

Changes In Channel Roughness Values Following Large Sediment Inputs

**Mary Ann Madej, U. S. Geological Survey Western Ecological Research Center
Arcata, California, USA**

(Gravel-Bed Rivers 2000 Conference Proceedings, New Zealand)

Abstract

Large inputs of coarse sediment entering a river can change the flow resistance characteristics of the channel. Trends in channel roughness values at five gauging stations were examined for a 20-year period of record, using measurements of velocity and channel geometry. At four stations, the river had aggraded one to two meters during floods and associated landslide input in the 1970's, and the streambed was relatively smooth. Since the mid-1970's the channel has downcut through the flood deposits, bed topography has become more variable, bed relief has increased, and bedload transport rates have decreased. Concomitantly, the value of Manning's roughness coefficient ('n') has significantly increased through time at these stations, after adjusting for discharge. During the same period, there was no statistically significant increase in channel roughness in the control stream, which did not aggrade.

The relationship of channel roughness and discharge was also explored. The control stream exhibited the typical pattern in gravel-bed rivers of decreasing flow resistance with increasing discharge. In contrast, however, the other four stations with high sediment supplies displayed a pattern of decreasing flow resistance with discharge only at low to moderate flows. At flows greater than a 1.1-year recurrence interval, values of Manning's n increase with increasing discharge. This may be due to high

bedload transport rates and scour of the stream bed at higher flows, which leads to greater bed relief and turbulence, and consequently greater flow resistance.

Introduction

Both skin friction and form drag contribute to flow resistance in a channel. If a channel bed becomes coarser, the roughness due to boundary materials (skin friction) increases. Alternatively, as bed topography becomes more complex, and the heterogeneity of the channel bed increases, form roughness should also increase. Increases in form roughness should have the most influence at low to moderate flows; whereas the roughness due to bed topography would be drowned out at very high flows, when mean depth of water is much greater than the vertical dimension of bed topography.

Watershed disturbances, such as mining, wildfires, landslides, and volcanic eruptions, can greatly increase the sediment load supplied to streams within short time periods. Associated mechanisms of increased sediment supply (sediment pulses) in a channel network, such as mass movements, surface erosion or release of stored sediments, are stochastic processes that can generate regions of high bedload transport and bed material storage in channels (Benda and Dunne, 1997a). Disturbances such as major floods and large sediment inputs can modify bed topography, and so influence channel roughness. In gravel-bed rivers, low gradient ($<2\%$) reaches commonly display a pool-riffle morphology, and disturbances can decrease the size and frequency of deep pools. Consequently channel boundary conditions become smoother, and these changes in bed topography will be reflected in changes in velocity and shear stress distributions as well. For example, large inputs of coarse sediment in Redwood Creek in north coastal resulted in an aggraded channel bed with low relief and subdued

topography (Madej, 1999). In the years following channel aggradation, bars and pools became more strongly developed. The hypothesis tested here is that an increase in bed form development should manifest itself in a concomitant increase in Manning's n roughness coefficient at low to moderate flows. Water discharge measurements collected at five gauging stations along Redwood Creek were used to test this idea.

Field Area

The Redwood Creek basin is located in the northern Coast Ranges of California, USA (Figure 1) and is underlain by rocks of the Franciscan Assemblage, mostly sandstones, mudstones and schist. The 720 km² basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m, average hillslope gradient is 26%. Redwood Creek is a gravel-bed river with channel gradients ranging from 12% in the headwaters to 0.01% in the lower reaches. The downstream-most 80 km of the 100-km length of Redwood Creek has gradients less than 2% and is characterized by a pool-riffle morphology.

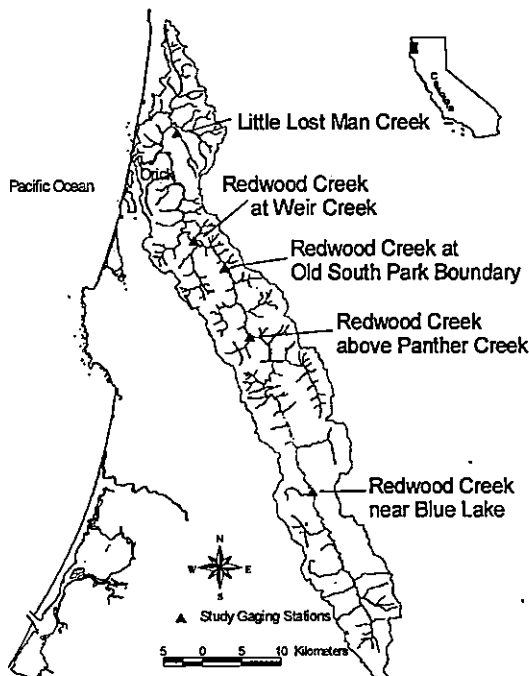


Figure 1: Location map of field area.

Prior to 1945, 85 percent of the Redwood Creek basin was forested with redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*) stands (Best, 1995). By 1978, more than 80 percent of the coniferous forest was logged. In 1964, a 50-year flood caused widespread landsliding, bank erosion and channel aggradation throughout the Redwood Creek basin. In the 1970's, several more large floods (10 to 25-year recurrence intervals) initiated further landsliding and redistributed sediment. The downstream third of the Redwood Creek channel is still responding to the pulse of sediment introduced by past floods (Madej and Ozaki, 1996). In 1997, a 12-year flood occurred, initiating many debris flows that contributed large volumes of sediment to the rivers and renewed aggradation in several areas.

Methods

Table 1 lists the gauging stations used in this study. Gauging stations were purposely constructed in straight reaches to avoid complicated hydraulics due to bends, so roughness due to channel curvature is negligible. Channel bed profiles (surveyed at the gauging stations at low flow) show no change in channel grade during the study period. In addition, an analysis of sequential aerial photographs from these sites showed that other factors that could affect channel roughness, such as changes in channel

planform, large in-channel wood, or streambank vegetation, were not important at the gauging stations.

