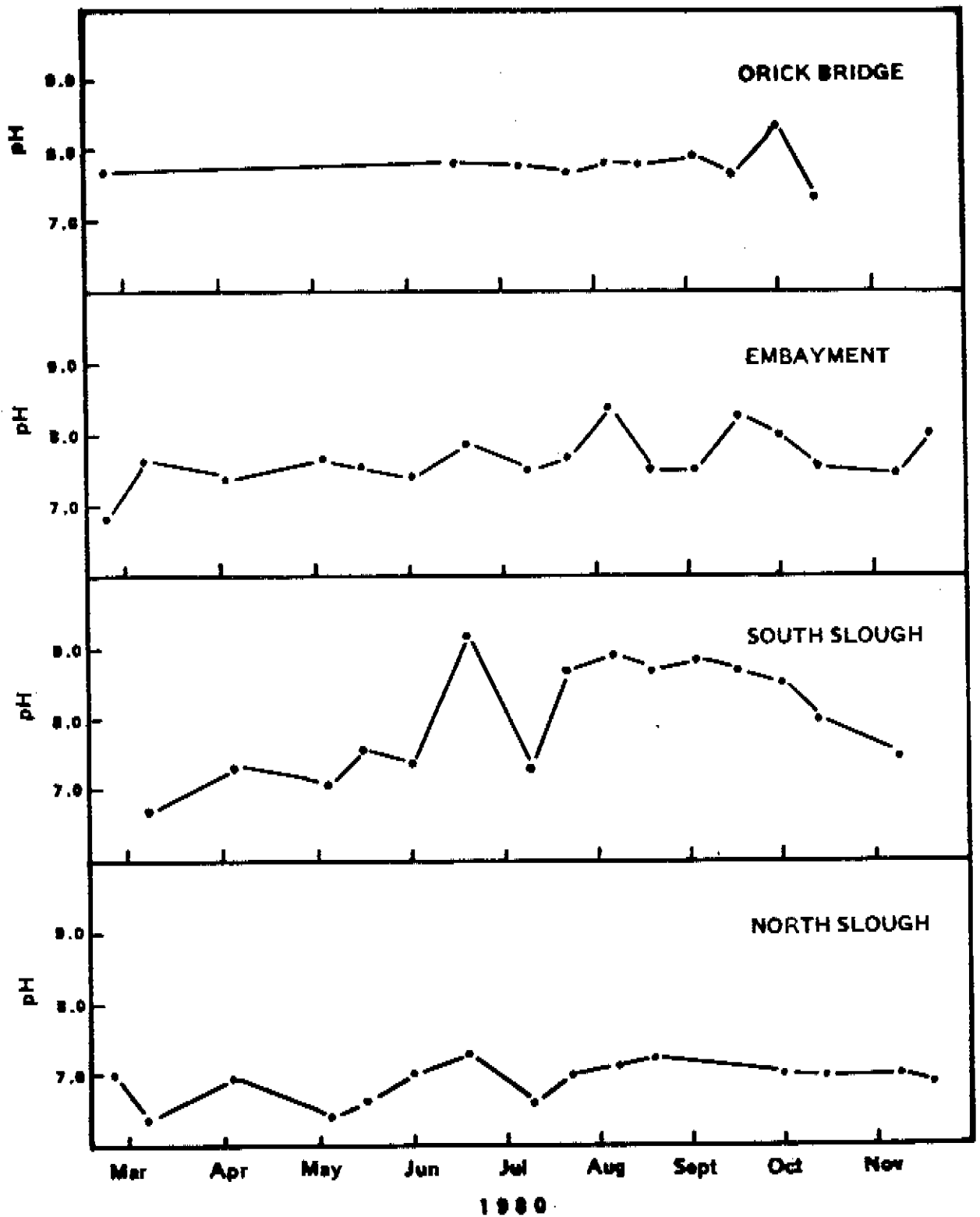


Figure 6. Monthly change in pH for Orick bridge, embayment, south slough, and north slough.

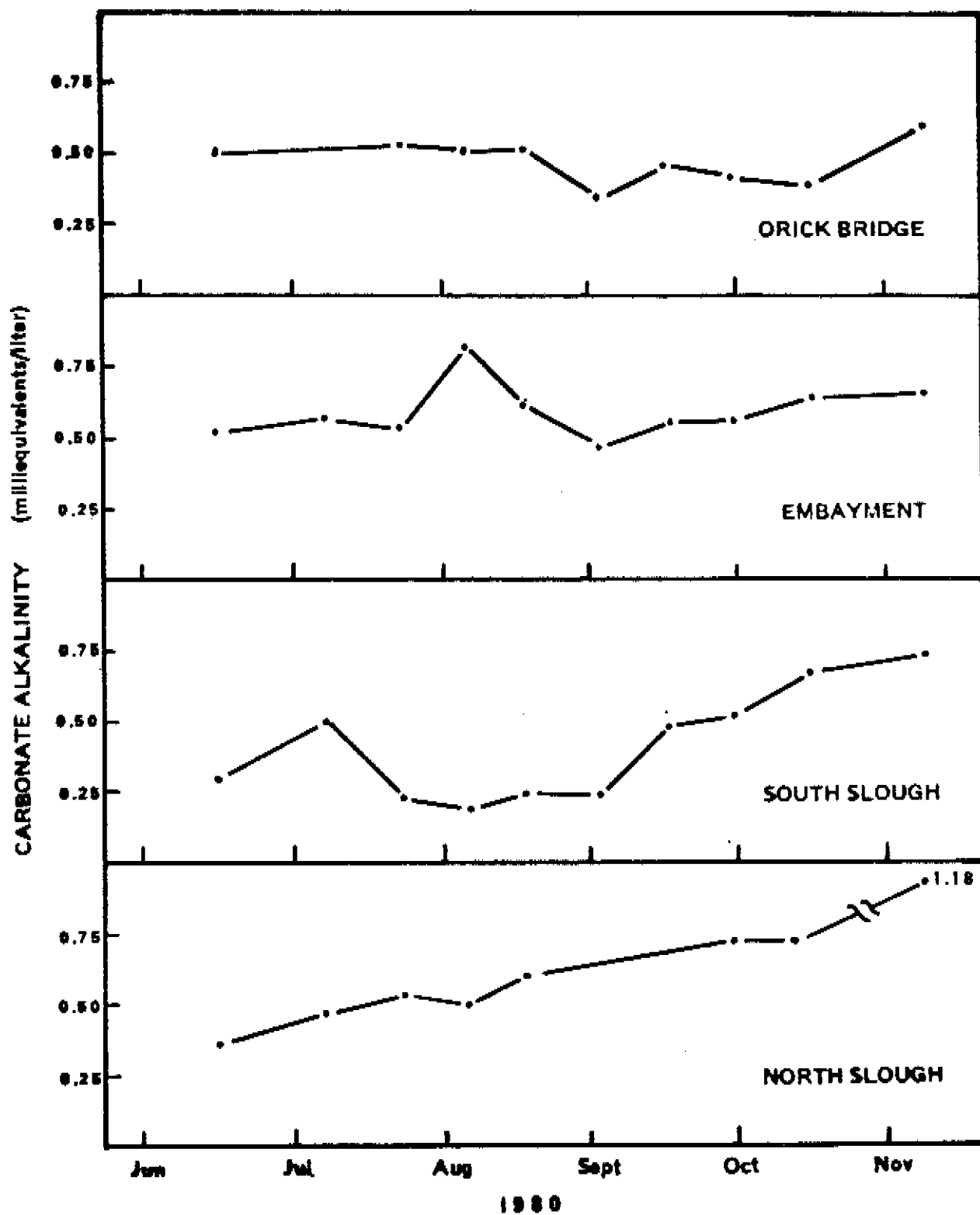


Figure 7. Monthly change in carbonate alkalinity for Orick bridge, embayment, south slough, and north slough.

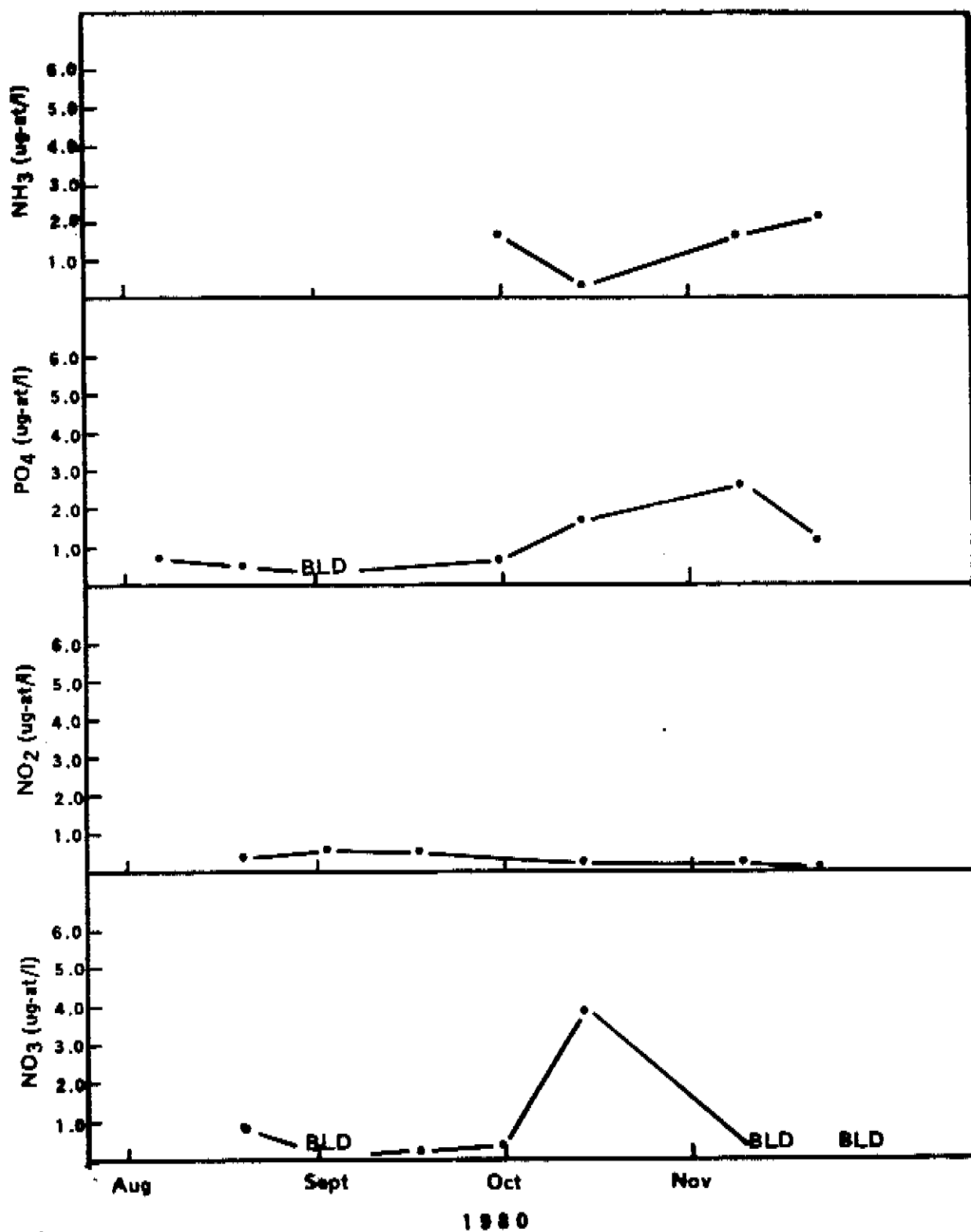


Figure 8. Nutrient concentrations at Orick bridge from August through November, 1980.

