Klein, R.D., and W. Weaver.
1989.Hydrologic Restoration of the Redwood Creek Estuary.
Redwood National and State ParksRedwood National and State Parks,January 1989.

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Hydrologic Restoration of the Redwood Creek Estuary[1]

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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 quality and availability for fish each summer. Restoration efforts undertaken by Redwood National Park include measures to partially restore

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[1]Presented at the Society for Ecological Restoration and Management Annual Meeting; January 16-20, 1989, Oakland, California.

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hydrologic and geomorphic processes responsible for maintaining a productive estuarine ecosystem. Recently, a large, gated culvert was constructed through a levee section, re-estabishing water circulation to the landward end of the largest slough. Results of initial field experiments on culvert operation are presented.

Located about 480 kilometers north of San Francisco, the Redwood Creek estuary (figure 1) is one of many on the Pacific Coast. Redwood Creek drains a long narrow basin 725 square kilometers in area flowing to the Pacific Ocean near the town of Orick, California. The basin lies largely within the Franciscan assemblage, consisting of tectonically deformed belts of sedimentary and metamorphic rocks (Baily and others 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 and others 1975).

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

HISTORICAL CHANGES

Undoubtedly, most estuaries in developed areas have been directly affected to varying degrees by human activities such as clearing of woody debris, land filling, and artificial channelization for flood control. These activities greatly simplify the estuarine environment and reduce or eliminate interaction of streams with their floodplains, sloughs, and side channels (Sedell and others, 1980). Additionally, greatly reduced tidal prisms reduce the effectiveness of tidal currents and terrestrial high flow events in maintaining the dimensions of remaining tidal channels. Indirect impacts from human activities involve increased sedimentation in low gradient, downstream areas from accelerated hillslope and channel erosion processes occurring upstream.

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 and others 1975). Flood control levees were completed in 1968 which channelized the lower 5.1 kilometers of Redwood Creek from the apex of the alluviated Orick valley to within 200 meters of the surf zone (figure 2).

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

Since channelization, floodwaters and sediment loads have been totally contained between the levees 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 extensive sedimentation in their oceanward ends since levee construction. Ricks (1985) estimates that 47 to 54 percent of the volume of the lower estuary (between 0 and 1.2 meters above mean sea level) has been filled in or become isolated from the main embayment since 1966. Sedimentation has been primarily due to the marine processes of beach overwash and surf-derived wave translation through the river mouth (Ricks 1985). Because surf-derived waves translate up through the river mouth most of the time (occasionally with great force), this process has probably caused much more sedimentation than beach overwash (which occurs relatively infrequently) in recent years.

Frequent closure of the mouth of Redwood Creek during low-flow periods forms an embayment. 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 completely and prematurely with respect to physiological development of juvenile salmonids rearing in the estuary (Hofstra and Sacklin, 1987).

As an interim method of improving estuarine conditions for fish, Redwood National Park has managed water levels in the estuary since 1982. When water levels approach flooding conditions on adjacent private lands, a "controlled breach" is performed. This is accomplished by excavating an outflow channel by bulldozer in a configuration and during tidal conditions which are likely to prevent the estuary from completely draining. The variability of hydrologic conditions in the estuary necessitates different numbers of controlled breaches from year to year (for example, twenty in 1987 and none in 1988).

PRESENT CONDITIONS AND PROCESSES

The focus of recent restoration efforts has been to partially restore favorable hydrologic and geomorphic processes to the South Slough (figure 2). 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 physically limits the lower tide range for the slough (figure 3), causing a decrease in tidal water circulation. Periodic 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 reduced circulation and isolation results in elevated 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).

At least once, and commonly several times each summer and early fall, the mouth of Redwood Creek closes when the sand berm builds to sufficient height across the mouth, forming an embayment. After closure, water levels rise gradually due to wave overwash at high tide and summer base flows from the watershed. Figure 3 shows a plot of water level fluctuations in the estuary 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 meter tidal range while water level fluctuations in the South Slough were limited to a 0.3 meter range above the maximum elevation in the aggraded slough neck (0.8 meter above MSL). Surf conditions closed off the river mouth on day 258 (September 14), after which water levels rose gradually in both the slough and the embayment.