Table 1: Study Reach Characteristics

Gauging Station	Drainage Area (km ²)	Channel Gradient (percent)
Redwood Creek near Blue Lake	67.7	0.20
Redwood Creek above Panther Creek.	389	0.28
Redwood Creek at old South Park Boundary	479	0.31
Redwood Creek at Weir Creek	523	0.26
Little Lost Man Creek	9	1.50

Up to twenty-five years of water discharge measurement records (1972 to 1997) were examined, using the relationship defined by the Manning's equation:

$$n = \frac{(d^{\frac{2}{3}})(S^{\frac{1}{2}})}{v}$$

where 'n' is the roughness coefficient Manning's n, 'd' is mean flow depth in meters, as an approximation of hydraulic radius, 'S' is the water surface slope (m/m), and 'v' is mean velocity (m/sec). Values for these parameters were obtained from gauging station records

(U.S. Geological Survey (USGS) Form 9-207). Mean depth, not specifically listed on the USGS form, was calculated as 'area/width.' These data can be viewed on the adjoining Excel worksheets. Water surface slope was assumed to be equivalent to the gradient of the channel bed surveyed at low flow. Water surface slope may change with discharge, so this value is only an approximation of the true energy grade at the gauging station. Because slope was used as a constant in all calculations at a given site, absolute

values of roughness may be slightly off, but patterns in changing 'n' values should still be valid.

Before examining time trends in roughness values, roughness values must be adjusted for the influence of discharge. In a typical gravel bed channel, flow resistance is high at low flows, and resistance decreases with increasing discharge. As an exploratory tool, discharge and Manning's n were related by linear regression, and the resulting residual plots were examined for possible trends through time. Extreme summer low flows, when water depth and bed particle size are equivalent, were not used in the analysis. To test whether trends in time were significant, I used the method described by Helsel and Hirsch (1992, p. 335). A multiple regression analysis was constructed using both time and discharge as variables in the model:

$$\ln(\text{roughness}) = B_0 + B_1(\text{Time}) + B_2(\ln(\text{Discharge})) + e.$$

The t-statistic for B_1 tests for significant changes with time.

The size distribution of particles on the streambed at the gauging stations was determined through pebble counts (Wolman, 1954). In this study, pebble counts consisted of a random selection of at least 100 particles from a riffle crest near each gauging station. The intermediate axis of each pebble was measured and tallied using Wentworth size classes. Cumulative size distribution curves were constructed, and D_{84} (the particle size that is coarser than 84% of the bed material) was calculated

Three to five resurveys of the study reaches were performed between 1977 and 1997 to document the development of bed morphology, and especially pools and riffles, following the 1975 flood. In the summer of 1977, the U. S. Geological Survey surveyed a longitudinal thalweg profile of the lowest 22-km of Redwood Creek. The author resurveyed selected reaches of this area in 1983, 1986, 1995 and 1997. Surveyed long-

profiles began and ended at riffle crests and survey distances were measured along the centerline of the high-flow channel. Elevations of the thalweg and water surface were established using either an automatic level and stadia rod, or electronic distance meter and target. Survey readings were taken at all breaks in slope of the channel bed in order to characterize all major morphologic features (i.e., top, middle and base of riffles and pools) along the thalweg. The spacing of survey points averaged 15 m in Redwood Creek. Surveyors used staff plates at three gauging stations and twenty permanent bench marks established for channel cross-sectional monitoring as a control on survey accuracy. The total error in elevation between the surveys was less than 0.2 percent (0.8 m). The length of each surveyed profile was 20 to 55 channel widths (400 to 2500 m, depending on the stream reach). Bed topography was quantified by comparing sequential longitudinal profile surveys of the channel thalweg. From these profiles, mean residual water depth (Bathurst, 1981; Lisle, 1987), the variability of water depths, and the length of channel in riffles were calculated.

Results

Changes in Channel Roughness with Discharge

The trend exhibited by Little Lost Man Creek, the control stream, is typical of gravel-bed channels (Barnes, 1967) in that Manning's n decreases with increasing discharge (Figure 2). At the upstream-most gauging station along Redwood Creek (Redwood Creek near Blue Lake), Manning's n also decreases with higher discharge ($r^2 = 0.50$) (Figure 3). Figures 3a and b are photographs of Redwood Creek near Blue Lake at high flow showing the turbulent water

surface. As might be expected, there is more variability at summer low flows when skin friction

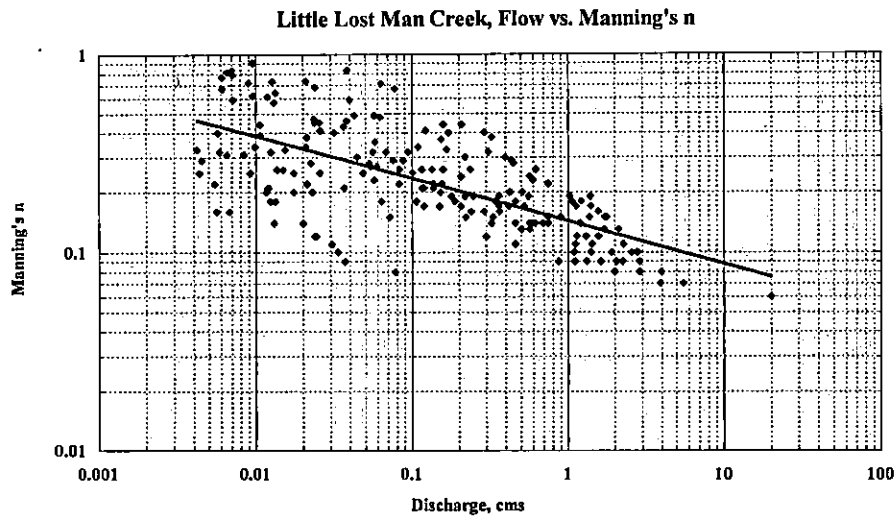


Figure 2: Plot of water discharge versus calculated Manning's n roughness coefficient for Little Lost Man Creek (the control stream).

dominates than at high flows when both grain and form roughness are low. However, logarithmic plots of discharge and channel roughness showed a distinct break in the linear relationship at higher discharges for several stations (Redwood Creek above Panther Creek, Redwood Creek at Old South Park Boundary, and possibly at high flows at Redwood Creek near Blue Lake) (Figure 4). Because of this non-linearity, the data were subdivided based on discharge and analyzed separately.

