Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability

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ABSTRACT

The long-term sustainability of California's beaches depends on periodic deliveries of sand and gravel from coastal rivers and streams. To assess the long-term health of California's beaches, this study characterized the current state of fluvial sediment delivery and quantified, on a littoral cell basis, the cumulative impacts of dams in decreasing annual discharge. Presently, more than 500 dams impound more than 42,000 km^2 (or 38%) of California's coastal watershed area. Flow modeling suggests that by diminishing flood hydrographs, these dams have reduced the average annual sand and gravel flux to 20 major littoral cells by 2.8 million m^3/yr (or 25%). In 70% of the streams considered in this study, suspended sediment loads during equivalent discharge events have declined over the past three decades, which indicates that dams have also significantly reduced downstream sediment supplies. Approximately 23% (or 274 km) of the 1193 km of beaches in California are downcoast from rivers that have had sediment supplies diminished by one-third or more. Moreover, 192 km (or 70%) of these threatened beaches are located in southern California, where most of the state's beach recreation and tourism activities are concentrated. Although past large-scale nourishment activities associated with coastal construction and harbor dredging have offset fluvial sediment supply reductions, particularly in southern California, many of these threatened beaches can be expected to undergo long-term erosion in the future.

Introduction

During the 1982–1983 and 1997–1998 El Niño winter storms, high wave energy coupled with elevated sea levels caused extensive beach and cliff erosion in California, while coastal structures experienced more than $200 million in damages from wave impacts and flooding (Griggs and Johnson 1983; Storlazzi et al. 2000). Policy makers and coastal-advocacy groups responded by lobbying the state for public funds directed toward beach restoration and nourishment projects. In 1999, these lobbying efforts were successful in securing $10 million for beach restoration projects and research through California State Assembly Bill 64, the California Public Beach Restoration Act. The state legislature mandated that research first be conducted to describe the current condition of major sediment sources, including coastal bluffs and rivers, and to investigate methods of increasing natural sediment supplies to the coast before embarking on an expensive, long-term beach nourishment program for California (Coyne and Sterrett 2002).

Littoral sediment budgets developed for California have estimated that, on average, rivers and streams provide 75%–90% of sand-sized material (>0.062 mm) and bluff and gully erosion provides the remaining 10%–25% (Bowen and Inman 1966; Best and Griggs 1991). However, the rates and magnitudes of fluvial sediment delivery have been significantly altered from long-term natural rates by (1) land use changes that have modified watershed erosion rates (i.e., sediment production), (2) the alteration of stream hydrographs (reduction of peak discharges), and (3) the construction of barriers to sediment transport. As early as 1938, researchers recognized the implications of the proliferation of dams in California's coastal watersheds on beach sand supply (Grant 1938). Not until the latter half

Manuscript received January 14, 2002; accepted April 30, 2002.

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[The Journal of Geology, 2003, volume 111, p. 167–182] 0022-1376/2003/11102-0003$15.00

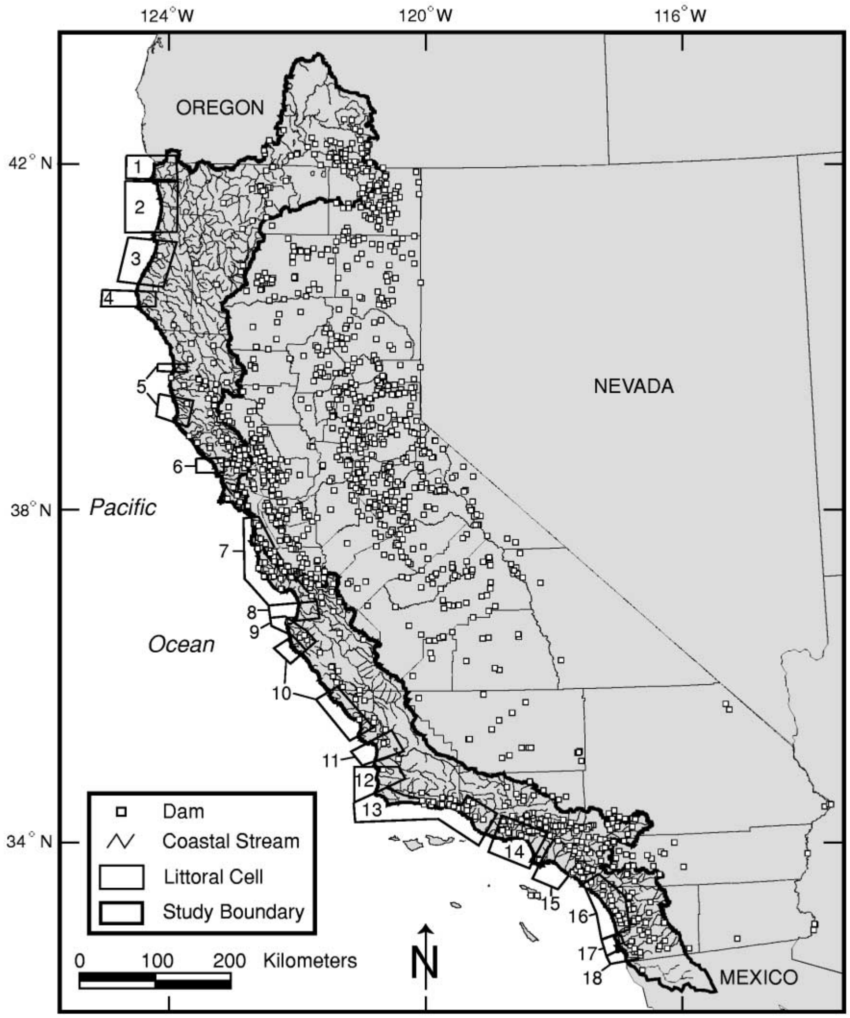

Figure 1. Map of the study area showing the locations of more than 1400 dams over 7.5 m in height or impounding more than 0.06 hm^3 that have been constructed in California's coastal watersheds that drain directly to the Pacific Ocean and 20 major littoral cells along the California coast. Numbered littoral cells correspond to table 1.

of the century, however, did researchers attempt to quantify the volumes of sediment impounded by dams (Norris 1963; Department of Navigation and Ocean Development 1977; Brownlie and Taylor 1981; Griggs 1987; Flick 1993). Brownlie and Taylor (1981) completed the most rigorous estimation of the impacts of dams in reducing average annual sand discharge from southern California watersheds through the 1978 water year. Since 1978, California's climate has been dominated by El Niño events that have generated above-average precipitation and river discharges. Both the shift in California's climate and the significant expansion of sediment discharge records warrant a revision of existing estimates of long-term fluvial sediment discharges and the role of dams in reducing coastal sediment supplies. Thus, the purpose of this study was to characterize the present state of fluvial sediment supplies to 20 California littoral cells (fig. 1) and to quantify, on a littoral cell basis, the cumulative impacts of dams in decreasing fluvial sediment discharge. The results of this study provide fundamental information for current research on strategies for increasing sediment supplies to the coast through dam removal, dam retrofitting, or the removal and transport of impounded sediment to the coast (Coyne and Sterrett 2002).