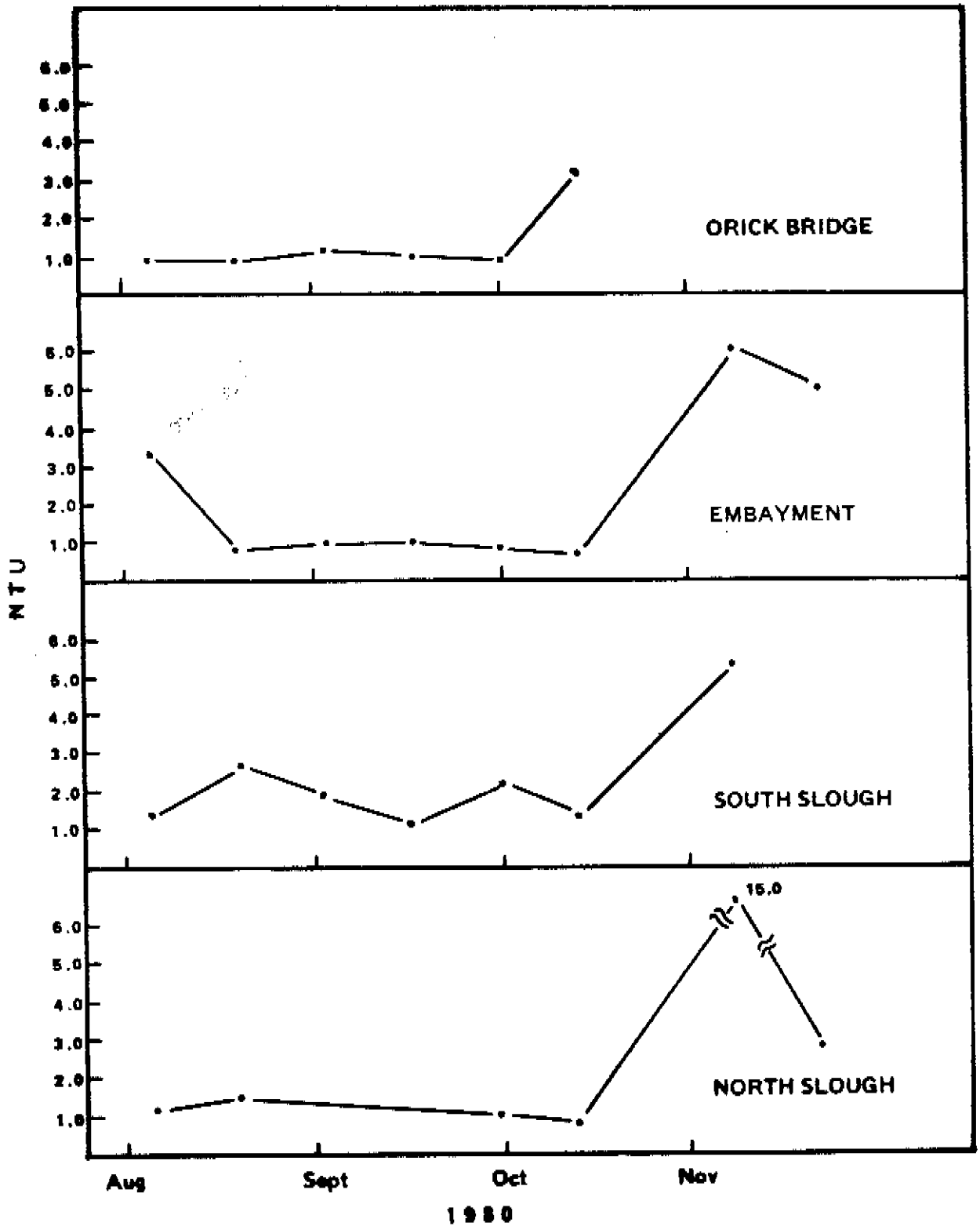


Figure 9. Change in turbidity at Orick bridge, embayment, south slough and north slough from August through November, 1980.

approaching during the winter months. Winter swells steepen the beach and narrow the berm by pulling beach material into the surf (Boyd et al 1977). In April, 1980, coastal processes began to widen the berm along the beach. Bascom (1964) describes the building of a berm as the result of an average decrease in swell height, moving sand onshore from the bars. The increase in berm width and height along Redwood Creek beach continues throughout the summer and into the fall (Boyd et al 1977).

The location and size of the inlet cutting through the berm also changes with the seasons. During February and March of 1980, when stream discharge averaged $71 \text{ m}^3/\text{sec}$, the inlet was positioned either directly across from the levees or next to the headland to the north (figure 10). The location and length of the inlet changed depending on direction of approaching swells and stream discharge. During the winter, swells approach from the southwest and the inlet migrates north. In April, the length and direction of the inlet changed as it began to bend and migrate south. This migration of the inlet was also seen in aerial photographs prior to construction of the flood control levees. In May the inlet again migrated north after a storm brought swells in from the west-southwest (figure 10). A change of inlet direction appears to be caused by swells adding material to one side of the inlet while discharge from the embayment undercuts the inlet's other side.

Discharge from Redwood Creek decreased to $8 \text{ m}^3/\text{sec}$ during May and June. Water level fell and the sloughs were often disconnected from the embayment. In June, the inlet again migrated south while waves filled the previous inlet with sand and increased the height of the berm. The inlet began to lengthen, running along the top of the berm and gradually sloping down the beach to the ocean (figure 11). By mid-June, impoundment of water behind the high berm raised the water level of the embayment to connect both sloughs. Depths within the embayment reached 3.5 m and the inlet averaged 2.5 m wide and 1 m deep.

By the end of June, water levels rose above the banks of the sloughs and flooded surrounding pastures. Pastures along the north slough were covered with woody debris, causing an economic hardship on the owner. The owner was given a permit to dig a trench through the berm and drain the embayment and sloughs on July 2, 1980 by California Department of Fish and Game. Using only shovels, four men released the impounded water and created a new inlet directly across from the levees. The new inlet began as a rivulet but eventually became 10 m wide and eroded 4 m off the berm's height. On July 3, 1980, only a small stream, 5 m wide and .7 m deep ran between the levees and into the ocean (figure 11). The sills in front of the sloughs protected them from completely

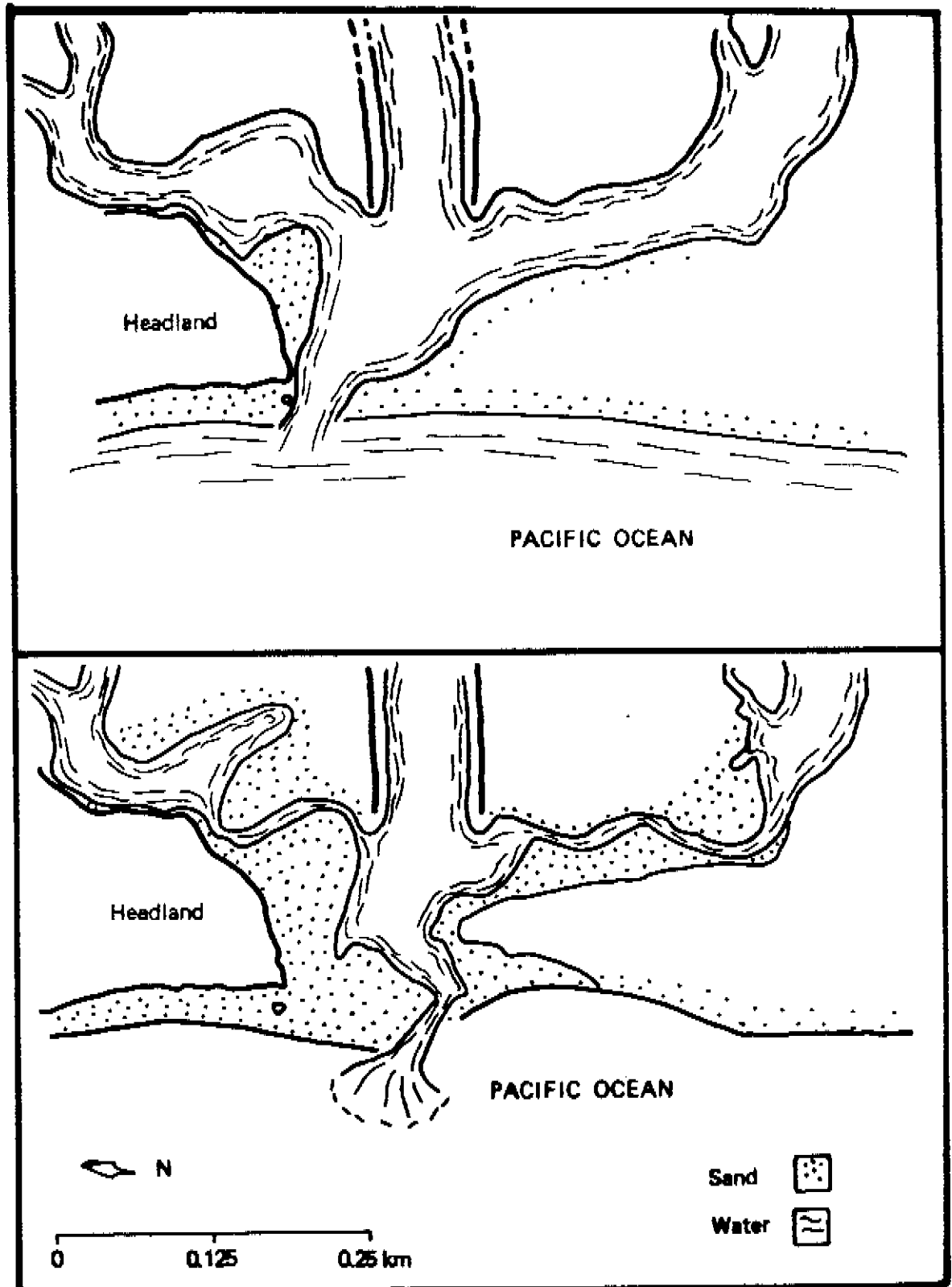


Figure 10. Winter position of Redwood Creek inlet during high discharge (top). A change in swell direction during May forced the inlet to migrate north (bottom).

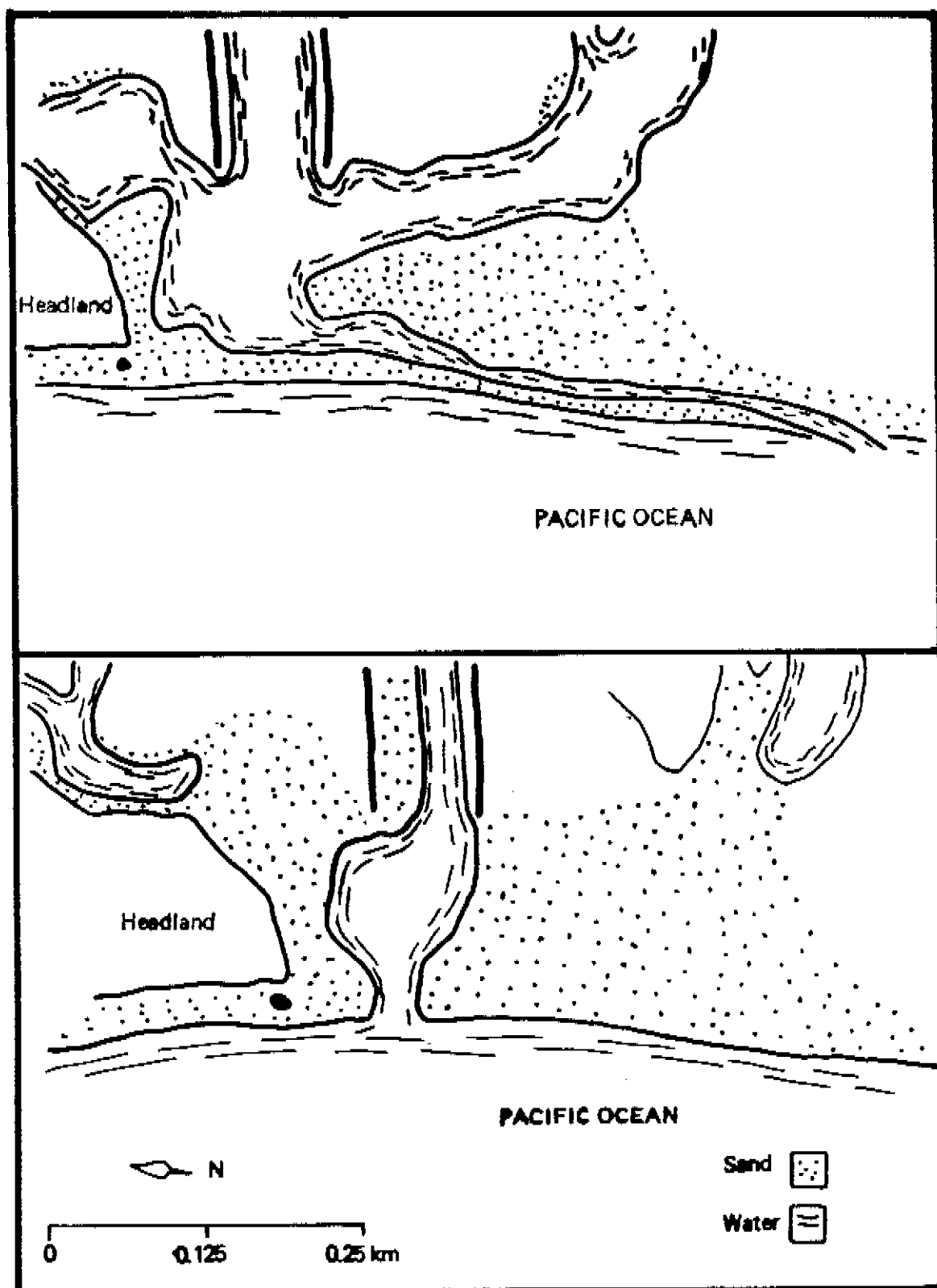


Figure 11. In June the inlet gradually sloped down the beach, migrating to the south (top). On July 2 a new inlet was created after a trench was dug through the berm (bottom).