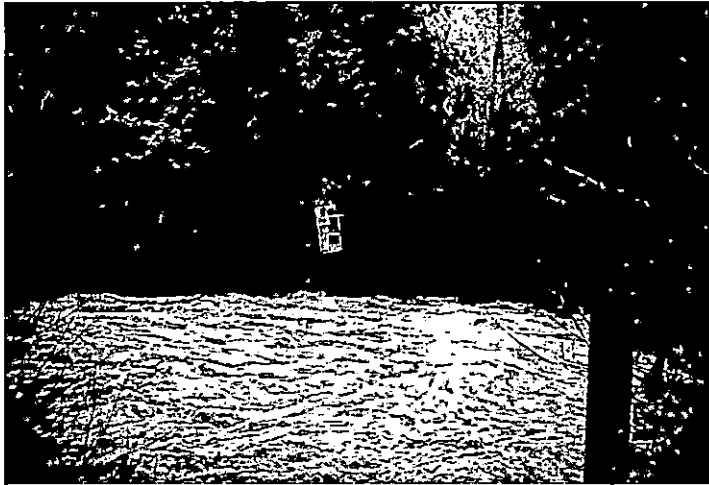
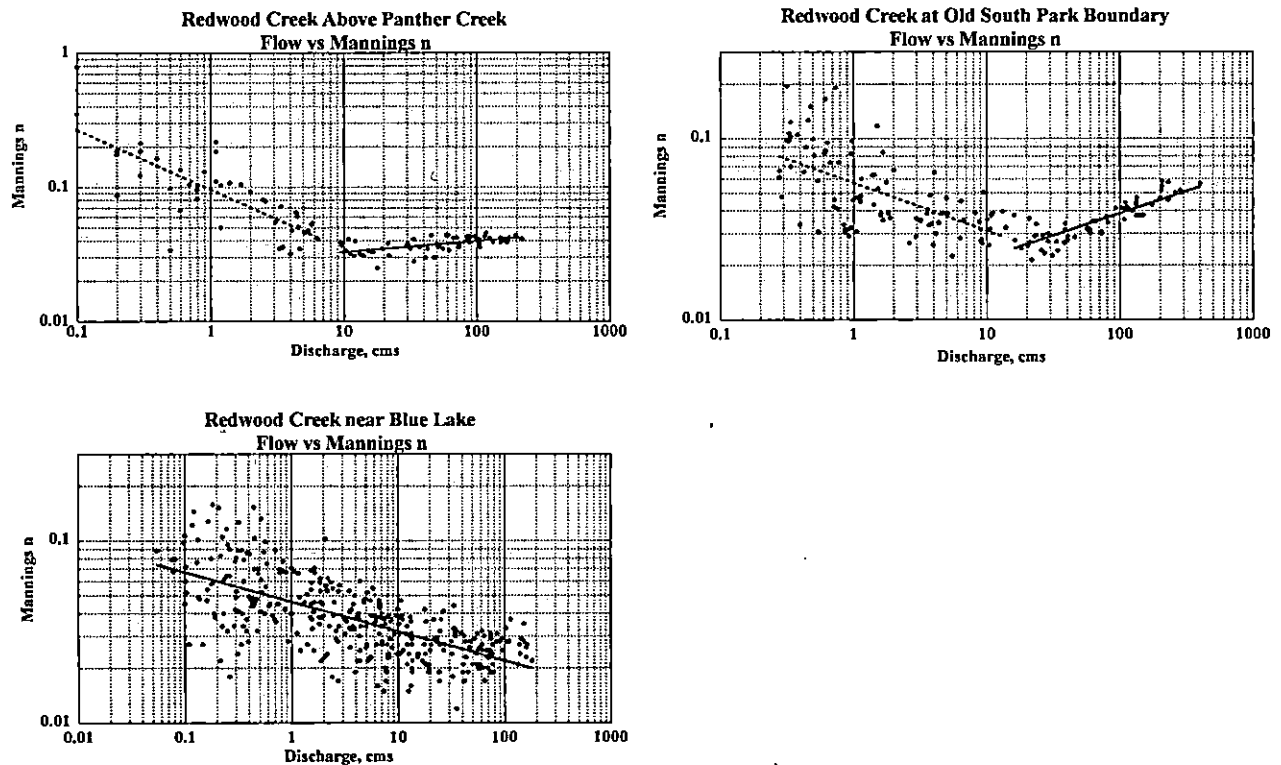


Figure 3: Conducting discharge measurements for a 2-year flood at Redwood Creek near Blue Lake.

No low flow measurements were available at Redwood Creek at Weir Creek. The much smaller sample size at this station hinders a complete analysis. Unfortunately, the gauging station was discontinued and the cableway used for sampling was dismantled, so additional high flow measurements were no longer possible.

