ANALYZING SEDIMENT YIELDS IN THE CONTEXT OF TMDL'S

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Abstract: In 1998, the California Regional Water Quality Control Board established a Water Quality Attainment Strategy for Sediment and Total Maximum Daily Loads (TMDL) for Redwood Creek, California. In the TMDL, a 10-year rolling average of sediment yield of 1900 t of total sediment/mi^2/year (equivalent to about 500 Mg of suspended sediment/km^2/yr) was used as a threshold of concern. We investigate the relevance of this value by analyzing trends in suspended sediment yields at two gaging stations in Redwood Creek, north coastal California. The TMDL reported that at both the upstream and downstream gaging stations, the 10-year rolling average exceeded the threshold between 1973 and 1992, and was below threshold from 1993-1996. A comparison of suspended sediment-discharge rating curves shows a significant shift from higher sediment transport rates in the 1970's (following large storms and extensive landslide activity) to lower rates in the 1980's and 1990's, and even lower rates in the 2000's. In recent years the upstream and downstream gaging stations, monitoring sediment transport from drainage areas of 175 and 725 km^2, respectively, have similar sediment concentrations on a per unit area basis. This lack of a significant shift in sediment transport curves suggests that the trends in the TMDL rolling average are more dependent on flow magnitude rather than being indicative of changes in sediment transport relationships in the basin.

INTRODUCTION

Section 303(d) of the federal Clean Water Act of 1972 requires states to identify waterbodies that do not meet water quality standards and are not supporting their beneficial uses. These waters are placed on the Section 303(d) List of Impaired Waterbodies. This Act gave the State Water Resources Control Board and the US Environmental Protection Agency (EPA) the authority to establish a pollution control plan called a Total Maximum Daily Load (TMDL) for each water body and associated pollutant on the list. The Total Maximum Daily Load (TMDL) process leads to a "pollution budget" designed to restore the health of a polluted body of water. Many rivers and streams in north coastal California are listed as sediment impaired, and within the North Coast Region, sediment TMDLs have been established for 16 rivers (described at http://www.swrcb.ca.gov/rwqcb1). The sediment TMDL's calculate the maximum amount of sediment that a river can receive and still meet water quality standards, and outlines sediment reductions necessary to reach those goals.

The Redwood Creek Sediment TMDL (1998) identified major sediment sources to Redwood Creek as streamside landslides, gully erosion, and cutbank and fillslope failures on unpaved logging roads. Landslides are prominent sources during large floods. For example, Pitlick (1995) reported that 45 percent of the total landslide material delivered to 16 tributaries of

Redwood Creek between about 1936 and 1978 was generated during a 50-year flood that occurred in December, 1964, and another 23 percent was delivered during 25-year floods in the early 1970's. Kelsey et al. (1995) similarly found that the 1964 flood accounted for much of the volume generated by streamside landslides along the mainstem of Redwood Creek, with a secondary peak of landslide activity occurring during the 1972 and 1975 floods. A storm in 1997 (10-year flood) initiated an additional 365 landslides (Redwood National and State Parks unpublished data, Arcata, CA).

Sediment measurements and stream gaging on Redwood Creek did not commence until the early 1970's, so the sediment loads during the 1964 flood are unknown. Based on an analysis of sediment sources, the Redwood Creek TMDL recommends a total allowable sediment load of 665 $Mg/km^2/yr$, which includes both bedload and suspended sediment load. On average, 77% of the total load is transported as suspended sediment, so the TMDL target load is equivalent to about 500 $Mg/km^2/yr$ as suspended load. Now that the Redwood Creek TMDL is in place, it is an opportune time to evaluate sediment loadings measured at gaging stations to determine if and when sediment goals have been reached. This analysis examines changes in trends in the suspended sediment loads by comparing suspended sediment transport curves from the 1970's to the present.

