An indication of recent bed-elevation trends is given by the record of bed elevation at the "Near Sumner" gage (RM 4.9) maintained by the U.S. Geological Survey. Figure 19 shows a 4.5-foot rise between 1945 and 1961, after which time the bed remained stable until the gage was discontinued in 1971. The gage site is located downstream of the canyon on the fan reach and would be expected to aggrade because of the sharp reduction in the river gradient at the junction of the canyon reach and the lowland. The record of accumulation is extended in time and space in Figure 20 which shows degradation and aggradation as measured from channel capacity surveys made in 1974/1977 and 1984 between the mouth and RM 11. The record shows a general trend of aggradation in the lower reach downstream of extraction operations and of degradation upstream. The survey results indicate that in a 10-year period, 43,000 cubic yards of bed material accumulated in the channel downstream of RM 11.

These data are difficult to evaluate without more completely documented extraction amounts. The abrupt apparent stabilization of bed elevation at RM 4.9 may be related to increased extraction, which may have begun at that time, or it may be unrelated. Similarly, whether the degradation upstream of RM 9, in the lower part of the White River canyon, reflects long-term geologic trends or the effects of gravel extraction that may have taken place in this reach is not known. However, if extraction has been confined to the two identified locations, present data are consistent with an interpretation of long-term aggradation in the lower fan reach, and degradation in the upper canyon reach, with local degradation related to gravel removal operations.

A minimum rate of bedload transport into the lower White River may be derived from the combined cross-sectional and extraction data. If an average of 43,000 yd$^3$/yr of material is accumulating in spite of a minimum of 78,000 yd$^3$/yr of removal during the 10-year period, then the minimum transport must be 121,000 yd$^3$/yr. This is a minimum influx because some of the bed material is transported out of the reach into the Puyallup River and because gravel extraction records are incomplete. As more complete extraction records and sediment transport measurements become available, it may be possible to determine the locations and rates at which the channel aggrades and degrades in the absence of gravel extraction, and to define a transport rate more precisely.

## Redwood Creek, California

Redwood Creek drains a 720 square kilometer (278 square mile), northwest-trending, elongate basin in north-coastal California (Figure 21). The basin has undergone rapid tectonic uplift within the last two million years and is underlain by highly sheared and mechani-

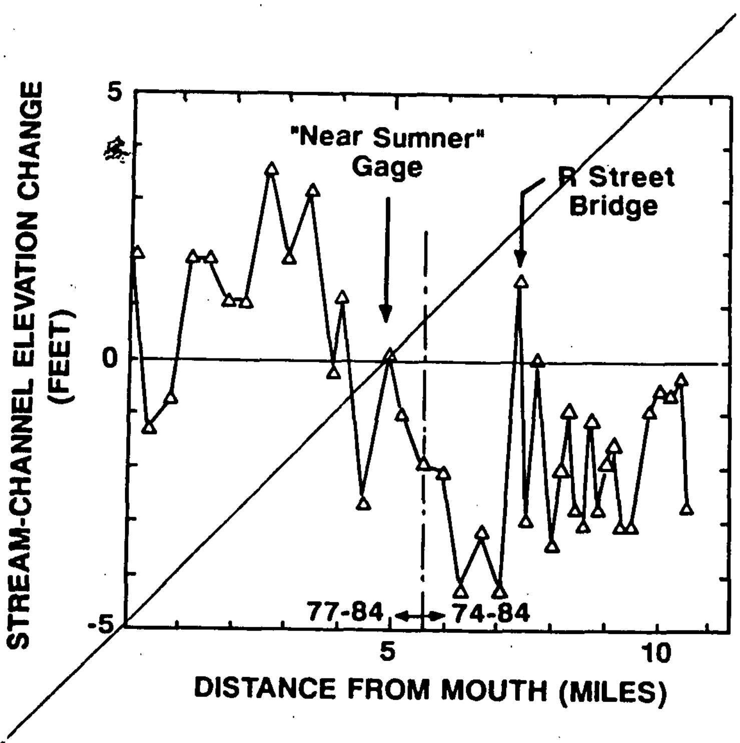


Figure 20. Changes in elevation of surveyed stream channel cross-sections.