At three stations, and possibly four, the expected pattern in gravel-bed rivers of decreased flow resistance at high discharges was actually reversed. There are two possible explanations for this. First, at two of those stations, old-growth redwood trees up to 3 m in diameter line the streambanks. Although there is no floodplain in these

confined reaches, as the stream stage increases, some flow resistance is contributed by the very large trees growing on the inundated banks. Nevertheless, channel widths are 35 to 60 m at these stations, and width/depth ratios are greater than 20, so the influence of

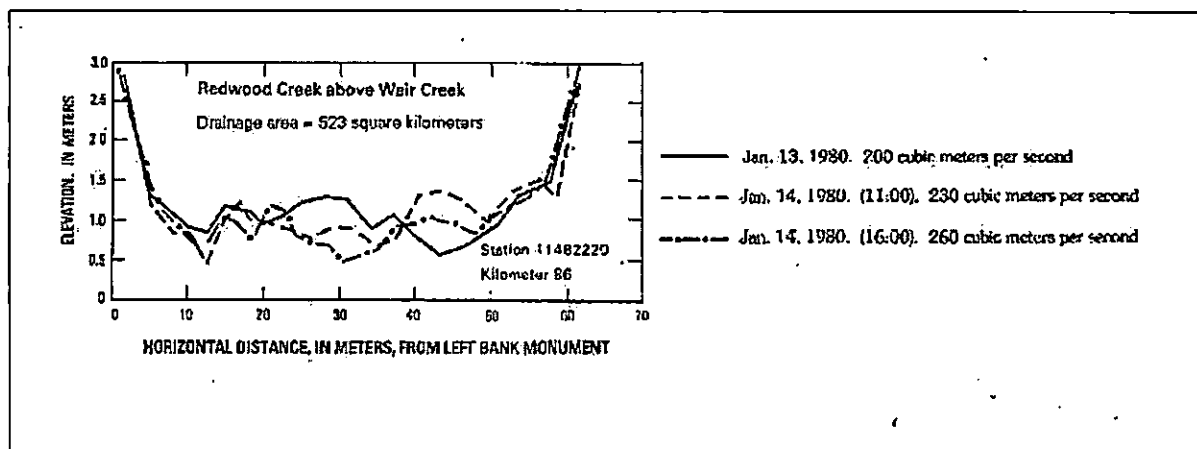
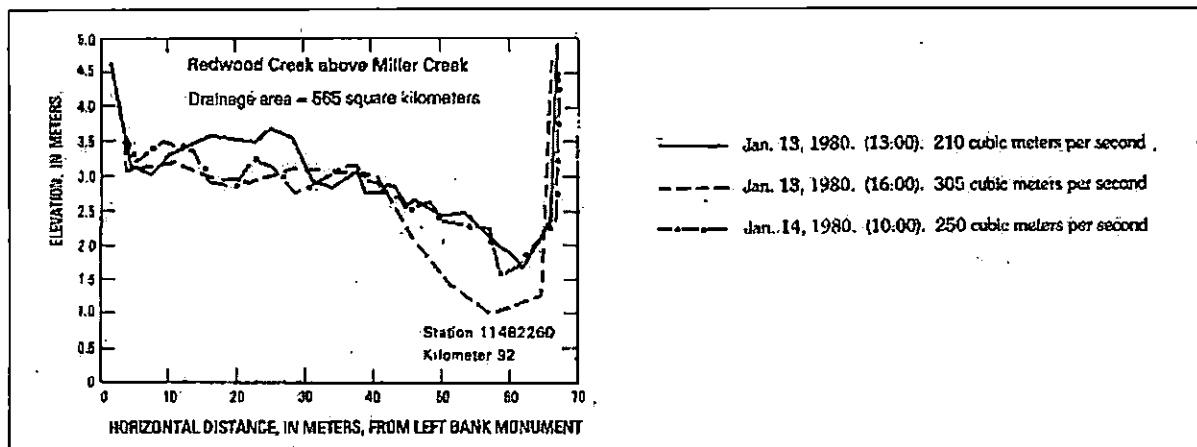


streambank vegetation on flow hydraulics across

Figure 4: Plots of Manning's n roughness coefficient versus water discharge for three gauging stations along Redwood Creek.

the entire channel is probably minimal. Another explanation for increases in flow resistance with increasing discharge is the change in bed topography at high discharges. Madej (1995) used soundings of water depth at gauging stations during floods to determine the depth of scour of the channel bed (Figure 5). The increase in cross-sectional relief of the bed topography during a single flow event varied from 0.6 m at

Redwood Creek at Weir Creek to 1.2 m at Redwood Creek at Miller Creek. Following the flood wave, the channel bed returned to about its pre-flood configuration. This suggests that changing bed-forms under high sediment transport rates, analogous to ripples and dunes in sand-bed rivers, contributes to flow resistance in the easily