FIELD AREA

Redwood Creek, north coastal California, drains an area of 725 km^2 (Figure 1). For much of its 108-km length, Redwood Creek flows along the trace of the Grogan Fault, which juxtaposes unmetamorphosed or slightly metamorphosed sandstones and siltstones against a quartz-mica schist of the Franciscan assemblage. The basin receives an average of 2,000 mm of precipitation annually, most of which falls between October and March. Total basin relief is 1,615 m; average hillslope gradient is 26 percent.

Aerial photographs taken in 1936 show that most of the basin was covered with old-growth redwood and Douglas-fir forests. Timber harvest began in earnest in the early 1950's, and by 1966, 55 percent of the old growth coniferous forest had been logged (Best, 1995). During this period, extensive landsliding and gully erosion, especially prominent on logging roads, resulted in widespread channel aggradation that affected most of the length of Redwood Creek. Currently 18 percent of the old growth forest remains, almost exclusively within Redwood National and State Parks (RNSP) in the downstream third of the basin. The old-growth redwood groves have been designated as a World Heritage Site and an International Biosphere Reserve, but the alluvial redwood groves have been threatened by sedimentation and bank erosion. In 1978, park lands were expanded in the downstream third of the watershed, timber harvest was terminated in this area, and a large-scale watershed restoration program was initiated. Due to the concern about accelerated erosion and sedimentation, RNSP, in cooperation with the U.S. Geological Survey (USGS), established a stream gaging network within the Redwood Creek basin. Two gaging stations have been operating on Redwood Creek for over three decades. "Redwood Creek near Blue Lake" (USGS Station "O'Kane" #11481500) monitors the upper basin, an area of 175 km^2, and "Redwood Creek at Orick" (USGS Station "Orick" #11482500) is located near the mouth of the river, where the basin is 720 km^2 in size (Figure 1).

Figure 1 Redwood Creek watershed in northern California showing streams and gaging stations.

METHODS

Stream gaging and sediment measurements are conducted by the USGS and RNSP. Between 1970 and 1992 suspended sediment samples were collected daily during high flows from October 1 to April 30, and from 1993 to 2004, sediment was measured intermittently, mostly during high flows. Sediment samples were analyzed in USGS and RNSP laboratories, and concentration results were used to construct suspended sediment concentration–discharge rating curves for the O'Kane and Orick stations. Sediment rating curves express the rates of suspended sediment transport as a function of flow magnitude. Differences in the slopes and intercepts of the rating curves for different time periods and between the two stations were tested using a multiple slopes model of the rating curves.

RESULTS

Floods: Large floods occurred in the Redwood Creek basin in 1861 and 1890, as reported in historical documents. Since the establishment of the Orick gaging station in 1953, annual peak flows in Redwood Creek have been recorded. They are highly variable, ranging from 66 cubic meters per second (cms) in Water Year 2001 to 1429 cms in December, 1964 (Figure 2). (A water year extends from October 1 to September 30). The period from 1953 to 1975 had five large floods, whereas the subsequent two decades were relatively mild in terms of floods. The period of 1996-1999 again had some moderate events, but they were not as high as the earlier period. The largest flow since 1975 was in January, 1997, which had a recurrence interval of 10 years.