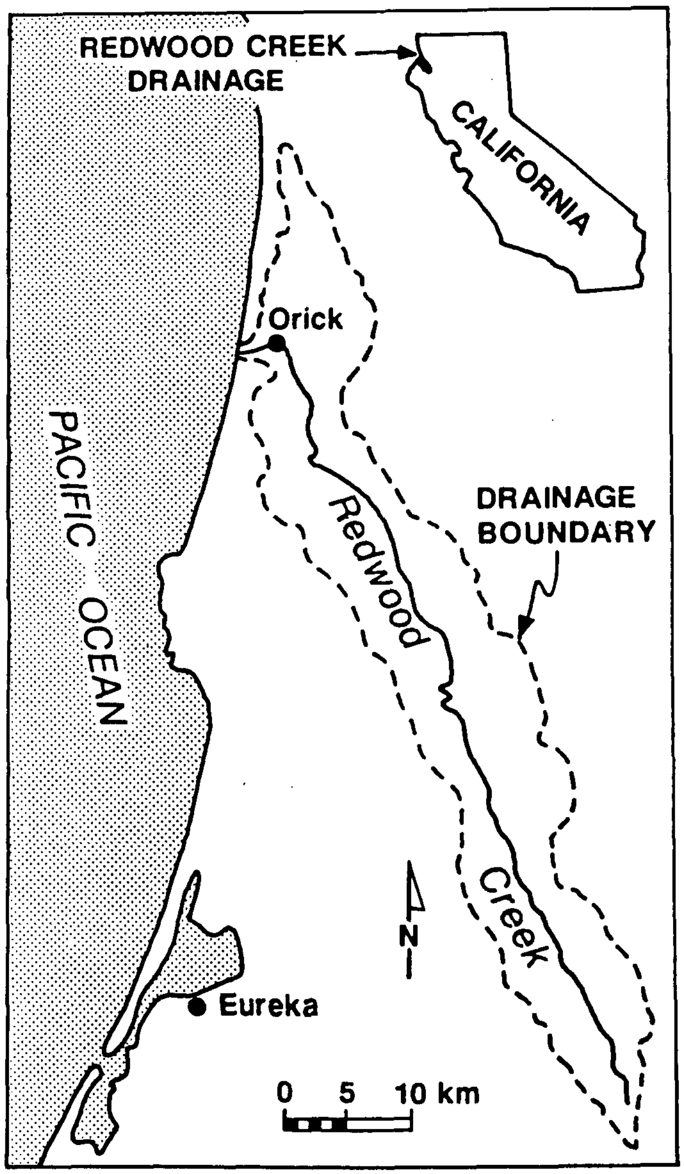


Figure 21. Location of the Redwood Creek drainage basin.