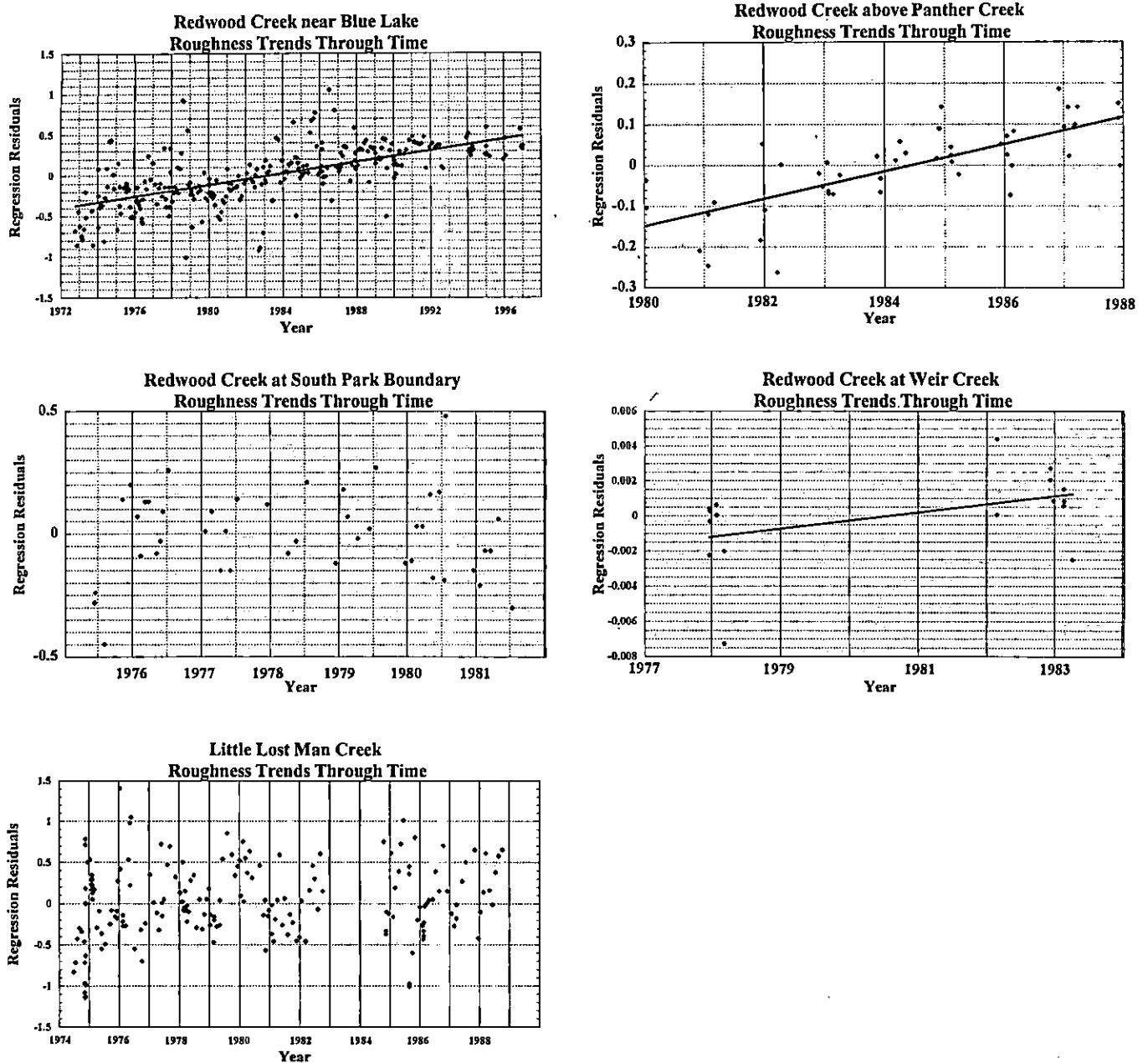
mobilized, gravel-rich reaches of Redwood Creek at high flows. This topic warrants further investigation.

Figure 5: Plots showing changes in bed elevation during a single flood event, determined by depth soundings made from cableways above the river. The plots show that the bed can scour up to a meter during the flood, and revert back to its previous elevation during the recessional limb.

Changes in Channel Roughness Through Time

Channel roughness increased through time at three of the Redwood Creek gauging stations, where channel aggradation was followed by downcutting and bedform development. In contrast, there was no significant change in roughness values in a pristine, unlogged stream used as the control reach. The statistical results are listed in Table 2. As a visual aid, residual plots from a regression of log (discharge) against log (Manning's n) show this time trend as well (Figure 6). The increases through time were evident both at low flows, and moderate flows (> 1.1-year recurrence interval). The increases in flow resistance through time are consistent with either a coarsening of the channel bed or increased development of bed topography, or both.

Figure 6: Residual plots based on regression fit of $\ln(\text{Manning's } n)$ versus $\ln(\text{discharge})$.



Redwood Creek near Blue Lake is the only gauging station with data from the 1950's, before the channel aggraded. For a given discharge, roughness values were higher in the 1950's, and lower following the floods in the early 1970's. By 1997 values of Manning's n have returned to about the 1957-58 levels (Figure 7).

**Manning's n vs. Discharge, by Time Period,
Redwood Creek near Blue Lake**

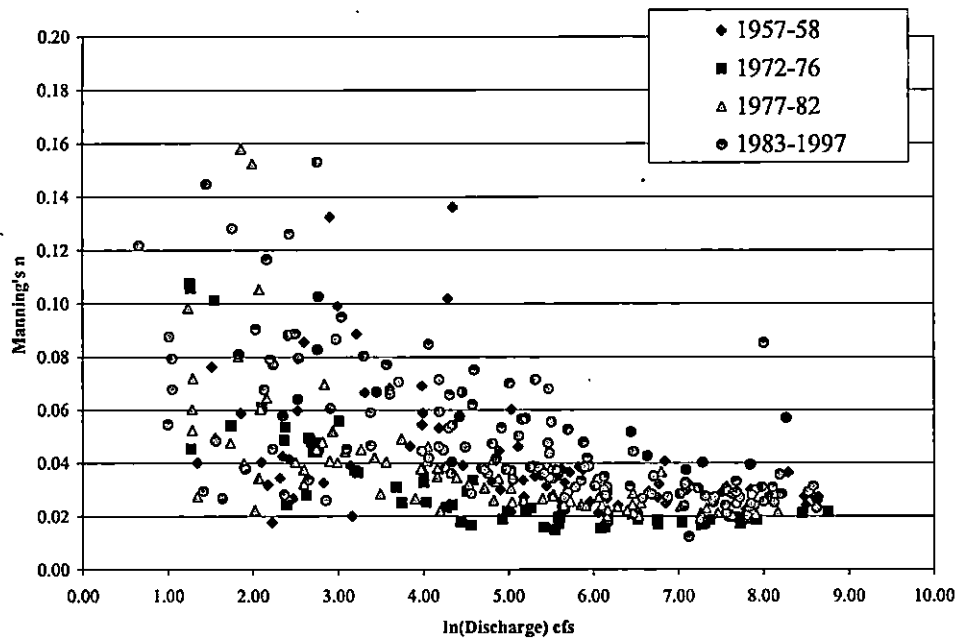


Figure 7: Plots of Manning's n roughness coefficient for different time periods.

Bedload transport rates have also decreased during this period. Figure 8 shows bedload measurements at Redwood Creek near Blue Lake during three periods spanning 25 years, and for any given discharge, bedload transport rates were noticeably higher in the 1970's than they were in the 1990's.

