

HYDROLOGIC RESTORATION OF THE REDWOOD CREEK ESTUARY¹

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ABSTRACT: The ecological structure and functioning of the Redwood Creek estuary and surrounding lowlands have been vastly altered over the last several decades due to: 1) conversion of riparian habitat to pasturelands, 2) excessive sedimentation from upstream land use and large floods, 3) annual, multiple artificial breaches of the barrier beach, and, most importantly, 4) channelization for flood control. Sedimentation associated with levee construction has reduced tidal circulation and caused periodic isolation of two sloughs which compose potentially valuable components of the estuarine rearing habitat for juvenile salmonids. Resultant water quality and accessibility problems limit habitat for fish each summer. Restoration efforts undertaken by Redwood National Park include measures to partially restore hydrologic and geomorphic processes responsible for maintaining a productive estuarine ecosystem. A large, gated culvert was recently constructed through a levee section, re-establishing water circulation to the landward end of the largest slough. Results of initial field experiments on culvert operation show marked improvement in estuary water quality and hydrologic function.

INTRODUCTION

Located about 480 kilometers north of San Francisco, the Redwood Creek estuary (Fig. 1) is one of many on the Pacific Coast. Redwood Creek drains a long narrow basin 725 square kilometers (km) in area flowing to the Pacific Ocean near the town of Orick, California. The basin is largely underlain by the Franciscan assemblage, which consists of tectonically deformed belts of sedimentary and metamorphic rocks (Baily *et al.* 1964). For most of its length, Redwood Creek follows the northwest-trending Grogan Fault. A combination of rapid tectonic uplift, highly erodible terrain, and intense winter rainstorms is responsible for the relatively high rates of natural erosion and sedimentation characteristic of the region (Janda *et al.* 1975).

Local tides range to about two meters (m) in amplitude with a mean of about 1.4 m and are classified as mixed semidiurnal (two high tides and two low tides per day with consecutive highs and lows being of different height, as described in Bascom 1964, p. 89). Swells in excess of 8 m in height occur several times each year, usually during the winter.

HISTORICAL CHANGES

Most estuaries in developed areas have been directly affected to varying degrees by human activities such as clearing of woody debris, diking, land filling, dredging, and artificial channelization for navigation and flood control. These activities restrict or prevent the

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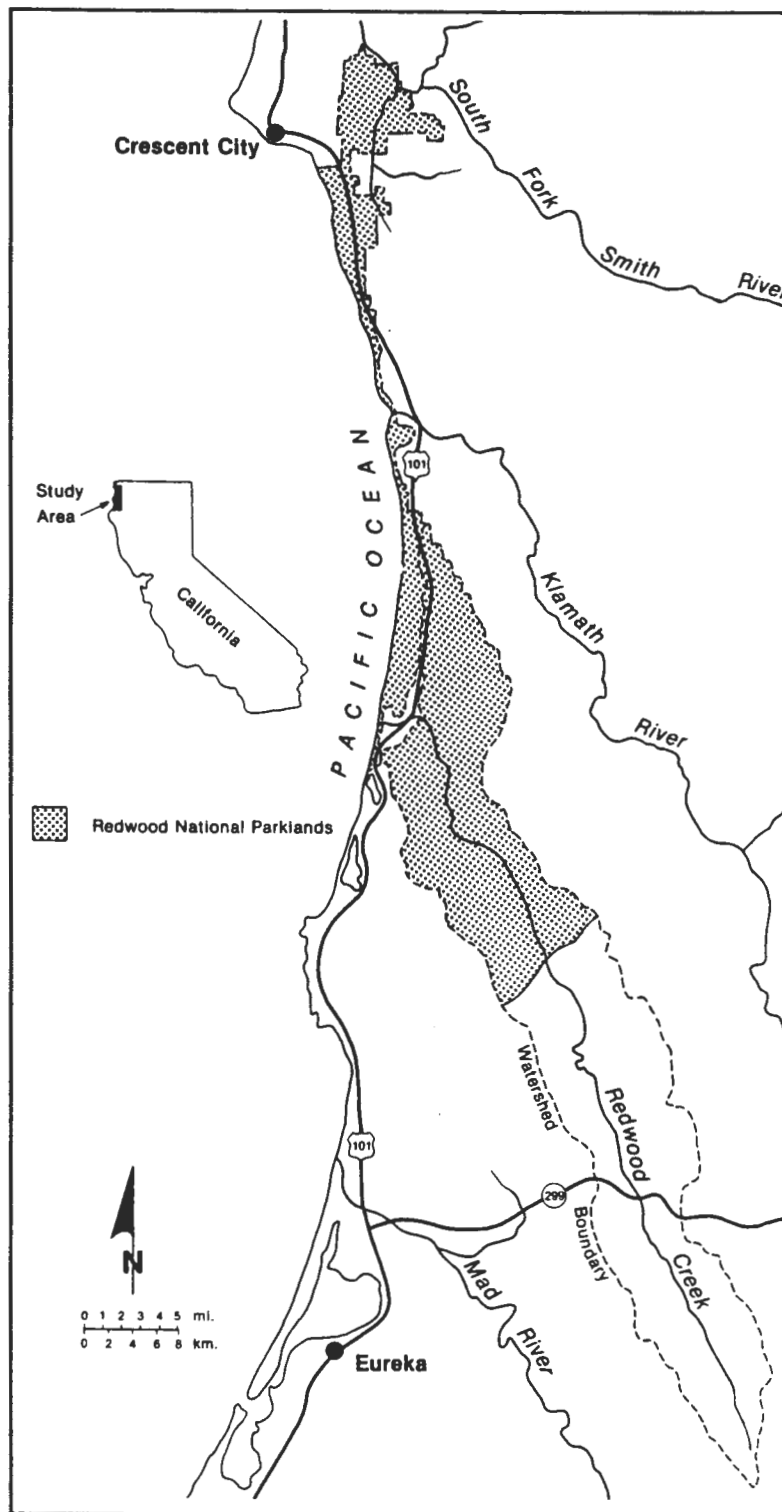