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).

If the amounts of hydrologic gains and losses in the estuary are approximately equal, water levels can become nearly static (figure 3, days 259 through 263). Such conditions reflect a 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). When this happens, the river mouth will remain closed until the first fall rainstorm increases river discharge. Water levels may rise very slowly in a stepwise fashion related to the tides.

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 which alter the groundwater gradient through the barrier beach. 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), returning normal tidal fluctuations to the estuary.

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

When a sand sill builds across the river mouth to an elevation higher than mean sea level (MSL), the mouth is considered to be functionally closed. Figures 5a and 5b show the estuary area just before and just after functional closure of the mouth in August and September of 1988, respectively. When the mouth is closed, the consistently higher water levels improve fish accessibility to the sloughs, however only slight improvements in water quality occur due to limited circulation. 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 as the spilling water cuts a deep channel through the sand sill at the mouth (figure 4).

Figure 5--Aerial photographs of the estuary of Redwood Creek during August (a) and September (b), 1988; before and after functional closure, respectively.

RESTORATION EFFORTS

To restore 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 improved circulation by allowing more of the slough water to be exchanged with new water from the main embayment on each tidal cycle. While there has been no overwash since the 1983 excavation, the slough neck had re-filled to an elevation of 0.8 meter above mean sea level (MSL) by the summer of 1988 due to wave translation through the creek mouth and up into the neck.

With the intention of providing a longer term solution to the sedimentation and water quality problems of the South Slough, a large, gated culvert was constructed through the south levee in 1988 (figure 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 structure consists of three, 2.5 meter square box culverts, each with its own gate, connecting the main channel of Redwood Creek with the upstream end of the South Slough. Two objectives were formulated for which the culvert was designed: 1) to increase tidal water circulation during the summer for improving water quality in the South Slough, and 2) to 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.

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 tidal range, then, is an amount determined by the slough's bathimetry between the high tide elevation and the elevation of aggradation in the slough neck.

Figure 6 is a plot of water surface elevation versus water volume retained in the South Slough, derived from a map of the slough's bathimetry. The bathimetric configuration of the South Slough (very gently sloping bottom topography) causes large increases in water volume with slight increases in water surface elevation. By opening the culvert gates, the base water level in the slough was lowered by about 0.3 meters below the slough neck elevation in 1988 (ie., the culvert bottom is 0.3 m lower than the elevation of aggradation in the slough neck). The lowering of the slough's base water level by a mere 0.3 m was responsible for an additional 12,000 m^3 of tidal water exchange (figure 6). In addition to increasing the volume of tidal water exchange, opening of the culvert gates allows tidal circulation at the landward end of the slough, thereby improving dispersion of new water as well.

Preliminary results of water quality monitoring in the South Slough showed substantial improvements in temperature and dissolved oxygen following gate opening.[3]

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[3] Data on file, Redwood National Park, Arcata, California.

Figure 6--Plot of water surface elevation versus water volume in the South Slough, showing the effect of opening the culvert gates on reducing the residual volume of water remaining in the slough at low tide. The net result was a 0.3 meter increase in tidal range which caused the volume of tidal water exchanged to increase by 12,000 m^3 in 1988.

To illustrate the effect of culvert opening on the hydrology of the South Slough, figure 7 shows tidal hydrographs encompassing one complete tidal cycle which occurred August 2, 1988. Inflow and outflow rates are plotted which reflect water entering both ends of the slough on the flood (incoming) tide and leaving the slough on the ebb (falling) tide (outflow is shown as discharge in the negative range). The inflow rate for the slough neck peaks higher than the culvert due to its far greater width and because surf-derived waves help move the incoming tidewater up into the slough. This condition is reversed during for the ebb tide, when incoming waves work against the ebb current in the slough neck. Flood and ebb tidal currents are only minimally affected by surf-derived wave action at the culvert because it is farther away from the river mouth. Particulaly strong wave action in the slough neck during peak ebb flow precluded reliable measurements at this location between 15:00 and 17:00 hours. It is estimated that outflow rate through the slough neck peaked near 3 cms as the tide fell.

