Cumulative Losses of Sand to the California Coast by Dam Impoundment

Final Report to the
California Coastal Sediment Management Workgroup
and the
California Department of Boating and Waterways

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December 2006

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ABSTRACT

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California beaches depend on rivers for the majority of their sand supply, but coastal dams, which prevent sand from getting to beaches and nourishing them naturally, have significantly reduced this supply. Cumulative sand impoundment volumes for each littoral cell provide insight into which littoral cells have been impacted by human activities and where there may be a potential need to augment the littoral budget. Suspended sediment rating curves were created for the 21 major coastal streams in the state to estimate present-day sand fluxes based on relationships between suspended load and bedload. We then compared these 'post-dam' sand fluxes to estimated sand fluxes under 'pre-dam' conditions to determine the effects that dams have had on fluvial sand delivery to the coast. The cumulative sand impounded by California's 66 major coastal dams was then calculated on a littoral cell basis.

Under pre-dam conditions, California rivers delivered an average of about 10,000,000 m^3/yr of sand to the coast, but this flux has been reduced by about 2,300,000 m^3/yr due to dams. The reductions vary regionally: in northern California, the pre-dam annual sand flux has been reduced by about 5%, in central California, the pre-dam annual sand flux has been reduced by about 31%, and in southern California, the pre-dam annual sand flux has been reduced by about 50%. Cumulatively, about 152,000,000 m^3 of sand have been trapped by all of California's coastal dams since 1885.

INTRODUCTION

The beaches of California are world-famous and attract large numbers of visitors each year. During the 2003-2004 fiscal year, the 10 most visited State Parks were located in coastal counties, and seven of these parks were State Beaches (California Tourism, 2005). In southern California, Los Angeles County, Orange County, and San Diego County combined to host about 125 million person-trips during the 2003-2004 fiscal year, and the total direct spending affiliated with this travel was about $34 billion (California Tourism, 2005). California's beaches help to bolster the state's economy; however, these valuable resources may become increasingly diminished as sand inputs continue to be reduced due to sand impoundment behind coastal dams.

Funding for this study was provided by the California Resources Agency as part of a Coastal Impact Assistance Program grant for the California Sediment Master Plan. This Plan is being developed by the California Coastal Sediment Management Workgroup (CSMW), a taskforce of federal and state agencies whose mission is to preserve, protect and enhance California's coastal sediment resources. This report was prepared with significant input from CSMW personnel, but does not necessarily represent the official position of member Agencies.

California rivers naturally delivered between 70-85% of the sand to the coastline (BEST and GRIGGS, 1991). This fluvial sand delivery has been greatly reduced by dams, which prevent the sand from getting to the coast and nourishing the beaches naturally. Currently, more than 500 dams control over 42,000 km^2, or 38%, of

California's coastal watershed area (WILLIS and GRIGGS, 2003). Some of these coastal dams are relatively small and control only a few square kilometers of watershed whereas others are very large and control thousands of square kilometers. Approximately 23% of California's beaches are downcoast from river mouths that have had sediment supplies reduced by one-third or more due to dams (WILLIS and GRIGGS, 2003). Furthermore, 70% of these threatened beaches are in southern California, where beach-related tourism dollars are most significant (WILLIS and GRIGGS, 2003). As beaches continue to narrow from the reduced sand supply, California's economy may suffer due to fewer beach visitors and the increased risk to coastal property from direct wave exposure and coastal flooding.

Humans have simultaneously increased fluvial sediment transport through activities such as deforestation and poor agricultural practices and decreased the flux of this sediment to the coasts through dam building (SYVITSKI et al., 2005). Globally, the pre-human flux of sediment has been estimated to be about 14 billion metric tons per year, or 15.5 billion metric tons per year including bedload estimates (SYVITSKI et al., 2005). The global modern sediment flux has been calculated to be about 12.6 billion metric tons per year, so human impacts have led to a 10% reduction in global sediment delivery to the oceans (SYVITSKI et al., 2005). The trends in northern California agree well with this global 10% reduction, but central and southern California have experienced far greater reductions than the global average.

The purpose of this study is to determine the cumulative volumes of sand-sized material (0.063 mm < grain size diameter < 2.0 mm) that are trapped behind the major coastal dams of California. Since dams decrease peak floods, some sand may also accumulate in the river channel downstream. The altered flooding can lead to deposition of deltas where tributaries join the mainstem of the river (KONDOLF, 1997), but the sand volume in these deposits is negligible when compared to the volume of sand trapped behind the dams. More often, the release of sediment-starved water from dams leads to bed incision and bank erosion downstream (KONDOLF, 1997).

The focus of this study is primarily on sand-sized material because it would typically be large enough to remain on beaches. It is important to note that a beach is comprised of numerous physical parts, including the dry backshore above the mean high tide line, the foreshore, which includes the intertidal and swash zone portions of the beach, and the nearshore, which extends seaward into the surf zone (DAVIS JR. and FITZGERALD, 2004). On most California beaches, a smaller range of grain sizes exists defined by a minimum grain size threshold termed the littoral cut-off diameter, or LCD (LIMBER et al., 2005). Sediment larger than 0.063 mm but smaller than the LCD will not remain on the dry beach, but it may remain in the nearshore environment. This finer material does not contribute to the dry sand beach above the mean high tide line, but it is still considered littoral material because it supports the beach profile. Using the silt/sand cut-off of 0.063 mm rather than the LCD, which is typically around 0.125 mm for California beaches, can result in overestimates of the volume of fluvial sand that will actually remain on the dry backshore (LIMBER et al., 2005), but the estimated total littoral material fluxes are probably accurate. The remainder of this work focuses on the dry beach and the volumes of sand that are no longer reaching these areas due to dams.

Twenty-one coastal streams were considered in this study, from the Klamath River in the north to the Tijuana River in the south (Figure 1). The Sacramento River system was excluded because it empties into San Francisco Bay, where most of the sediment is deposited. On these 21 streams, we analyzed the sand reduction effects of 66 dams. Sedimentation behind dams is best characterized by sedimentation surveys; unfortunately, they are few in number in California, expensive to conduct, and very time consuming (SNYDER et al., 2004). Since the scope of this project included 66 major dams throughout the state of California, reservoir sedimentation surveys were not a feasible approach for calculating the sand volumes that have been trapped. Rather, we used a stream-based approach assuming constant sediment yields for individual basins to derive the volumes of sand that the 66 dams have impounded. Silt and clay sedimentation was also calculated because this material influences the reduction of reservoir capacity.

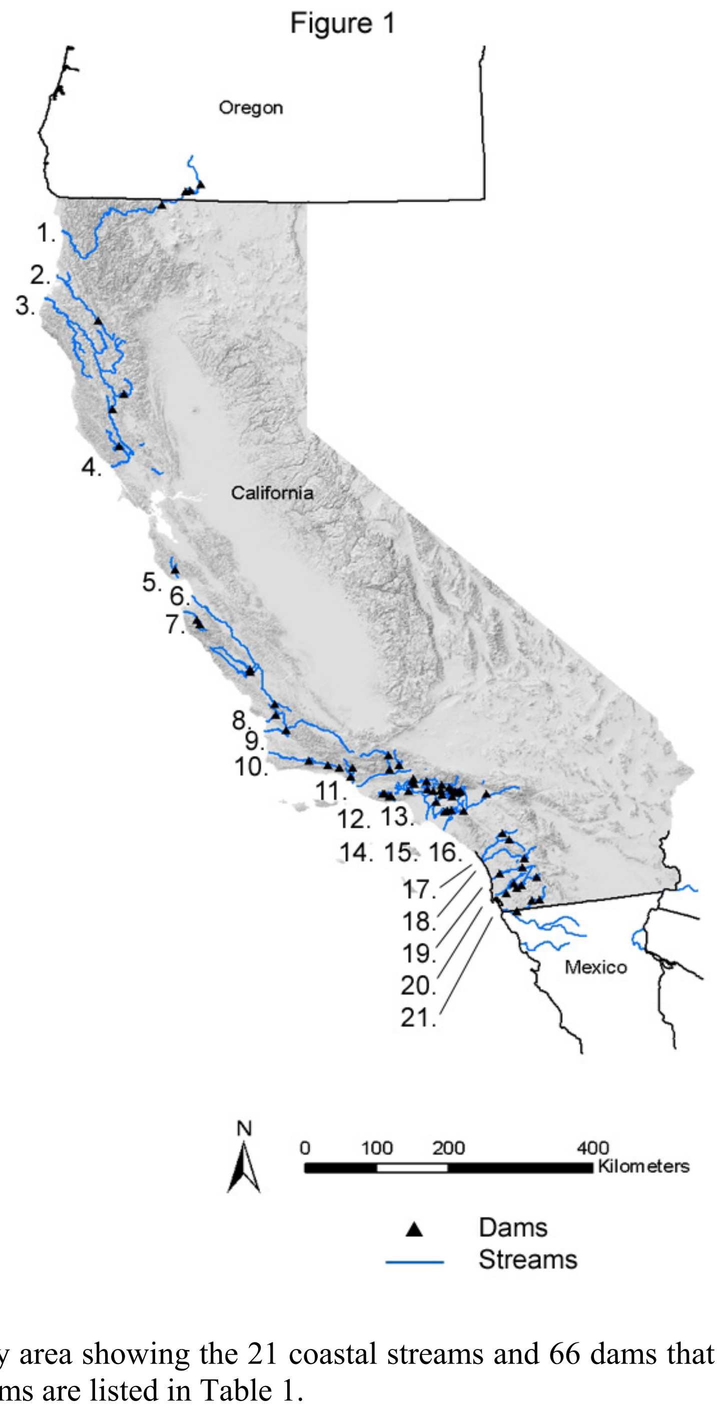

Figure 1. Study area showing the 21 coastal streams and 66 dams that were analyzed. Numbered streams are listed in Table 1.

METHODS

We obtained daily mean suspended sediment flux and daily mean water discharge data for the 21 coastal streams of interest from the United States Geological Survey's Suspended Sediment Database (USGS, 2004). Sediment rating curves were then created for each gauged river from the daily mean suspended sediment flux (English tons/day) and the daily mean water discharge (ft^3/s) data. We used daily values instead of annual or hourly values because only daily mean suspended sediment flux data are available from the USGS. The 21 gages were chosen based primarily on the period of record that they represented. Since these gages had the longest records of suspended sediment data for the streams of interest, representative rating curves could be created. In addition, most of the streams had only one gauging station with suspended sediment data. All of the calculated sediment flux values herein are for these individual 21 stations, and storage and exchange of sediment downstream from the gages may occur, which would influence the volumes of sand actually delivered to the coast. The suspended sediment measurements were correlated with water discharge by a power function of the form $Q_s = a * Q_w^b$ (BROWNLIE and TAYLOR, 1981), where Q_s is the daily mean suspended sediment flux in English tons/day, Q_w is the daily mean water discharge in ft^3/s, and a and b are constants for each river.