draining, but they no longer connected with the embayment. From July through September, only high spring tides would raise water levels enough to reach the south slough but apparently never the north slough.

The inlet curved and began migrating to the south again in late July. Throughout August, the inlet remained open while overwash from waves brought more sand into the embayment (figure 12). In early August, jelly fish, seaweed, and crab shells began collecting along the bottom of Redwood Creek's embayment. The berm continued to widen through August and September as discharge from the stream decreased. The inlet filled with sand and gravel by the second week of September, closing the embayment to the ocean (figure 12). Overwash continued to transport sand into the embayment, widening the berm.

Storms in early October increased the volume of water impounded behind the berm. By October 17, water levels had again risen over the banks of the sloughs, and flooded surrounding pastures. Local ranchers were denied a permit from California Department of Fish and Game to release the impounded water. Later that same week, the berm was breached and water levels fell 1.7 m. The inlet that was created did not erode the berm to the same extent as in July. A number of conditions had changed from July to October: 1) the berm had doubled in width and gradually sloped into the surf zone, 2) the swell had increased from .4 m on July 3 to an average swell of 1.3 m from October 17 to October 29. On October 29, the sloughs did not connect with the embayment but water, 2 m deep, was still held behind the berm. By the end of October, the inlet filled again isolating the embayment from the ocean.

In early November, 2-3 m swells washed over the berm at high tide and entered the north slough. Woody debris, piled along the water's edge of the embayment, was pushed into the sloughs. By low tide, waves no longer washed over the berm and the only discharge was percolation through the berm. The inlet remained closed through November, but waves often washed over the berm and into the embayment during high tides. The pastures were flooded again in December, but after this, discharge increased from Redwood Creek and eroded an inlet through the berm.

Salinity and Temperature

On February 17, a 2.2 m tide allowed a saltwater wedge to enter the embayment against stream discharge of $23 \text{ m}^3/\text{sec}$. Salinity reached a maximum of 18.8‰ along the bottom while temperatures of 10°C were constant throughout the water column (figure 13). This was the only recorded saltwater

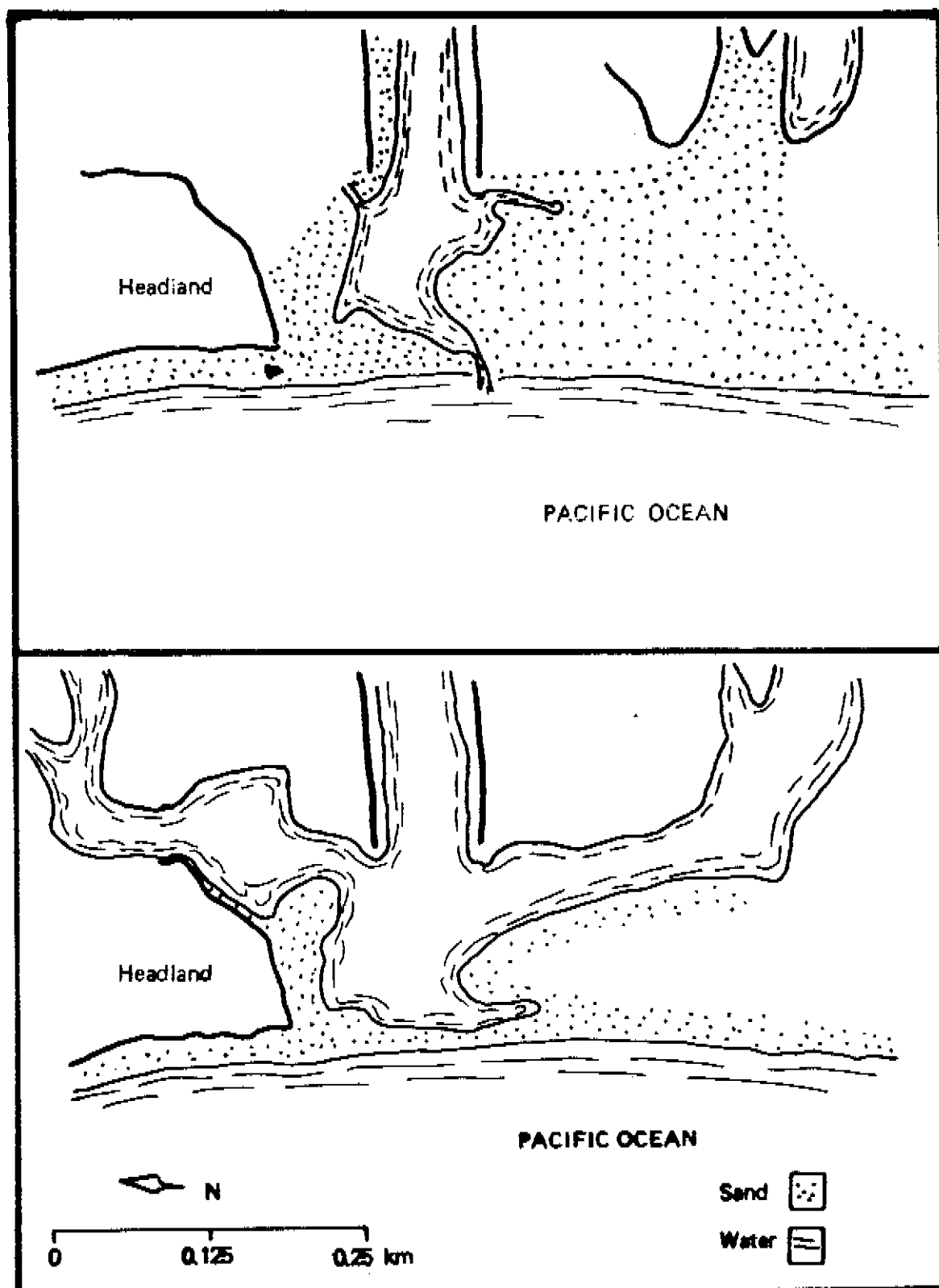


Figure 12. Water level remained low in the embayment from July through August (top). Continued widening of the berm through summer finally closed the inlet early September (bottom).

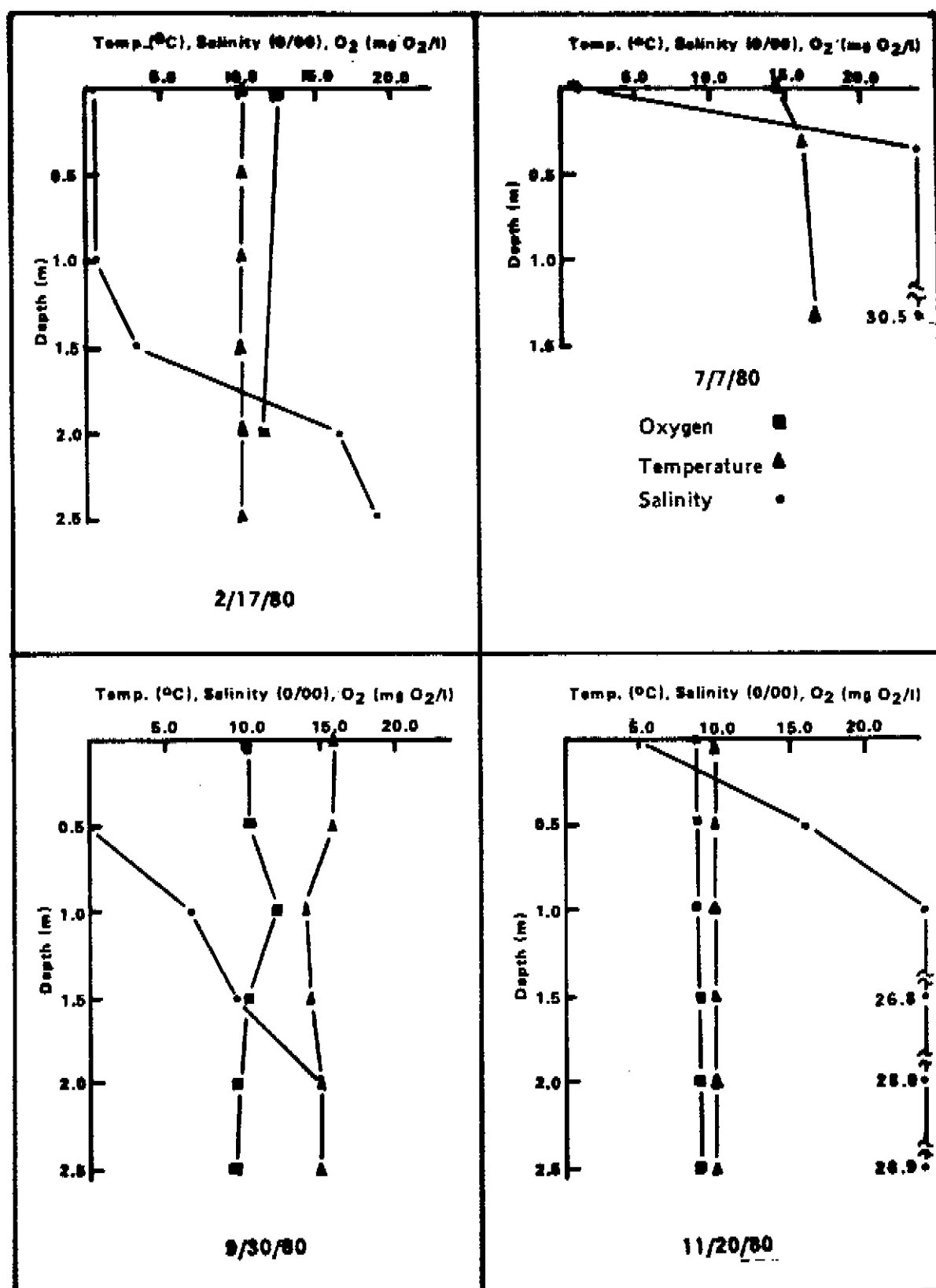


Figure 13. Seasonal change in temperature, salinity, and oxygen profiles in the embayment.

intrusion until June 1 when salinities of 12.5‰ were found in deep holes along the levee toe. Salt intrusion extended 45 m up the levee on a 2.0 m tide. Any trace of salt was washed from the embayment at low tide. The temperature throughout the water column was 14°C and stream discharge was 7.4 m³/sec. No salt intrusion was recorded on May 16 during a 2.1 m tide. The slope of the inlet and stream discharge of 12.1 m³/sec overwhelmed the tide.