Figure 7--Hydrographs spanning one complete tidal cycle for the South Slough. With the culvert gates open, inflow (shown as

positive discharge) and outflow (negative discharge) occurs at both ends of the slough during the flood and ebb tides, respectively.

By calculating the area under the tidal hydrographs in Figure 7, the volumes of water exchanged at both ends of the South Slough can be compared. Table 1 shows inflow (flood tide) and outflow (ebb tide) water volumes, as well as peak discharge rates, from the hydrographs. Although peak rates of inflow and outflow were lower at the culvert, the greater water volumes exchanged there are accounted for by the longer duration of flow.

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)		
	SloughNeck	Culvert	SloughNeck	Culvert	Total
Inflow	4.0	3.3	16,500	16,400	32,900
Outflow	3.0[1]	2.7	13,200	19,700	32,900

Sedimentation

Use of the culvert in attempting to scour sediment from the neck of the South Slough is a far more complex task than improving summer 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 waves and backwater effects prevalent in the estuary during stormflow events. Favorable hydraulic conditions for scour are optimized at low tide. Three interrelated conditions occur at low tide which increase the hydraulic effectiveness of stormflows routed through the culvert: 1) backwater effects from Redwood Creek are lessened, 2) the mean ocean surface elevation is lowest, and 3) the surf zone moves seaward and down in elevation. The first two of these conditions allow steepening of the energy slope in the slough neck. The third causes a reduction or elimination of surf-derived wave energy reaching the slough neck.

Listed below are culvert flow rates predicted by the Corps of Engineers at various discharge rates and return periods for Redwood Creek:

Redwood Creek discharge rate (cms)	return period (years)	Culvert design discharge rate (cms)
198	1	3.7
255	+1	10.3
481	+1.1	31.7
878	2.5	65.6
	5	
	10	
	25	
	50	

	100	
2181	500	96.7

During a stormflow event which occurred on November 22, 1988, the first 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. It is estimated that a peak of over 28 cms would have been routed through the culvert had the inlet been free of debris. This estimate is in fairly close agreement with the flows predicted in the tabulation above.

A subsequent survey of the slough neck showed no significant scour as a result of the first scour trial. Because of the wide, shallow hydraulic channel geometry of the slough neck, unit streampowers are an order of magnitude smaller than at the culvert. In order to increase the effectiveness of flows diverted through the neck of the South Slough, alternatives are being considered which involve developing a morphologically stable, self-maintaining stream pattern and hydraulic channel geometry, scaled to 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 management and restoration stategies for establishing more favorable physical conditions and processes for the biological community. Ongoing field experiments using the culvert to route both tidewater and stormflows into the South Slough are aimed at refining techniques of operation. Although each estuarine system is unique in structure and function, results of experiments conducted in the Redwood Creek estuary may have application in other estuaries with similar problems.