General Characteristics of the Coastal Fluvial Environment

California's coastal watersheds receive 82% of their annual precipitation between November and

March (National Climate Data Center 2001). As a result, almost all sediment is brought to the coast during storms throughout those winter months. This seasonal pattern of rainfall and streamflow is heightened by infrequent, exceptionally wet years when large floods flush enormous quantities of sediment out of coastal watersheds. A study of major rivers in central and southern California has shown that sediment discharge during flood years such as 1969, 1983, and 1998 averaged 27 times greater than during drier years (Inman and Jenkins 1999). For example, in 1969, more than 100 million tons of sediment were flushed out of the Santa Ynez Mountains, which was more than during the previous 25 yr combined (Inman and Jenkins 1999). Similarly, 63% of all the suspended sediment transported between 1936 and 1998 on the San Lorenzo River near Santa Cruz, California, occurred over just 62 d, less than 0.3% of the time over the 52-yr period. These infrequent, severe floods that take place every 10–20 yr are therefore responsible for delivering the majority of sediment to the coast.

California's coastal rivers have exceptionally high sediment loads as a result of the steep topography, the geologically young and tectonically active terrain, and, in central and southern California, the relatively sparse vegetative cover. California's coastal watersheds are of two general types: (1) the steep, erodible, conifer-forested Coast Range basins north of Monterey Bay, which are characterized by high seasonal rainfall and perennial streams, and (2) the more arid basins of central and southern California, which often drain chaparral- or grassland-covered headwaters but may cross broad alluvial valleys in their lower reaches (Griggs 1987). Sediment yield, the volume of sediment delivered per square kilometer of watershed, is typically very high in California relative to other major hydrographic regions of the United States. In fact, the Eel River in northern California has the highest sediment yield of any river its size in the United States (Brown and Ritter 1971) and discharges, on average, more sediment per year than any river in the lower 48 states after the Mississippi River (Meade and Parker 1984).

Quantifying Long-Term Fluvial Sediment Discharge

Methodology. Long-term average annual sediment discharge was estimated for 31 gaged coastal rivers using sediment transport data and sediment-rating curves to fill gaps in sediment discharge measurements. In the absence of sediment transport data, sediment accumulation records or sediment yield estimates of adjacent basins were used. All published water discharge, suspended sediment, and bed load data for USGS coastal stream gaging stations through the 1999 water year were compiled to develop suspended sediment and bed load rating curves (Freeman et al. 1999; Rockwell et al. 1999).

Suspended sediment transport was estimated using a standard rating curve technique (e.g., Riggs 1968; Glysson 1987) in which suspended sediment measurements are correlated with water discharge by a power function of the form $Q_s = a \times (Q_w)^b$, where Q_s is the mean daily suspended sediment flux (tons/d), Q_w is the mean daily water discharge in m^3/s, and a and b are empirical constants for individual streams (in this study, a ranged from 10^{-5} to 10^3, and b ranged from 0.6 to 3.5). Of the 4.9×10^5 d of water discharge data compiled for this study, mean daily suspended sediment discharge was measured on 1.0×10^5 d, while suspended sediment-rating curves were used to estimate suspended sediment flux for the remaining 79% of the days. All of the suspended sediment-rating curves were significant at the 0.01% level (r^2 values ranged from 0.5 to 0.96 and averaged 0.76). Daily measured and estimated suspended sediment fluxes for individual streams were summed by water year. Because this study is concerned with beach sediment supplies, only suspended sediment sizes coarser than 0.062 mm are relevant. The average percent of suspended sediment coarser than 0.062 mm was calculated from suspended sediment grain size distributions, and this average value was used to reduce the annual total suspended sediment flux to just the amount of sand-sized sediment discharged in that year.

Errors in estimating suspended sediment flux arise from measurement errors of suspended sediment in the field and statistical errors in rating curve calculations (Inman and Jenkins 1999). USGS sampling techniques are designed to ensure measurement errors are no more than ±15% (Edwards and Glysson 1999). To assess rating curve errors, we compared annual suspended sediment discharges calculated from sediment-rating curves with measured suspended sediment discharges. On average, our calculated annual discharges differed from measured annual discharges by ±22%. Therefore, we estimate the overall uncertainty for annual suspended sediment discharge to be a maximum of ±37%.

Bed load rating curves were developed when data were available, and grain size information from the bed surface was used to assess the sand and gravel fraction of the bed load. However, bed load mea-

Table 1. Impacts of Dams on Sand and Gravel Discharge (Q_L) from California Coastal Streams

Littoral cell and major rivers	Drainage area (km^2)	Controlled drainage area (km^2)	Percent controlled	Average annual sand and gravel flux (Q_L) (m^3/yr): Natural (no dams)	Average annual sand and gravel flux (Q_L) (m^3/yr): Actual (with dams)	Present Q_L reduction (%)
1. Smith River:						
Smith River	1823	0	0	136,475	136,475[a]	0
2. Klamath River:						
Klamath River	40,601	18,761	46	2,025,000[c]	1,275,371[a]	37
Redwood Creek	761	0	0	256,283	256,283[a]	0
Total	41,363	18,761	45	2,281,283	1,531,653	33
3. Eel River:						
Little River	121	0	0	40,680	40,680[b]	0
Mad River	1308	311	24	575,000[d]	525,509[a]	9
Eel River	9538	792	8	2,900,000[d]	2,869,455[a]	1
Total	10,967	1103	10	3,515,680	3,435,645	2
4. Matolle River:						
Matolle River	966	0	0	177,602	177,602[b]	0
5. Ten Mile and Navarro River:						
Noyo River	430	6	1	76,774	76,774[b]	0
Navarro River	818	0	0	159,691	159,691[a]	0
Total	1248	6	0	236,465	236,465	0
6. Russian River:						
Russian River	3845	747	19	168,500[d]	139,994[a]	17
7. Santa Cruz:						
San Gregorio–Pescadero	667	32	5	19,205	19,205[a,f]	0
San Lorenzo–Soquel	950	50	5	81,410[c]	79,608[a]	2
Pajaro	3393	495	15	49,000[c]	46,236[a]	6
Total	5010	577	12	149,615	145,050	3
8. Southern Monterey Bay:						
Salinas River	10,952	2077	19	555,000[d]	373,664[a]	33
9. Carmel River:						
Carmel River	808	324	40	59,500[c]	24,668[a]	59
10. Point Sur and Morro Bay:						
Little and Big Sur Rivers	1905	62	3	137,152	137,152[a,g]	0
11. Santa Maria:						
Arroyo Grande	396	183	46	85,500[d]	28,537[a]	67
Santa Maria River	4815	2939	61	620,000[d]	199,368[a]	68
San Antonio Creek	549	1	0	46,095	46,095[b]	0
Total	5760	3123	54	751,595	274,000	64
12. Santa Ynez:						
Santa Ynez River	2327	1100	47	545,000[c]	265,360[c]	51
13. Santa Barbara:						
Santa Ynez Mountain streams	974	16	2	149,171	149,171[b,h]	0
Ventura River	703	262	37	165,000[d]	78,177[a]	53
Santa Clara River	4178	1537	37	1,249,310[d]	912,192[a]	27
Calleguas Creek	982	56	6	49,644	49,644[a]	0
Total	6837	1871	27	1,613,126	1,189,185	26
14. Santa Monica:						
Malibu Creek	285	176	62	40,600[e,i]	18,200[e,i]	55
Santa Monica Mountain streams	331	1	1	33,130	33,130[b,h]	0
Ballona Creek	232	16	7	2209	2,209[a,h]	0
Total	848	193	23	75,939	53,539	29
15. San Pedro:						67
L.A. River	2163	1166	54	178,000[c,j]	59,014[a]	
San Gabriel	1837	1558	85	139,000[c,j]	45,297[b]	67
Santa Ana River	4381	4095	93	290,000[c,j]	95,811[a]	67
San Diego Creek	334	25.2	8	12,392	12,392[a]	0
Total	8715	6844	79	619,392	212,513	66