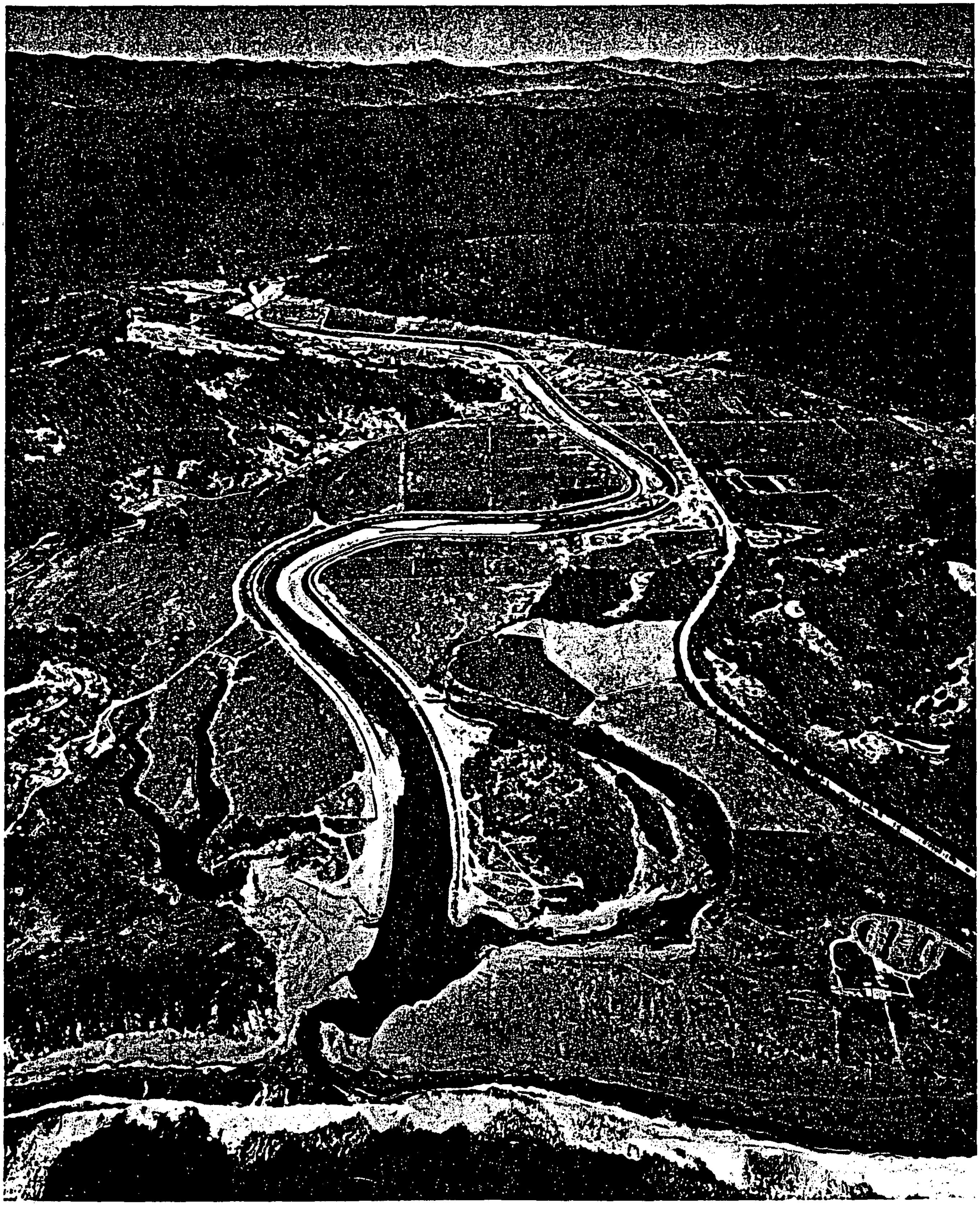

Photo 4. View of Redwood Creek as it enters the Pacific Ocean near Orick, California. Redwood Creek was mined in summer 1987 and in summer 1988, when this photo was taken.

cally weak sandstones, mudstones, and schists of the Franciscan Assemblage. The combination of rapid uplift, unstable materials, and seasonally high rainfall has resulted in high sediment yields. In addition, Madej (1984) indicates that sediment yields measured since extensive timber harvest began are several times yields estimated for the undisturbed condition. Timber harvest began in the mid-1950s, with 45 percent of old-growth having been logged by 1962, and 81 percent by 1978.

Redwood National Park was established in 1968, and included a 0.5-mile wide corridor along Redwood Creek in the lower one-third of the basin. Following establishment of the park, controversy arose over the damaging

Photo 5. Redwood Creek looking upstream toward Highway 101 bridge from near point A in Figure 22. Photograph taken in October, 1987 following mining. Note flat channel bed, shallow linear trough transmitting water in channel center.