REFERENCES

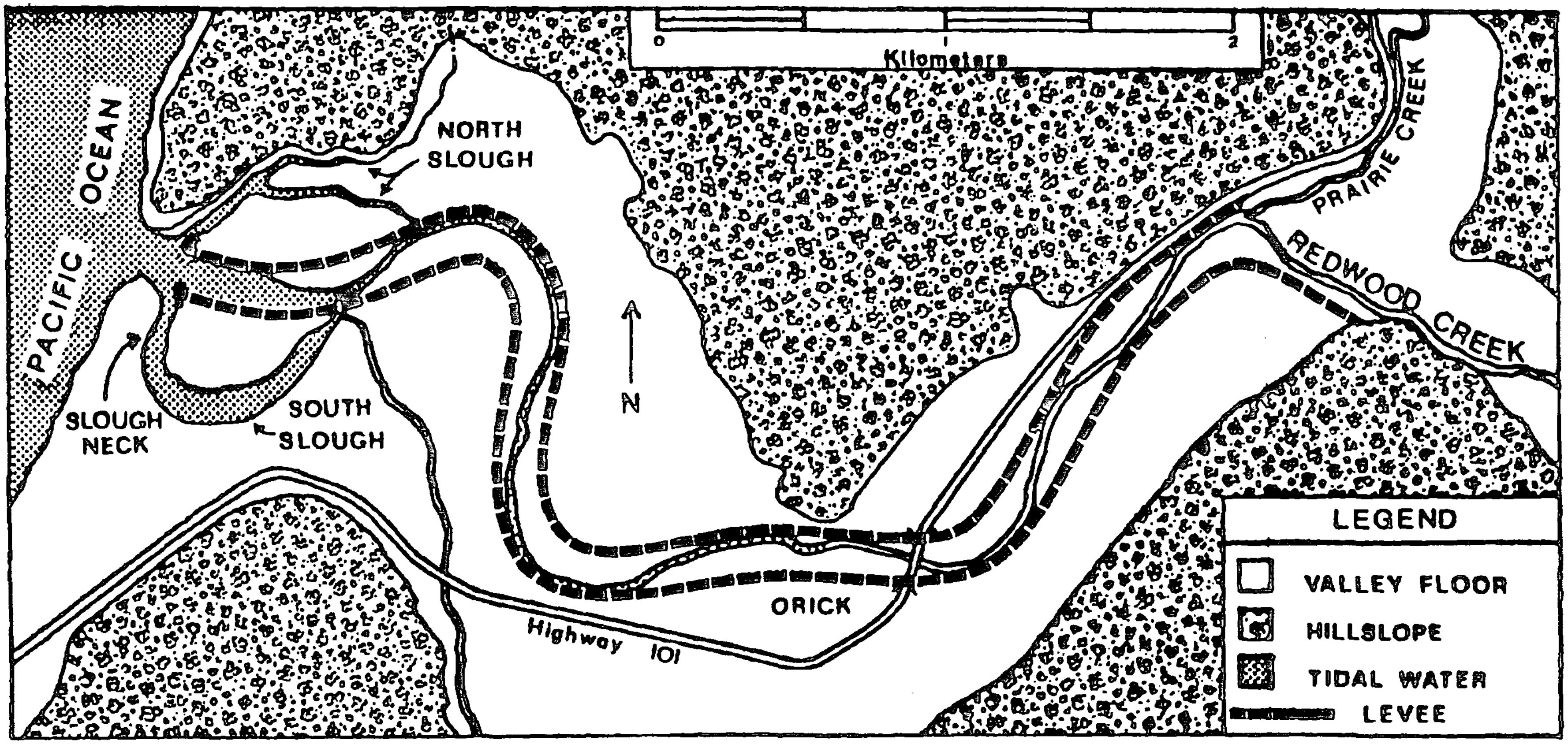
Baily, E.H.; Irwin, W.P.; Jones, D.L. 1964. Franciscan and related rocks, and their significance in the geology of Western California. Calif. Div. Mines and Geology. Bull. 183. 177p.

Hofstra, T.D.; Sacklin, J.A. 1987. Restoring the Redwood Creek estuary. In: Coastal Zone '87. WW Div., ASCE. Seattle, Wash. May 26-29, 1987. pp. 812-825.

Janda, R.J.; Nolan, K.M.; Harden, D.R.; Coleman, S.M. 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 p.