Table 2: Results of multiple regression analysis relating roughness values to discharge and time

Gauging Station	Period of Record	Number of Measurements	Adjusted r ²	p-value for Discharge	p-value for Time
Little Lost Man Creek	1974-1988	133	0.48	0.0001*	0.7024
Redwood Creek at Weir Creek	1977-1982	13	0.72	0.0004*	0.0922*
Redwood Creek at Old S. Park Boundary (1<Q<30 cms)	1975-1981	46	0.76	0.0001*	0.0001*
Redwood Creek at Old S. Park Boundary (Q>30 cms)	1975-1981	24	0.93	0.0001*	0.0295*
Redwood Creek at Panther Creek (Q < 16 cms)	1980-1988	41	0.66	0.0001*	0.0003*
Redwood Creek at Panther Creek (Q > 16 cms)	1980-1988	57	0.62	0.0001*	0.0001*
Redwood Creek near Blue Lake	1972-1997	287	0.72	0.0001*	0.0001*
* Variable is statistically significant at the 90% confidence level or better					

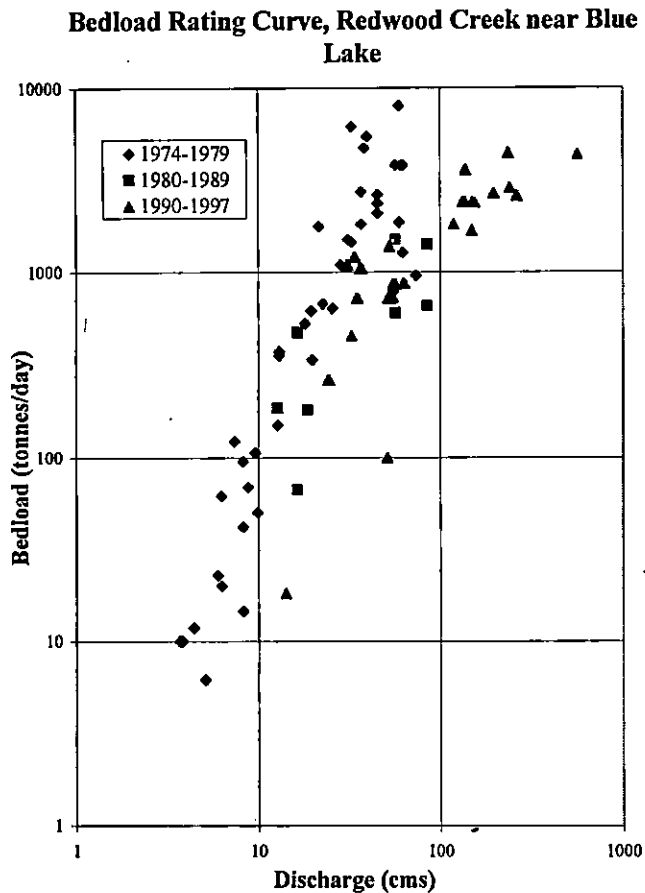


Figure 8: Plot of bedload measurements versus discharge for different time periods.

Effects of Particle Size on Manning's n

To analyze the possible effects of increased particle size on roughness values, size distribution data based on pebble counts at the gauging stations were analyzed. These results show mixed trends (Figure 9). Although pebble counts were centered on a given channel cross section each year, the total area of channel bed area sampled each year varied with different survey crews. This causes a problem in interpreting the results because, for example, a crew may have sampled a fine-grained eddy deposit one year, but not have included it in the sample area another year. Because the pebble counts were not necessarily conducted in a standardized manner, these results should be used cautiously.

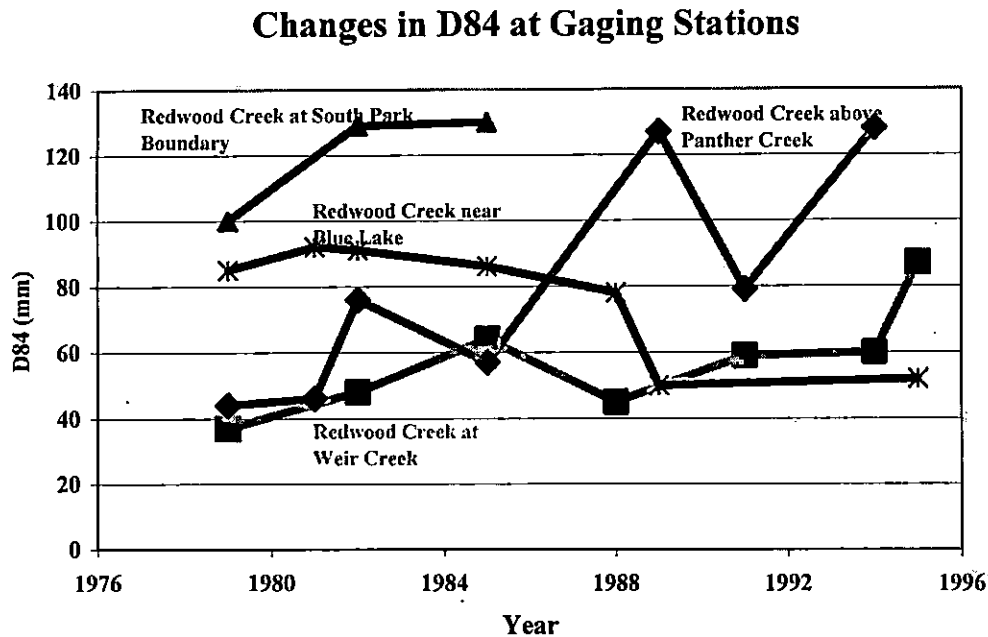


Figure 9: Changes in D₈₄ of bed surface particles at gauging stations, based on Wolman (pebble) counts.