Figure 1. Location map of the western U.S. showing Redwood Creek basin in northwestern California.

interaction of streams with their floodplains, sloughs, and side channels and greatly simplify the remaining aquatic habitat (Sedell and Luchessa 1981). Indirect impacts from human activities involve increased sedimentation in low gradient, downstream areas from accelerated hillslope and channel erosion processes occurring upstream. Channelization and sedimentation can greatly reduce tidal prism volumes in estuaries, thereby reducing the effectiveness of tidal currents in maintaining the dimensions and productivity of estuarine sloughs.

In Redwood Creek, extensive timber harvest in the contributing watershed, followed by large floods in 1964, 1972, and 1975, resulted in greatly increased sediment loads which caused aggradation and channel widening in the low gradient floodplains of the lower valley (Janda *et al.* 1975). Flood control levees were completed in 1968 which channelized the lower 5.1 km of Redwood Creek from the apex of the alluviated Orick valley to within 200 m of the surf zone (Fig. 2).

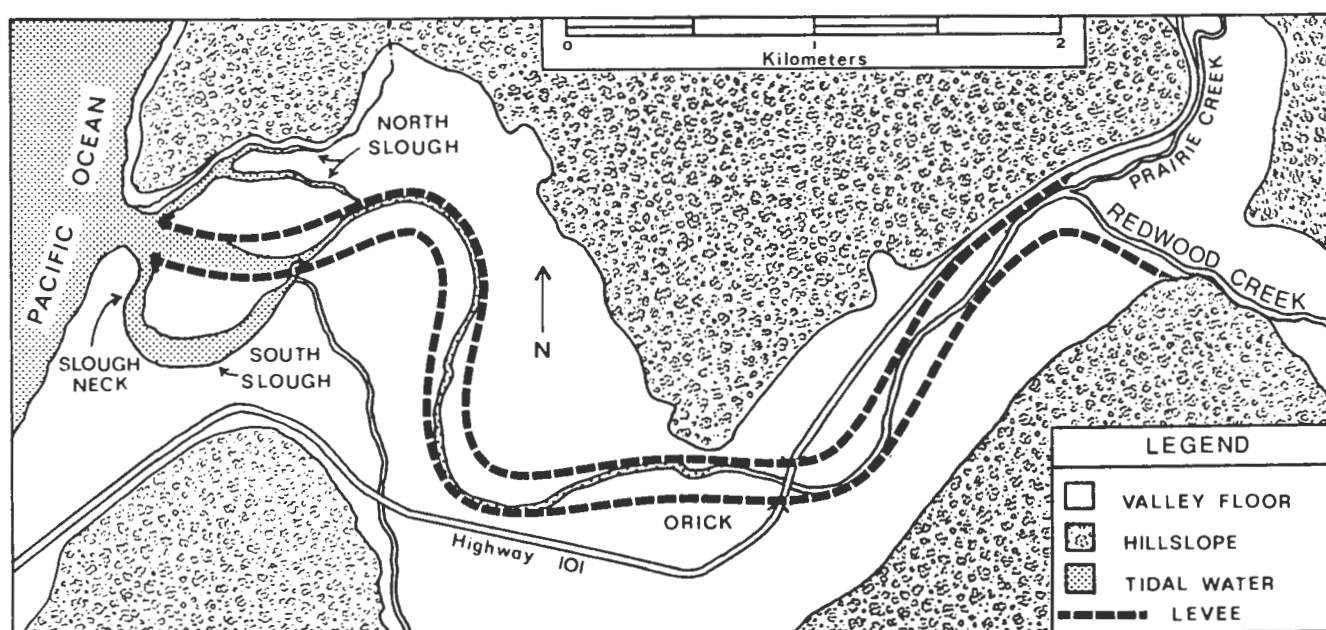


Figure 2. Local geography of lower Redwood Creek in the Orick valley.

Since channelization, Redwood Creek's floodwaters and sediment loads have been totally confined between levees (Fig. 2) and routed directly into the Pacific Ocean through the main embayment (that part of the estuary exclusive of the North and South Sloughs). Both the South Slough (which was formerly the main channel of Redwood Creek) and the North Slough (which formerly functioned as a high flow distributary) have experienced increased sedimentation in their oceanward ends since levee construction. Ricks (1985) estimated that as of 1981, approximately fifty percent of the volume of the lower estuary (between 0 and 1.2 m above mean sea level (MSL)) had been filled in or become isolated from the main embayment since 1966.

Sedimentation has been primarily caused by marine processes of beach berm overwash and flood tidal currents enhanced by surf-derived wave bores (FitzGerald 1988, p. 207) translating through the river mouth. Both processes transport and deposit sand in the lower sloughs of

Redwood Creek (Ricks 1985). Because wave bore-enhanced flood tidal currents translate up through the river mouth with great frequency (even during periods of moderate surf, and occasionally with great force), this process has resulted in much more sedimentation since 1981 than beach berm overwash (which occurs relatively infrequently, only during periods of extremely high tides and wave heights). The landward orientation of megaripples (Horne and Patton 1989, p. 814) on the channel beds of the lower sloughs suggests that flood tides dominate sediment transport processes in these areas during periods of low river discharge.