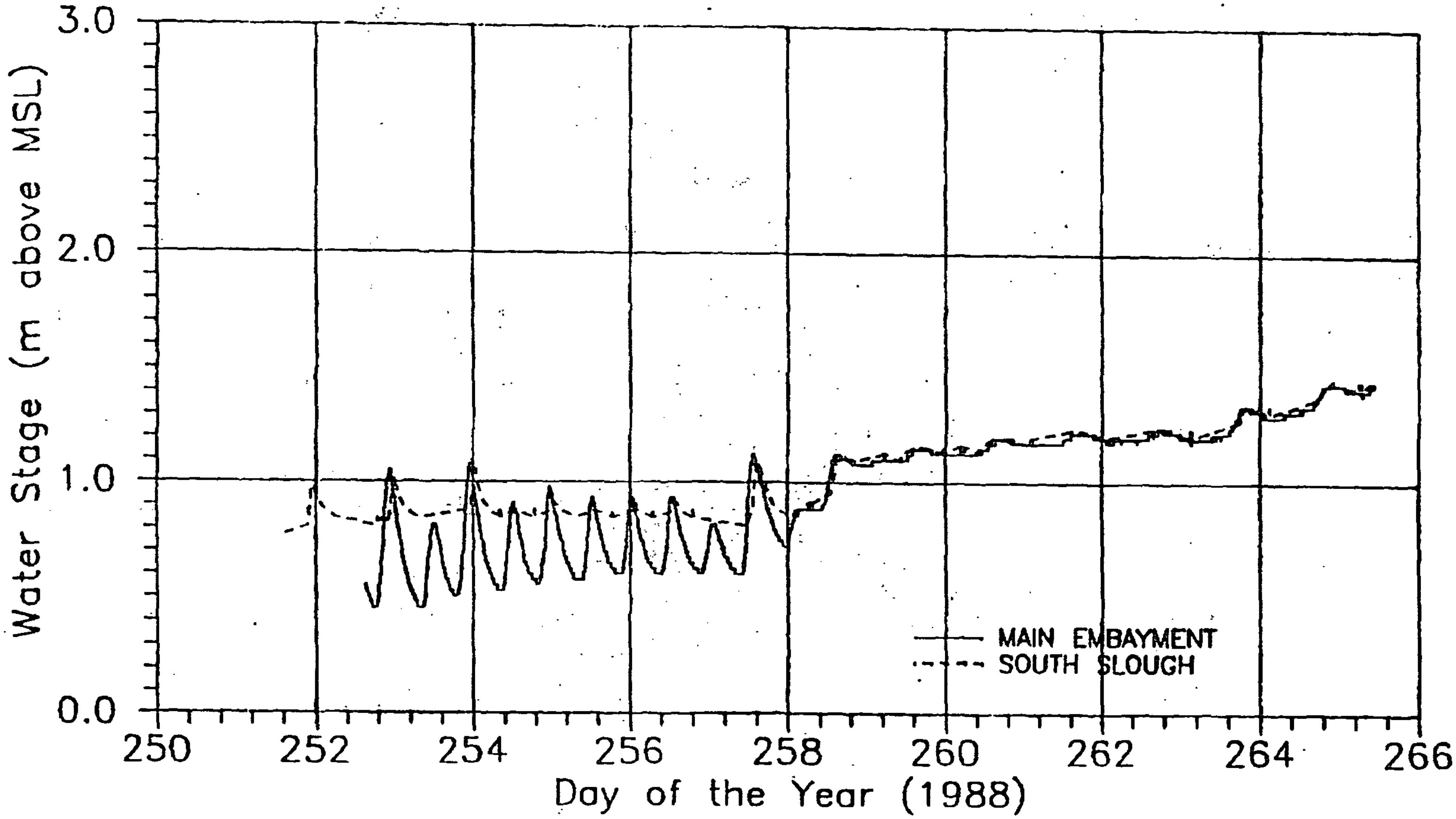
Ricks, C.L. 1985. Flood history and sedimentation at the mouth of Redwood Creek, Humboldt County, California. Redwood National Park Tech. Rpt. No15. National Park Service, Redwood Nat'l. Park. Arcata, Calif. 155 p.