Table 1. (*Continued*)

Littoral cell and major rivers	Drainage area (km^2)	Controlled drainage area (km^2)	Percent controlled	Average annual sand and gravel flux (Q_L) (m^3/yr) Natural (no dams)	Actual (with dams)	Present Q_L reduction (%)
16. Oceanside:						
San Juan–Aliso Creek	1120	64	5	30,486	30,486[a]	0
Santa Margarita River	1916	972	51	44,500[d,j]	30,488[a]	31
San Luis Rey River	1450	564	39	100,000[d]	30,511[a]	69
San Dieguito River	896	793	89	45,000[d,j]	9,563[a,j]	79
Total	5382	2393	44	219,986	101,048	54
17. Mission Bay:						
San Diego River	1111	698	63	55,000[d,j]	5,031[a,j]	91
18. Silver Strand:						
Tijuana River	4483	2880	64	63,500[d,j]	32,188[a,j]	49
Total	109,539	42,011	38	11,360,812	8,471,233	25

Note. Methods used to estimate sediment flux.
Source. Data derived in this study if not noted.
[a] Sediment rating curves.
[b] Sediment yield of adjacent basin.
[c] Sediment accumulation records.
[d] Flow modeling.
[e] Watershed sediment modeling.
[f] San Gregorio Creek from Best and Griggs (1991).
[g] Department of Navigation and Ocean Development 1977.
[h] Inman and Jenkins 1999.
[i] Knur 2001.
[j] Brownlie and Taylor 1981.

surements have not been made at coastal gages on 85% of the rivers considered in this study. Therefore, bed load was assumed to be 10% of the total annual suspended sediment flux and 100% sand-sized or coarser, an estimate based on the small amount of bed load data at coastal gages that has been used frequently by previous researchers (Brownlie and Taylor 1981; Hadley et al. 1985; Inman and Jenkins 1999). Given the lack of bed load data, we cannot rigorously determine the accuracy of these bed load estimates.

The annual suspended sand and bed load sand and gravel fluxes were summed together to determine the total annual flux of beach material (Q_L). The mean annual sand and gravel discharge (Q_L) was calculated over the period of record to reflect the long-term average sand and gravel discharge for each river. No suspended transport data were available for six rivers, so assessments of Q_L were based on reservoir sediment accumulation rates within the basin or sediment yields of adjacent watersheds. Previously published estimates of sand and gravel discharge for 10 rivers are included in this study.

Results. Average annual sand and gravel discharges are summarized in figure 2 and table 1. The sand discharge includes all sand-sized material (0.062–2.0 mm), but sediment budget studies along the California coast have found that much of the fine sand (between 0.062 and 0.125 mm) is too small to remain on the beach (Ritter 1972; Best and Griggs 1991). Therefore, the sand flux estimates provided should be considered maximum estimates of beach-quality material supplied from coastal streams. In general, the sand and gravel discharges from coastal watersheds decrease from north to south (fig. 2). The northern Coast Range and the Transverse Range are two distinct regions of high sediment discharge, while the Peninsular Range, on average, supplies the smallest quantity of sand and gravel. Precipitation and lithology are the primary sources of these regional differences in sand and gravel discharge. The northern Coast Range receives approximately twice the average annual rainfall (107 cm/yr) of the southern Coast Range (53 cm/yr) and the Transverse and Peninsular Ranges (43 cm/yr) (National Climate Data Center 2001). However, the frequency of precipitation events and antecedent conditions are more important than total annual precipitation for determining stream discharge. The northern Coast Range shares a climate more akin to the Pacific Northwest and receives a steady barrage of winter storms, so soils remain saturated and precipitation is translated directly into runoff. In contrast, the southern Coast, Transverse, and Peninsular Ranges experience more inconsistent storms that often arrive at intervals that are long enough for soils to dry out,

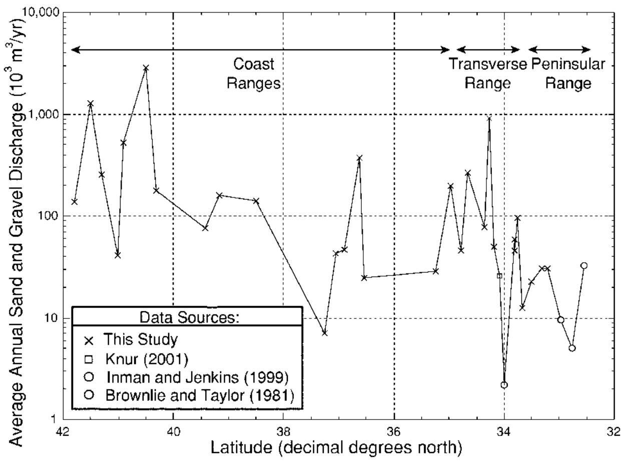

Figure 2. Latitudinal distribution of average annual sand and gravel discharge from 34 coastal rivers in California.

reducing the amount of runoff. The lithology of the Coast Range consists of a mixture of highly erodible Franciscan formation and younger sedimentary rocks as well as more resistant metamorphic and plutonic rocks. Inman and Jenkins (1999) attribute the high sediment yields of the Transverse Range to their composition—relatively young and unconsolidated Cenozoic sediments—and the region's structural complexity, which includes slip faults, thrust faults, and overturned beds. The Peninsular Range, in contrast, is principally composed of older and more resistant granitic rocks (Inman and Jenkins 1999). Despite the lithologic variations, streams draining the Coast, Transverse, and Peninsular Ranges transport suspended sediment that consistently averages 23%–25% sand with a median grain size of 0.15–0.19 mm.

Distribution of Coastal Dams

California suffers from an extreme mismatch between the distribution of its population centers and its surface water sources. Only 9% of California's population lives in northern California, where 73% of the state's surface water originates (Bateni et al. 1998). In contrast, 90% of Californians reside in central and southern California (primarily in the urban centers of San Diego, Los Angeles, and the San Francisco Bay Area), where the remaining 27% of the state's surface water is located (Bateni et al. 1998). Major centers of industrial-scale agriculture have also been established in central and southern California. The seasonal nature of California's precipitation further compounds this problem: 82% of the state's precipitation falls between November and April (National Climate Data Center 2001), while water demands peak in the summer months. Groundwater sources were tapped in the early nineteenth century to offset surface water shortages in central and southern California, particularly in the Central Valley. However, as demand exceeded groundwater sources, a massive water engineering solution was developed—a complex network of dams, reservoirs, and aqueducts capable of storing 2 yr of California's average annual runoff (after losses through evapotranspiration) and transporting it from water-rich northern California to water-poor central and southern California (Mount 1995).