We used surrogate stations to create rating curves for rivers that had water discharge data but no suspended sediment flux data, and these surrogates were chosen based on similar basin lithology and proximity to the gages they replaced. The surrogate stations are listed in Table 1 along with the 21 gages used in this analysis.

Table 1. Gage stations and periods of record used in calculating suspended sediment flux for each coastal river.

River	Gage Station	Station Number	Drainage Area Above Gage (km^2)	Period of Record	Surrogate Station Name/Number
1. Klamath and Trinity	Orleans	11523000	21,950	1927-2004	
2. Mad	Arcata	11481000	1,256	1910-1913, 1950-2004	
3. Eel	Scotia	11477000	8,063	1910-1914, 1916-2004	
4. Russian	Guerneville	11467000	3,465	1939-2004	
5. San Lorenzo	Big Trees	11160500	275	1936-2004	
6. Salinas	Spreckels	11152500	10,764	1929-2004	
7. Carmel	Carmel	11143250	637	1962-2004	Lockwood/ 11149700
8. Arroyo Grande	Arroyo Grande	11141500	264	1939-1986	Lopez/ 11141280
9. Santa Maria	Guadalupe	11141000	4,509	1940-1987	
10. Santa Ynez	Lompoc	11133500	2,046	1906-1918, 1925-1960, 1978-1980, 1988-1989, 1992-1998	Casitas Springs/ 11117500
11. Ventura	Ventura	11118500	487	1929-2003	
12. Santa Clara	Montalvo	11114000	4,128	1927-1932, 1949-1993, 1995-2004	
13. Malibu Creek	Crater Camp	11105500	272	1931-1979	Ventura/ 11118500
14. Los Angeles	Long Beach	11103000	2,140	1929-1983, 1988-1992	
15. San Gabriel	Spring Street	11088000	1,610	1936-1979	Long Beach/ 11103000
16. Santa Ana	Santa Ana	11078000	4,403	1923-2004	
17. Santa Margarita	Ysidora	11046000	1,917	1923-1926, 1930-1999, 2001-2004	
18. San Luis Rey	Oceanside	11042000	1,443	1912-1914, 1929-1941, 1946-2001, 2003-2004	
19. San Dieguito	Del Mar	11030500	875	1983-1989	
20. San Diego	Santee	11022500	976	1912-1923, 1925-1982	
21. Tijuana	Nestor	11013500	4,390	1936-1982	

The Los Angeles River, the San Gabriel River, and the Tijuana River did not have enough data points to create representative rating curves, so we obtained post-dam sand fluxes for these rivers from a previous study by WILLIS and GRIGGS (2003).

Figure 2 shows an example of a rating curve from the Ventura River. The best-fit power function line through the data points underestimates the suspended sediment flux at high water discharges, and it is important for the high water discharges to be accurately represented because the vast majority of the suspended sediment is transported during these very high discharge events. Thus, we created stratified rating curves by dividing the data into low, medium, and high flow regimes for each river. We chose the divisions based on the apparent changes in the slope of the rating curves, and the divisions were different for each river because of each river's unique characteristics. Figure 3 is an example of a stratified rating curve from the Ventura River, showing the recalculated power functions for the different flow regimes and the better fit of the power function lines through the high flow discharges.

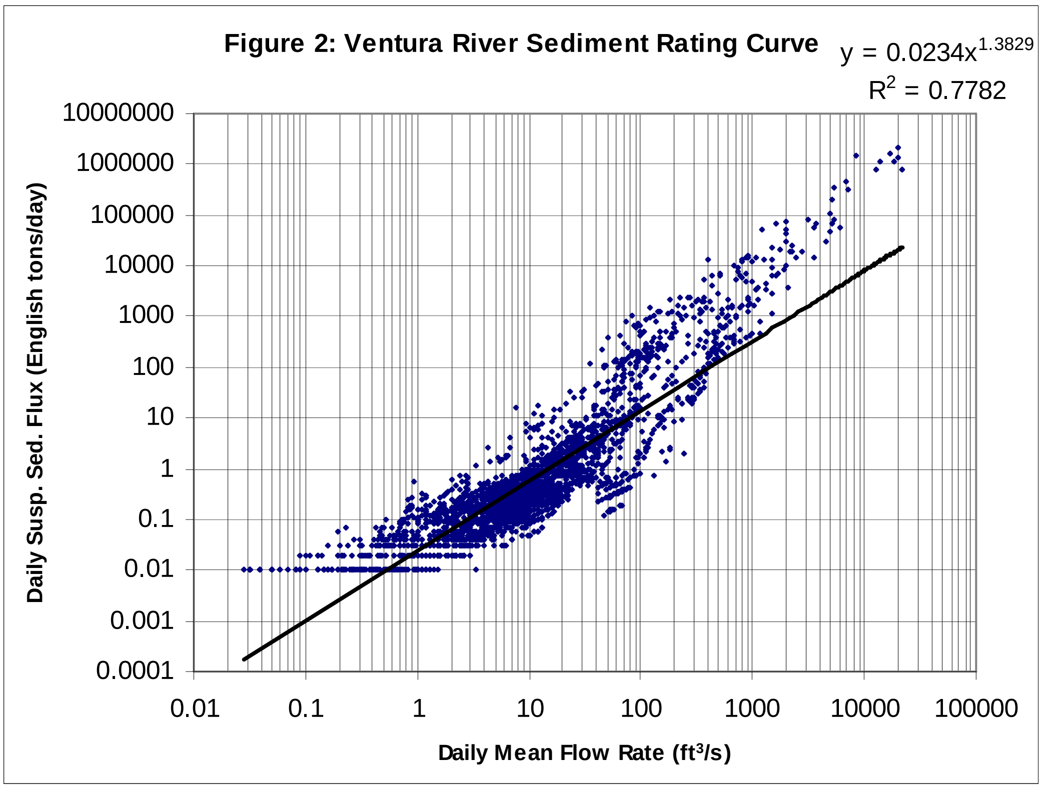

Figure 2. Example of a suspended sediment rating curve for the Ventura River using data from the USGS gauging station # 11118500.

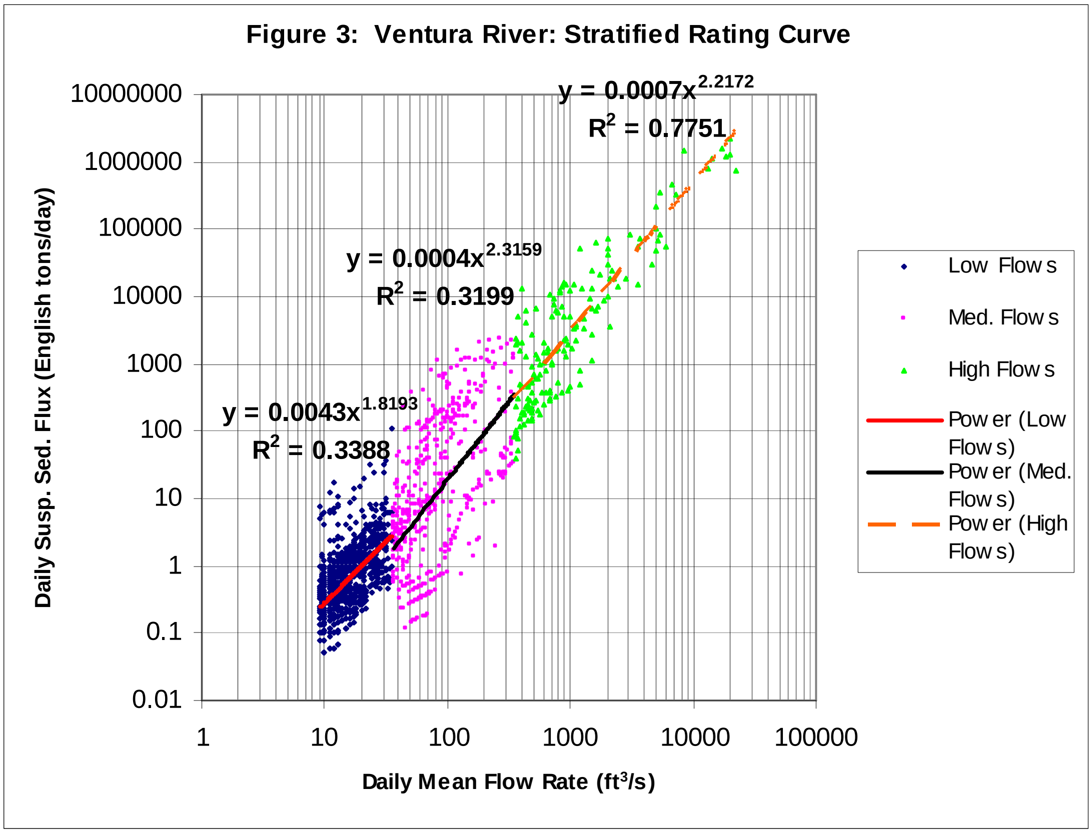

Figure 3. Stratified suspended sediment rating curve for the Ventura River. For this river, the flow regimes were divided as follows: Low ($Q_w \leq 35$ ft^3/s), Medium (35 ft^3/s $< Q_w \leq 350$ ft^3/s), High ($Q_w > 350$ ft^3/s).

After the stratified rating curves were created, we obtained all the available daily water discharge data through the 2004 water year from the USGS NWISWEB online database for California, and we applied the power functions to determine the cumulative volume of suspended sediment that had passed the gauging stations during the entire period of record on each stream (USGS, 2005). We then calculated the annual mean suspended sediment flux for each river by dividing the cumulative volumes by the number of years that each gage had recorded data. From these annual mean *suspended sediment* fluxes, we calculated the annual mean *suspended sand* fluxes by multiplying the annual mean suspended sediment fluxes by the fraction that is sand-sized material. A description of this process and example calculations for the Ventura gauging station (# 11118500) are found below. The USGS reports suspended sediment flux in units of English tons/day, so we converted these values to metric tonnes (t)/day by multiplying by 0.9072. To convert from units of mass (t) to units of volume (m^3), we assumed a dry sand bulk density of 1.61 t/m^3 as done by GRIGGS and HEIN (1980). These sand fluxes are considered 'present-day' because they take into account the effect of dams on the rivers.