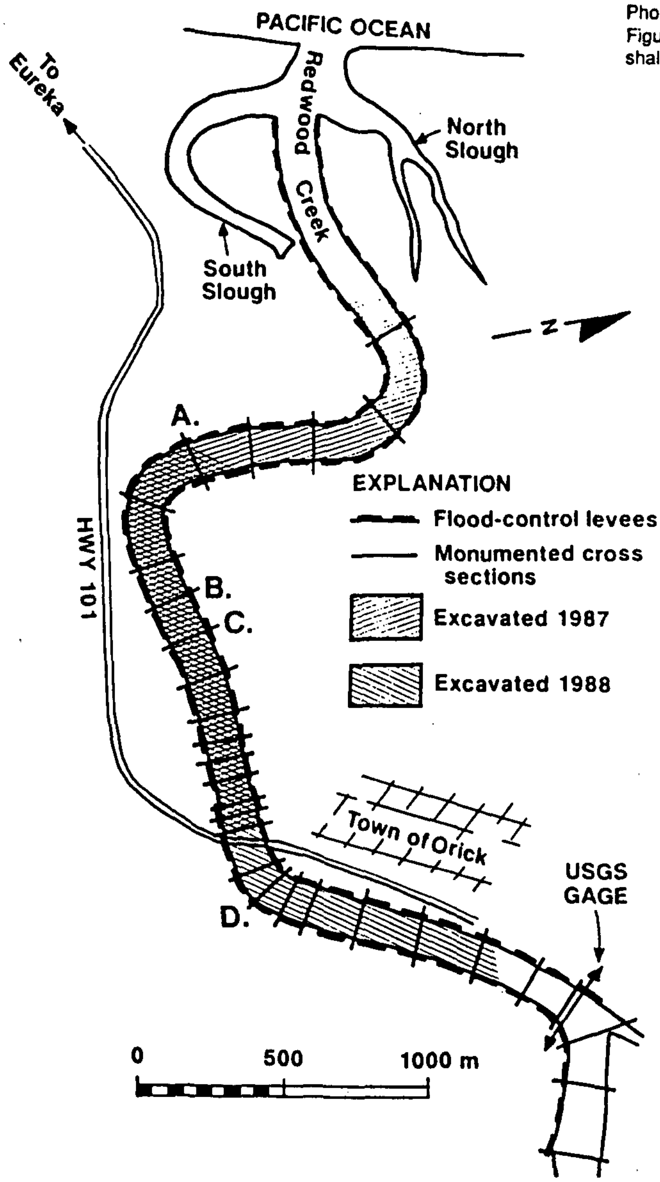


Figure 22. Map of the mined reach of Redwood Creek near Orick. Twenty-nine cross sections document channel changes in the 5-km reach, and the U.S. Geological Survey gaging station at the upstream end of the reach provides water and sediment discharge data. Cross-sections A-D refer to Figure 23.

effects of logging upstream and adjacent to Redwood Park, especially in conjunction with a large flood in December 1964. The U.S. Geological Survey documented significant aggradation in Redwood Creek and the impacts of clearcut logging on forest ecology and the aesthetic values of the Park. A decade of political discussion and scientific research culminated in the expansion of Redwood National Park in 1978 to include the lower 197 square kilometers of the basin, from the watershed divides to the creek. The balance of the watershed remains in timber production. Downstream of Redwood Park, the channel of Redwood Creek was channelized between levees constructed in 1968 by the U.S. Army Corps of Engineers (Photo 4).

At Rkm 5, at the upper end of the channelized reach and 1 km upstream of the town of Orick and Highway 101, the U.S. Geological Survey since 1953 has measured the discharge of water and suspended sediment, and since 1971, bedload. Long-term estimates of suspended sediment discharge for the period 1954-1980 were estimated to be 1,480,000 tons/yr (U.S. Geological Survey, written communication to Redwood National Park, 1981). Estimated bedload discharge for the same period was 191,000 tons/yr, or 11 percent of the total load (13 percent of suspended load). Ratings for bedload were shown earlier in this publication as Figure 4.