This study compiled a geographic information systems database of all regulated dams, watersheds, and digital elevations models for California to map the distribution of coastal dams and the watershed areas they impound. More than 1400 dams over 7.5 m high or impounding more than 0.06 hm^3 (Division of the Safety of Dams 1998) have been constructed across California (fig. 1), with 539 of these dams located in the coastal watersheds that drain directly into the Pacific Ocean (59 dams are in watershed areas that extend into Oregon and Mexico). Since the construction of the first coastal dam in California in 1866, an average of 3.5 dams has been built each year (fig. 3). The period of the most rigorous construction of dams coincided with the post–World War II population expansion in California from 1945 to the mid-1970s (California Department of Finance 2000). Dam construction trends can be evaluated by either the number of individual dams built or the total design capacity established in a year. By both accounts, maximum activity occurred between 1945 and 1977, when 61% of the water storage capacity and 50% of the total number of dams in the study area were established. This time period also coincided with a prolonged period of below-average rainfall in southern California (below-average precipitation fell in 27 of the 33 yr; National Climate Data Center 2001). The majority of these coastal dams were built for water supply and irrigation (54%) or flood control (19%) (Environmental Protection Agency 1998) and are operated primarily by local governments and water districts (52%) or private entities (31%) (Division of the Safety of Dams 1998).

Downstream Impacts of Dams on Sediment Discharge

Dams affect sediment transport in two ways: (1) they alter the annual hydrograph and typically reduce peak discharges and sediment transport down-

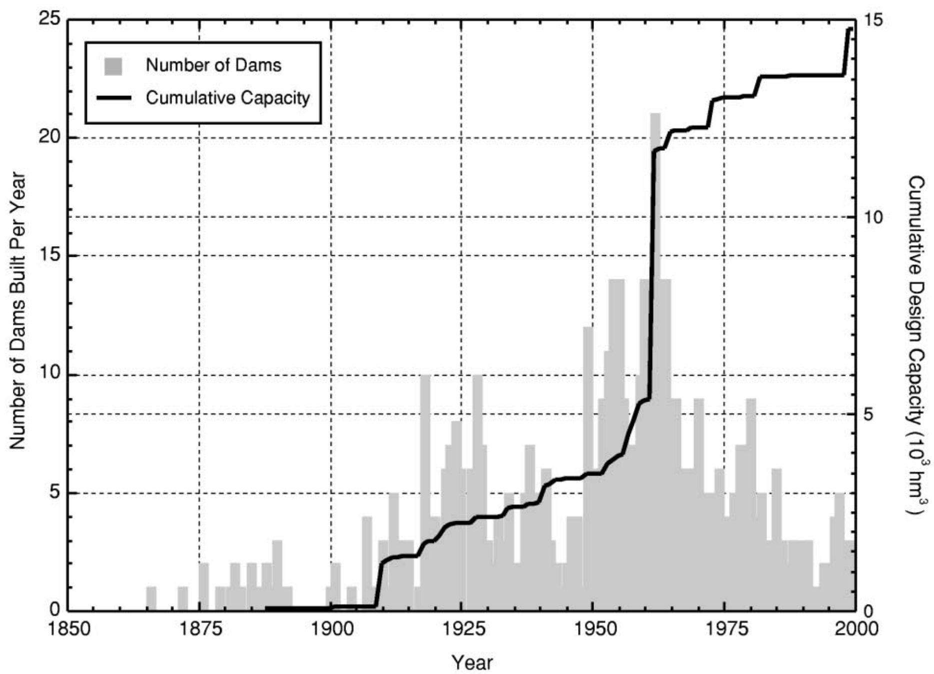

Figure 3. Number of coastal dams built per year in California and their cumulative design storage capacity

stream, and (2) dams trap sediment and reduce the amount of upstream sediment that reaches the downstream river network (fig. 4). The most obvious impacts of dams are on water flow downstream of the dam. Most of the large coastal dams in California impound reservoirs with capacities sufficient to absorb high flows while releasing little or no water downstream and dampening or completely eliminating the flood hydrograph from propagating downstream. With the decrease in peak discharges downstream, the rivers' competence and capacity are reduced. In addition, tributary discharges may become decoupled from flows on the main stem as the timing of flows is altered, causing problems for transporting tributary sediment inputs downstream (Kondolf and Matthews 1991; Topping et al. 2000). The downstream impacts of dams on sediment supply are less well understood. When rivers enter reservoirs, flow velocities rapidly decrease such that all bed load in transport is deposited at the head of the reservoir and all but the finest suspended sediment settles farther down the channel within the reservoir. Reservoir surveys of bed sediment typically show evidence of delta deposits at the entry points of rivers into reservoirs with gradients in grain size from gravel to sand to silt and clay (e.g., Scott et al. 1968). Various empirical relations have been developed to measure the degree of suspended sediment trapping, or "trapping efficiency." Using the simplest of these empirical methods, Brune's (1953) watershed-reservoir size ratio, we found that California's major dams have an average trapping efficiency of 84%. Bed degradation, bed coarsening, and bank erosion have been widely documented just downstream of dams because of the release of "hungry water," water that has excess stream power as a result of low sediment loads (Williams and Wolman 1984; Kondolf and Matthews 1991). However, sediment loads hundreds of kilometers downstream have also been shown to decrease over time because

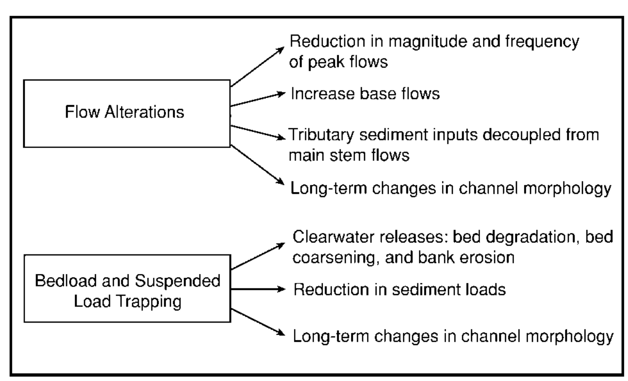

Figure 4. Schematic of the major downstream impacts of dams on water flow and sediment supply.

the downstream river network no longer has access to impounded upstream sediment sources (Andrews 1986; Topping et al. 2000). If sediment budgets are significantly disrupted, channel morphology adjustments will occur (Andrews 1986).

Quantifying the effects of dams on coastal sediment discharge in California is particularly challenging because of the lack of predam sediment transport data and the large annual variability in streamflow. We were not able to find any published suspended sediment or bed load data for coastal gages before dam construction. Most sediment records have been collected since the late 1960s; however, most rivers have been regulated by dams since the early to mid-1900s. In addition, California has an irregular climate and receives highly variable amounts of precipitation from year to year. Thus, flow frequency analysis is often not a viable technique for quantifying the impact of dams on downstream flows because it is difficult to distinguish between climatic variations and flow regulation. In regions where good pre- and postdam sediment transport data are available, the effects on sediment supply can be clearly documented. For example, after the completion of the Glenn Canyon Dam in 1963, suspended sand concentrations at the Grand Canyon gage on the Colorado River have declined, on average, by an order of magnitude over the entire range of measured discharge (Topping et al. 2000). Given the lack of data for California, this study attempted to tackle the problem in two steps: first addressing the effects on downstream flows to predict alterations to long-term sediment discharge at coastal stream gages and then investigating trends in historical suspended sand data to assess qualitatively the degree of sediment supply reductions.