The mouth of Redwood Creek commonly closes during summer low-flow periods (late summer through early fall) when coastal nearshore processes can build a berm at the river mouth higher than estuary water levels. The mouth may re-open prior to the onset of fall rains if the estuary water level rises enough to cause the berm to be overtopped (depending on the elevation of the beach berm relative to the rate of accretion of fresh water in the embayment). If the mouth closes late in the dry season, when Redwood Creek discharge is very low, it will usually remain closed (unless mechanically opened) until the first fall rains increase river discharge.

While the mouth is closed, estuary waters can rise to the point where flooding occurs on adjacent private properties. Prior to management by Redwood National Park, landowners commonly breached the mouth, causing the estuary to empty almost completely and prematurely with respect to the natural occurrence of hydrologic conditions which caused breaching. Because the late summer and early fall estuary habitat is especially important for the physiological development of juvenile salmonids about to make the transition to the marine environment, the artificial breaches became an important management concern for Redwood National Park (Hofstra and Sacklin 1987).

As an interim method of improving estuarine rearing conditions for fish, Redwood National Park has actively managed summer water levels in the estuary since 1982. When water levels approach flooding conditions on adjacent private lands (at about 1.6 m in elevation, MSL), a "controlled breach" is performed. This is accomplished by cutting an outflow channel at the river mouth by bulldozer in a configuration and during tidal conditions which are likely to prevent the estuary from completely draining (Hofstra and Sacklin 1987). The variability in hydrologic and coastal processes which control river mouth closures and natural breaches necessitates different numbers of controlled breaches from year to year. For example, twenty breaches were necessary in 1987, while in 1988 the mouth remained open virtually all summer and no artificial breaches were needed.

PRESENT CONDITIONS AND PROCESSES

Except for the aggraded "neck", the South Slough retains a relict pattern and hydraulic geometry typical of a meander bend (its fluvial role from the pre-levee period). Aggradation in the slough neck now physically limits the lower tidal range for the slough while the river mouth is open, causing a substantial decrease in tidal water circulation. Hydrologic isolation of the slough occurs when tidal water levels in the main embayment drop lower than the elevation of aggraded sediments in the slough neck. During the summer and early fall, the limited circulation and isolation results in elevated water temperatures and depressed levels of dissolved oxygen as eutrophication progresses. Because the South Slough composes a large

portion of the potential (and historic) rearing habitat for juvenile salmonids, improving water quality and accessibility is a major restoration goal (Hofstra and Sacklin 1987).

Continuous monitoring of water levels in the main embayment and South Slough since 1987 has provided insights into the hydrologic functioning of the Redwood Creek estuary. Figure 3 shows a plot of water level fluctuations at the two locations for calendar days 251-265, 1988 (September 7 through 21). During the period preceding day 258 (September 14), water levels in the main embayment fluctuated within a 1 m tidal range while water level fluctuations in the South Slough were limited to a 0.3 m range above the maximum thalweg elevation in the aggraded slough neck (0.8 m above MSL). Surf conditions closed off the river mouth on day 258 (September 14), after which water levels rose gradually in both the main embayment and the slough.