Significant uncertainty exists when estimating suspended sediment flux using the rating curve technique described above because both sampling error and statistical error must be considered. The field measurements performed by the USGS typically involve an error of ± 15% (EDWARDS and GLYSSON, 1999). We compared the annual mean suspended sediment fluxes calculated from the stratified sediment rating curves to measured annual mean suspended sediment load data from the USGS National

Suspended Sediment Database (2004). The USGS daily load data were converted to annual data by adding the values and dividing by the period of record, and the units were converted to metric tonnes by multiplying by 0.9072. On average, the difference was ± 25%, so the total error associated with this technique is approximately ± 40%.

Rough estimates of the percent bedload and the percent sand in the suspended load of 15 of the 21 rivers in this study were obtained from a previous study by GRIGGS (1987). Most of the original sediment transport data used by GRIGGS came from USGS annual Water Resources Data reports, stream-specific USGS studies, and BROWNLIE AND TAYLOR (1981). For the six remaining rivers not considered in this earlier study, we employed surrogate data from adjacent rivers with similar basin drainage areas. We calculated the annual total sediment flux for each river according to the equation: 1) $Q_{TOT} = Q_{SuspSed} / \alpha_{SuspLoad}$, where Q_{TOT} is the annual total sediment flux, $Q_{SuspSed}$ is the annual suspended sediment flux, and $\alpha_{SuspLoad}$ is the fraction that is suspended load. Then, we calculated the bedload sand flux according to the equation: 2) $Q_{BED} = Q_{TOT} * \alpha_{BED}$, where Q_{BED} is the bedload sand flux and α_{BED} is the fraction that is bedload. Next, we calculated the suspended sand flux according to the equation: 3) $Q_{SuspSand} = Q_{SuspSed} * \alpha_{SAND}$, where $Q_{SuspSand}$ is the suspended sand flux and α_{SAND} is the fraction of sand in the suspended load. Finally, 4) we determined the total post-dam annual sand flux by adding the bedload sand flux and the suspended sand flux (Table 2). For this analysis, we assumed that bedload is comprised of 100% sand-sized material. The following are example calculations using data from the Ventura gauging station (# 11118500):

1) $Q_{TOT} = Q_{SuspSed} / \alpha_{SuspLoad}$
$Q_{SuspSed} = 283{,}000\ m^3/yr$
$\alpha_{SuspLoad} = 0.87$
$Q_{TOT} = (283{,}000\ m^3/yr) / (0.87) = \sim 325{,}000\ m^3/yr$

2) $Q_{BED} = Q_{TOT} * \alpha_{BED}$
$\alpha_{BED} = 0.13$
$Q_{BED} = (325{,}000\ m^3/yr) * (0.13) = \sim 42{,}000\ m^3/yr$

3) $Q_{SuspSand} = Q_{SuspSed} * \alpha_{SAND}$
$\alpha_{SAND} = 0.18$
$Q_{SuspSand} = (283{,}000\ m^3/yr) * (0.18) = \sim 51{,}000\ m^3/yr$

4) Post-dam annual sand flux $= Q_{BED} + Q_{SuspSand}$
$= 42{,}000\ m^3/yr + 51{,}000\ m^3/yr$
$= 93{,}000\ m^3/yr$

We compared the post-dam annual sand fluxes for each river to the pre-dam annual sand fluxes calculated by WILLIS and GRIGGS (2003) in an effort to describe quantitatively the effects that dams have had on the delivery of sand-sized material to the California coast. For nine rivers, WILLIS and GRIGGS described pre-dam conditions by analyzing reservoir inflow and outflow volumes (2003). In their analysis, dams played a role in reducing stream discharges when the reservoir inflow volumes were greater than the reservoir outflow volumes. For rivers without reservoir inflow and outflow data, they used reservoir sediment accumulation data and sediment yield data from above and below reservoirs to estimate the decreases in fluvial sediment discharge (WILLIS and GRIGGS, 2003). We calculated the reduced annual sand fluxes attributable to dams by subtracting the annual post-dam sand fluxes using the rating curve technique from WILLIS and GRIGGS' annual pre-dam sand fluxes (2003).

Table 2. Calculation of post-dam mean annual sand flux for individual coastal rivers. The mean annual suspended sediment flux values were calculated from stratified rating curves, and the % bedload and % sand in suspended load values were applied to calculate the mean annual total sediment flux, bedload, suspended sand load, and post-dam sand flux values for each river (see text).

River	% Bedload[a]	% Sand in Suspended Load[a]	Suspended Sediment Flux (m^3/yr)	Total Sediment Flux (m^3/yr)	Bedload (m^3/yr)	Suspended Sand Load (m^3/yr)	Post-Dam Sand Flux (m^3/yr)
1. Klamath and Trinity	20	35	3,200,000	4,000,000	800,000	1,120,000	1,920,000
2. Mad	10	27	1,400,000	1,556,000	156,000	378,000	534,000
3. Eel	4	24	10,000,000	10,417,000	417,000	2,400,000	2,817,000
4. Russian	10	10	550,000	611,000	61,000	55,000	116,000
5. San Lorenzo	4	24	240,000	250,000	10,000	58,000	68,000
6. Salinas	20	15	950,000	1,188,000	238,000	143,000	381,000
7. Carmel[b]	4	24	125,000	130,000	5,000	30,000	35,000
8. Arroyo Grande[c]	17	38	30,000	36,000	6,000	11,000	17,000
9. Santa Maria	17	38	366,000	441,000	75,000	139,000	214,000
10. Santa Ynez[d]	13	18	740,000	851,000	111,000	133,000	244,000
11. Ventura	13	18	283,000	325,000	42,000	51,000	93,000
12. Santa Clara	5	25	3,050,000	3,211,000	161,000	763,000	924,000
13. Malibu Creek[d]	13	18	80,000	92,000	12,000	14,000	26,000
14. Los Angeles	10	44	---	---	---	---	59,014[f]
15. San Gabriel	10	44	---	---	---	---	45,297[f]
16. Santa Ana	27	25	167,000	229,000	62,000	42,000	104,000
17. Santa Margarita	8	24	74,000	81,000	7,000	18,000	25,000
18. San Luis Rey	8	24	79,000	86,000	7,000	19,000	26,000
19. San Dieguito	28	25	5,000	7,000	2,000	1,000	3,000
20. San Diego[e]	28	25	9,000	12,000	3,000	2,000	5,000
21. Tijuana[e]	28	25	---	---	---	---	32,188[f]

[a] Values from GRIGGS, 1987.

[b] San Lorenzo's values of % bedload and % sand in suspended load used as surrogate.

[c] Santa Maria's values of % bedload and % sand in suspended load used as surrogate.

[d] Ventura's values of % bedload and % sand in suspended load used as surrogate.

[e] San Dieguito's values of % bedload and % sand in suspended load used as surrogate.

[f] Post-dam sand flux from WILLIS and GRIGGS, 2003 because rating curves did not have sufficient data points.

If multiple dams existed within a single watershed, we proportioned the sediment reduction on each river by the ratio of the area that each dam controls. This technique assumes a constant sediment yield, or erosion rate, throughout the watershed. However, since we are assuming that dams are solely responsible for the reductions in fluvial sediment delivery to the coast, multiple dams in a single watershed have had different sedimentation rates throughout their lifetimes. For example, in the Ventura River basin, Matilija Dam was built in 1949 and Casitas Dam was built in 1959 (Figure 4). For ten years, between 1949 and 1959, Matilija Dam trapped 72,000 m^3 of sand each year, which is the annual fluvial sand reduction we calculated for the Ventura River. After Casitas Dam was built, Matilija was no longer responsible for 100% of the controlled basin. Currently, Matilija controls 142 km^2 and Casitas controls 107 km^2 of the Ventura River basin. Proportioning the annual sand reduction of 72,000 m^3/yr to the area that each dam impounds, Matilija Dam now traps 41,000 m^3 of sand/yr and Casitas Dam traps the remaining 31,000 m^3 of sand/yr.

Table 3 lists the current sand sedimentation rates for each dam in this study, but these rates have changed over time for watersheds with multiple dams that were constructed at different times. Since the sand sedimentation rate behind a dam changes depending on when other dams are built within the watershed, we calculated the cumulative volume of sand behind each dam by multiplying the sand sedimentation rate by the number of years that one set of conditions existed within the watershed. Each time a new dam was built in a watershed and the sediment contributing area changed, we adjusted the sand sedimentation rates to take the new dam into account.