Quantifying Reductions in Sediment Flux due to Flow Alterations

Methods. Using a methodology established by Brownlie and Taylor (1981), we estimated natural flows and sediment discharges for time periods when reservoir inflow and release data were available to quantify the impact of dams on average annual sediment discharge at coastal gaging stations. Inflow and release rates are typically recorded on a daily basis at major reservoirs in water discharge units of m^3/s or ft^3/s. Daily inflow and release data were gathered from dam operators for reservoirs on nine California rivers. The influence of a dam on mean daily flow downstream was estimated by subtracting the mean daily outflow (Q_{out}) from the mean daily inflow (Q_{in}). When a dam was releasing more water than was entering the reservoir, the $\Delta Q = (Q_{in} - Q_{out})$ value would be negative, and natural flows would be predicted to be less than actual flows measured at the coastal gage. Alternatively, if a reservoir was receiving more water than was being released, the ΔQ value would be positive, and natural flows would be predicted to be greater than actual flows measured at the coastal gage. The natural mean daily discharge at a coastal gage was estimated by adding ΔQ from all reservoirs within the basin to the actual mean daily discharge measured at the coastal gage, after accounting for percolation losses using empirical data specific to each river. Once the natural mean daily discharge was estimated, the same suspended sediment and bed load rating curves described in "Methodology" were used to predict the natural daily sediment discharge. By using the same rating curves, we are assuming that the predam and postdam rating curves are equivalent. In the following section, we will present evidence that the rating curves have shifted over time and discuss the implications of our estimates of reductions in sediment discharge.

An example of the flow modeling for the Spreckels gage on the Salinas River is shown in figure 5, in which we have plotted the predicted natural mean daily discharges subtracted from actual mean daily discharges. Actual mean daily discharges have

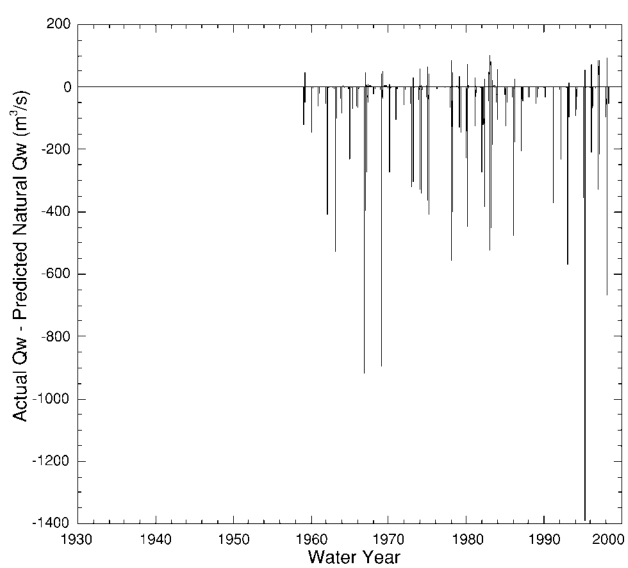

Figure 5. Predicted natural mean daily water discharges subtracted from the measured mean daily water discharges at the Speckels gage on the Salinas River, showing the influence of dams on flows since 1959. Actual mean daily water discharge has been decreased by a maximum of nearly 1400 m^3/s and increased by as much as 100 m^3/s in the past 40 yr.

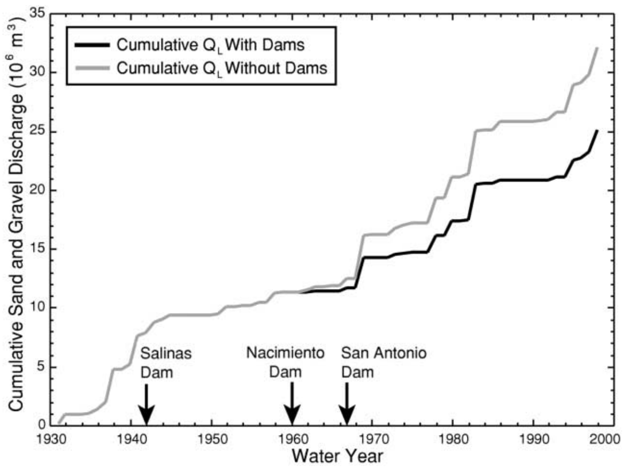

Figure 6. Actual (with dams) and natural (without dams) cumulative sand and gravel discharge for the Salinas River for water years 1930–1999. Average annual sand and gravel discharge has been reduced by 32%, or 7 million cubic meters.

been reduced by as much as 1400 m^3/s since Nacimiento Dam began regulating flows significantly in 1959. Since completion of the third major dam on the Salinas River in 1965, the average annual sand and gravel discharge has been reduced by 32% (fig. 6). To check our flow modeling methodology, sediment transport estimates were made using the same rating curves but with natural daily flow estimates for the Spreckels gage provided by the Monterey County Water Resources Agency (MCWRA). The MCWRA's natural flow estimates were generated using a more robust hydrologic model, the U.S. Army Corps HEC-2 model (Montgomery Watson 1998). The MCWRA data suggest that the average annual sand and gravel discharge has been reduced by 35%. Although the simple modeling approach used in this study is not likely robust enough to predict daily flows accurately, the close agreement between the average annual sediment reductions bolsters the credibility of this technique for predicting long-term reductions in sediment discharge.

For seven watersheds for which dam inflow and outflow data were not available, reservoir sediment accumulation data were used to evaluate the decrease in sediment discharge to the coast. Long-term sediment yields for impounded watersheds were estimated from the volumes of reservoir sediment, the duration of deposition, and the basin areas above the reservoirs. Natural long-term sediment yields (i.e., without dams) were estimated from averages of the impounded basins' sediment yields and the sediment yields of the basins below the reservoirs (determined previously by sediment-rating curves), weighted by the respective basin areas. There were relatively few new data for seven streams in southern California, so previously published estimates of reductions in sediment flux were included in this study.

Results. The cumulative impacts of dams on sediment delivery to the coast have been dramatic. Dams currently impound more than 42,000 km^2 (or 38%) of California's total coastal watershed area draining to the Pacific (fig. 7). The single largest impounded watershed (nearly 17,000 km^2, or 40% of the total impounded area) is the upper Klamath basin, an important region for hydroelectric power generation. Approximately 19,000 km^2 of watershed area is impounded in southern California, chiefly in the Santa Maria, Santa Ynez, Santa Clara, Los Angeles, San Gabriel, Santa Ana, and Tijuana basins. Smaller impounded areas are scattered across northern and central California on the Trin-