Although the pebble count data have these constraints, some generalizations can be made. Redwood Creek near Blue Lake, which had a significant increase in roughness values through time, actually showed a decrease in surface bed particle size during the same period. Other factors, such as more pronounced bed relief, must be responsible for the increase in flow resistance. At the two other stations exhibiting increased roughness values through time (Redwood Creek above Panther Creek, and Redwood Creek at Weir Creek), the channel bed surface did coarsen during the same period. Skin friction at the gauging stations has the vertical dimension of 30 to 130 mm (range of D₈₄ in the channel bed). In contrast, the vertical dimension of bed topography (the depth of pools and

heights of bar faces) is 1 to 3 m. Because the increase in flow resistance is seen at all stages, not just low flow, it is probably due to the development of bed topography as well as coarsening of the bed. This idea is supported by Prestegard (1983), who showed that bar resistance accounts for 50 to 75% of total resistance in wide, low sinuosity gravel-bed streams.

Effect of Bed Topography on Channel Roughness

In Redwood Creek, the mean residual water depths were very low in 1977, due to the impacts of the 1975 flood. The mean, median, and maximum residual water depths then increased up until 1995, before decreasing, in response to the flood of 1997, to approximately their 1983 levels (Madej, 1999) (Figure 10). The percentage of channel length classified as

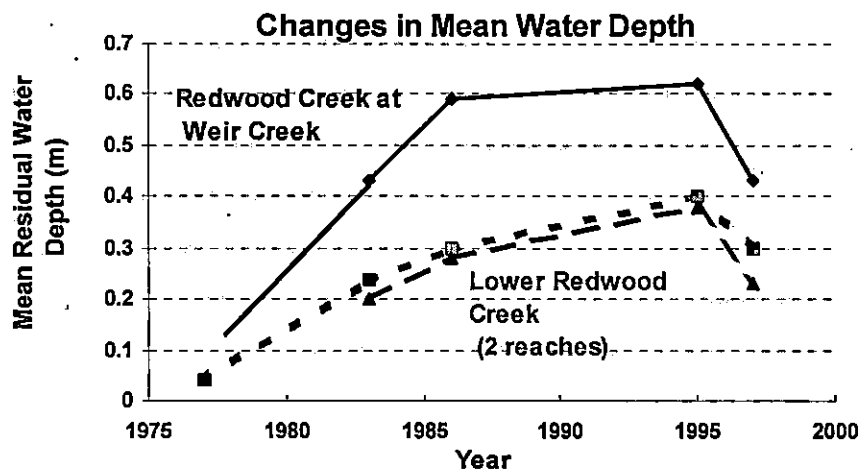


Figure 10: Changes in mean water depth for three reaches of Redwood Creek.

riffle (locations where the residual water depth = 0) in the study reaches varied through time as well (Figure 11). Trends in percentage of channel length in riffle are the inverse of those in residual depths. Hence, the percentage of channel length occupied by riffles decreased in the years following the 1975 flood, rapidly up until the mid-1980s, and then more slowly. The percentage of channel occupied by riffles increased to about mid-1980s levels following the 1997 flood (Madej, 1999).

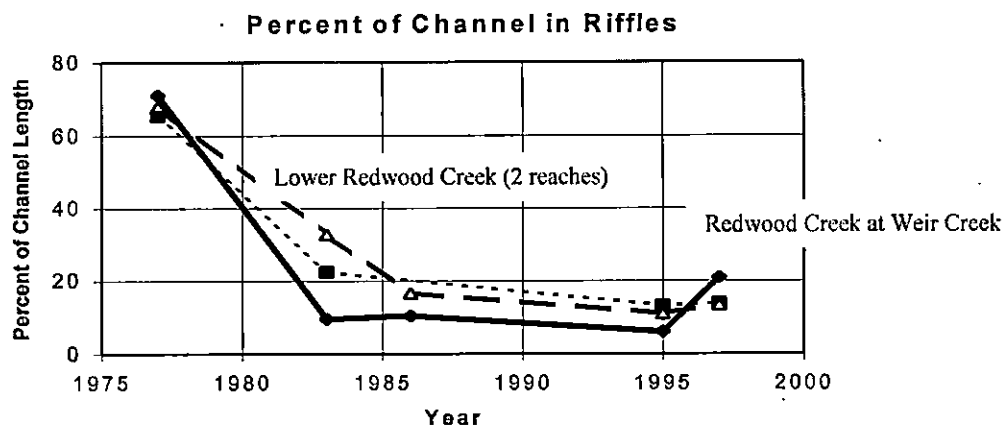


Figure 11: Percentage of channel length classified as riffles for three reaches of Redwood Creek.

The variance of bed elevations was evaluated by using the standard deviation of the population of residual water depths. The underlying assumption is that increased variance in bed elevations reflects increased morphologic diversity in the channel bed. In Redwood Creek, standard deviations increased rapidly for 10 years following the 1975 flood, but between the mid-1980s and 1995 standard deviations increased only slightly (Figure 12). This flattening of the curve may indicate that bed variability was approaching the upper limit of morphological diversity that can develop in this river under the present flow and sediment regimes. Standard deviations decreased in all

reaches after the 1997 flood, although they remained higher than the levels observed in 1977 level (immediately following the larger, 1975 flood).

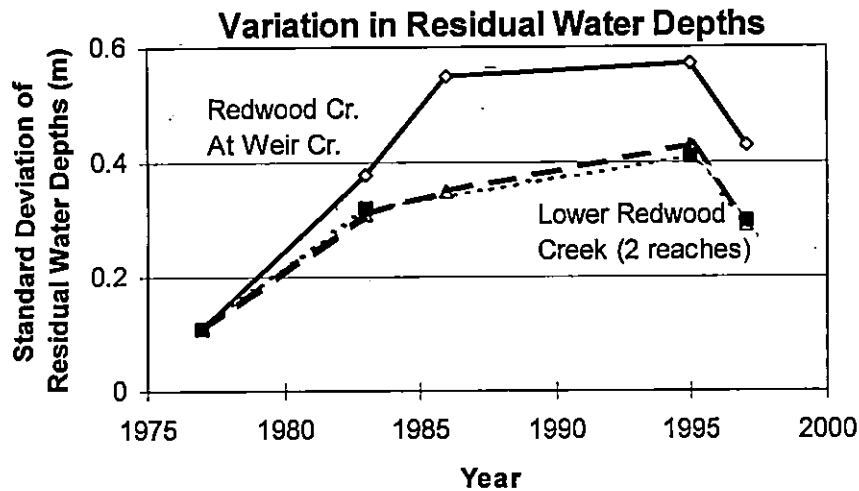


Figure 12: Changes in the standard deviation of residual water depths for three reaches of Redwood Creek.