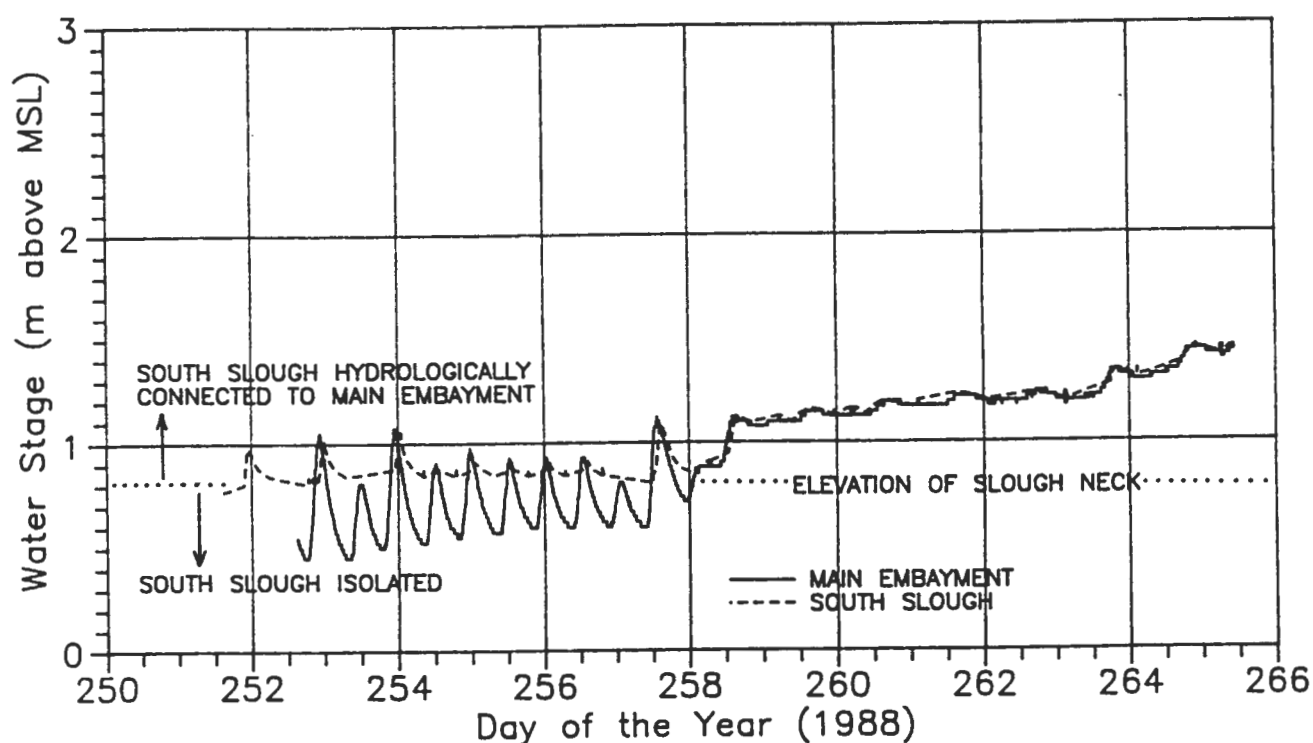


Figure 3. Plot of water levels in the South Slough and the Main Embayment of Redwood Creek for calendar days 251-265 (September 7 through 21, 1988).

When hydrologic gains and losses in the estuary are approximately equal, water levels become nearly static or rise gradually in a stepwise fashion related to the tides (Fig. 3, days 259 through 265). Such conditions reflect a near balance between surface and subsurface hydrologic contributions from the watershed, evapotranspiration losses, and ocean conditions (which affect both the rate and direction of groundwater seepage through the barrier beach and seawater inputs from wave overwash). Under these conditions, the river mouth will remain closed (unless artificially opened) until the first fall rainstorm increases river discharge.

Figure 4 shows estuary water levels for calendar days 304 through 312, 1988 (October 30 through November 7, 1988), encompassing a rainy period which caused the mouth to breach. Prior to day 307 (November 2), water levels were nearly static, showing only minor fluctuations corresponding to higher-high tides. A rainstorm which began on day 307 (November 2) increased discharge in Redwood Creek, which caused estuary water levels to rise sharply. The river mouth breached on day 309 (November 4) when embayment water levels overtopped and eroded through the sand berm, returning tidal fluctuations to the estuary.

Figures 5a and 5b show the estuary immediately before and after functional closure of the mouth in August and September of 1988. When the mouth is closed, the consistently higher water levels improve fish accessibility to the sloughs, however only slight improvements in slough water quality occur due to the absence of tide-driven circulation (Hofstra and Sacklin 1987). When the estuary water level reaches the crest elevation of the sand sill at the mouth, water from the embayment spills into the ocean and the sill is breached by rapid erosion. Water levels can drop two to three meters in a few hours (see Fig. 4) as the spilling water cuts a deep channel through the sand.

RESTORATION EFFORTS

The focus of recent restoration efforts has been to partially restore natural hydrologic and