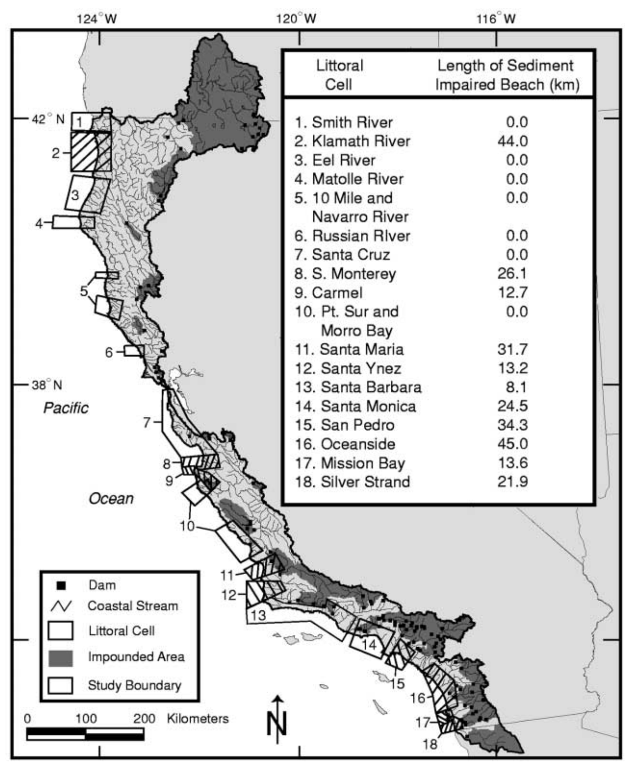

Figure 7. Map depicting the major watershed areas impounded by dams. The littoral cells with the hatched patterns indicate that fluvial sediment supplies have been diminished by 33% or more. Dams shown are the 70 dams that are responsible for 90% of the sediment discharge reductions. Numbered littoral cells correspond to table 1.

ity, Eel, Russian, and Salinas Rivers. By reducing downstream flows, these dams have decreased average annual sand and gravel discharges into the 20 littoral cells addressed in this study by 25%, or about 2.8 million m^3/yr (table 1). Nearly half of the 41 rivers included in this study discharge less than 75% of an average annual volume of sand and gravel that would occur without these dams in place. More important, nine of 20 littoral cells have had average annual fluvial sediment supplies reduced by one-third or more (these cells are denoted by a hatched pattern in fig. 7). Six of the nine cells that have experienced significant declines in sediment supply bound the southern California coast. The length of beach that is in a net transport direction from rivers that have had sediment discharge reduced by one-third or more is tabulated for each cell in figure 7 (termed "sediment-impaired beach").

The flow modeling results from this study and Brownlie and Taylor (1981) indicate that a nearly 1 : 1 relationship exists between the percent of a basin area impounded by a dam and the percent reduction in the average annual sediment discharge (fig. 8). This relationship suggests that a balance exists in these coastal watersheds among the source areas for runoff, the distribution of the dams in relation to runoff source areas, and the degree to which the dams stop flows from propagating downstream. Most of the watersheds considered here have precipitation gradients that run parallel to the river channel (predominately flowing east to west), such that the highest precipitation falls in high-elevation headwaters and decreases down slope to the coast. The largest deviations from the least squares best-fit line occur when dams fully impound the high-relief, high-precipitation zones. For example, the average annual sand discharge on the Salinas River has decreased by 32%, while less than 20% of the basin is impounded by dams. The two largest dams impound two subbasins draining the eastern side of the Santa Lucia Mountains, best known for their dramatic expression along the Big Sur coastline of central California. The Santa Lucia Mountains have a strong rain shadow effect on the Salinas Valley to the east; the impounded basins receive, on average, 63 cm of precipitation per year, while the Salinas Valley receives only 38 cm/yr. Thus, the dams block an important source area for runoff and streamflow. In the absence of other data, the nearly 1 : 1 relationship in figure 8 between impounded basin area and average annual reduction in sediment flux provides a good, first-order predictor of the influence of dams on long-term sediment discharge.

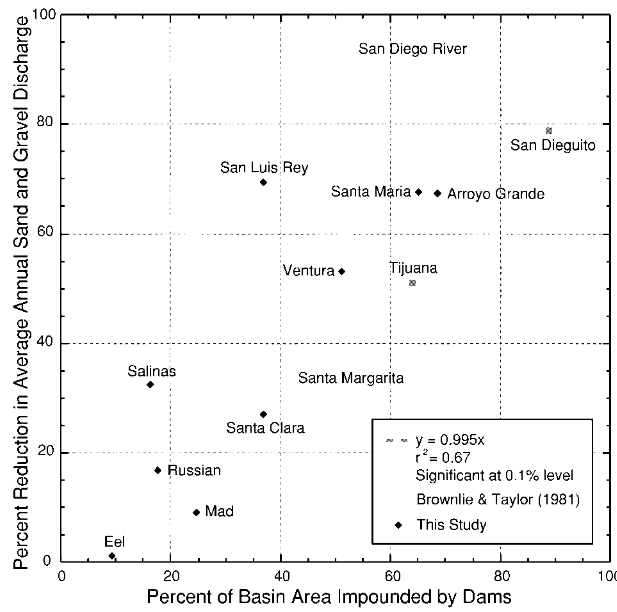

Figure 8. Flow modeling suggests a nearly 1 : 1 relationship between the watershed area impounded and the reduction in average annual sediment discharge.

Downstream Impacts of Sediment Trapping

Methods. As mentioned previously, researchers have shown with pre- and postdam suspended sediment measurements that suspended sediment loads for equivalent discharge events decrease after the construction of major dams upstream, in some cases hundreds of kilometers upstream (Williams and Wolman 1984; Andrews 1986; Topping et al. 2000). These decreased suspended sediment loads have been attributed to sediment trapping behind the dam and the resulting sediment-deprived environment that evolves downstream (Andrews 1986; Topping et al. 2000). In lieu of direct, predam suspended sediment measurements at coastal gages in California, temporal trends in suspended sand concentrations were investigated to detect consistent declines in suspended sand loads for equivalent discharge events that would be indicative of the gradual proliferation of dams within California watersheds and the evolution of a sediment-deficient river network. Our investigation was modeled after that of Dinehart (1997), who used similar techniques to document the decline in sediment loads in streams draining Mount St. Helens in the decade following the volcano's eruption in 1980. Fourteen coastal streams were identified as having suspended sampling records at coastal gages with grain size information over at least a 10-yr period. These watersheds had a minimum of 5% to a maximum of 91% of upstream basin area affected by dams. For each station, the time series of suspended sand concentrations and water discharge were sorted into six discharge ranges that were based on flow frequency: (1) 2%–10% range: the highest flows that occur between 2% and 10% of the time; (2) 10%–20% range: the second-highest flows that occur between 10% and 20% of the time; (3) 20%–30% range; (4) 30%–50% range; (5) 50%–70% range; and (6) 70%–90% range. Trends in suspended sand concentrations over time were examined for all six discharge ranges both graphically and statistically. A graphical example for the Santa Ana River (91% of the upstream basin is impounded by dams) is shown in figure 9. A sharp decline in suspended sand concentrations since the late 1960s is clearly evident for the two highest discharge ranges (2%–10%: fig. 9*A*; 10%–20%: fig. 9*B*). The nonparametric Kendall's tau analysis was used to determine whether temporal trends were statistically significant (Dinehart 1997). Because California streamflow is extremely variable over time, a significantly wide range of discharge events often fell within each of our six discharge ranges. Therefore, to avoid biasing the results, the Kendall's tau analysis was also performed to check for temporal trends in discharge for our six discharge ranges. If any trend in discharge was found to be significant at the 90% confidence level, the data were discarded; thus, all data reported in this study are statistically independent of discharge.