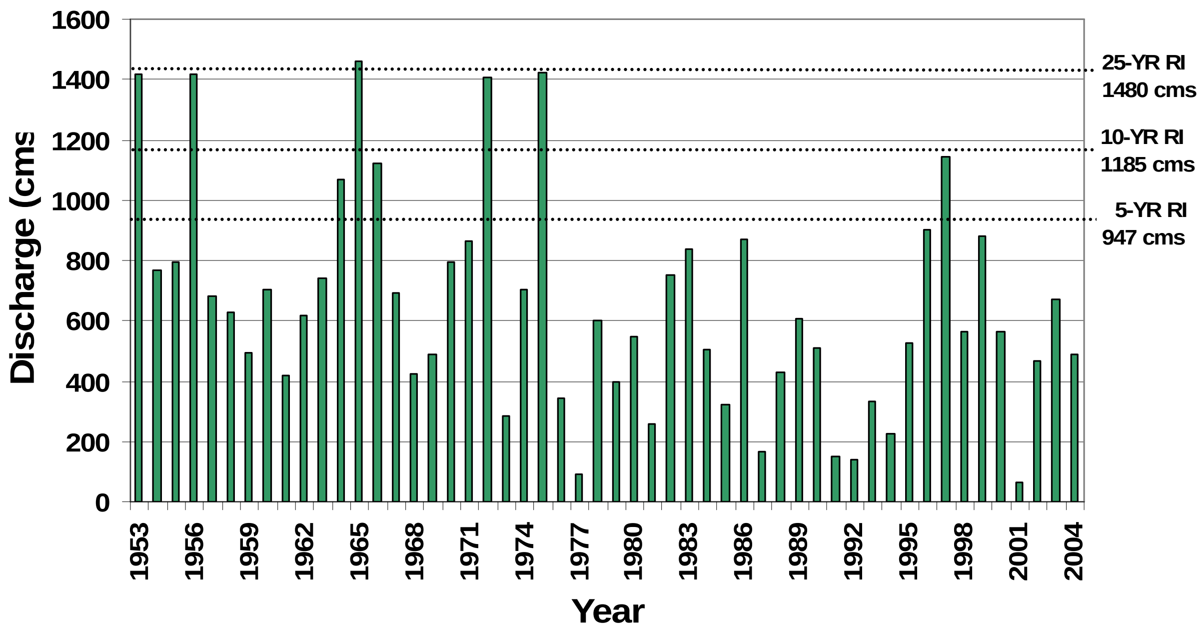

Figure 2 Annual peak flows at Redwood Creek at Orick, California (USGS Station #11482500).

The Redwood Creek TMDL target of 500 Mg/km^2/yr as a 10-year rolling average of suspended load was exceeded for two decades, from 1972 to 1992, then was below threshold until 1996. (Figure 3). It is unclear from the rolling average data, but important to determine, if the occurrences of TMDL target exceedence were a consequence of high flows, new hillslope erosion sources, or re-mobilization of channel-stored sediment. This question is important in terms of management issues in the watershed, such as the magnitude of hillslope destabilization from older and newer timber harvest and the role of watershed erosion prevention activities.

Sediment Transport: To examine trends in sediment transport, we compared suspended sediment rating curves for four periods at the two gaging stations (Figure 4 a and b). A downward shift in the intercept of the regression lines represents a lower sediment concentration for a given discharge, whereas a shift in the slope represents a change in the rate of sediment transport with increasing discharge.

From 1970 to 1975, sediment concentrations were significantly higher than in later years at the Orick and O'Kane gaging stations ($p < 0.001$ and < 0.02 for differences in intercepts, respectively). During this period, even at low flows Redwood Creek was transporting moderate levels of suspended sediment. This may be due to the high sediment supply delivered to the Redwood Creek channel during the large floods of 1972 and 1975. Between the periods of 1977-1995 (when no flows exceeded 850 cms) and 1996-1999, when several moderate flows