Sedell, J.R.; Bisson, P.A.; June, J.A. 1980. Ecology and habitat requirements of fish populations in South Fork Hoh River, Olympic National Park. In: Proceedings of the second conference on scientific research in national parks. Wash. D.C. National Park Service; NPS/ST-80/02/7 Vol. 7:47-63.



0
1
2
Kilometers
PACIFIC OCEAN
NORTH SLOUGH
SOUTH SLOUGH
SLOUGH NECK
N
PRAIRIE CREEK
REDWOOD CREEK
ORICK
Highway 101
LEGEND
VALLEY FLOOR
HILLSLOPE
TIDAL WATER
LEVEE

Figure 2.



3.0
2.0
1.0
0.0
Water Stage (m above MSL)
250
252
254
256
258
260
262
264
266
Day of the Year (1988)
MAIN EMBAYMENT
SOUTH SLOUGH

Fig 3

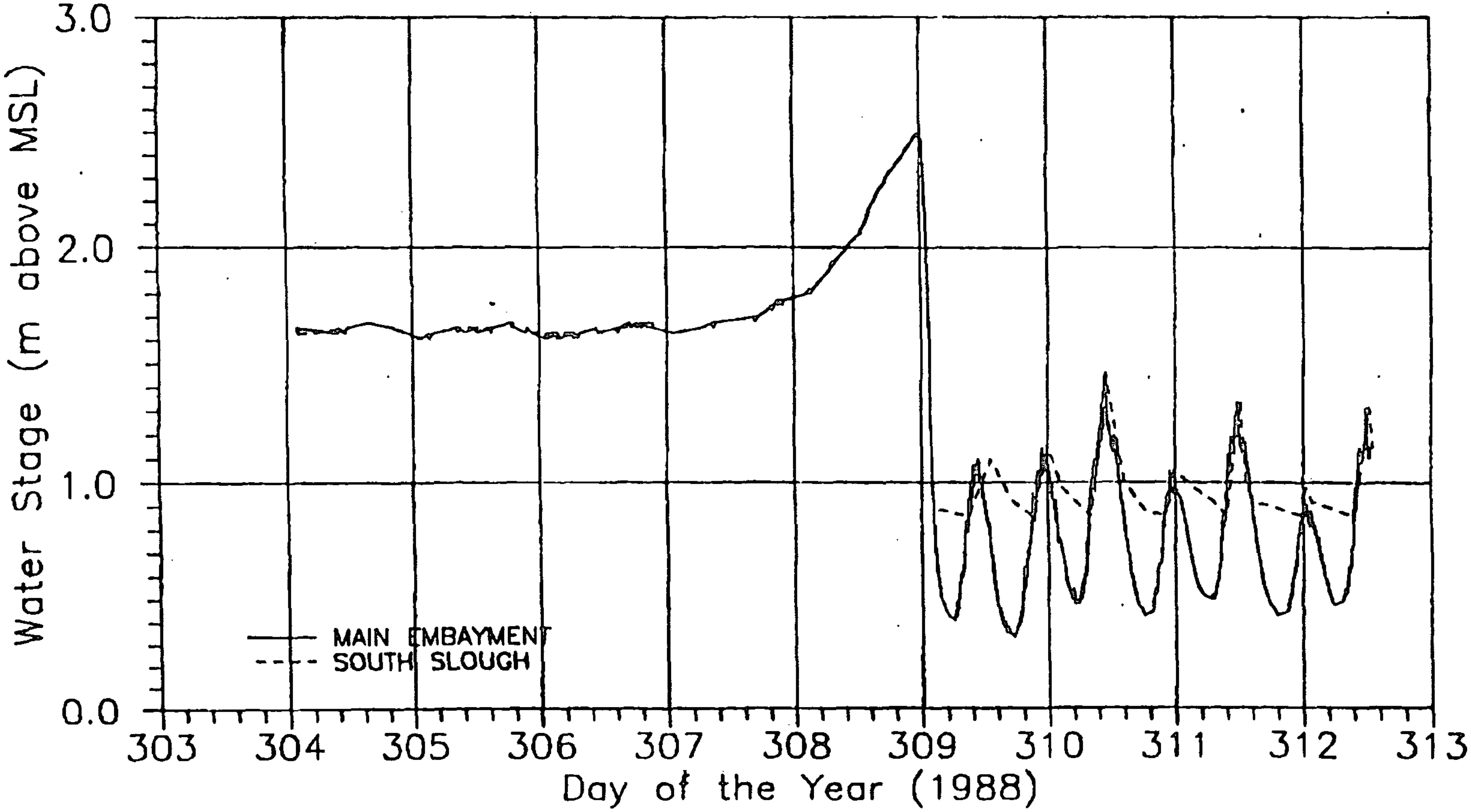

3.0
2.0
1.0
0.0
Water Stage (m above MSL)
MAIN EMBAYMENT
SOUTH SLOUGH
303
304
305
306
307
308
309
310
311
312
313
Day of the Year (1988)