Results. We have focused our analysis on the temporal trends evident in just the two highest discharge ranges (2%–10% and 10%–20%) because the high-flow events transport the bulk of the sediment to the coast. Statistically significant temporal declines in suspended sand concentrations were present in 10 of 14 rivers (71.4%), as shown in figure 10. Four of these 10 rivers exhibited a sharp decline in sand concentrations of similar magnitude to the trends present in figure 9. Significant increases in suspended sand concentrations through time were present in two rivers (or 14.3%), and no positive or negative trend was present for another two rivers (or 14.3%). Although none of the 14 streams investigated here is completely free from the influence of dams, three of the rivers have 8% or less of their watershed impounded by dams. Yet two of

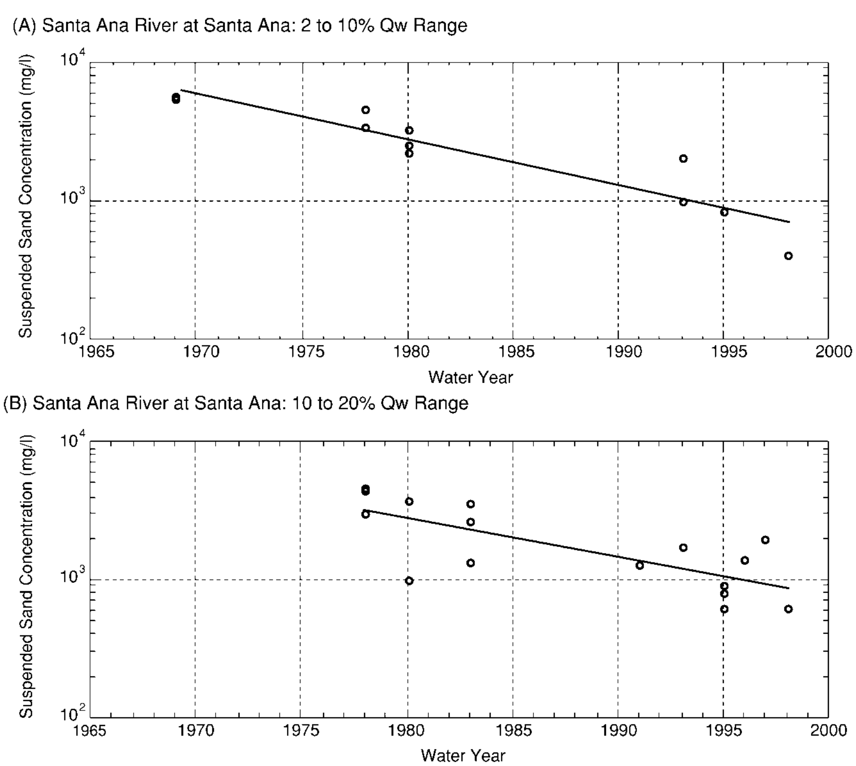

Figure 9. Measured suspended sand concentrations over time on the Santa Ana River at Santa Ana, California, for the discharge events that occur between (*A*) 2% and 10% and (*B*) 10% and 20% of the time. Suspended sand concentrations have declined exponentially over the past three decades.

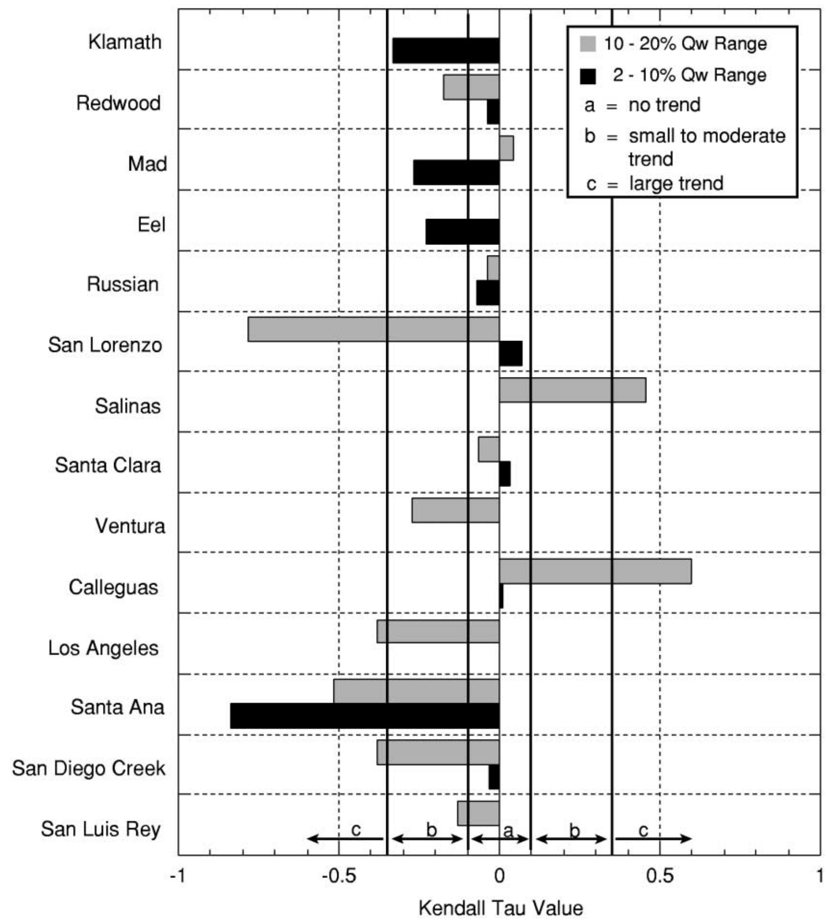

Figure 10. Significant trends in suspended sand concentrations for 14 coastal rivers since 1960. Here, Kendall's tau value indicates the strength and direction of the trend in suspended sand concentrations through time.

those rivers still showed evidence of declining suspended sand loads. More difficult to explain is the strong trend of increasing suspended sand concentrations on the Salinas River, where dams impound approximately 20% of the basin. Clearly, there are other watershed modifications—including urbanization, agricultural practices, in-stream sand mining, and timber harvesting—that can also influence suspended sand concentrations through time. At present, it is not possible to attribute temporal changes in sand concentrations to specific land-use changes in individual watersheds. However, these results confirm that many California rivers are experiencing supply limitations and decreasing sediment loads for equivalent discharge events. Therefore, the cumulative impacts of coastal dams, presented in "Results" in the section "Quantifying Reductions in Sediment Flux due to Flow Alterations," should be considered conservative estimates because they do not fully account for decreasing sediment loads and shifting sediment-rating curves through time.

Discussion

Given that rivers provide, on average, 75%–90% of beach material in California (Bowen and Inman 1966; Best and Griggs 1991), significant reductions in fluvial sediment discharge over decadal time scales will cause beaches to diminish in size, assuming constant longshore, onshore, and offshore transport over the same time scale. Figure 11 depicts an idealized stretch of sandy beach backed by a coastal bluff in a net downdrift direction from a coastal stream mouth. In this simplified sediment budget, we have ignored on- and offshore sediment transport and sediment contributions from the eroding cliff backing the beach. If the longshore transport potential remains constant and fluvial sediment flux decreases, the only way to balance