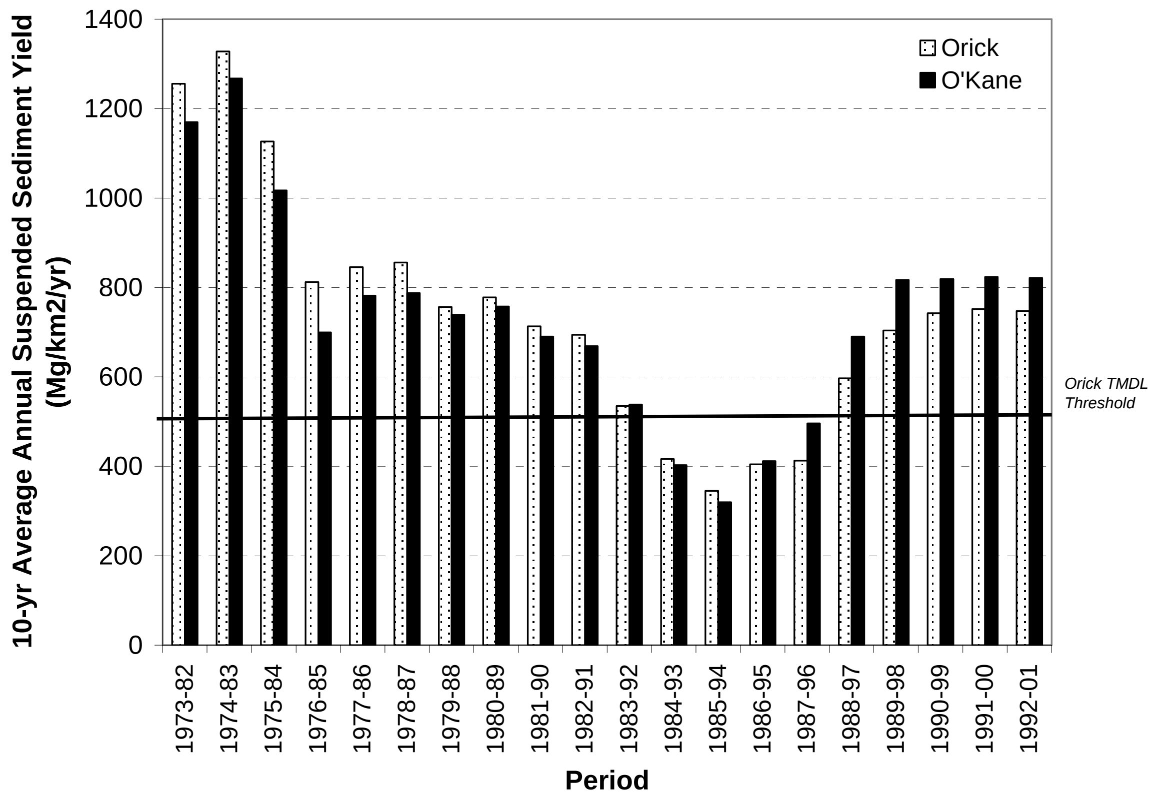

Figure 3 10-year rolling average of suspended sediment yield in Redwood Creek at Orick