In summer 1987, Humboldt County began a program of annual gravel mining from between flood levees (Figure 22). Because of concern over potential effects of the mining on riverbed morphology, which could in turn affect the quality of habitat provided for fish migrating upstream to spawning grounds within the Park, Redwood National Park personnel initiated a monitoring program prior to gravel removal in summer 1987. An additional concern was the potential for undermining of the flood levees due to bed degradation. A series of cross-sections was installed (Figure 22), to be periodically resurveyed, with the goal of determining offtake and replenishment during the intervening high-water seasons and to document changes in channel morphology. Gravel was to be excavated by scrapers to the low-water level, and a low-flow trough was to be maintained (Photo 5). There was concern that the stream would have a limited efficacy at reestablishing its pool-riffle structure, because the tidal influence on the reach would limit the scour depth, and morphologic recovery would depend on the rebuilding of bars from replenished material. Offtake was to be limited to the average annual bedload transport estimated from the 1954-1980 data.

Comparison of cross-sections surveyed in the spring and fall of 1987 indicated that 102,000 cubic meters were excavated during summer of 1987. Resurvey of cross sections in April 1988 indicated that the winter floods redeposited 49,000 cubic meters. Bedload measurements by the U.S. Geological Survey during the 1987-1988 high-flow season indicated a transport of 29,000 cubic meters. Field observations by Redwood National Park personnel suggested that the surveyed replenishment may have been greater than the measured upstream transport because some of the replenished volume could have eroded from the unmined channel downstream of the gage. It is also possible that the coarsest portion of the suspended load deposited in the mined reach. Finally, channel changes caused by mining may have added to the existing sources of imprecision associated with estimating annual bedload transport from bedload sampling. Cross-sectional changes between the summer and fall of 1988 indicated offtake of 87,000 cubic meters. More current replenishment and transport data are not available at the time of writing in spring 1989.

Figure 23 shows how the channel cross-section has changed at four representative sites in the mined reach. The channel changes are described in detail in the figure caption. Taken together, the cross-sectional changes illustrate several findings. First, bars were able to rebuild only a fraction of the topography removed by mining during the course of a high-flow season (although this was complicated by the 1987-1988 rainy season having transported lower than average bedload). The channel bed was destabilized with some bars rebuilt along the opposite bank from their original location. Channel bed degradation proceeded upstream of the mined reach. Finally, low-flow channel depths were not restored by scour during high flows.

As a result of the implications for aquatic habitat of the morphologic changes indicated from these preliminary results, the California Department of Fish and Game, an agency responsible for permitting the mining, has proposed revisions to the permit. Rather than allowing mining down to the low-water level, mining will be restricted to one-half the channel width and will be focused in the low-water channel. The low-water channel will be temporarily dewatered to minimize sedimentation during extraction. The sinuous channel plan form and bed morphology existing prior to mining will be conserved during mining. The monitoring program being carried out by Redwood National Park will be continued to document and evaluate the results from this modified approach. Limits to annual offtake may also be reviewed as more years of annual transport data become available. Analysis of this data can determine whether average annual transport has changed or remained the same compared to the 1954-1980 period.

## Skykomish River, Washington.

Because of increased pressure to mine gravel from the channel bars in the Snohomish River system, in 1979 the Snohomish County Planning Department commissioned a study of existing levels of gravel removal on channel changes. The case study illustrates how analysis of sequential aerial photographs can be used along with knowledge of transport rates and offtake amounts to determine rates at which gravel can be extracted without major disruptions to the adjoining bars and banks (Dunne, 1979; Dunne and others, 1981). The analysis did not consider changes to bed elevations, which may or may not have occurred.