During June, water depth increased to 3.5 m but no layer of saltwater remained on the bottom. As the berm continued to gain height, the effect of tidal action became damped. By the end of June, any saltwater entering the embayment by overwash or through the inlet was diluted and/or then forced through the sand to the ocean. Temperature throughout the water column was 19°C on June 17.

On July 7, a saltwater wedge entered the embayment through the inlet on a 1.9 m tide (figure 13). Salinities of 25‰ extended 100 m up the levees but the tide was not high enough to reach the north and south sloughs. Salinity was 1.0‰ on the surface and 30.5‰ on the bottom at 1.3 m. Temperature was 14.5°C on the surface and 17.0°C on the bottom.

High tides on July 28, 29 and possibly July 12, pushed a saltwater wedge upstream to River Station Number ~~910~~ (R.S. 910) (figure 4). At this station salinities ranged from 1‰ on the surface to 23‰ on the bottom at 1 m while temperatures were homogenous at 15°C.

On August 5, the depth of water in the embayment had increased to 1.5 m at low tide with a layer of saltwater .4 m thick, 17‰ and 14°C, remaining on the bottom. At high tide, salinity increased to 19‰ on the surface and 28‰ along the bottom.

The embayment had increased in depth to 2 m by August 18 with a saltwater layer of .3 m remaining on the bottom. Tidal action was damped by the widening of the berm and narrowing of the inlet. On September 2, only a thin layer of saltwater remained on the bottom and by September 16, salinities dropped to 0‰ on the bottom. During August and September, water temperatures averaged 19°C.

Throughout October and November, waves washed over the berm giving the water in the embayment a dark green color. During these storms, salinity would range from 4‰ on the surface to 28‰ at 2.5 m.

On November 20, salinity of 22‰ at a depth of .6 m was recorded at River Station Number 8 (R.S. 8) around the bend of the levees (figure 4 and 13). This was the most

upstream point that saltwater intrusion had been recorded during the study.

Oxygen

Water entering the embayment from either the ocean or upstream was saturated with oxygen by physical turbulence. Only in the summer and fall when water is retained behind the sill does respiration and photosynthesis affect oxygen concentrations. Decreases in the level of oxygen below saturation occurred when marine detritus accumulated on the bottom of the embayment (figure 5). Oxic conditions were always found in the embayment, with the lowest value recorded on the bottom at 77% saturation.

pH and Alkalinity

During August and September, pH and alkalinity in the embayment increased above levels found at either Orick Bridge or the ocean (figure 6 and 7). The high values of pH, 8.41, and total alkalinity, 0.81 milliequiv./l CaCO_3 , occurred on August 5 and are suspected of being caused by primary production in the surface layer of the embayment. Ocean values for pH ranged from 7.6-8.2 and were reported at 7.9 on August 5, 1980 (Fred Telonicher Marine Station, Data Report 1980).

Nutrients

Nutrient concentrations in the embayment were higher than any other station in the study. Values for ammonia averaged 2.4 ug-at N/l and phosphates were lower at 0.5 ug-at PO_4 /l (figure 14).

Crandel (1980) found the ocean to be a major nutrient source during October and November for the Mad River Estuary, 20 miles south of Redwood Creek. Concentration of nitrate and phosphate were found to correlate very highly with salinity, becoming depleted farther up estuary. Concentrations of ammonia and phosphate found in the embayment are comparable to values found near shore but nitrate decreased from 17 ug-at N/l in the ocean to below the limit of detection in the embayment.

Turbidities

Increased turbidity during August and September occurred when a layer of saltwater was retained behind the sill (figure 9). A relatively high value of 3.3 NTU measured

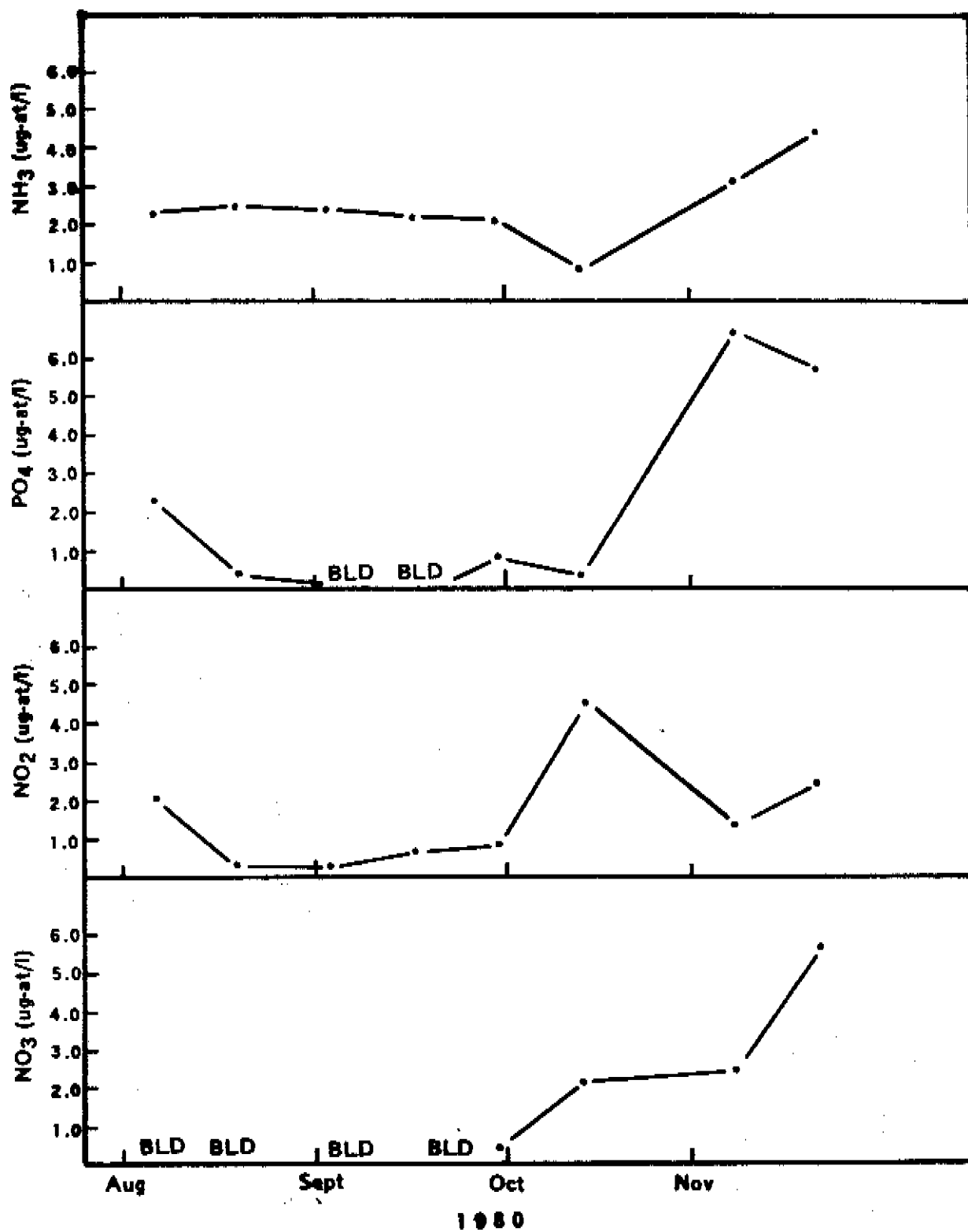


Figure 14. Change of nutrient concentrations in the embayment from August through November.

near the surface on August 5, could be indicating an increase of phytoplankton on the surface. In October, turbidities of 1.5 and 2.0 NTU were found on the bottom of the embayment. This coincided with a dark green color of water retained behind the berm and suggested an increase in marine phytoplankton and detritus along the bottom.

SOUTH SLOUGH

The south slough was the main channel of Redwood Creek prior to construction of flood control levees. The slough is 1.6 km in length and has a channel depth of 2-3 m along the southern edge. The deepest part of the channel is only a few meters wide before sloping up to a shallow bottom extending across the remainder of the slough. The channel fills with sand as it nears the curve connecting with the embayment. This sill has enough height to prevent all but the highest spring tides from entering during the summer. A grove of trees line the northern bank while the southern bank is predominantly covered with grass.

Strawberry Creek feeds into the east end of the south slough. The watershed feeding Strawberry Creek is the surrounding hillsides to the south of Highway 101 and local grazing land. Discharge from Strawberry Creek could be significant in eroding the sill at the entrance of the south slough and in pushing woody debris into the embayment. During storm events in November, woody debris was forced into the slough on high tides. At low tides, the flow reversed and discharge carried the debris back into the embayment.

Salinity and Temperature

Winter discharge from Strawberry Creek washes out any saltwater remaining in the south slough from summer and fall. Winter temperatures averaged 8°C (figure 15 and 16).

In spring and summer, as discharge decreased, the south slough was isolated from the embayment by a sill across the channel. Temperatures steadily increased from April to June (figure 17).

Salt intrusion into the south slough occurred on a 2.2 m tide on July 12 after the berm had been opened by local ranchers. The entire water column had a temperature of 20°C and salinity of 2‰. Spring tides entered the south slough again on July 28 and 29 when high tides of 2.1 m pushed a salt wedge, 2 m wide and 0.2 m deep, with salinity 20‰ and temperature 15°C, into the slough. The input of saltwater into the slough created a halocline with a gradient from 2‰ at .3 m to 18.5‰ at 1.5 m. Throughout

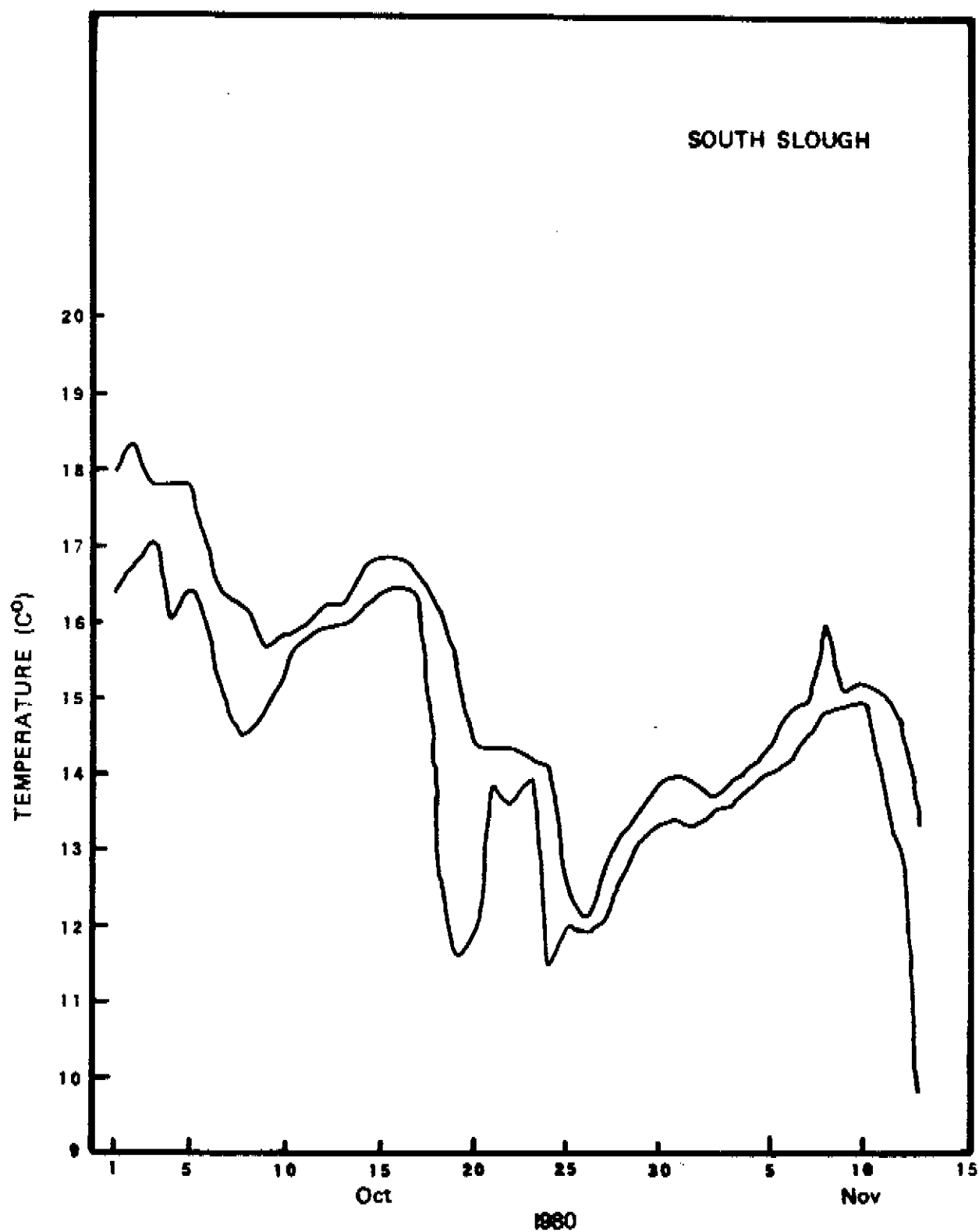


Figure 15. The range of daily temperatures approximately one meter below the south slough's surface during fall.