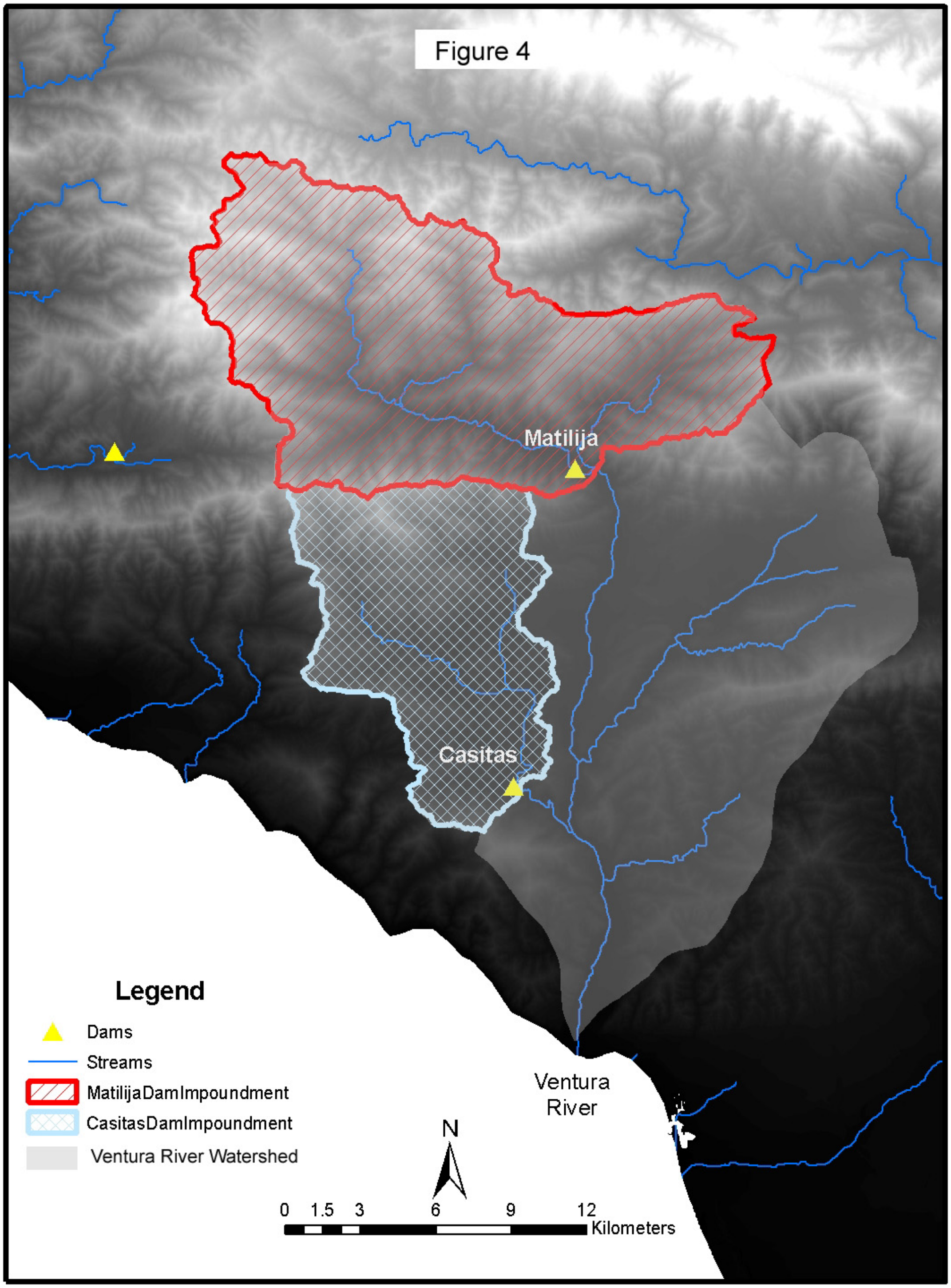

Figure 4. Areas controlled by dams on the Ventura River. Matilija Dam currently controls 142 km^2 (57% of the controlled basin) and Casitas Dam controls 107 km^2 (43% of the controlled basin).

We followed this process for dams that are upstream of each other on the same river and for those that simply exist in the same watershed since our dam filling calculations are based on the sediment contributing area that each dam controls relative to others in a watershed. Continuing with the previous example, Matilija Dam, trapped 72,000 m^3/yr of sand for ten years, or a total of 720,000 m^3 of sand before Casitas Dam was built. For the remaining 46 years of its lifetime, Matilija has trapped about 41,000 m^3/yr of sand (total volume of about 1,900,000 m^3). Over its 56 year lifetime, Matilija has trapped a cumulative volume of about 2,600,000 m^3 of sand.

For management purposes, it is also useful to know the total volume of sediment trapped behind each dam and how this relates to the reservoir capacity. We calculated the volumes of silt and clay trapped behind each dam according to the equations: 5) $V_{TOT} = V_{sand} / \alpha_{s+g}$ and 6) $V_{fines} = V_{TOT} - V_{sand}$, where V_{TOT} is the total sediment volume that has been trapped behind a given dam, V_{sand} is the volume of sand that has been trapped, α_{s+g} is the fraction of sand and gravel of the total sediment load, and V_{fines} is the volume of silt and clay trapped. The following are example calculations for Casitas Dam on the Ventura River:

α_{s+g} = Post-dam sand flux / Total sediment flux (from Table 2)

Post-dam sand flux = 93,000 m^3/yr

Total sediment flux = 325,000 m^3/yr

$\alpha_{s+g} = (93,000\ m^3/yr) / (325,000\ m^3/yr) = 0.29$

5) $V_{TOT} = V_{sand} / \alpha_{s+g}$

$V_{sand} = 1,426,000\ m^3$ (from Table 3)

$V_{TOT} = (1,426,000\ m^3) / (0.29) = \sim 4,900,000\ m^3$

6) $V_{fines} = V_{TOT} - V_{sand}$

$= (4,900,000\ m^3) - (1,400,000\ m^3) = \sim 3,500,000\ m^3$

We determined the extent to which each reservoir's capacity has been reduced based on these estimates of total sediment impoundment (Table 3). For most of the rivers, we obtained dam characteristic data including age, sediment contributing area, and original capacity from the California Department of Water Resources, Division of Safety of Dams (2006). We gathered the characteristic data for some of the dams on the Los Angeles, San Gabriel, and Santa Ana rivers from the U.S. Army Corps of Engineers, Los Angeles District, Reservoir Regulation Section (2006; Table 3).

RESULTS

Post-dam average annual sand fluxes as computed from the rating curve technique for each of the 21 rivers are presented in Table 2 (p.14), and Figure 5 (p.24) graphically depicts the magnitudes of these fluxes along the California coast. With dams, the rivers discharge about 7,700,000 m^3/yr of sand on average. Generally, sand loads decrease from north to south. The Klamath/Trinity and the Eel Rivers dominate the state's sand delivery as they combine to deliver approximately 4,700,000 m^3/yr of sand to the coastline on average. The Salinas River is the major sand contributor in central California, with an average annual sand flux of about 380,000 m^3/yr. In southern California, the Santa Clara River discharges about 920,000 m^3/yr of sand on average. The five greatest discharging rivers (the Klamath/Trinity, the Mad, the Eel, the Salinas, and the Santa Clara) combine to deliver approximately 6,600,000 m^3/yr of sand to California's beaches on average, or 86% of the state's total. In contrast, the other 16 coastal rivers considered in this study only discharge about 1,100,000 m^3/yr of sand on average.

The reduced annual sand fluxes from dams for each of the 21 rivers are shown in Table 3. The cumulative reduced sand flux is about 2,300,000 m^3/yr on average. This suggests that prior to dam construction, the rivers discharged about 10,000,000 m^3/yr of sand on average. Interesting comparisons can be made with the geographic divisions of northern, central, and southern California (Figure 6). For northern California, the Klamath/Trinity, Mad, Eel, and Russian Rivers would deliver about 5,700,000 m^3/yr of sand to the coast on average if there were not dams on these four rivers. Dams have reduced this flux by 5%, or by about 280,000 m^3/yr (Figure 6). Central California includes the San Lorenzo, Salinas, and Carmel Rivers, and prior to dam construction, these three rivers delivered about 700,000 m^3/yr of sand to the coast on average. The six dams on these rivers have reduced this flux by 31%, or by about 215,000 m^3/yr (Figure 6). Southern California contains the rest of the rivers in this study, from Arroyo Grande Creek in the north to the Tijuana River in the south. These 14 rivers naturally delivered about 3,600,000 m^3/yr of sand to the coast on average, but the large number of dams on these rivers has reduced this flux by 50%, or by about 1,800,000 m^3/yr (Figure 6). Therefore, much greater sand reductions to beaches due to dams have occurred in southern California than in northern California. Using the data tabulated in Table 3 for the 66 dams in the study area, we computed the cumulative sand volume that has been trapped by these dams to be 152,000,000 m^3. Southern California is shown to have the greatest total sand impoundment (Figure 7).

Table 3. Annual reduced sand fluxes for each river, individual dam sedimentation, and cumulative losses of sand. The post-dam sand flux values were calculated in Table 2, and the pre-dam sand flux values are from WILLIS and GRIGGS, 2003. Sediment contributing area is the area that each dam currently impounds. The current sand sedimentation rate values were calculated for each dam by proportioning the reduced sand flux on each river to the sediment contributing area. The cumulative sand volumes behind each dam were calculated by proportioning the reduced sand flux for each river to the changing sediment contribution areas through time within the watershed and the age of each dam. The cumulative silt and clay volumes behind each dam were calculated according to relationships between total sediment flux and sand flux (see text). Unless otherwise noted, each dam's age, sediment contributing area, and original capacity were obtained from the California Department of Water Resources, Division of Safety of Dams, 2006.

Streams	Pre-Dam Sand & Gravel Flux[a] (m^3/yr)	Post-Dam Sand & Gravel Flux (m^3/yr)	Reduced Sand & Gravel Flux (m^3/yr)	Dams	Age (yrs)	Current Sediment Contributing Area (km^2)	Current % of Controlled Basin	Estimated Current Sand Sed. Rate (m^3/yr)	Estimated Cumulative Sand Behind Dam (m^3)	Estimated Cumulative Silt and Clay Behind Dam (m^3)	Estimated Total Sediment Behind Dam (m^3)	Original Capacity (m^3)	Estimated % Full
1. Klamath	2,025,000[b]	1,920,000	105,000	Up. Klamath Lk. (OR)[c]	84	9,842	83	87,000	7,600,000	8,200,000	15,800,000	1,077,000,000	1
				Copco #1	83	570	5	5,000	430,000	470,000	900,000	95,000,000	1
				J.C. Boyle (OR)[c]	47	414	3	4,000	170,000	190,000	360,000	4,000,000	9
				Iron Gate	43	707	6	6,000	270,000	290,000	560,000	72,000,000	1
				Keno (OR)[c]	39	311	3	3,000	110,000	120,000	230,000	23,000,000	1
								TOTAL:	8,580,000	9,270,000	17,850,000		
2. Mad	575,000	534,000	41,000	Robert W. Matthews	43	311	100	41,000	1,800,000	3,400,000	5,200,000	64,000,000	8
3. Eel	2,900,000	2,817,000	83,000	Scott	84	746	100	83,000	7,000,000	19,000,000	26,000,000	90,000,000	29
4. Russian	169,000	116,000	53,000	Coyote Valley	46	272	45	24,000	1,800,000	7,500,000	9,300,000	151,000,000	6
				Warm Springs	23	337	55	29,000	670,000	2,900,000	3,570,000	470,000,000	1
								TOTAL:	2,470,000	10,400,000	12,870,000		
5. San Lorenzo	81,000	68,000	13,000	Newell	45	21	100	13,000	590,000	1,600,000	2,190,000	11,000,000	20
6. Salinas	555,000	381,000	174,000	Salinas	63	290	14	25,000	4,000,000	8,400,000	12,400,000	29,000,000	43
				Nacimiento	48	834	41	71,000	3,900,000	8,200,000	12,100,000	432,000,000	3
				San Antonio	40	914	45	78,000	3,100,000	6,600,000	9,700,000	432,000,000	2
								TOTAL:	11,000,000	23,200,000	34,200,000		
7. Carmel	60,000	35,000	25,000	San Clemente	84	207	64	16,000	1,600,000	4,300,000	5,900,000	1,800,000	100
				Los Padres	56	117	36	9,000	500,000	1,400,000	1,900,000	3,900,000	49
								TOTAL:	2,100,000	5,700,000	7,800,000		
8. Arroyo Grande	86,000	17,000	69,000	Lopez	36	181	100	69,000	2,500,000	2,800,000	5,300,000	65,000,000	8
9. Santa Maria	620,000	214,000	406,000	Twitchell	47	2,940	100	406,000	19,000,000	20,000,000	39,000,000	296,000,000	13

Table 3 continued.