The Snohomish River basin drains 1,780 square miles of the western Cascade Range (Figure 24). The Snohomish River is formed by the confluence of the Snoqualmie River from the south and the Skykomish River from the north. The upper parts of both rivers flow

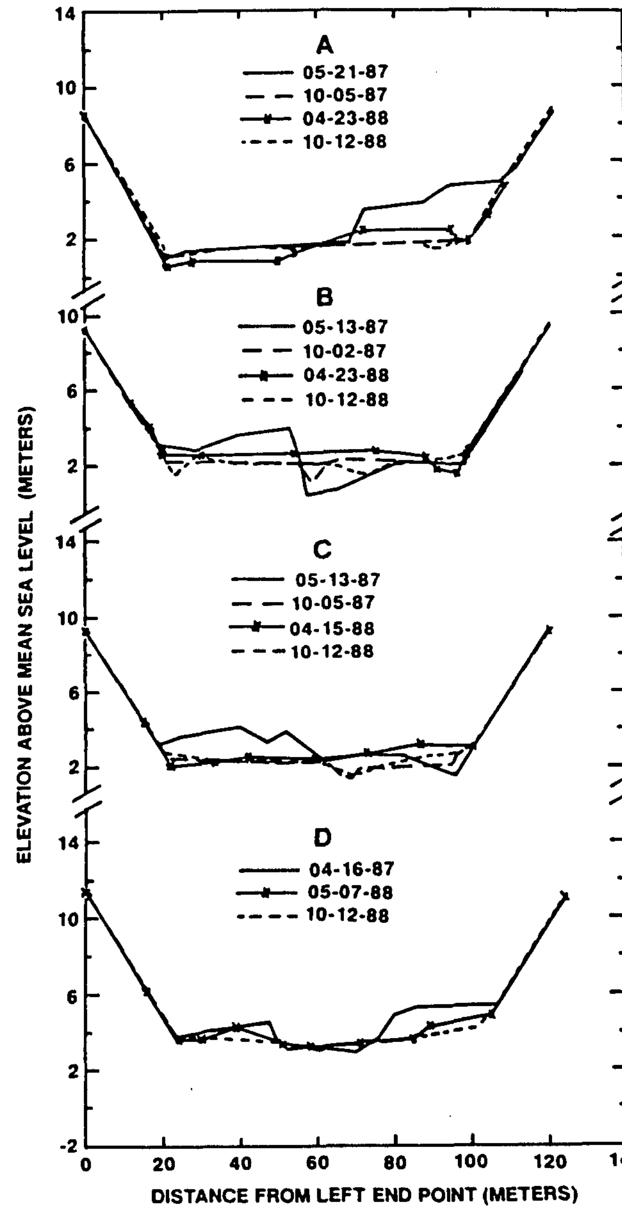


Figure 23. Record of periodic cross section resurvey in the mined reach of Redwood Creek. Data provided by D. K. Hagans, Redwood National Park.

(A) Large right-bank point bar, shown in May 1987 survey, was removed in the subsequent summer, leaving a flat bed. Winter flows replenished less than a third of the bar (April 1988 survey), and downcut the channel thalweg almost one meter. Excavation in summer 1988 lowered the channel bed by one-half meter, and returned the channel to a flat configuration (October 1988 survey). Bar replenishment in this downstream location was less than in upstream locations.

(B) Low-flow channel is well developed in May 1987 survey; following mining the bed appears flat with small center incision (October 1987). Winter flows did not rebuild the left-bank bar, but shifted the thalweg to the base of the right bank and filled the channel to a depth of one-half meter (April 1988). Excavation in summer 1988 lowered the channel by one-half meter, and created a flat bed (October 1988).

(C) Well-developed left-bank bar, replaced by flat bed with a poorly defined incised channel after mining in summer 1987. Subsequent winter flows filled the channel on the opposite, right bank side. Excavation in 1988 replaced topography with flat bed.

(D) Cross-section site was not mined in 1987, but gravel was extracted immediately downstream. Prominent right-bank gravel bar (April 1987) degraded substantially during subsequent winter flows (May 1988) in response to downstream mining. Gravel extraction in 1988 created flat bed (October 1988).