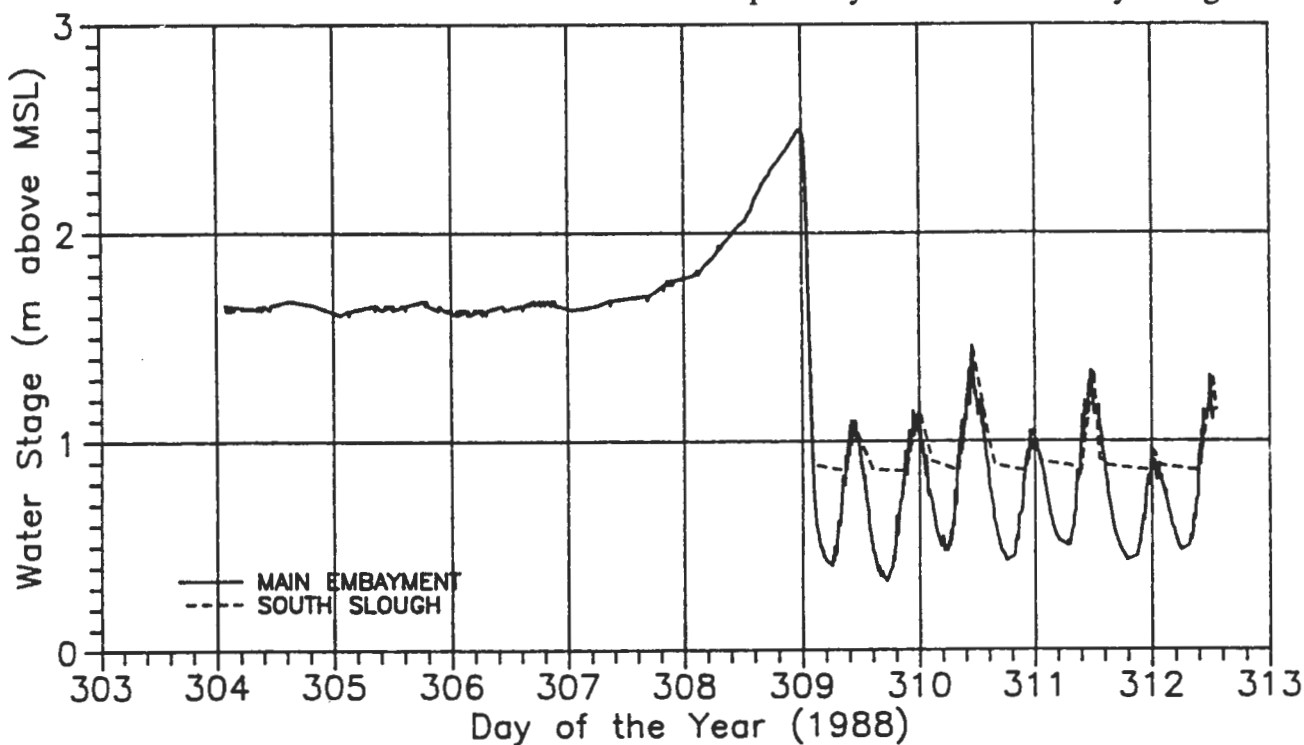


Figure 4. Plot of water levels in the Main Embayment and South Slough for calendar days 304-312 (October 30 through November 7, 1988).

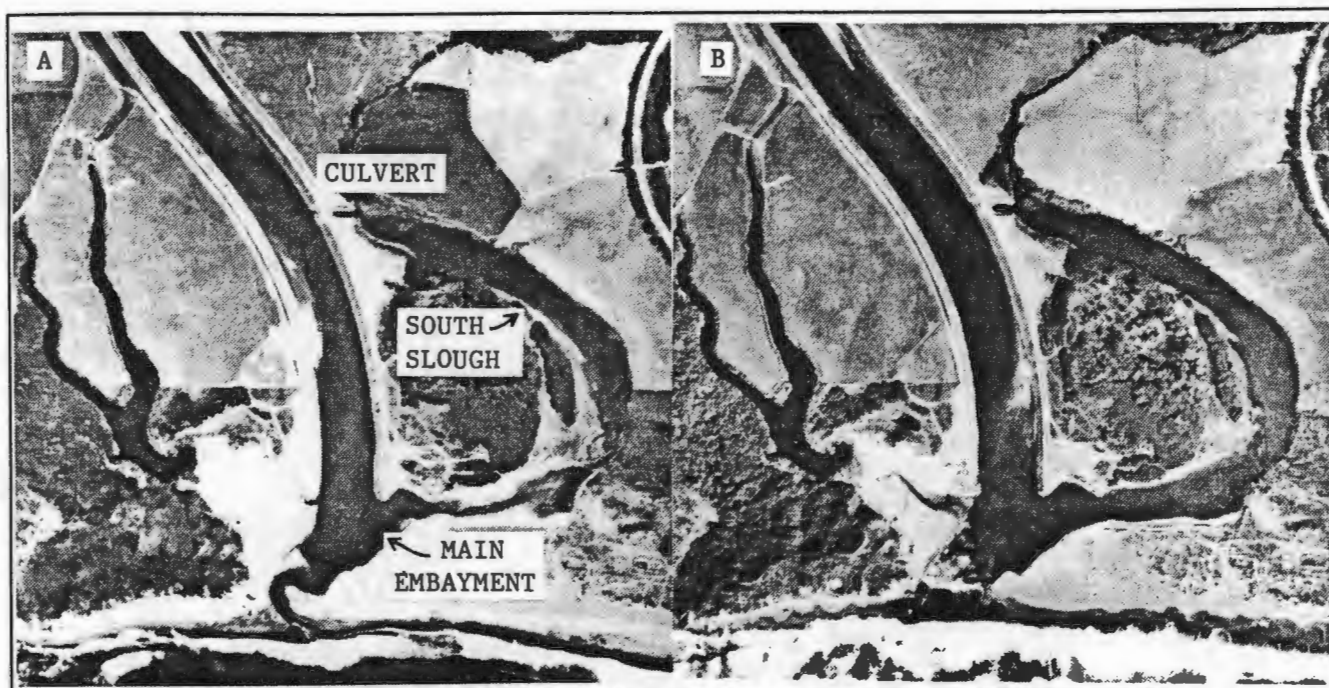


Figure 5. Aerial photographs of the estuary of Redwood Creek during August (a) and September (b), 1988 and after river mouth closure, respectively.

geomorphic processes to the South Slough. To re-establish low stage communication between the main embayment and the South Slough, sediment was excavated from the slough neck by bulldozer in summer, 1983. Removal of the sediment temporarily improved circulation by allowing more of the slough water to be exchanged with new water from the main embayment on each tidal cycle. Following the 1983 excavation, however, the slough neck had re-filled with sand to its former elevation of 0.8 m MSL by the summer of 1988. Because there was no significant beach berm overwash during this period, re-filling was due primarily to wave bore-enhanced flood tidal currents which carried sand up into the neck.

To help provide a long term solution to the sedimentation and water quality problems of the South Slough, a large diversion culvert was constructed through the south levee in 1988 (Fig. 5). Funding for the project was provided by the California Department of Transportation as mitigation for anticipated loss of fishery values resulting from a nearby highway construction project. Design and construction supervision of the structure was provided by the U.S. Army Corps of Engineers.

The culvert (Fig. 6) consists of three 2.5 m square chutes, each with its own manually operated gate, connecting the main channel of Redwood Creek with the landward end of the South Slough. The structure was designed to 1) increase tidal water circulation during the summer for improving water quality in the South Slough, and 2) scour sediment from the slough neck by routing winter stormflows of up to 97 cubic meters per second (cms) from Redwood Creek through the slough.