Streams	Pre-Dam Sand & Gravel Flux[a] (m^3/yr)	Post-Dam Sand & Gravel Flux (m^3/yr)	Reduced Sand & Gravel Flux (m^3/yr)	Dams	Age (yrs)	Current Sediment Contributing Area (km^2)	Current % of Controlled Basin	Estimated Current Sand Sed. Rate (m^3/yr)	Estimated Cumulative Sand Behind Dam (m^3)	Estimated Cumulative Silt and Clay Behind Dam (m^3)	Estimated Total Sediment Behind Dam (m^3)	Original Capacity (m^3)	Estimated % Full
10. Santa Ynez	545,000	244,000	301,000	Gibraltar	85	518	48	144,000	17,000,000	42,000,000	59,000,000	28,000,000	100
				Juncal	75	36	3	10,000	970,000	2,400,000	3,370,000	7,600,000	44
				Bradbury	52	526	49	147,000	7,600,000	19,000,000	26,600,000	253,000,000	11
								TOTAL:	25,570,000	63,400,000	88,970,000		
11. Ventura	165,000	93,000	72,000	Matilija	56	142	57	41,000	2,600,000	6,500,000	9,100,000	4,685,400[d]	100
				Casitas	46	106	43	31,000	1,400,000	3,500,000	4,900,000	314,000,000	2
								TOTAL:	4,000,000	10,000,000	14,000,000		
12. Santa Clara	1,249,000	924,000	325,000	Santa Felicia	50	334	22	73,000	8,200,000	20,000,000	28,200,000	124,000,000	23
				Pyramid	32	759	51	165,000	5,300,000	13,000,000	18,300,000	222,000,000	8
				Castaic	32	399	27	87,000	2,800,000	6,900,000	9,700,000	400,000,000	2
								TOTAL:	16,300,000	39,900,000	56,200,000		
13. Malibu	41,000	26,000	15,000	Lake Sherwood	101	41	10	1,500	310,000	780,000	1,090,000	3,320,000	33
				Century	92	10	2	500	160,000	400,000	560,000	650,000	86
				Malibu Lake	82	166	42	6,000	590,000	1,500,000	2,090,000	933,000	100
				Rindge[e]	79	106	27	4,000	350,000	900,000	1,250,000	708,019	100
				Potrero	38	75	19	3,000	110,000	270,000	380,000	976,000	39
								TOTAL:	1,520,000	3,850,000	5,370,000		
14. Los Angeles	178,000	59,014[f]	119,000	Devil's Gate	85	78	3	3,500	1,600,000	1,600,000	3,200,000	3,200,000	100
				Sawpit	78	8	0.5	500	78,000	78,000	156,000	501,000	31
				Pacoima	76	73	3	3,000	520,000	520,000	1,040,000	4,700,000	22
				Big Tujunga	74	212	8	9,500	1,200,000	1,200,000	2,400,000	7,100,000	34
				Eaton Wash	69	26	1	1,000	110,000	110,000	220,000	890,000	25
				Hansen[g]	65	1,808	67	80,000	5,300,000	5,300,000	10,600,000	33,000,000	32
				Sepulveda[g]	64	394	14.5	17,500	1,100,000	1,100,000	2,200,000	22,000,000	10
				Lopez[g]	51	88	3	4,000	200,000	200,000	400,000	550,000	73
								TOTAL:	10,108,000	10,108,000	20,216,000		

Table 3 continued.

Streams	Pre-Dam Sand & Gravel Flux[a] (m^3/yr)	Post-Dam Sand & Gravel Flux (m^3/yr)	Reduced Sand & Gravel Flux (m^3/yr)	Dams	Age (yrs)	Current Sediment Contributing Area (km^2)	Current % of Controlled Basin	Estimated Current Sand Sed. Rate (m^3/yr)	Estimated Cumulative Sand Behind Dam (m^3)	Estimated Cumulative Silt and Clay Behind Dam (m^3)	Estimated Total Sediment Behind Dam (m^3)	Original Capacity (m^3)	Estimated % Full
15. San Gabriel	139,000	45,297[f]	94,000	Live Oak	83	5	0.5	500	110,000	110,000	220,000	295,000	75
				San Dimas	83	41	2	2,000	920,000	920,000	1,840,000	1,900,000	97
				Puddingstone	77	85	5	4,500	860,000	860,000	1,720,000	20,000,000	9
				Thompson Creek	77	10	0.5	500	100,000	100,000	200,000	670,000	30
				Big Dalton	76	10	0.5	500	98,000	98,000	196,000	1,600,000	12
				Cogswell	70	98	6	5,000	570,000	570,000	1,140,000	11,000,000	10
				San Gabriel	67	531	30	28,500	2,500,000	2,500,000	5,000,000	55,000,000	9
				Fullerton[g]	64	13	1	1,000	55,000	55,000	110,000	900,000	12
				Brea[g]	63	57	3	3,000	240,000	240,000	480,000	5,000,000	10
				Santa Fe[g]	56	80	4.5	4,500	270,000	270,000	540,000	38,000,000	1
				Whittier Narrows[g]	48	824	47	44,000	2,100,000	2,100,000	4,200,000	43,000,000	10
								TOTAL:	7,823,000	7,823,000	15,646,000		
16. Santa Ana	290,000	104,000	186,000	Prado[g]	64	3,756	61	114,000	11,000,000	13,000,000	24,000,000	473,000,000	5
				San Antonio[g]	49	287	5	9,000	430,000	510,000	940,000	12,000,000	8
				Carbon Canyon[g]	44	49	1	2,000	66,000	79,000	145,000	9,000,000	2
				Seven Oaks[g]	6	2,020	33	61,000	370,000	440,000	810,000	180,000,000	1
								TOTAL:	11,866,000	14,029,000	25,895,000		
17. Santa Margarita	45,000	25,000	20,000	Vail	56	793	85	17,000	1,000,000	2,300,000	3,300,000	63,000,000	5
				Robert A. Skinner	32	135	15	3,000	93,000	210,000	303,000	54,000,000	1
								TOTAL:	1,093,000	2,510,000	3,603,000		
18. San Luis Rey	100,000	26,000	74,000	Henshaw	82	536	100	74,000	6,100,000	14,000,000	20,100,000	62,000,000	32
19. San Dieguito	45,000	3,000	42,000	Lake Hodges	87	785	85	36,000	3,300,000	4,400,000	7,700,000	47,000,000	16
				Sutherland	51	140	15	6,000	320,000	430,000	750,000	37,000,000	2
								TOTAL:	3,620,000	4,830,000	8,450,000		

Table 3 continued.

Streams	Pre-Dam Sand & Gravel Flux[a] (m^3/yr)	Post-Dam Sand & Gravel Flux (m^3/yr)	Reduced Sand & Gravel Flux (m^3/yr)	Dams	Age (yrs)	Current Sediment Contributing Area (km^2)	Current % of Controlled Basin	Estimated Current Sand Sed. Rate (m^3/yr)	Estimated Cumulative Sand Behind Dam (m^3)	Estimated Cumulative Silt and Clay Behind Dam (m^3)	Estimated Total Sediment Behind Dam (m^3)	Original Capacity (m^3)	Estimated % Full
20. San Diego	55,000	5,000	50,000	Cuyamaca	118	31	4	2,000	2,300,000	3,200,000	5,500,000	15,000,000	37
				Murray	87	10	1.5	500	250,000	340,000	590,000	8,000,000	7
				El Capitan	71	492	67.5	34,000	2,500,000	3,500,000	6,000,000	140,000,000	4
				San Vicente	62	192	26	13,000	820,000	1,100,000	1,920,000	112,000,000	2
				Chet Harrit	43	5	1	500	14,000	19,000	33,000	12,000,000	1
								TOTAL:	5,884,000	8,159,000	14,043,000		
21. Tijuana	64,000	32,188[f]	32,000	Morena	93	295	9.25	3,000	730,000	770,000	1,500,000	62,000,000	2
				Barrett	83	358	11.25	4,000	490,000	530,000	1,020,000	56,000,000	2
				Rodriguez (Mexico)[h]	69	2,530	79.5	25,000	1,800,000	1,900,000	3,700,000	134,000,000	3
								TOTAL:	3,020,000	3,200,000	6,220,000		
							TOTALS:	**2,299,000**	**151,944,000**	**277,179,000**	**429,123,000**		

[a] Pre-dam sand & gravel flux values from WILLIS and GRIGGS, 2003

[b] Value from GRIGGS and HEIN, 1980 to account for Trinity River discharge.

[c] Dam characteristics from the Oregon Water Resources Department, Dam Safety Program, 2006.

[d] Matilija Dam was notched in 1965 and 1978 to reduce the original capacity from 9,000,000 m^3 to 4,685,400 m^3.

[e] Rindge Dam filled with sediment after only 34 years.

[f] Post-dam sand flux from WILLIS and GRIGGS, 2003 because rating curves did not have sufficient data points.

[g] Dam characteristics from the U.S. Army Corps of Engineers, Los Angeles District, Reservoir Regulation Section, 2006.

[h] Dam characteristics from MALINOWSKI, 2004.