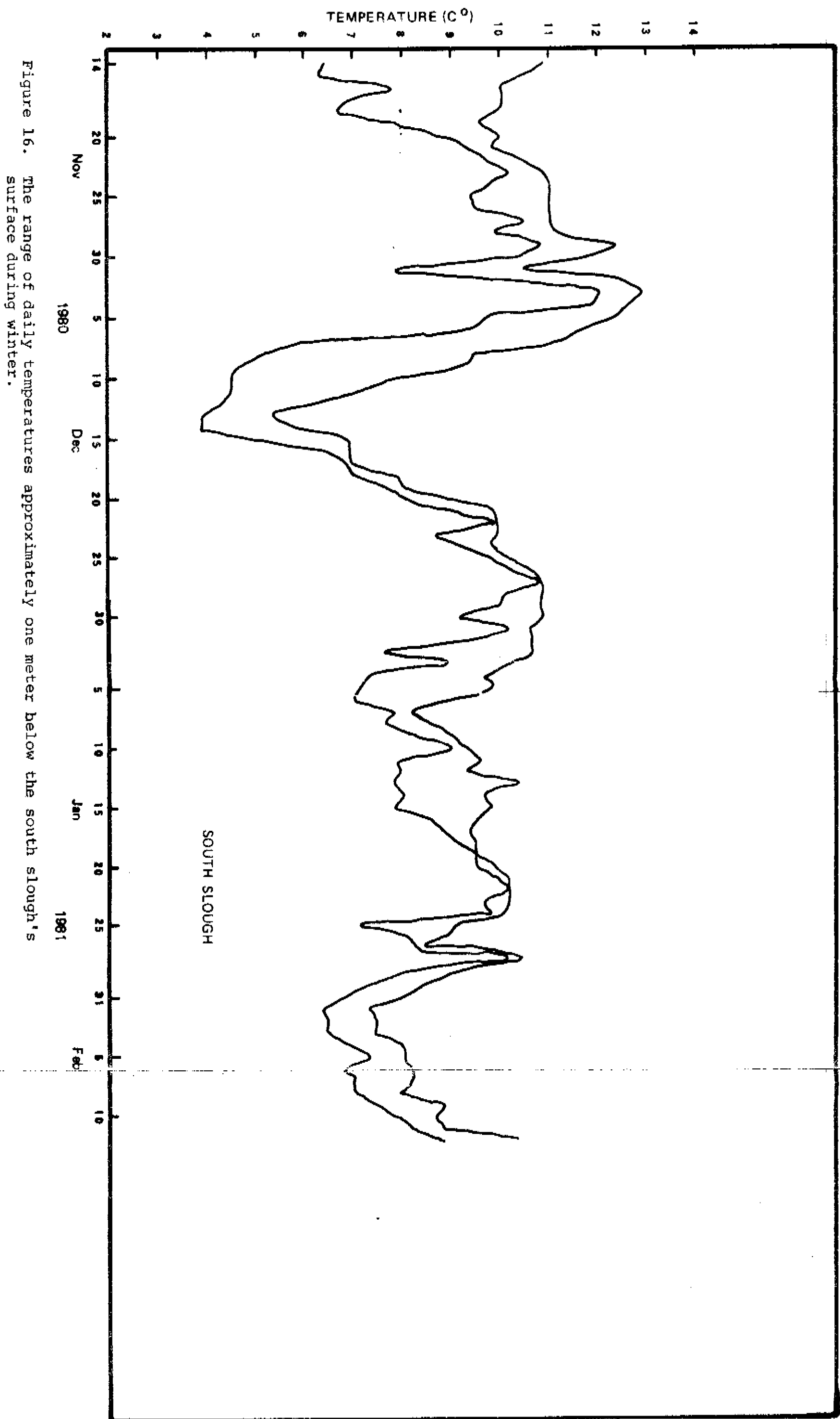


Figure 16. The range of daily temperatures approximately one meter below the south slough's surface during winter.

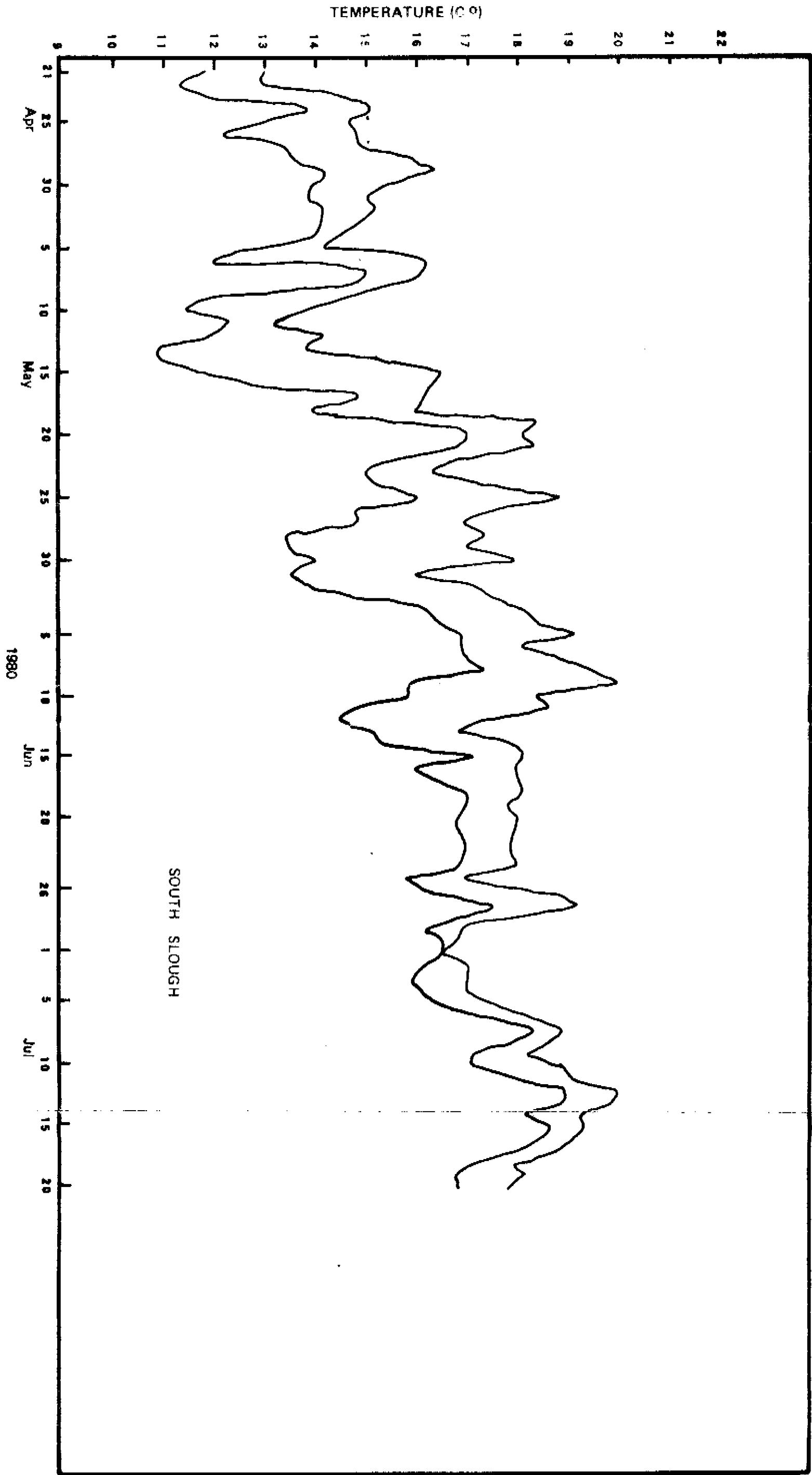


Figure 17. Daily range of temperatures approximately one meter below the south slough's surface during spring.

August a 1 m layer of saltwater remained on the bottom (figure 18). A temperature gradient developed along the halocline with the bottom 2°C warmer than the surface. By the end of September water below the halocline was 7°C warmer than the surface (figure 18).

High tides and surf increased salinity throughout the water column in late October (figure 18). By the end of the study in November, salinity still ranged from 3.4‰ and 15.9‰ on the surface to 20.6‰ and 17.3‰ on the bottom. The farthest extent of salt intrusion was on November 7, when salinity at the entrance to Strawberry Creek ranged from 1.8‰ on the surface to 8.9‰ at 1.3 m depth.

Oxygen

During the winter, water entering the south slough from Strawberry Creek and the embayment is close to being saturated with oxygen. As water velocity decreased in summer, respiration and photosynthesis controlled the level of oxygen saturation (figure 5).

Oxygen supersaturated the water column in the south slough throughout May and June. On June 17 oxygen saturation was 130% on the surface and 144% at 1.5 meters. Physical turbulence such as the wind over the water's surface and discharge from Strawberry Creek were partly responsible for this high oxygen concentration on the surface. The supersaturation of oxygen at 1.5 m was a result of increased primary production during spring.

A decrease to 36% saturation in early July could have been caused by a large input of organic material, from surrounding pastures, draining after the berm was breached on July 3. Decomposition and saltwater intrusion, stratifying the water column, depleted oxygen and could have caused the bottom of the south slough to become anaerobic. On July 22 surface concentrations of oxygen were 87% saturated and bottom values were 25%.

During August and September oxygen concentrations continued to be above the saturation limit (supersaturated). On August 18 oxygen concentrations were 150% of saturation in water along the slough's bottom. This high value must have been the result of primary production by macrophytes attached to the slough's bottom.