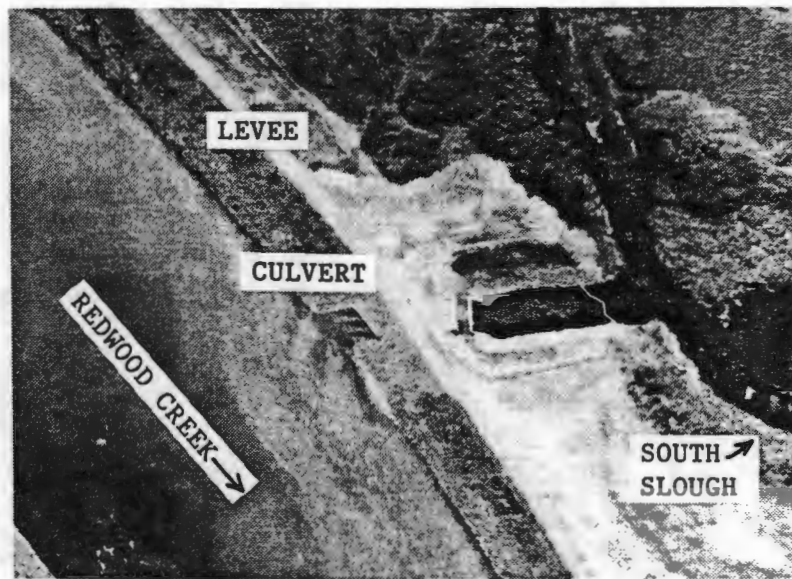


Figure 6. Gated culvert drainage structure built through the south levee of Redwood Creek in 1988.

Tidal Circulation

Several trials were conducted during the summer of 1988 to quantify the effects of culvert gate opening on increasing tidal circulation within the South Slough. Without the gates open, the lower end of the tidal range in the slough is determined by the elevation of aggraded sediments in the slough neck. Continued aggradation further elevates the lower end of the tidal range in the slough, making it increasingly narrow. The volume of slough water exchanged on any given tide cycle, then, is determined by the slough's bathymetry between the maximum water level at high tide and the elevation of aggradation in the slough neck.

Figure 7 is a plot of water surface elevation versus water volume retained in the South Slough, derived from a map of the slough's bathymetry. The bathymetric configuration of the South Slough (wide cross section with very gently sloping bottom topography) causes large increases in water volume with slight increases in water surface elevation. Because the culvert bottom is 0.3 m lower than the elevation of the aggraded slough neck, opening the culvert gates caused the base water level in the slough to be effectively lowered by about 0.3 m in 1988. This slight lowering of the slough's base water level was responsible for an additional 12,000 m³ of potential tidal water exchange (Fig. 7), which represents approximately 37 percent of the water remaining in the slough at low tide. In addition to increasing the volume of tidal water exchange, opening of the culvert gates also allows tidal circulation at the landward end of the slough, thereby improving dispersion of new water as well.

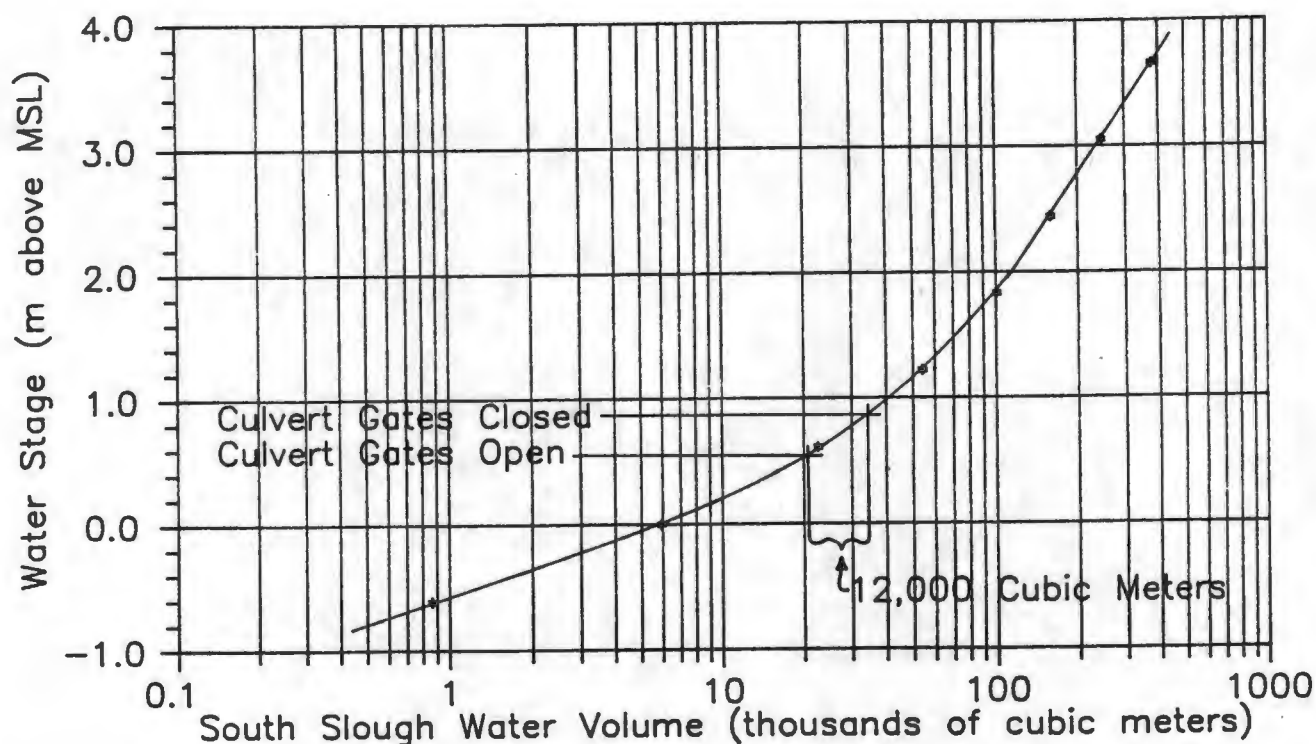


Figure 7. Plot of water surface elevation versus water volume in the South Slough, showing the effect of opening the culvert gates on increasing volumetric water exchange between the main embayment and the South Slough.