Fig 4

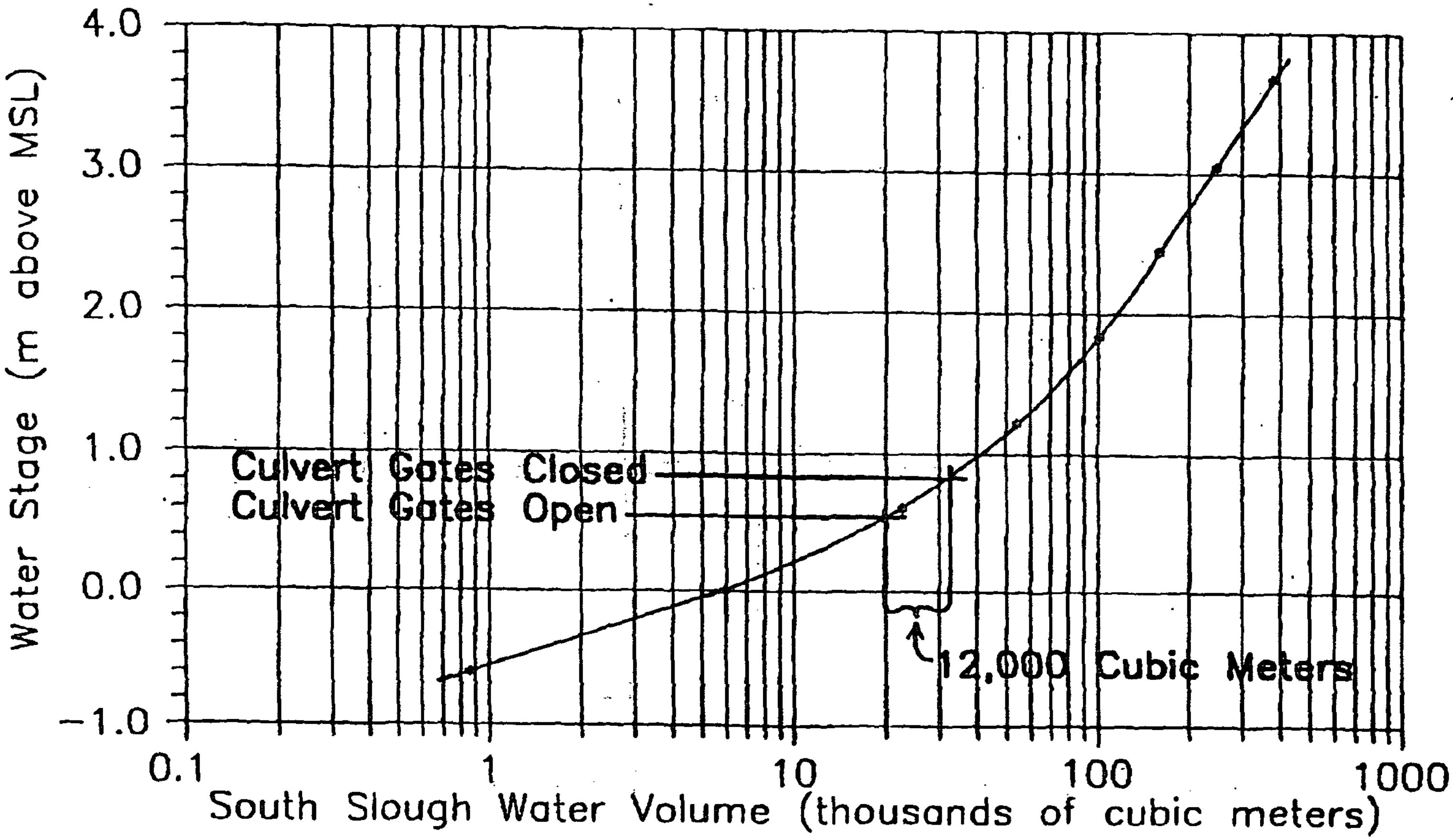

4.0
3.0
2.0
1.0
0.0
−1.0
Water Stage (m above MSL)
Culvert Gates Closed
Culvert Gates Open
12,000 Cubic Meters
0.1
1
10
100
1000