Alkalinity and pH

The south slough had a steady rise in pH from March through August (figure 6). The higher values for pH in the

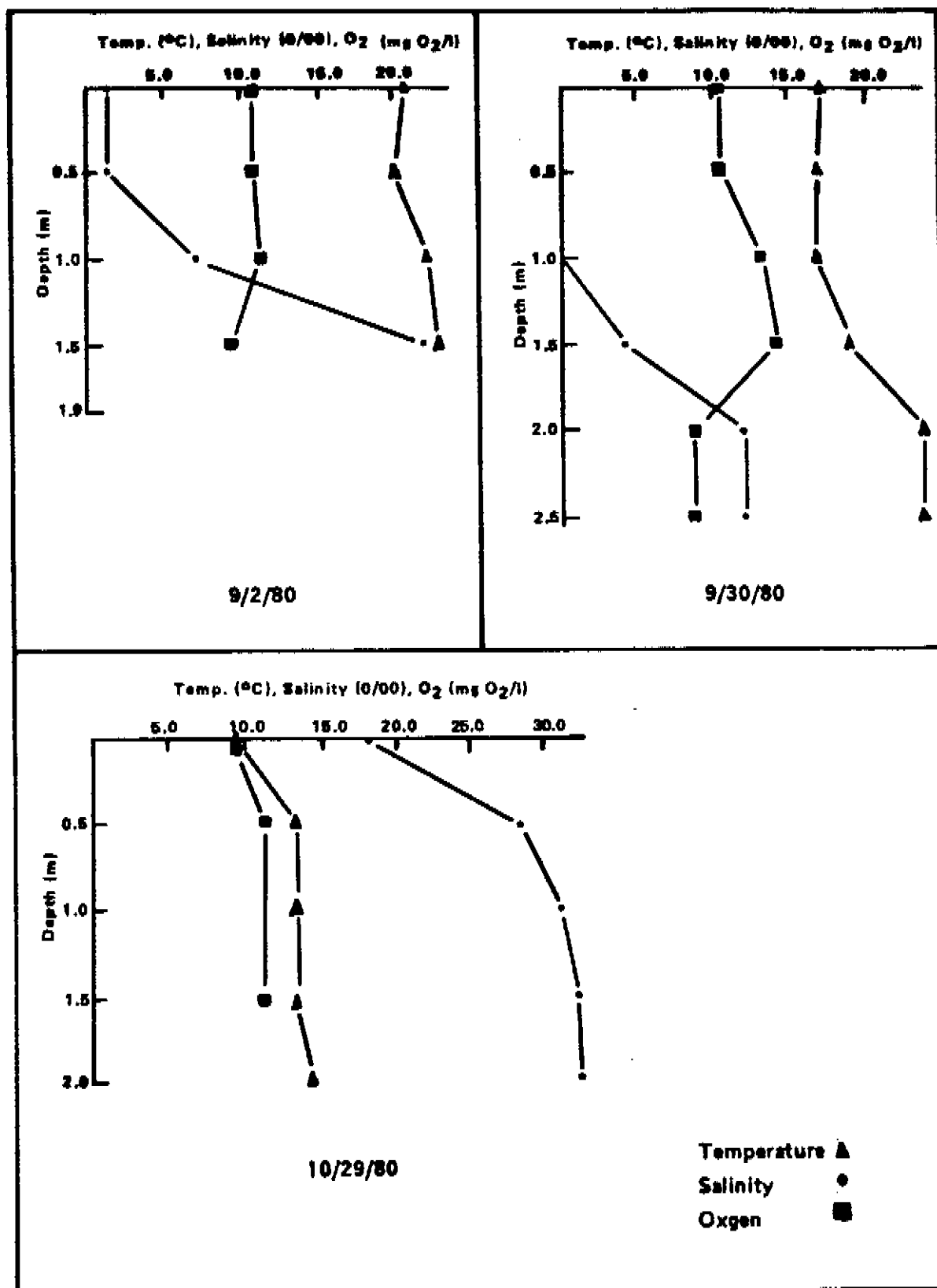


Figure 18. Change of temperature, salinity, and oxygen in the south slough's water column.

surface water occurred during spring and summer, suggesting that they were at least partially caused by bicarbonate degradation by carbonic anhydrase concomitant with photosynthesis (Ruttner, 1963). Photosynthesis may be responsible for this increase due to the relatively low values of alkalinity reported in the south slough (figure 7).

The large drop in pH, along with oxygen saturation, in early July indicated the respiration of organic material washing off the pastures temporarily overloaded the slough.

Alkalinities steadily increased in September as runoff from local pastures washed carbonate and bicarbonate, stored in ground water during the summer, into the slough. High values in October and November were due to runoff from the Redwood Creek watershed mixing with saltwater and entering the south slough.

Nutrients

Ammonia was the predominant form of nitrogen in the south slough. Nitrate and nitrite were found in very low concentrations from August through October, but increased in early November when runoff and saltwater, with higher nutrient concentrations, entered the slough (figure 19).

Turbidities

Water in the south slough was very clear with visibility often reaching the bottom. Algae growth along the bottom of the slough often extended to the surface blocking light during the summer. Turbidities were very small and would not have affected light dispersal (figure 9). An increase in turbidity did occur in early November when waves washed into the slough.

NORTH SLOUGH

The north slough could have been a main channel for Redwood Creek at one time. During this study there were two small tributary channels in the slough, 2-3 m deep with very steep banks and an average width of 15 m. The banks were covered with dense foliage giving way to surrounding grazing land. The watershed feeding into the north slough is minimal, including only a steep hillside to the north and a few acres of pasture on the flood plain. The two channels intersect downstream to form one larger channel that connects with the embayment of Redwood Creek. The channel was filled with sand and woody debris between the levee and headland. Connection between the north slough and the embayment occurs

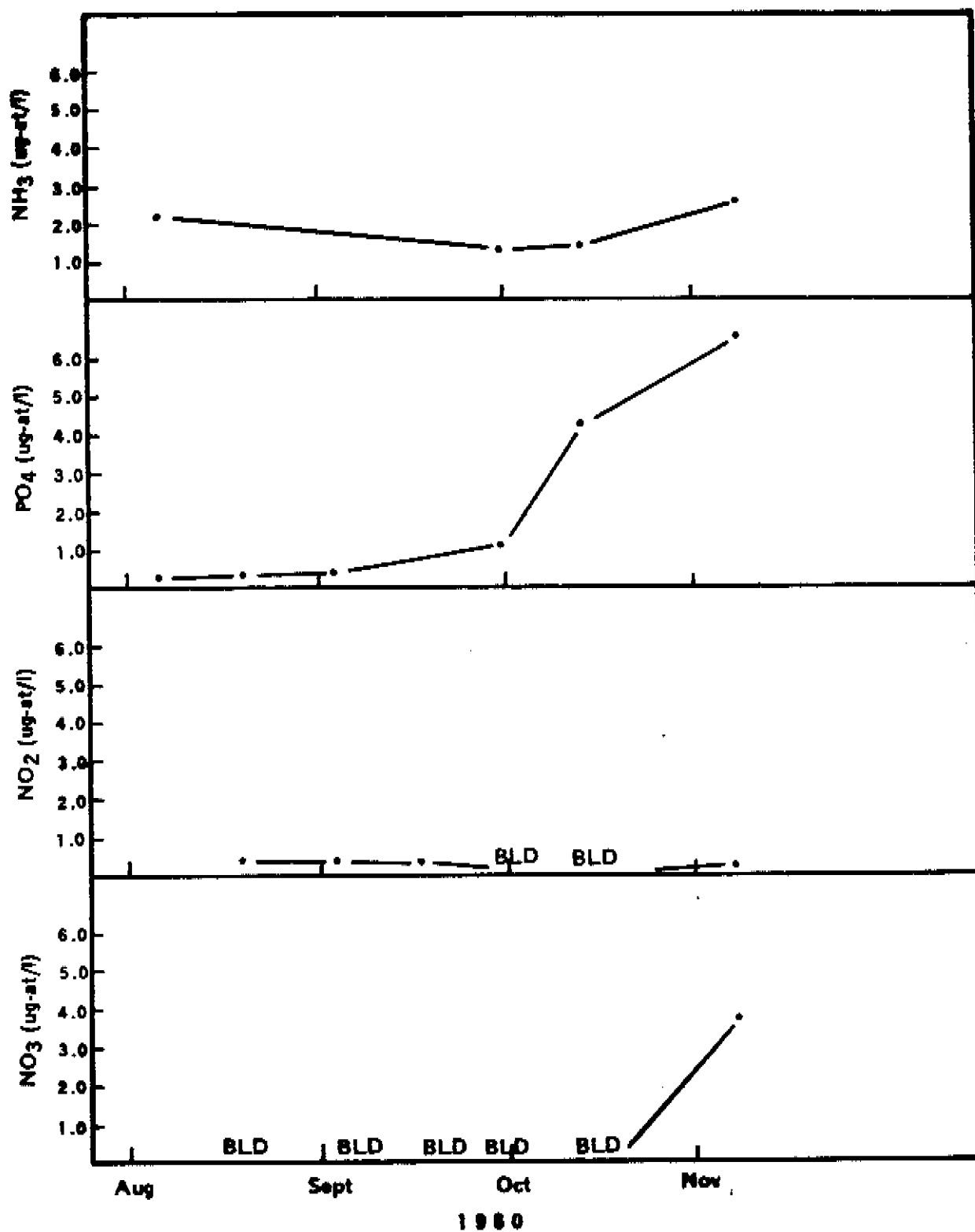


Figure 19. Change of nutrient concentrations in the south slough from August through November.

during high winter discharge, ~~spring~~ high tides, and when flooding occurs from development of the berm at the mouth.

Woody debris from the Redwood Creek watershed floats downstream during winter storms and is deposited on the beach north of the inlet and along the headland. Storms in February and November 1980 washed woody debris, piled around the base of the headland, into the north slough. Both events occurred during high tides when water levels of the embayment exceeded the sill at the entrance of north slough. At low tide, water levels receded below the sill, preventing the woody debris deposited earlier from drifting out of the slough. Onshore winds pushed the debris farther up the slough into both channels.

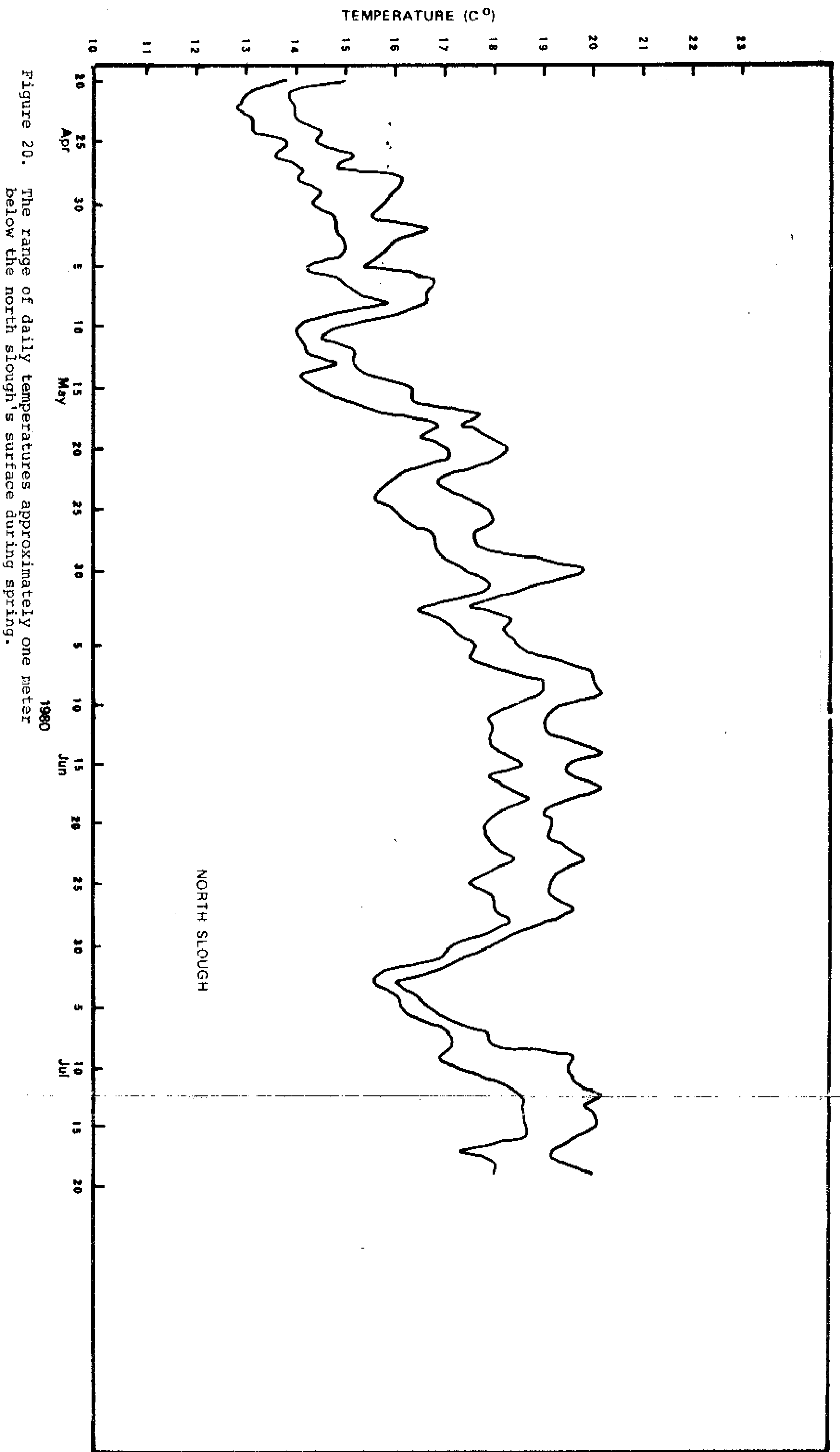
Woody debris clogged the surface of the north slough often during the year, blocking light penetration into the water column. Under these conditions, any light reaching the surface was dispersed by tanins leaching from the wood.