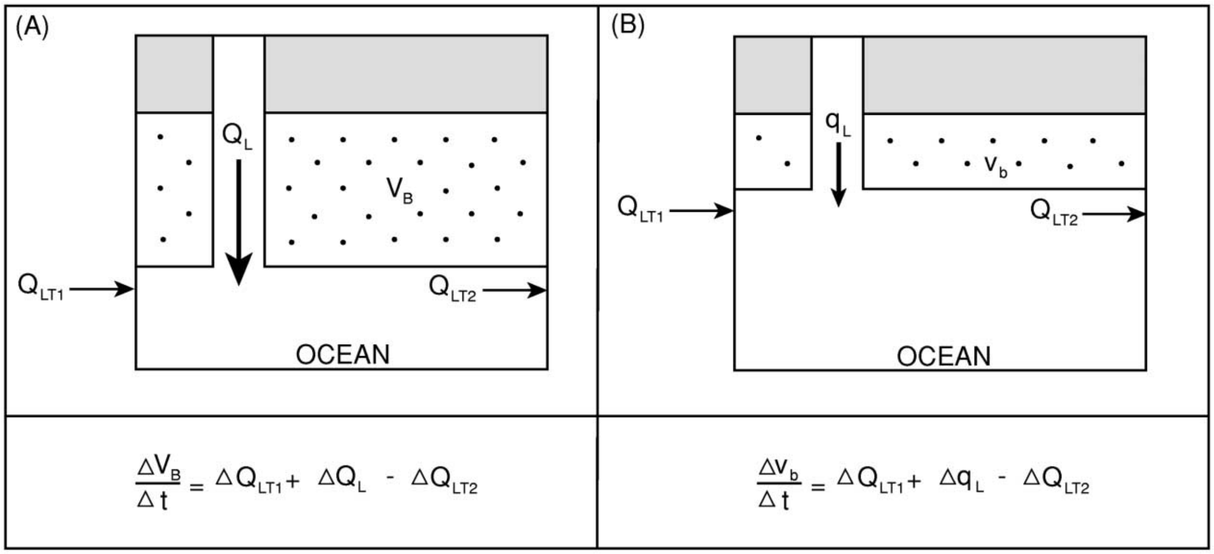

Figure 11. Schematic of an idealized littoral sediment budget for a California beach, ignoring onshore and offshore transport and sediment contributions from cliff erosion. If fluvial sediment flux, Q_L in *A*, diminishes significantly to q_L in *B* and littoral transport, Q_{LT}, remains constant, the initial beach volume, V_B, must decrease to v_b to balance the budget.

this sediment budget is to decrease the volume of the downdrift beach. Clearly, sediment budgets in California are not this simple. Longshore transport has been significantly disrupted by coastal structures up and down the California coast, sediment contributions from eroding cliffs have been diminished by coastal armoring, and beach nourishment projects have periodically added sand to the littoral system. In addition, fluvial discharge events are highly episodic. California beaches have evolved in littoral systems in which large pulses of sediment are delivered to the coast at 5–10-yr intervals, with very little sediment being delivered in the intervening years. The large submerged deltas at stream mouths that often form after large flood events have been shown to serve as a sand source for downdrift beaches for several years (Hicks and Inman 1987). We selected four rivers to compare how dams affected sand and gravel discharges in low-discharge versus high-discharge years. While the absolute volume of sediment denied delivery to the coast by dams is much larger during high-discharge years, dams on the Salinas, Santa Clara, and San Luis Rey Rivers have a larger relative impact during the low-discharge years (table 2). Thus, the dams have enhanced the episodicity of fluvial sediment delivery, and the beaches downcoast of these rivers are likely even more dependent on the high-discharge years for replenishing sediment supplies.

In southern California, artificial nourishment has kept pace with sediment losses from dam construction during the twentieth century. As large harbors were excavated along the southern California coast between 1940 and 1960, more than 100 million cubic meters of sand were placed on the region's beaches (Flick 1993). In some areas, the nourishment likely built beaches that were larger than what was previously maintained by the natural system. In other areas, the nourishment simply offset sand losses caused by dams. However, since the early 1970s, harbor construction and the associated nourishment activities have been curtailed; therefore, in the nine littoral cells where current fluvial sediment input is at only two-thirds or less of predam levels, beaches can be expected to narrow over the long term (fig. 7). Approximately 67% (or 1200 km) of California's coast has been characterized as sandy beaches (Habel and Armstrong 1978). About 23% (or 275 km) of California's beaches are located in a net downdrift direction from rivers that have had sediment supplies reduced by 33% or more and have a high potential for future long-term, permanent beach erosion (fig. 7). Significantly, the majority of these beaches with high potential for long-term erosion (192 km, or 70%) are located in southern California, where most of the state's beach recreation and tourism is concentrated. To date, there have been few comprehensive studies to determine whether long-term beach loss is occurring in California. However, per-

Table 2. Sediment Discharge Reductions in High- and Low-Discharge Water Years

River	Low-discharge years[a]		High-discharge years[b]	
	Frequency (%)	Average reduction in Q_L (%)	Frequency (%)	Average reduction in Q_L (%)
Russian	50	17	21	17
Salinas	67	69	20	27
Santa Clara	71	48	21	20
San Luis Rey	87	76	10	36

Note. Definitions of low- and high-discharge years; Q_L = gravel discharge.
[a] Low-discharge years are defined as less than one-half of average annual Q_L.
[b] High-discharge years are defined as >2 times average annual Q_L.

sistent exposure of cobble beaches that have been historically covered with sand in Ventura County (Capelli 1999) and in northern San Diego County are indicative of sand-deficient environments; in response, the San Diego Association of Governments has recently initiated a $16 million beach nourishment project for San Diego County (Kulchin et al. 2001).

Conclusions

Dams have dramatically reduced fluvial sediment supplies to the California coast, but a number of factors may permit watershed management actions to increase present rates of sediment delivery. First, 70 dams (or just 13%, shown in fig. 7) are responsible for 90% of the sediment reductions to the coast and make any sediment management efforts far more localized and tractable problems than if all 539 coastal dams were equally responsible for reducing sediment supplies. Second, half of these 70 dams are more than 50 yr old and are losing significant quantities of storage capacity as a result of sediment infilling; therefore, they are providing minimal flood control or water storage benefits. Dams that have lost much of their storage capacity, such as Matilija Dam on the Ventura River in southern California, may be good candidates for removal (Capelli 1999). Other dams, such as San Clemente Dam on the Carmel River, are structurally compromised and are in need of expensive repairs (Evans 1999). Such extensive repairs may not be justified when balanced against the water storage benefits and environmental costs that will be incurred, and dam removal may be the preferred alternative. Dam removal is an increasingly popular management choice in the United States, where more than 450 dams have been removed (Maclin and Sicchio 1999). In some cases, structural repairs may provide opportunities for design improvements or retrofitting with engineering devices designed to mobilize impounded sediments and move them below the dam (Wasyl et al. 1978). Regardless of the strategy, some form of large-scale, continuous sediment management will be necessary in the San Pedro, Oceanside, Mission Bay, and Silver Strand littoral cells—the cells that bound the California coast from Los Angeles to San Diego—to prevent permanent beach losses.

ACKNOWLEDGMENTS

We would like to thank the California Coastal Conservancy for providing the primary funding for this research. American Rivers in Washington, D.C., provided additional funding. We would like to thank the following groups for providing data essential to this study: Monterey County Water Resources Agency, United Water Conservation District, Santa Clara Valley Water District, San Benito County Water District, City of Escondido, Humboldt Bay Municipal Water District, Vista Irrigation District, Rancho California Water District, U.S. Army Corps of Engineers, San Luis Obispo County, and Steiner Environmental Consulting. We would also like to thank D. M. Rubin, C. D. Storlazzi, P. D. Komar, J. D. Milliman, and one anonymous reviewer for their critical reviews and suggestions that greatly improved this manuscript.

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