Preliminary results of water quality monitoring in the South Slough showed substantial improvements in temperature and dissolved oxygen following gate installation and opening.³ On June 29, 1988 (prior to opening the gates), depth-averaged water temperature near the middle of the slough had risen to 17.4 degrees Centigrade (C), ranging from 22.5 degrees C near the surface to 14.5 degrees C near the bottom. Depth-averaged dissolved oxygen was 3.5 parts per million (ppm), ranging from 9.5 ppm near the surface to 0.3 ppm near the bottom, on the same day. The gates were opened on July 1, 1988, and these same water quality parameters improved markedly over the next several weeks. By July 29, 1988, depth-averaged temperature dropped to 15.8 degrees C, ranging from 18 to 14.5 degrees C, top to bottom. Depth-averaged dissolved oxygen rose to 8.0 ppm, ranging from 10.6 to 7.4 ppm, top to bottom.

To illustrate the effect of culvert opening on the hydrology of the South Slough, Figure 8 shows tidal hydrographs encompassing one complete tidal cycle which occurred August 2, 1988. Discharge rates are plotted which represent water entering both ends of the slough on the flood tide and leaving the slough on the ebb tide (ebb flow rate is shown as discharge in the negative range). Because it is lower in elevation than the slough neck, flood tidal water begins entering the slough earlier and ebb tidal water continues leaving the slough later at the culvert. The peak flood and ebb tidal discharge rates were highest at the slough neck due to its far

³Data on file with Terry Hofstra, Ecologist, Redwood National Park, Arcata, CA.

greater cross sectional area, although the greatest velocities were measured at the culvert. Particularly strong wave bore action in the slough neck precluded reliable measurements at

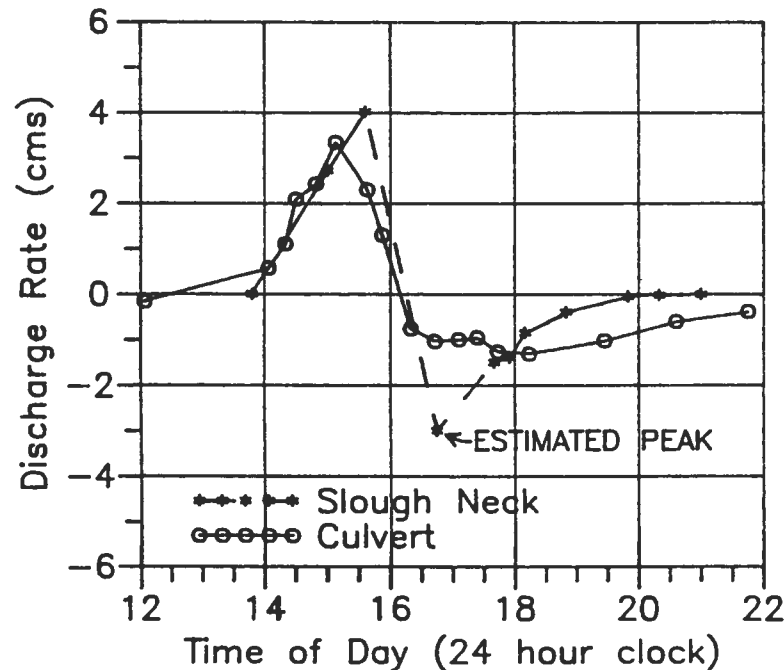


Figure 8. Hydrographs spanning one complete tidal cycle for the South Slough. With the culvert gates open, flood tidal flow (shown as positive discharge) and ebb tidal flow (negative discharge) can occur at the landward as well as the seaward end of the slough.

this location between 15:30 and 17:30 hours. It is estimated that the peak ebb flow rate through the slough neck was about 3 cms as the tide fell (the dashed line in Figure 8 indicates the estimated portion of the slough neck tidal hydrograph).

By calculating the area under the tidal hydrographs in figure 8, the volumes of water exchanged at both ends of the South Slough can be compared. Table 1 shows flood tidal and ebb tidal water volumes, as well as peak discharge rates, from the hydrographs. Although peak rates of both flood and ebb tidal flow were lower at the culvert, the greater ebb flow water volume passing through the culvert is accounted for by the longer duration of flow (see Fig. 8). Similar flood flow volumes for the slough neck and the culvert indicate the effects of surf-derived wave bores, which apparently enhance flood tidal currents and retard ebb tidal currents at the slough neck (FitzGerald 1988). Because it is further upstream, wave bore effects were minimal at the culvert inlet.

Table 1. Peak discharge rates and water volumes for the South Slough from a complete tidal cycle on August 2, 1988.