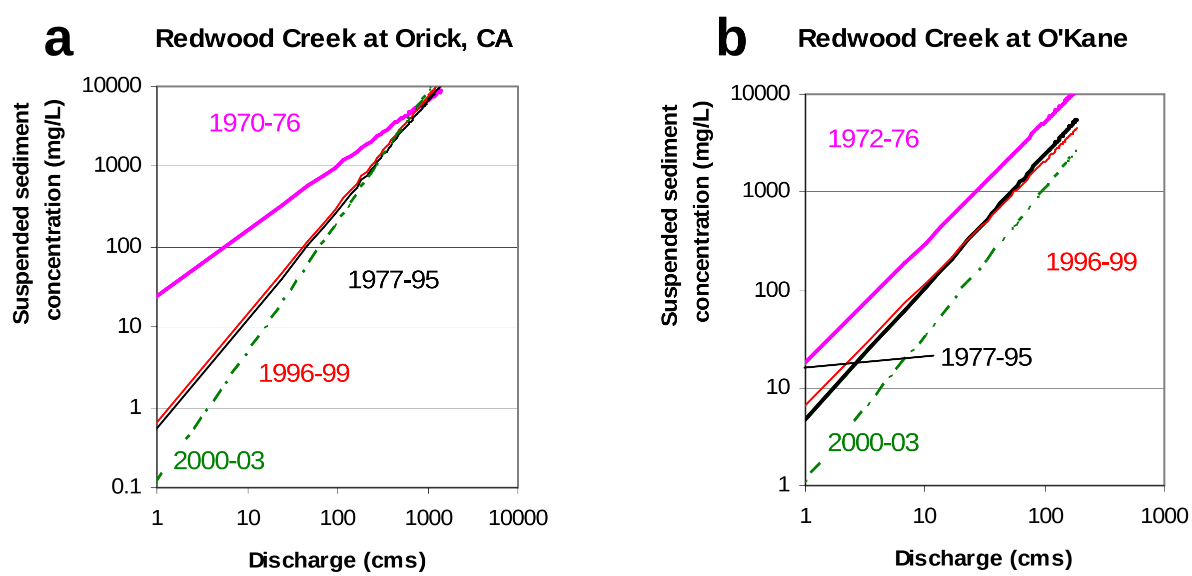

Figure 4 a and b: Suspended sediment rating curves for Redwood Creek near the mouth of the river (a) and at the upstream gaging station (b).

occurred, there were no significant differences in intercepts or slopes (Figure 4). However, in recent years (2000-2003), sediment concentrations for a specific discharge are significantly lower than in the period 1996-1999 for both stations ($p = 0.0161$ and $p < 0.001$ for difference in intercepts for Orick and O'Kane, respectively). At Orick, there were significant differences in slopes between the period 1970-1975 and later periods ($p<0.001$), but differences in slope between other periods were weak ($0.05 < p < 0.10$). At O'Kane, there was a difference in slopes between the periods of 1996-1999 and 2000-2003 ($p = 0.0348$) and a weaker difference between the earliest and latest periods ($p=0.0680$).

The moderately high flows of 1995 to 1999 provided the first 'test' since the flood of 1975 to see if there is a change in the sediment transport characteristics of the upstream basin (the location of active timber harvest and road construction) and the downstream basin (where more of the basin is revegetated and 300 km of abandoned logging roads have been removed through a watershed restoration program). Figure 5 compares the suspended sediment rating curves at the Orick and O'Kane stations. There is no significant difference between the two stations in either slope or intercept ($p> 0.10$ for both).

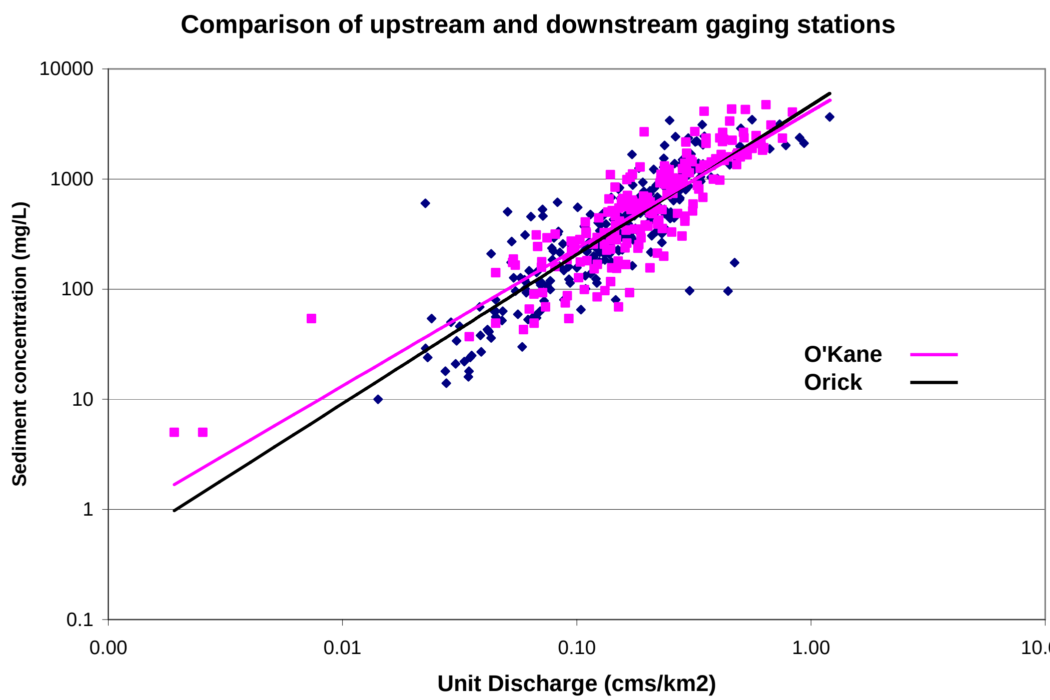

Figure 5 Comparison of upstream (O'Kane) and downstream (Orick) gaging stations for the period 1995-1999.