Figure 5

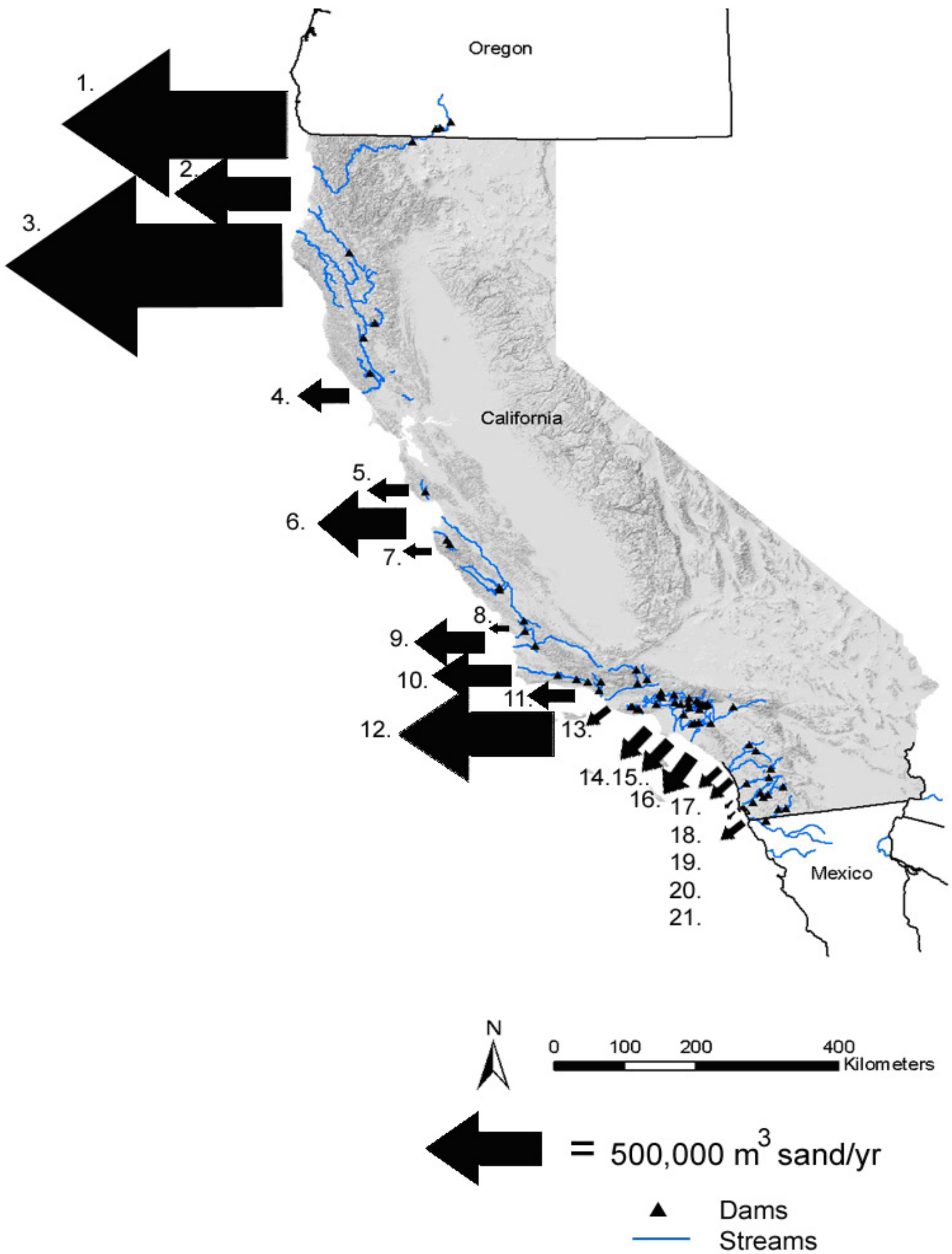

Figure 5. Present-day post-dam annual sand delivery by California's 21 major coastal streams. Numbered streams are listed in Table 2. The arrows are scaled in size to accurately depict the relative magnitudes of sand delivery to the coast.

Figure 6

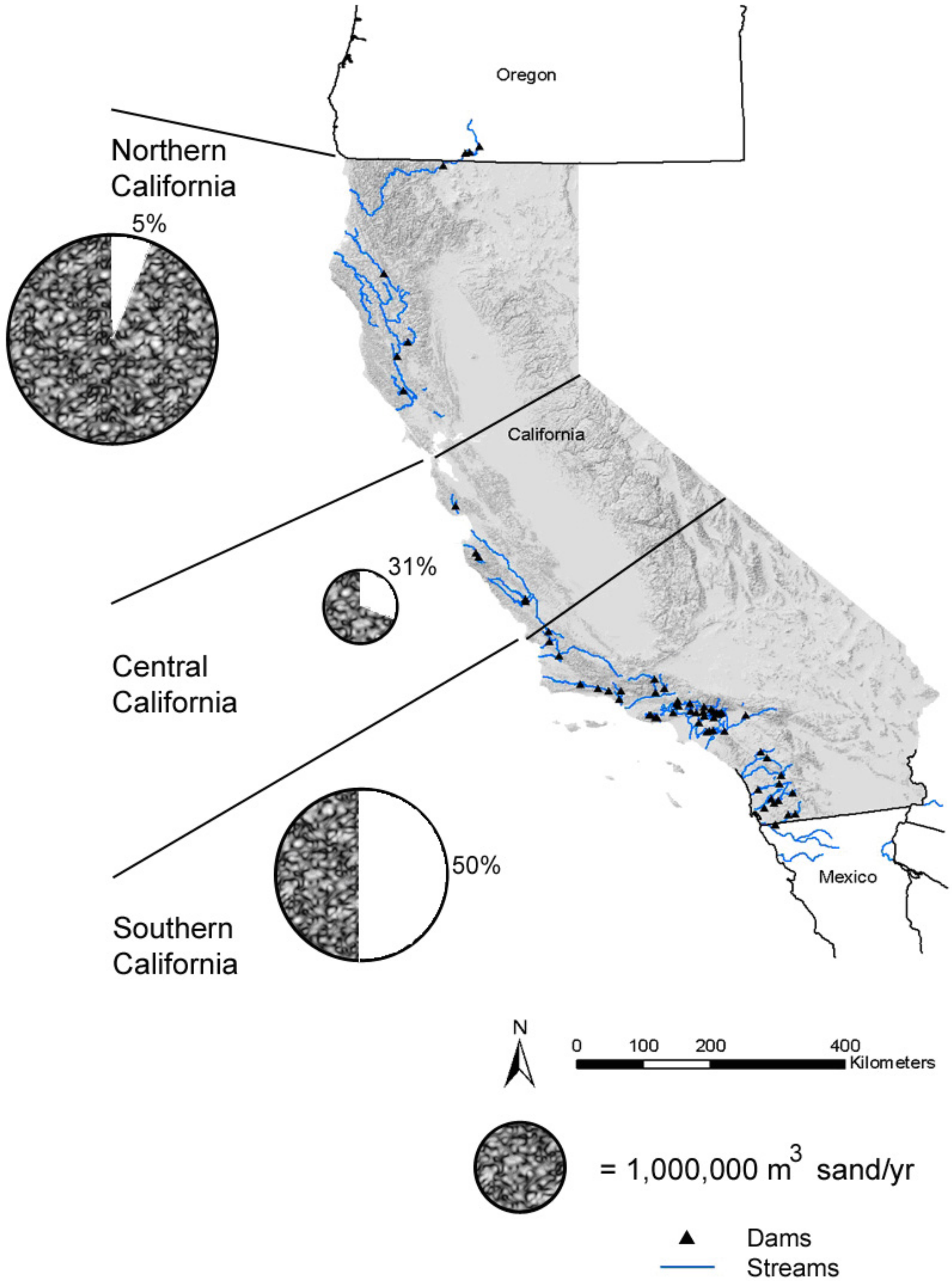

Figure 6. Pre-dam annual sand flux and the percent that has been reduced by dams for the rivers in northern, central, and southern California. The sizes of the whole pies are 1) scaled relative to each other and 2) represent the pre-dam annual sand flux for each region. The pieces of the pies that are missing represent the percent reduction in annual sand flux attributable to dams.

Figure 7

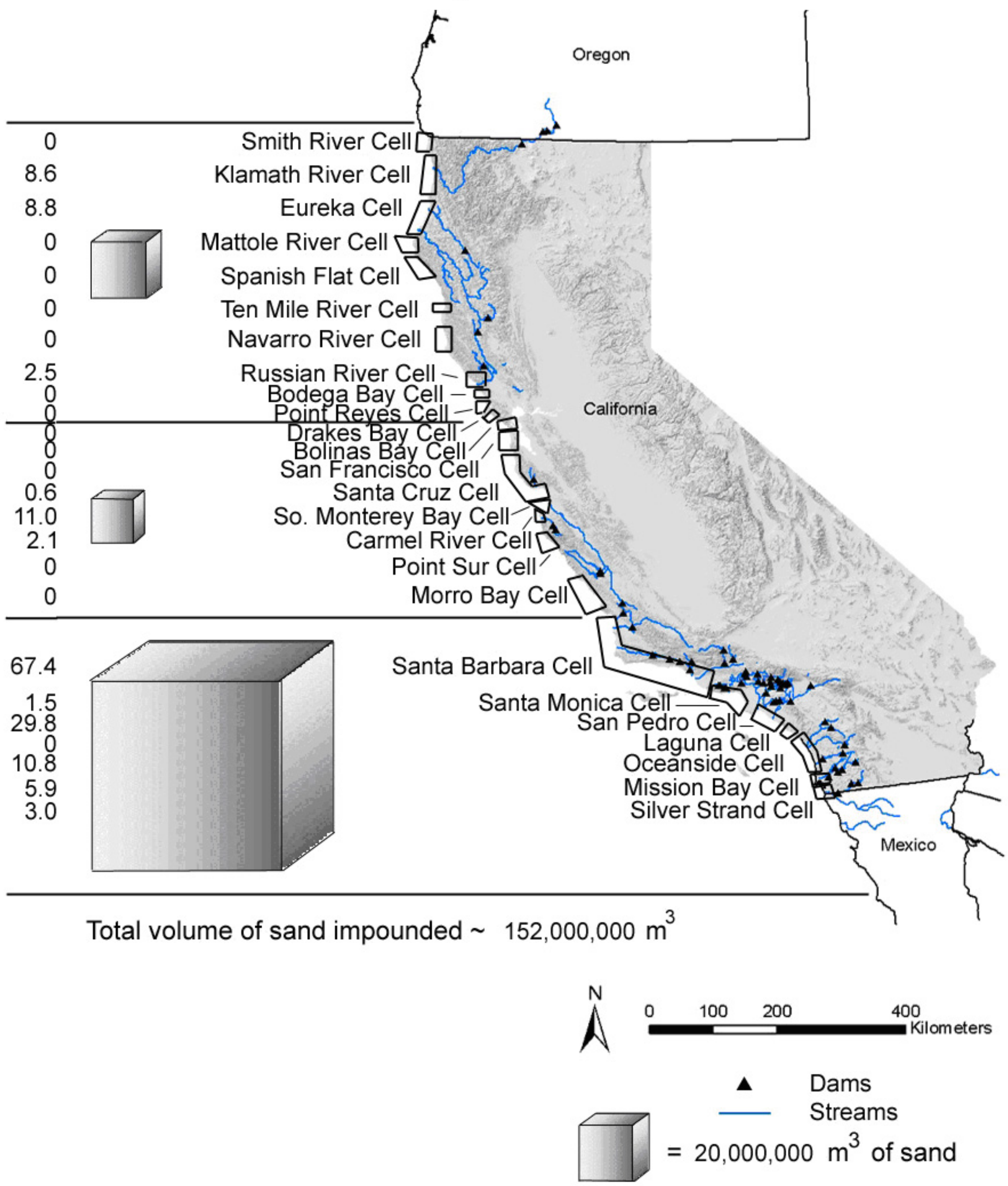

Figure 7. Cumulative sand impounded by dams in each of California's 25 major littoral cells. The numbers are millions of cubic meters of sand that have been trapped by dams in the watersheds draining into each littoral cell. The cubes are scaled in size relative to each other to depict impoundment in northern, central, and southern California. Littoral cell names and divisions are from PATSCH and GRIGGS, 2005.