	Peak discharge (cms)		Water volume (m ³)		Total
	Slough Neck	Culvert	Slough Neck	Culvert	
Flood flow	4.0	3.3	16,500	16,400	32,900
Ebb flow	¹ 3.0	2.7	13,200	19,700	32,900

¹Estimated

Sedimentation

Fulfilling the second objective of culvert operation (scouring aggraded sediments from the slough neck) is a far more complicated task than that of improving summer tidal circulation. Mobilizing and flushing sediments from the slough neck is dependent on generating shear stresses great enough to entrain and transport these materials against the force of wave bores and backwater effects present in the estuary during stormflow events. Predicted culvert discharge rates at various discharge rates and return periods for Redwood Creek are shown in Table 2 (from U.S. Army Corps of Engineers 1989):

Table 2. Predicted discharge rates of water diverted through the culverts

Redwood Creek discharge rate (cms)	return period (years)	Culvert design discharge rate (cms)
550	1.5	36.5
662	2	46.4
986	5	55.8
1206	10	62.9
1489	25	67.1
1702	50	69.4
1916	100	71.4
2181	500	96.7

Backwater effects in the estuary result from the combination of both river stage and ocean height (a product of the combination of tides, storm surges, and swells). Although predicted culvert discharges increase with increasing discharge in Redwood Creek (as shown in the tabulation above), the scouring ability of higher culvert flows is largely offset by increased backwater effects due to elevated river stage on Redwood Creek near the mouth. Optimal hydraulic conditions for scour exist just before and during low tide. Two interrelated conditions occur at low tide which increase the hydraulic effectiveness of stormflows routed through the culvert: 1) backwater effects in the estuary are lessened, and 2) the surf zone moves seaward and down in elevation. The first of these conditions allows steepening of the energy slope in

the slough neck, and the second causes a reduction or elimination of wave bore energy reaching the slough neck and opposing slough outflows.

During a stormflow event which occurred on November 22, 1988, the first culvert trial was conducted for attempting to scour sediment from the South Slough neck. Discharge in Redwood Creek was about 510 cms while the culvert gates were open, a relatively moderate event of about 1.5 years return period. The gates were left open for a falling tide period of six hours, during which a peak of 22 cms was diverted into the slough. Because of a build-up of storm debris on the inlet of the culvert (on the Redwood Creek side of the levee), the maximum possible rate was not attained for the existing hydraulic conditions.

A subsequent topographic survey of the slough neck showed no significant scour as a result of the first trial. Because of its wide, shallow hydraulic channel geometry, unit streampowers are about an order of magnitude smaller in the slough neck than at the culvert. In order to increase the hydraulic effectiveness of flows diverted through the neck of the South Slough, various alternatives are being considered which include structural measures to dissipate wave bore energy at the seaward end of the South Slough and construction of a morphologically stable channel (with respect to stream pattern and hydraulic channel geometry) through the slough neck which would be capable of being maintained by culvert design flows.

SUMMARY

The task of restoring estuarine environments requires an understanding of complex interactions between highly variable and sometimes violent processes. Monitoring of these processes in the estuary of Redwood Creek has led to insights used to develop and refine management and restoration strategies. Although implementation of restoration measures has improved physical conditions and resulting aquatic habitat, these activities can only hope to restore a fraction of the historic biological productivity to the Redwood Creek estuary. Ongoing field experiments using a gated culvert to route both tidal water and stormflows into the South Slough of Redwood Creek are aimed at refining operational techniques to be employed in active estuary management. Although each estuarine system is unique in structure and function, results of studies and experiments conducted in Redwood Creek may have direct application in other estuary restoration and management programs.

ACKNOWLEDGEMENTS

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REFERENCES

- Baily, E.H., W.P. Erwin, and D.L. Jones. 1964. Franciscan and related rocks, and their significance in the geology of Western California. Calif. Div. Mines and Geology. Bull. 183. 177pp.
- Bascom, W. 1964. Waves and beaches. Doubleday and Co., Inc. Garden City, N.Y. 267 pp.
- FitzGerald, D.M. 1988. Shoreline erosional-depositional processes associated with tidal inlets. Pages 186-225 in: Hydrodynamics and Sediment Dynamics of Tidal Inlets. D.G. Aubrey and L. Weishar, eds. Springer-Verlag Inc. New York.
- Hofstra, T.D., and J.A. Sacklin. 1987. Restoring the Redwood Creek estuary. Pages 812- 825 in: Coastal Zone '87. WW Div., ASCE. Seattle, WA.
- Horne, G.S., and P.C. Patton. 1989. Bedload-sediment transport through the Connecticut River estuary. Geological Society of America Bulletin. v. 101. June. pp. 805-819.
- Janda, R.J., K.M. Nolan, D.R. Harden, and S. M. Coleman. 1975. Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California, as of 1973. U.S. Geological Survey Open-File Report 75-568. 266 pp.
- Ricks, C.L. 1985. Flood history and sedimentation at the mouth of Redwood Creek, Humboldt County, California. Redwood National Park Tech. Rpt. No. 15. National Park Service, Redwood National Park. Arcata, CA. 155 pp.
- Sedell, J.R., and K.J. Luchessa. 1982. Using the historical record as an aid to salmonid habitat enhancement. Pages 210-223 in: Proceedings of a Symposium on Acquisition and Utilization of Aquatic Habitat Inventory Information. N.B. Armantrout, ed. Western Division, American Fisheries Society. Portland, OR.
- U.S. Army Corps of Engineers. 1989. Draft operation and maintenance manual, Redwood Creek culvert project, Redwood National Park, Humboldt County, California. Attachment 4, Redwood Creek Drainage Structure Rating Curves.