The north channel of the north slough is interrupted by a road crossing blocking exchange of bottom water on either side of the road. Two metal culverts underneath the road do allow exchange of water along the surface.

Salinity and Temperature

Circulation of water in the north slough is impeded by the sill at the entrance and woody debris floating on the surface. The sill traps saltwater along the bottom of the slough and limits freshwater flow from the embayment into the slough. Woody debris, covering the water's surface, prevents wind driven circulation and blocks sunlight from reaching the bottom. The effect of the sill and wood on the surface caused stratification and stagnation of the water column. There appears to be a permanent halocline which fluctuates from 1.5 m to 2.0 m below the surface, depending on the season and water levels.

Temperatures steadily increased, with minimal diurnal fluctuation, from April through June (figure 20). The small range in temperature was attributed to stratification of the water column and floating wood, which acted as insulation between the air and water surfaces. Woody debris, blocking sunlight to water below the halocline, limited any heat storage that could have occurred. A decrease in temperature from June 28 through July 3 was caused by water levels steadily increasing which left the Ryan thermograph deeper in the water column. After the berm was opened, water levels dropped and the thermograph floated closer to the surface where temperatures had a wider range.



The only salt water intrusion into the north slough that was recorded during this study, occurred on November 7 when a high tide and large swells washed over the sill. Fresh saltwater mixed with water above and possibly below the halocline at 1.5 meters (figure 21). Comparison of the salinity and temperature structure on September 30 with November 7 suggest anoxic saltwater, one meter off the bottom, was probably not displaced (figure 21). However, the strong smell of hydrogen sulfide at the surface suggest that some of the anoxic water below the halocline was displaced. The water column appears to remain stratified through November 20 with oxygen concentrations decreasing below 0.5 meters.

Oxygen

The peak oxygen concentrations occurred in February, when oxygen saturated water from the embayment and mixed with the north slough (figure 5). Oxygen concentration decreased through spring and summer as water levels receded and respiration increased. The water column was permanently oxic above 1 m depth and permanently anoxic below 2 m (figure 21). Oxygen concentrations increased on the surface in late fall as water began flowing into the slough again.

pH and Alkalinity

The north slough was the most acidic compartment within the lower reach of Redwood Creek (figure 6). The small range and low values of pH, along with low oxygen concentrations, indicate the amount of respiration and photosynthesis are approximately equal. The alkalinities for the north slough ranged from 0.40 milliequiv./l CaCO_3 in mid-June and steadily increased to 1.18 milliequiv./l CaCO_3 on November 7 (figure 7). This steady increase of alkalinity reflects the buildup of carbonates entering the north slough from local ranch lands. The values of carbonate alkalinity would be expected to decrease as winter rains dilute concentrations of carbonates with runoff.

Nutrients

Nutrient sources in the north slough are runoff from surrounding pastures and regeneration of decomposed organic material in the water column and from off the bottom. Runoff in mid-October was partly responsible for the increase in ammonia and nitrite (figure 21). Anoxic decomposition of organic material, below the sloughs halocline by sulfate reduction, liberates ammonia and phosphate (Richards 1965). Lack of circulation within the water column allows

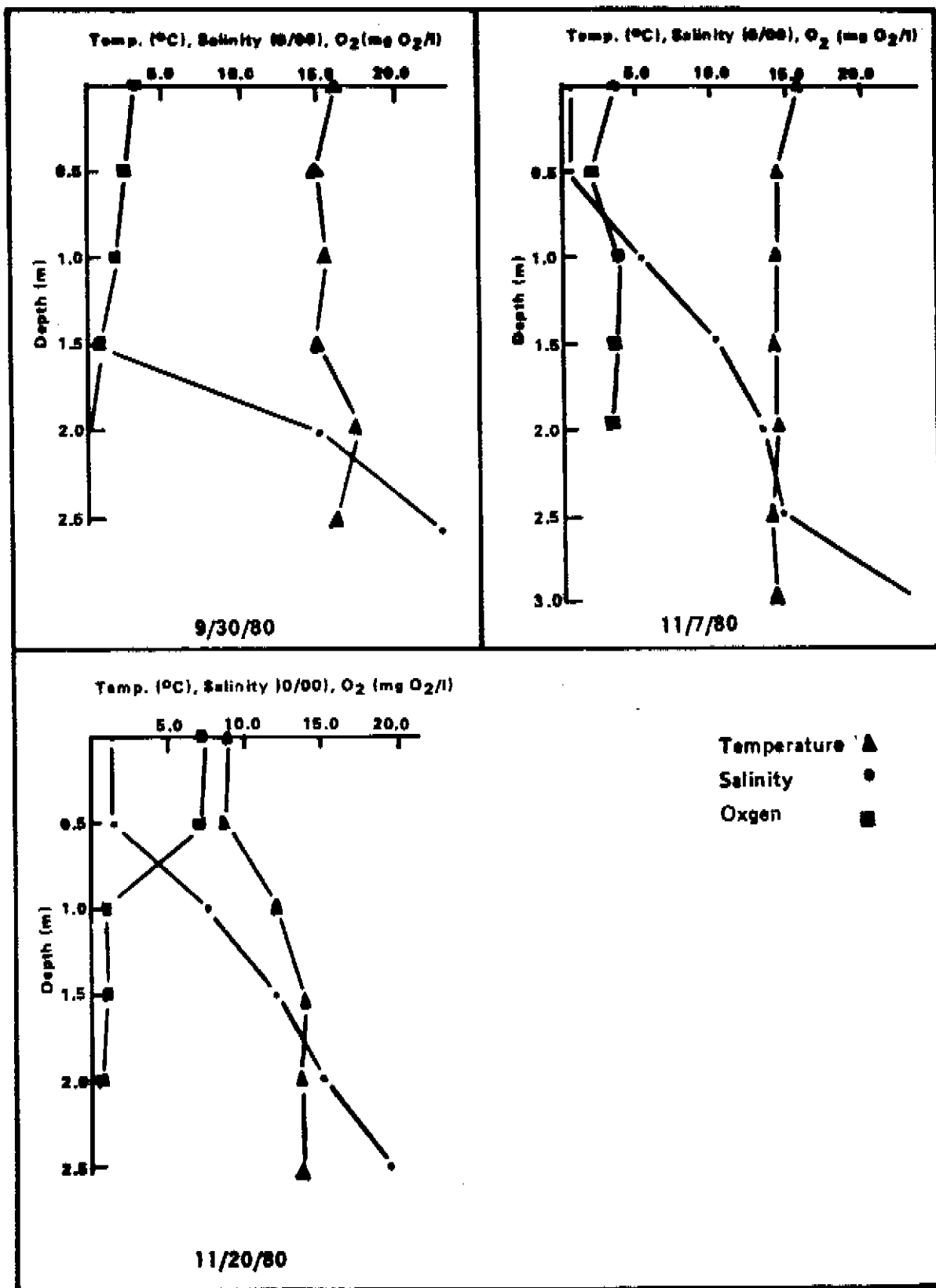


Figure 21. Temperature, salinity, and oxygen profiles from the north slough's water column.

for these nutrients to concentrate along the bottom. When water at the halocline was displaced on November 7, values for ammonia and phosphate increased above the limit of detection (figure 22). Nitrates and nitrites were low in concentration from August through November.

Turbidity

The water color of the North Slough was a light brown, from the leaching of tanins out of wood floating on the surface. These tanins did not appear to increase the turbidity (figure 9). Samples from below 2 m had turbidities of 140 NTU. This appeared to be caused by silt and other fine material suspended in the saltwater. On November 7, turbidities 1 m below the surface, only rose to 15 NTU, less than one tenth of the maximum reported below 2 m. Turbidity would have been a larger value if any significant portion of the anoxic water below 2 m had been displaced.

DISCUSSION

The lower reach of Redwood Creek is a transitional environment between the watershed and the Pacific Ocean. From February through June fluvial processes dominated stream morphology and water quality. The embayment and sloughs were tidal influenced; freshwater flow through the inlet would decrease at high tide causing the water level to rise high enough to enter the sloughs. Onshore processes began increasing the height of the berm on Redwood Creek's beach in April. The movement of sand from upstream onto the beach narrowed the inlet and decreased flow over the berm. As discharge decreased in April, coastal processes continued to build the berm and the volume of water along with the water's residence time increased in the lower reach. Increase in berm height and lengthening of the inlet dampened water level fluctuations and salt intrusion in response to tides.

The lower reach of Redwood Creek could have remained a freshwater system throughout the summer. Salt intrusion through the inlet and from overwash appears to have been diluted by mixing and washing out through the inlet at low tide. Any saltwater settling to the bottom would have been forced through the berm by positive hydraulic pressure caused by overlying freshwater (Bradford and Iwatsubo 1978). The berm would have continued to widen through the summer and possibly fill the inlet with sand, forming a lagoon similar to Stone, Freshwater, and Big Lagoon. The berm would have been opened in fall when discharge from the

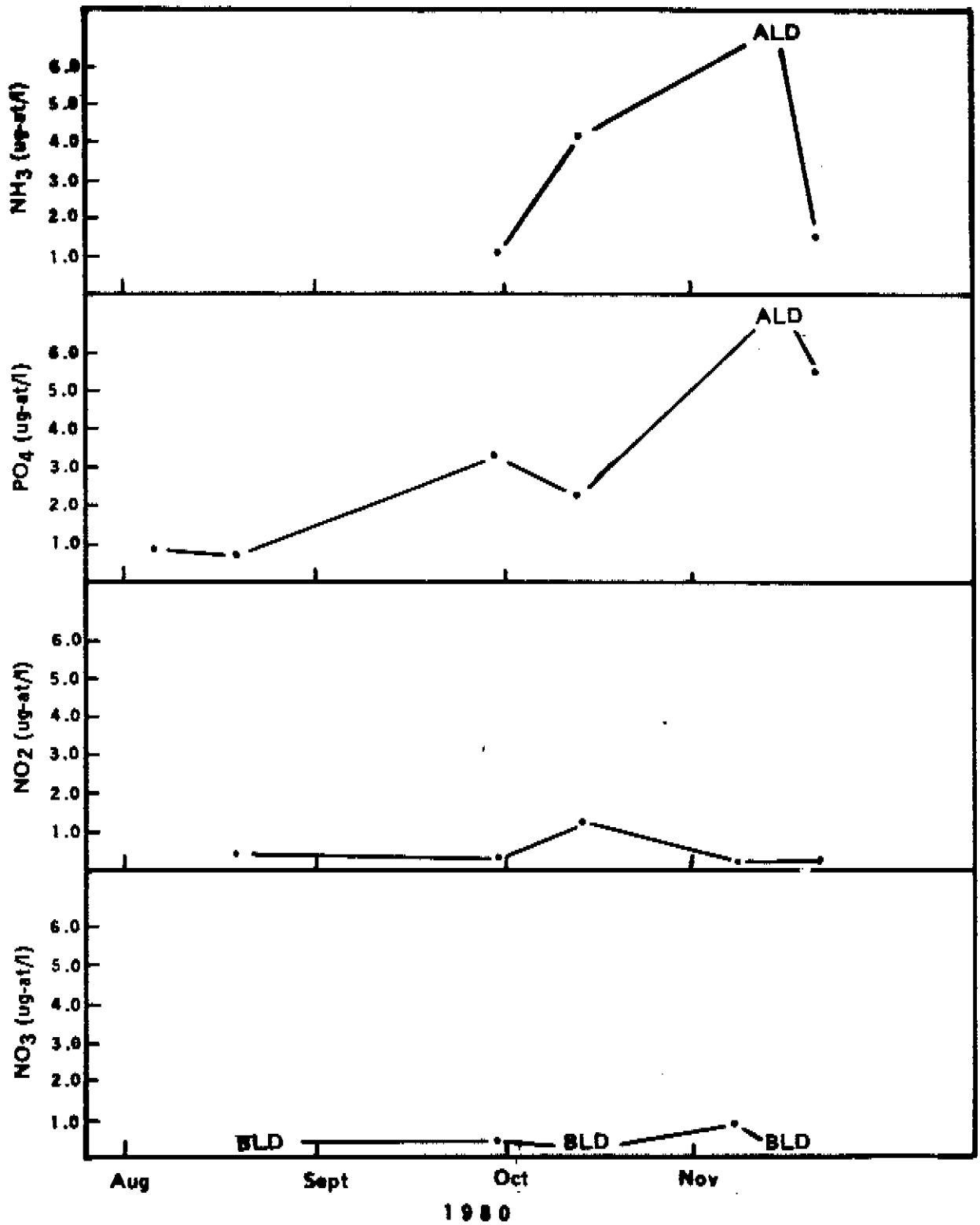


Figure 22. Change of nutrient concentrations in the north slough from August through November.

watershed increased.