The San Pedro littoral cell, which includes the Los Angeles, San Gabriel, and Santa Ana Rivers, has experienced about 30,000,000 m^3 of sand impoundment since 1920 when Devil's Gate Dam, the first dam on the Los Angeles River, was built.

These results reveal good correlation with reservoir sedimentation surveys. The California Beach Restoration Study lists the original reservoir capacity, year of last survey, % capacity remaining, and sedimentation rate values for 16 dams in central and southern California (2002; Table 4). The original source data used to calculate sedimentation rates came from water district reports, where the method of calculation was not specified. We corrected the remaining capacity values to the year 2005 so that they could be compared to the values derived in our study. The following discussion explains how we did this for Bradbury Dam on the Santa Ynez River. According to the California Beach Restoration Study, the original capacity behind Bradbury Dam was approximately 253,000,000 m^3, but after the last survey in 2000, 92% (or 232,760,000 m^3) of this original capacity remained (2002). The sedimentation rate behind this dam is approximately 446,000 m^3/yr, so multiplying by five years, the 2005 corrected remaining capacity is 230,530,000 m^3 (91% of the original capacity). This value was calculated as follows: 232,760,000 m^3 - (446,000 m^3/yr * 5 yrs) = 230,530,000 m^3. We plotted this remaining capacity value of 91% against the remaining capacity value calculated in this study of 89% based on the use of rating curves. We followed this procedure for the 16 dams in the California Beach Restoration Study.

Table 4. Comparison of rating curve dam filling results from this study with results of sedimentation surveys for 16 dams in California. Unless otherwise noted, reservoir capacity, year of last survey, % capacity remaining, and sedimentation rate values from California Beach Restoration Study, 2002. Values from the Study in cubic yards were converted to cubic meters by dividing by 1.3. The capacity remaining values were corrected to current (2005) values by subtracting the product of the years since the last survey and the sedimentation rate for each dam.

Dam	Basin	Reservoir Capacity (m^3)	Year of Last Survey	% Capacity Remaining	Capacity Remaining after Last Survey (m^3)	Years since Last Survey	Sedimentation Rate (m^3/yr)[a]	Capacity Remaining (m^3) (corrected to 2005)	% Capacity Remaining (corrected to 2005)	**% Capacity Remaining from This Study**
Bradbury	Santa Ynez	253,000,000	2000	92%	232,760,000	5	446,000	230,530,000	91%	**89%**
El Capitan	San Diego	140,000,000	1998	96%	134,400,000	7	123,000	133,539,000	95%	**96%**
Hansen	Los Angeles	33,000,000[b]	1983	71%	23,430,000	22	323,000	16,324,000	50%	**68%**
Hodges	San Dieguito	47,000,000	1994	91%	42,770,000	11	100,000	41,670,000	89%	**84%**
Los Padres	Carmel	3,900,000	2000	67%	2,613,000	5	23,000	2,498,000	64%	**51%**
Matilija	Ventura	9,000,000	1999	7%	630,000	6	154,000	0	0%	**0%**
Prado	Santa Ana	473,000,000[b]	1996	86%	406,780,000	9	869,000	398,959,000	84%	**95%**
Robert A. Skinner	Santa Margarita	54,000,000	n/a	100%	54,000,000	n/a	trivial	54,000,000	100%	**99%**
San Clemente	Carmel	1,800,000	1996	10%	180,000	9	23,000	0	0%	**0%**
San Vicente	San Diego	112,000,000	1998	98%	109,760,000	7	31,000	109,543,000	98%	**98%**
Santa Felicia	Santa Clara	124,000,000	1996	87%	107,880,000	9	385,000	104,415,000	84%	**77%**
Sepulveda	Los Angeles	22,000,000[b]	1980	100%	22,000,000	25	trivial	22,000,000	100%	**90%**
Sutherland	San Dieguito	37,000,000	1998	99%	36,630,000	7	8,000	36,574,000	99%	**98%**
Twitchell	Santa Maria	296,000,000	1999	71%	210,160,000	6	1,331,000	202,174,000	68%	**87%**
Vail	Santa Margarita	63,000,000	n/a	100%	63,000,000	n/a	trivial	63,000,000	100%	**95%**
Whittier Narrows	San Gabriel	43,000,000[b]	1977	97%	41,710,000	28	trivial	41,710,000	97%	**90%**

[a] Original source data from water district reports. Method of calculation not provided.

[b] Values from U.S. Army Corps of Engineers, Los Angeles District, Reservoir Regulation Section, 2006.

When plotted against each other, these data show reasonable agreement (Figure 8). Unfortunately, reservoir sedimentation survey data are not available for many of the dams in this study, so this comparison could not be made for every dam. However, since the "percent capacity remaining" values for most of the dams were similar for the two methods, the rating curve method used in this analysis appears to provide a reasonable approximation of impounded sand.

The cumulative volume of sand that has been impounded by coastal dams in California between 1885 and 2005 is shown in Figure 9. The cumulative volume of trapped sand increased dramatically after 1955 as California's population grew and numerous, larger dams were built to provide water and flood control for the newly urbanized areas. The current rate of cumulative sand impoundment is the greatest it has ever been at 2,300,000 m^3/yr, but this rate has been fairly constant since the 1970s, when the last major dams were constructed. This constant rate is due to the fact that no dams have been decommissioned, sediment is not being bypassed around the structures, and very few dams are full enough with sediment to allow sand to spill over the structures. A few possible exceptions include the San Clemente, Gibraltar, Matilija, Malibu Lake, Rindge, and Devil's Gate Dams, which are almost completely full of sediment.

In 2005, the cumulative volume of sand that the 66 dams in this study have trapped is about 152,000,000 m^3 (Figure 9). The cumulative volume of trapped sand will continue to increase unless some dams are removed, a sand bypassing strategy is established, or dams progressively fill to the point that sand spills over them.

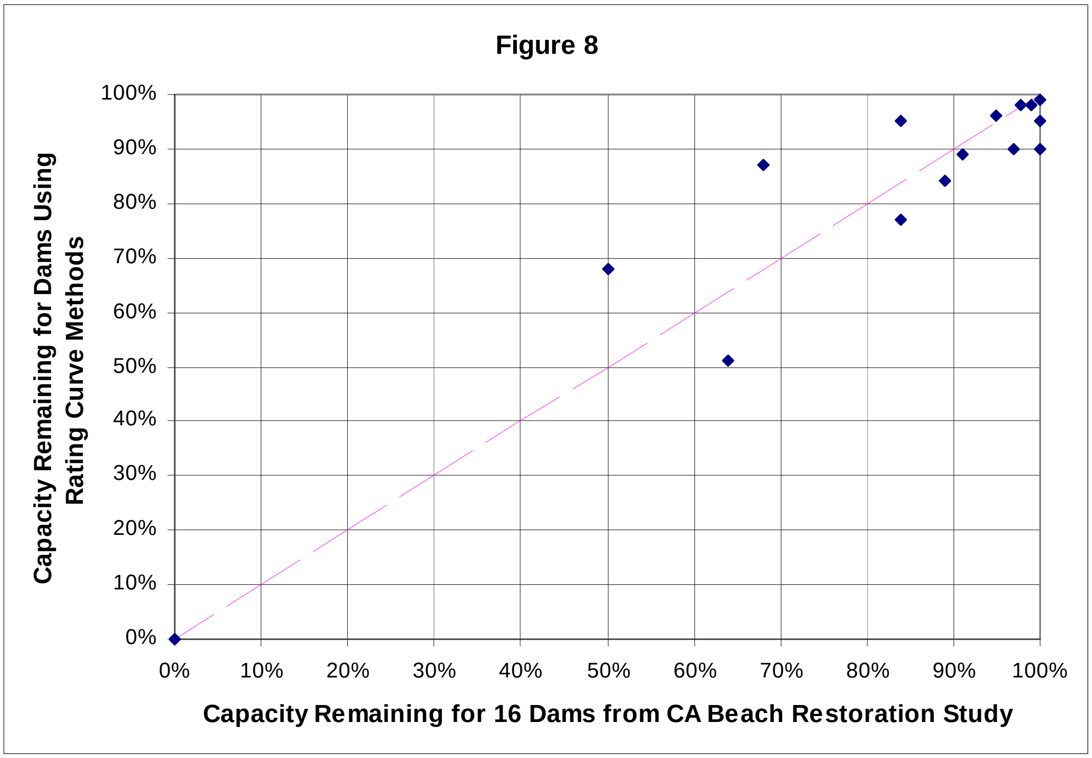

Figure 8. Comparison of results using rating curve technique with measurements from reservoir sedimentation surveys from the California Beach Restoration Study, 2002. The dashed line represents a 1:1 relationship.