DISCUSSION AND CONCLUSIONS

We can examine suspended sediment data from two perspectives: changes at a single station through time, and differences between stations. The TMDL considers changes in sediment loads averaged over 10-year periods. Redwood Creek exceeded the threshold of concern in the 1970's, when sediment rating curves showed a significantly higher rate of sediment transport. The TMDL threshold of concern in Redwood Creek was not exceeded in the period of 1984 to 1995. At-a-station analysis shows that during this period there was a downward shift in the sediment rating curves at both the upstream and downstream gaging stations, but it was also a period of low flows (all less than a 5-year recurrence interval). Moderate flows during the 1996-99 period transported more total sediment than the previous decade, but this was not due to an increase in sediment concentrations for a given discharge. Instead, higher precipitation resulted in greater total water discharge and sediment yield. Data from the low flow period of 2000 to 2003 show a significant shift in the sediment rating curves at both stations, meaning that suspended sediment concentrations are now significantly lower than in any of the earlier periods. Whether or not this shift will continue through the next large flood, however, is a major question for land managers, but it must wait until further stream monitoring during high flows.

Between-station analysis shows that during the recent period of moderately high flows, from 1996 to 1999, the upstream and downstream gaging stations displayed similar suspended sediment rating curves on a per unit water discharge basis. The similarity of transport rates at the two stations is somewhat surprising because there was higher landslide sediment delivery to channels in the upper basin area. The Redwood Creek watershed experienced accelerated landsliding during the wet period of 1996-1999, particularly during the January, 1997, storm period. A landslide inventory, based on 1997 air photos and intensive field mapping, documented the location and size of 365 new landslides (unpublished data, RNSP, Arcata, CA). Total landslide mass as well as the portion of the total mass that was delivered to the stream system were determined for the watershed areas above each of the gaging stations. For the area above O'Kane (the upper basin area), landslide mass delivered to channels was about 173,000 Mg, or 990 Mg/km^2, and for the area above Orick (entire watershed), the mass delivered was about 485,000 Mg, or 676 Mg/km^2. The lower basin produced less landslide mass delivered to channels than the upper basin on an area-weighted basis. There are several possible explanations for the discrepancy between sediment transport and landslide activity. The middle portion of the basin, downstream of O'Kane but upstream of Orick, is also undergoing timber harvest, but contemporary erosion sources are unquantified there. In addition, sediment previously stored in the channel bed in the middle and lower basin is being reworked and remobilized (Madej and Ozaki, 2001), contributing to the downstream station's sediment yield. Sediment from landslides in the upper watershed may be stored in the channel.

We expect that as the sediment supply in the lower basin diminishes due to revegetation, road decommissioning, channel bed scour and the cessation of timber harvest, there will be a detectable shift in the sediment transport curve at the downstream, Orick station. No large flows (return period of 25 years or more) have occurred since 1975, however. Continued stream monitoring and field evaluation of hillslope erosion sources, especially during the next large flood, will be used to test this premise further.

The TMDL's use of a rolling average gives a general picture of sediment yields in the watershed, but it does not differentiate between decreases in sediment supply and decreases due to low water yield. Such a differentiation is critical in guiding land management decisions. The use of suspended sediment rating curves strengthens the interpretation of the TMDL threshold by comparing the relationship of sediment concentrations for a given discharge across several time periods. For example, the rolling average showed an increase in sediment yield in the late 1990's following several years of low flow and low sediment yields, but the rating curve analysis demonstrated that the increase was not due to lower sediment concentrations per unit discharge, rather to higher total runoff for the period.

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