During the 22 years following a large flood and associated landsliding in 1975, the distributions of residual water depths changed significantly, and the degree of bed heterogeneity was related to the time since disturbance. Mean residual water depth and depth variability increased through time, while the length of channel occupied by riffles decreased. Following a 12-year return period flood in 1997, and its associated sediment inputs, these trends in recovery reversed, and variation in the thalweg profiles decreased.

Summary

Following large sediment inputs from a flood in 1975, the Redwood Creek channel was relatively flat and smooth. Channel roughness increased through time at several gauging stations in Redwood Creek during the same time period as the relief of bed topography was increasing. Bed particle size also increased at some station, but the development of bedforms probably plays an important role in the observed increase in

flow resistance in the channel. The development of bed topography in a gravel bed river contributes to channel roughness and flow resistance, and can influence bed particle mobility. Besides bed topography, other factors, such as in-channel wood, meanders, abrupt changes in channel geometry and hydraulic jumps can theoretically contribute to flow resistance, but field observations show these factors are not important at the gauging stations used in this study. The channels at the gauging stations are highly confined, and have no floodplains; consequently energy loss during overbank flow is not a factor.

At all the gauging stations, channel roughness was high at low flows, and decreased with increasing discharge. However, at several of the gauging stations, this trend reversed at flows was greater than a 1.1 year recurrence interval, and Manning's n increased with increasing discharge. This maybe caused by increased sediment transport, and scour and fill of the channel bed at high flows, leading to more turbulence and bed relief.

There are several geomorphic and biological implications of this study. For example, the development of channel structure and organization influences the roughness of a channel. Increasing bed variation and development of bedforms should lead to higher roughness values due to form drag. Increased development of bedforms and increased variability of bed topography will influence the distribution and magnitude of secondary flows within a channel. An understanding of the spatially varied conditions of the channel bed may further the understanding of non-uniform flow. Increased development of channel structure can decrease the mobility of the channel bed (Church et

al., 1998) and hence influence the sediment transport regime. Channel structure plays an important role in providing aquatic habitat, and the types and scales of roughness elements influence the distribution of microhabitats, benthic invertebrates, and channel complexity. Several aspects of aquatic habitat can be defined by the degree of spatial variation and structure of the channel bed.

The development of channel bed structure and organization through changes in bed topography also affects the hydraulics of a river. Increased bed relief may cause increased flow resistance, turbulence in the flow, and secondary circulation patterns. This study of channel morphologic changes in a gravel-bed river will help future efforts in modeling hydraulics in gravel-bed rivers.

References cited:

- Barnes, H. H. 1967. Roughness characteristics of natural channels. U.S. Geological Survey Water-Supply Paper 1849. 213 p.
- Bathurst, J. C. 1981. Bar resistance of gravel-bed streams - Discussion. American Society of Civil Engineers Journal of the Hydraulics Division. HY10: 107: 1276-1278.
- Bathurst, J. C. 1982. Theoretical aspects of flow resistance. p. 83-108 in Gravel-bed Rivers. R. D. Hey, J. C. Bathurst and C. R. Thorne, eds. John Wiley & Sons. Ltd.
- Bray, D. I. 1982. Flow Resistance in Gravel-Bed Rivers. p. 109-137 in Gravel-bed Rivers. R. D. Hey, J. C. Bathurst and C. R. Thorne, eds. John Wiley & Sons. Ltd.
- Benda, L. and T. Dunne. 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resources Research. 33(12): 2849-2863.

Best, D.W., H.M. Kelsey, D.K. Hagans, and M. Alpert. 1995. Role of fluvial hillslope erosion and road construction in the sediment budget of Garrett Creek, Humboldt County, California. Chapter M in U.S. Geological Survey Professional Paper 1454. Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. K.M. Nolan, H.M. Kelsey, and D.C. Marron, eds.

Church, M., M. A. Hassan, and J. F. Wolcott. 1998. Stabilizing self-organized structures in gravel-bed stream channels: Field and experimental observations. *Water Resources Research* 34(11): 3169-3179.

Helsel, D.R. and R. M. Hirsch. 1997. *Statistical Methods in Water Resources*. Studies in Environmental Science 49. Elsevier. New York. 529 p.

Lisle, T. E. 1987. Using "Residual Depths" to monitor pool depths independently of discharge. USDA Pacific Southwest Forest and Range Experiment Station Research Note PSW-394. 4p.

Madej, M. A. 1995. Changes in Channel-Stored Sediment, Redwood Creek, Northwestern California. Chapter O in U.S. Geological Survey Professional Paper 1454. Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. K.M. Nolan, H.M. Kelsey, and D.C. Marron, eds

Madej, M. A. 1999. Temporal and spatial variability in thalweg profiles of a gravel-bed river. *Earth Surface Processes and Landforms*, 24: 1153-1169.

Madej, M. A. and V. Ozaki. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. *Earth Surface Processes and Landforms* 21: 911-927.

Prestegard, K. L. 1983. Bar resistance in gravel bed streams at bankfull stage. *Water Resources Research* 19(2): 472-476.

Rouse, H. 1965. Critical analysis of open-channel resistance. *J. ASCE Hydraul. Div.* 91:1-25.

Wolman, M. G. 1954. A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union* 35(6): 951-956.