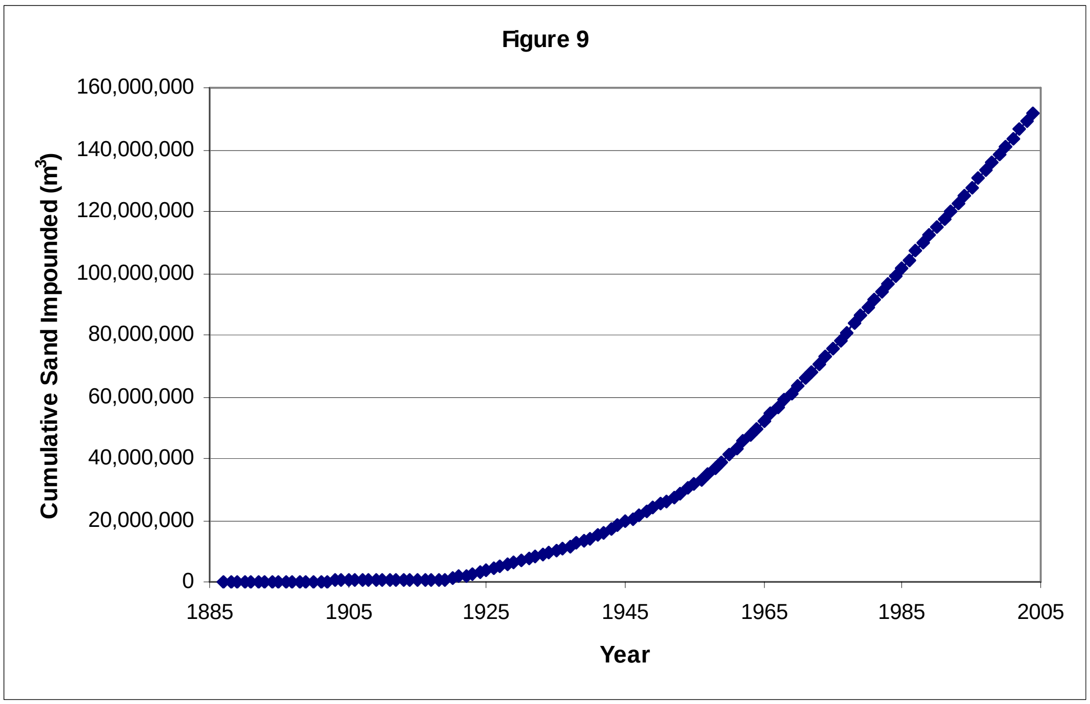

Figure 9. Cumulative sand impounded by California's coastal dams over time.

DISCUSSION

The methodology discussed herein relied upon a couple of key assumptions. First, we assumed that each individual watershed produced a constant sediment yield, so that we could directly compare sediment contributing areas upstream of dams. Sediment yield is not actually constant due primarily to local variations in bedrock and soils, precipitation, slope, and human forcing (LAVÉ and BURBANK, 2004). Second, we assumed that large coastal dams and reservoirs caused all of the fluvial sand reductions. Small debris basins, which we did not consider in this work, may trap the same order of magnitude of sand as the large dams (RENWICK et al., 2005). Debris basin effects are complicated because the sediment within them is frequently removed and the cumulative volumes that have been trapped are not always recorded or certain. Furthermore, it has been shown that sand mining in northern California coastal watersheds has removed about 11,000,000 t/yr of sand and gravel on average, and similar operations in southern California have removed about 55,800,000 t/yr on average (MAGOON and LENT, 2005). It is unclear how much of this sand and gravel would naturally be delivered to the coast by rivers, but sand mining may play a major role in fluvial sand reductions.

It should be noted that the long-term average fluxes presented here do not necessarily portray the temporal scale of the fluxes. For example, in southern California, about 95% of the sediment discharged from coastal rivers occurs during a major flood event of less than a few days duration during the winter months (GRIGGS and HEIN, 1980). The long-term, annual average sediment flux rates remove this episodic signal from the data. To more accurately calculate this long-term value, it is important to include sediment transport data from both wet and dry years when creating rating curves. In their study of the episodic nature of the sediment discharge of small rivers in southern California, INMAN and JENKINS (1999) found that the climate was dominated by an El Niño period from the mid-1930s until 1944, dry from 1944 until 1968 (1978 in northern California), and then El Niño dominated once again through at least 1998. In southern California, mean annual stream flow during wet periods exceeded the dry periods by a factor of about three, and the mean annual suspended sediment flux during the wet periods exceeded the dry periods by a factor of about five (INMAN and JENKINS, 1999).

In our analysis, 19 of the 21 USGS gauging stations have periods of record that include both wet and dry periods (Table 1). The stations on the Santa Ynez River (#11133500) and the San Dieguito River (#11030500) only include wet years, so the calculated annual average sand fluxes for these two rivers may be overestimates. Since the other gauged streams have periods of record that include full wet/dry cycles, the calculated sediment discharge values from the rating curves are reasonably accurate.

The rivers of California flow through different geological terrains, and these appear to influence the results presented above. The rivers from the Klamath in the north to the Carmel in the south drain the Coast Ranges, which are relatively older and more resistant formations with intrusive igneous rocks (INMAN and JENKINS, 1999). Although these formations are more resistant to weathering, much of the bedrock in this region has undergone tectonic deformation due to rapid uplift rates. The rivers from Arroyo Grande Creek to Malibu Creek drain the Transverse Ranges, which consist of unconsolidated and easily eroded Cenozoic sedimentary rocks (INMAN and JENKINS, 1999). The Los Angeles, San Gabriel, and Santa Ana Rivers drain the urban Transverse Ranges, and the remainder of the rivers, from the Santa Margarita to the Tijuana, drains the Peninsular Ranges, which consist of mostly granitic type rocks that are more resistant to erosion (INMAN and JENKINS, 1999). These differences in erodibility as well as precipitation patterns can help explain some of the trends found in sand delivery to the coast and impoundment behind dams.

The Coast Ranges in northern California have a high precipitation climate similar to the Pacific Northwest. High rainfall, steep slopes, and weak bedrock and soils combine to produce very high regional erosion rates. The rivers in this region were shown to discharge the largest volumes of sand in California.

The Coast Ranges in central California on the other hand do not experience such high precipitation. Slopes, geology, and vegetation cover vary widely in this area from the steep, redwood covered, high rainfall watershed of the San Lorenzo River to the lower relief, lower rainfall, grassland and chaparral covered hillsides of the Salinas River drainage basin. The rivers in this region do not deliver as much sand to the coastline as their northern counterparts.

The Transverse Ranges in southern California also do not experience high precipitation, but they do occasionally experience high intensity rainfall during the winter months and have exceptionally weak bedrock (INMAN and JENKINS, 1999).

The orographic effect of the Transverse Ranges on El Niño storms causes the rivers in this area (Arroyo Grande Creek, the Santa Maria, the Santa Ynez, the Ventura, the Santa Clara, and Malibu Creek) to have exceptionally high discharges during these events (INMAN and JENKINS, 1999). This high runoff over the unconsolidated and easily eroded sediments of the Transverse Ranges promotes large fluvial sand loads. However, dams trap much of the sand during these peak discharges, so the sand does not make it to the coast to nourish the beaches.

Lastly, the Peninsular Ranges in southern California do not experience high annual precipitation, and the rocks are much more resistant to erosion than those found in the Transverse Ranges. Therefore, stream flows for the rivers in this region are usually low due to the dry climate, and these flows do not tend to transport much sediment. Stream channelization and urbanization may also have an effect on this reduced sand flux because channelization prevents erosion of the bed of the streams and urbanization prevents erosion of the sediments beneath the large metropolitan areas of Los Angeles and San Diego (TRIMBLE, 1997).

California has removed 14 small dams for environmental reasons, none of which were included in this study. Since these removed dams were very small, they had little effect on coastal sediment budgets. At least nine of these removals were partially or entirely funded by CalFed, which is an organization consisting of numerous state and federal agencies (POHL, 2002). The benefits of dam removal are numerous, including delivery of impounded sand to the coast and ultimately, the restoration of aquatic and riparian ecology. For a complete discussion of the benefits, see PEJCHAR and WARNER, 2001.

Management of the sediment impounded by dams is a primary concern when considering dam removal. Although results presented here would suggest that sediment released into a river after dam removal would benefit littoral systems, this option could also destroy sensitive riparian habitat, choke the gills of fish, smother nesting grounds, and kill endangered amphibians downstream (BOOTH, 2000). Ironically, these are some of the same issues that dam removal is supposed to remediate. A second option is to remove the sediment, but this is potentially very expensive and time consuming. For example, to mechanically remove the sediment from behind Matilija Dam, which is almost completely full, it would require a dump truck load of sediment every five minutes, 24 hours a day, for six or seven years (BOOTH, 2000). Managers must weigh the costs and the benefits to determine which dams should be candidates for removal and what techniques should be employed to deal with the impounded sediment.

Assuming constant longshore, onshore, and offshore transport rates of sand over time, reduced fluvial sand fluxes from coastal watersheds would gradually lead to beach narrowing (WILLIS and GRIGGS, 2003). However, it is difficult to determine when these sand reductions might actually affect the beaches because it is unclear how the sediment flux reductions propagate downstream. This is to say that the results produced from USGS gages may not be completely representative of the conditions at the coastline. Most rivers extend many kilometers below these gages.

Some of the rivers, such as the Tijuana and the San Dieguito, pass through an extensive coastal lagoon before emptying into the Pacific Ocean. Sediment may fall out of suspension in the lower river and estuary or be deposited on the flood plain, so gages probably overestimate the sand delivery to the shoreline by these rivers. Sediment transport could be better characterized by a series of bedload and suspended sediment gages along each river as well as above and below major dams, but such a sampling system would be very expensive to operate and maintain using present technology. In addition to increased fluvial sediment sampling, more reservoir sedimentation surveys behind dams are needed, especially in northern California, to determine how much sediment, sand in particular, has been trapped.

CONCLUSIONS

During pre-dam conditions, the 21 major coastal rivers in California formerly delivered about 10,000,000 m^3/yr of sand to the coast. With dams, the rivers discharge about 7,700,000 m^3/yr of sand. Therefore, dams have reduced the annual sand flux to the California coast by 2,300,000 m^3/yr or 23%. The pre-dam annual sand flux for the northern California rivers has only been reduced by about 5%, the annual central California sand flux has been reduced by 31%, and the annual southern California sand flux has been reduced by 50%. These differences in sand reduction are due to precipitation patterns, watershed characteristics (slopes, geology, soils, and vegetative cover), urbanization, and the percentage of the watersheds that have been impounded. Overall, the 66 dams analyzed in this study have impounded a cumulative volume of about 152,000,000 m^3 of sand. This volume will continue to increase unless some dams are removed or some form of sand bypassing strategy is established. Reduced fluvial sand fluxes to the coast of California should eventually cause beaches to narrow as they also cope with sea level rise and periodic severe El Niño winters. Continued work is needed to decipher the effects of sand mining, debris basins, and the role that the littoral cut-off diameter plays when estimating fluvial sediment delivery to the coast.

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