South Slough Water Volume (thousands of cubic meters)

Fig 7

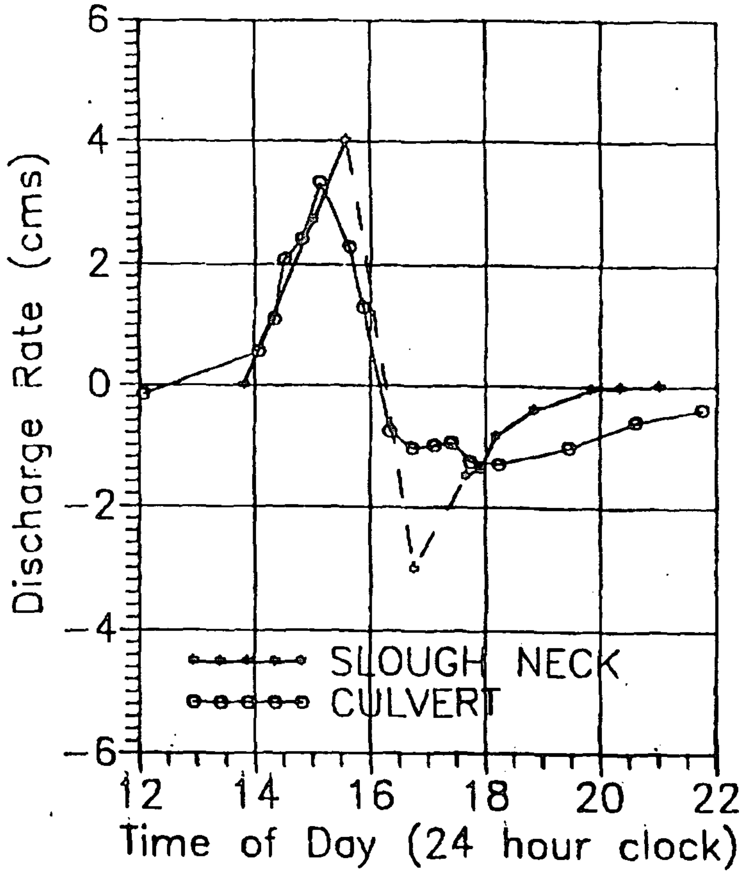

Discharge Rate (cms)
6
4
2
0
-2
-4
-6
12
14
16
18
20
22
Time of Day (24 hour clock)
SLOUGH NECK
CULVERT

Fig 8