Instead, water impounded behind the berm was released in July which created a new inlet and allowed the embayment to develop conditions similar to a stratified estuary (Dyer 1973). The sill at the mouth acted as a barrier which held a saltwater layer along the bottom at ebb tide, similar to conditions reported for Sixes River, Oregon and Mad River, California (Reimers 1973 and Crandel 1981). Unfortunately, opening of the berm decreased the volume of water by half ^{75%} (Ricks 1981). The decrease in volume reduced available habitat for juvenile salmonids by more than half, and prevented their access to either slough. Juvenile salmonids probably entered the ocean rather than remaining in the embayment where competition for food, space, and shelter was much greater (Reimers 1973).

Oxygen, pH, and Alkalinity

Welch (1969) describes fluctuations of dissolved oxygen concentrations in the Duwamish River Estuary, Seattle, Washington, as being dependent on retention time and the vertical stability of the water column. Minimum concentrations of dissolved oxygen along the bottom were related to an increase of retention time and phytoplankton blooms on the surface. Phytoplankton settling below the compensation depth increased the biological oxygen demand caused by decomposition. Stability of the water column and the compensation depth of primary productivity are the processes which affected oxygen concentrations in the lower reach of Redwood Creek.

The sills at the entrance of both the sloughs prevented circulation of bottom water with the embayment. Turnover of bottom water within the sloughs was prevented by positive stability of the water column caused by saltwater intrusion.

The effect of having a saltwater layer was remarkably different in either slough. The south slough was an oxidizing environment, where primary productivity exceeded the systems respiratory requirements. High values for pH and oxygen saturation throughout the summer, support this finding (Indrebo et al 1979, Pomeroy et al 1965, and Ruttner 1963). Even though the water column was stratified, the bottom layer remained oxic because the compensation depth of photosynthesis was greater than the depth of the water. Primary production by macrophytes on the bottom helped prevent anoxic conditions in July when the system was stressed by the opening of the berm.

The north slough was a reducing environment, where primary productivity, convection, and diffusion were able to

meet the respiratory requirements found close to the water's surface. Light penetration through the water to the bottom was often prevented by floating log jams. The compensation depth for primary productivity must have been very close to the surface, below the floating debris. Since the location of the floating debris varied with wind direction, macrophytes were probably prevented from establishing on the bottom by the lack of light. Accumulation of detritus settling to the bottom created a high oxygen demand that eventually caused the bottom layer to become anoxic. The anoxic layer did not appear to be overturned during this study and possibly has remained in place since the sill was built at the entrance to the slough.

Indrebo et al (1979) suggested a rough model of seasonal biological activity in a stratified estuary assuming that primary productivity during the summer increases the quantity of material available for decomposition. The detritus settles into the anoxic region where mineralization releases ammonia and produces sulfide. Material that degrades slowly, such as redwood, would be deposited on the bottom. Sulfate reducing bacteria would continue decomposition at the same rate during the winter but appear to increase because of the decline in primary productivity.

Nutrients

Nutrient sources for the lower reach of Redwood Creek are runoff from the upstream watershed, runoff from pastures, plant and bacterial fixation within the stream, regeneration by decomposition, and the ocean. The relative importance of these sources to productivity in the lower reach depends on their seasonal variability. Bradford and Iwatsubo (1978) suggest nutrients accumulate in the watershed's soil during the dry season and are washed out as the rainy season progresses. Nutrients entering from the pastures were likely to have highest concentration at the onset of winter ~~also~~. These contributions, however, were washed out to sea before they could affect the estuaries productivity. This could have been beneficial though, because there was minimum chance for eutrophication.

Regeneration by decomposition had substantial impact on the north slough when salt intrusion in November partially mixed the water column. Displacement of the slough's anoxic water raised values of ammonia and phosphate above the limit of detection. This probably only occurred in early November during storms, when salt intrusion could reach the north slough and mix with water below the halocline. Indrebo et al (1979) suggest the depth of an anoxic layer in a stratified estuary increases in winter as photosynthesis decreases and particulate organic material produced in summer settles to

the bottom. Partial exchange of the slough's water in November could have prevented the anoxic interface from reaching the surface in winter. Products of anoxic decomposition, ammonia, phosphate, hydrogen sulfide, and bicarbonate, were washed from the surface by later storms but could have had a brief lethal effect on life in the slough.

Upwelling of nutrient rich ocean water during the summer could be the most important nutrient source to Redwood Creek estuary. Upwelling occurs from June through August with concentrations of nitrate and phosphate reaching approximately 30 and 2.5 $\mu\text{g-at/l}$, respectively (Smith 1974, Pattullo and Denner 1965). Reimers (1973) suggested the sill at the mouth of Sixes River, Oregon created an effective nutrient trap in a manner similar to that reported for fjords with a shallow outer sill (Indrebo et al 1979). At high tide, nutrient rich water enters the estuary over the sill, mixes at the mouth with estuarine water, and the entire water mass moves upstream. During ebb tide, the sill acts to hold dense sea water in the estuary, thereby trapping the nutrients. These nutrients allow higher productivity from algae and other primary producers in the estuary. Unfortunately, Redwood Creek's long inlet and high berm prevented salt intrusion, with accompanying nutrients, in late June. The decrease in the volume of water after the berm was opened would negate any added benefit nutrients would have to the estuary.

CONCLUSION

The quantity and quality of salmonid habitat along the lower reach of Redwood Creek has been severely degraded by the construction of flood control levees. Aggradation at the entrance to the north slough has caused the water column to become stratified and anoxic along the bottom. The top of the water column has characteristics of a reducing environment. Aggradation at the entrance of both sloughs caused them to be isolated from the embayment for most of the summer, preventing access to juvenile salmonids migrating downstream.

A decrease in the volume of water held in the lower reach during early summer reduced available salmonid nursery area by half. ¹⁵Oxygen, pH, and alkalinity values indicated that water draining from flooded pastures placed a heavy respiration demand on the south slough. This also occurred in the north slough, already a reducing environment.

Year round circulation needs to be improved in both of the sloughs. An alternative is to remove the last 1.5 km of levee and allow the main channel to run through the south slough and into the north (figure 23). Aerial photographs

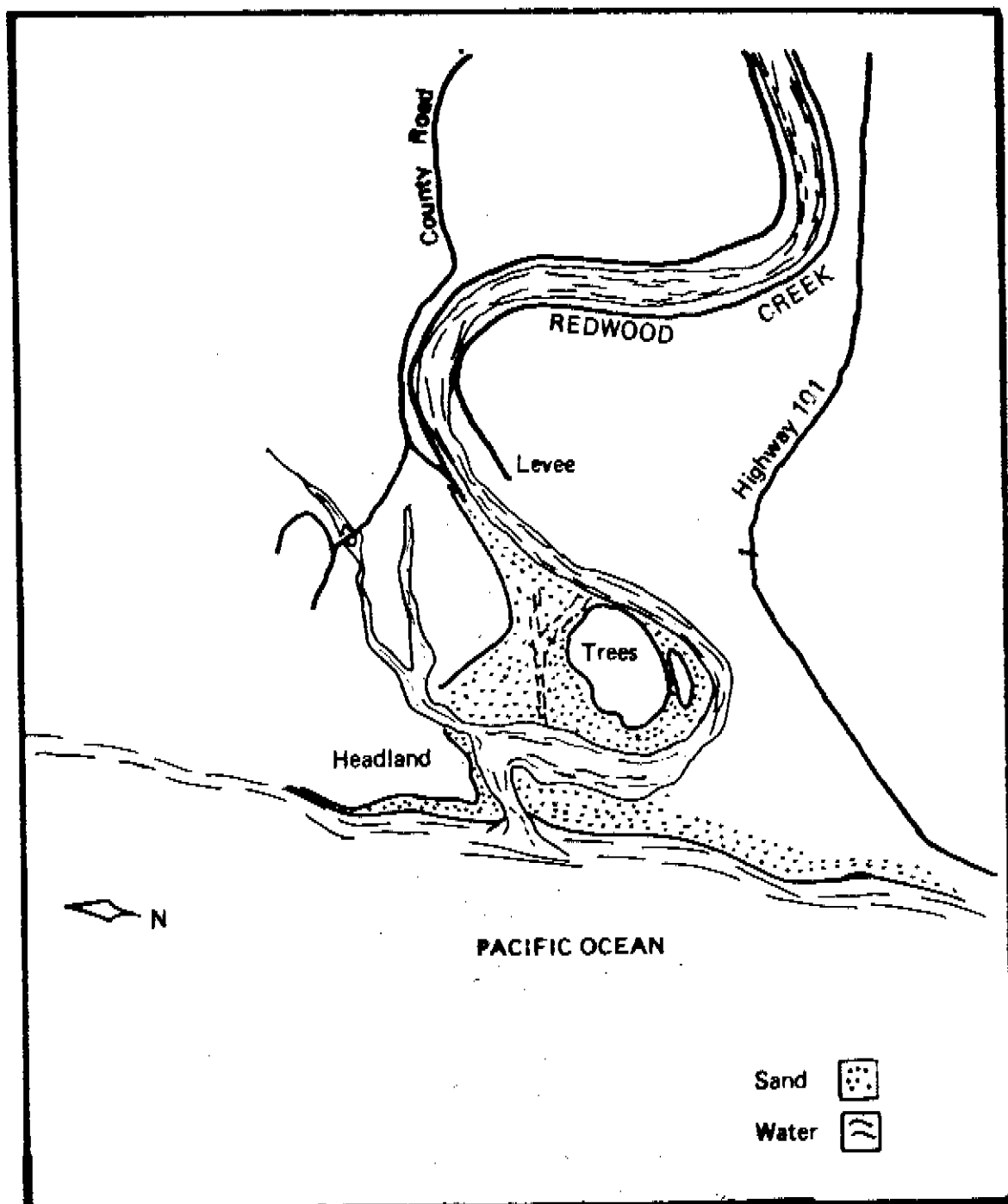


Figure 23. Removal of the levees to a position allowing permanent connection of the stream with the north and south slough would substantially increase salmonid nursery habitat.

of the lower reach of Redwood Creek prior to construction of the levees do not show the accumulation of woody debris in the north slough. Restoration of the original stream channel would erode the sills at the entrance of the sloughs and allow the woody debris to be washed out to the ocean. Erosion of the sills would also allow better circulation of bottom water possibly preventing the north slough from becoming anoxic.

Any restoration project of the Redwood Creek estuary will have to limit the flooding of local pastureland without completely draining the entire estuary. The loss of habitat and poor water quality resulting from the opening of the berm caused a severe degradation of the salmonid nursery.

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