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Retention of Beach Sands by Dams and Debris Basins in Southern California

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ABSTRACT

The sediment budgets of most beaches in southern California are dominated by sand contributions from coastal streams. Extensive alteration of fluvial systems by the construction of dams and debris basins has reduced substantially the volume of sand reaching the shore. This is one factor in the chronic erosion of these beaches. The purpose of this research is to assess the magnitude of the impacts of coastal dams and debris basins on sand delivery using direct measurements of sediment impoundment rates within eight watersheds.

Sediment impoundment data were obtained for 28 dams and more than 150 debris basins in the watersheds of eight rivers: the Santa Ynez, Ventura, Santa Clara, Los Angeles, San Gabriel, Santa Ana, San Dieguito, and San Diego. The cumulative effect of these structures is the impoundment of more than 4,000,000 m^3 yr^{-1} of sediment. This is equivalent to a potential deprivation of beach sand of roughly 3 m^3 yr^{-1} per m of shoreline in the five southern California coastal counties.

The sedimentation records for individual watersheds are interpreted in the context of wet and dry climate episodes in the last century. The data are compared to estimates of sediment delivery derived from stream gauge records. In most watersheds, the majority of sedimentation occurs behind one dam, and the contributions of debris basin impoundment are secondary. The net effect is a substantial reduction of potential sand supply to the coast.

ADDITIONALINDEXWORDS: *sediment budget, watershed sedimentation, human impacts, coastal streams*

INTRODUCTION

Chronic erosion of beaches in California represents a substantial threat to an important coastal resource. These beaches are prized not only for their aesthetic attributes and for the life styles that they support, but also for the part they play in the economic health of the state. A recent report by KING (1999) indicates that beach activities (mainly recreation and tourism) in California in 1998 generated about $73 billion in direct, indirect, and induced benefits and nearly 900,000 jobs. However, the mythical California beach - sandy, vast and pristine - (e.g., FLICK, 1993) is disappearing. GRIGGS (2000) estimated that 86% of California's 1760 km of shoreline is eroding. About 29% of that shoreline is eroding at a rate that is termed "high risk" (GRIGGS and SAVOY, 1985).

There are several reasons why California's beaches are eroding, most of them linked to a decreasing sediment supply (e.g., INMAN, 1976), especially from fluvial sources. It is estimated that between 70% and 85% of the state's beach sand is delivered by rivers (BEST and GRIGGS, 1991), but that contribution is being reduced by human impacts. The suite of potential human impacts is variegated. For example, sediment yield may be increased because of land cover changes associated with deforestation or over grazing. Urbanization renders large tracts of land virtually immune to erosion while increasing peak flood discharges (e.g., MOUNT, 1995). Channelization of streams effectively isolates the flow from surrounding alluvium, thereby reducing sediment supply. In California, the impact that has drawn the greatest attention is sediment impoundment behind dams and within debris basins. For example, the State Legislature found that "many state beaches are in an advanced state of erosion and are disappearing because of human-induced impacts produced by inland development and watershed modifications such as concrete channels, flood control structures, and water supply dams" (AB64, 1999, Sec. 1e).

It is well understood that the impoundment of sediment in artificial catchments formed by dams and debris basins in coastal watersheds reduces the volume of sand delivered to beaches (e.g., BROWNLIE and TAYLOR, 1981; INMAN, 1985; SHERMAN, 1997). What is much less certain is the magnitude of the disruption. There have been a few attempts to estimate average sediment flux from coastal streams in southern California under natural conditions (BROWNLIE and TAYLOR, 1981; FLICK, 1993). Attempts to quantify fluvial sediment delivery under present conditions rely primarily on modeling approaches developed by the USGS (PORTERFIELD, 1972) that incorporate stream gauge and suspended sediment measurements. Uncertainties in data quality coupled with the assumptions used in that approach suggest that errors in predicted transport may be as large as 35% (INMAN and JENKINS, 1999).

Differences between the natural and current rates of sediment flux in these studies show widespread decreases under present conditions. These differences are generally attributed to sediment impoundment behind structures. The purpose of this research is to develop comparable estimates of sediment impoundment behind dams and within debris basins in southern California. Most major reservoirs have been surveyed repeatedly and changes in capacity recorded. Debris basins are subject to cleanout, and the volumes of material removed are recorded. Collectively, these data provide an important, independent estimate of the potential disruption of coastal sediment supply by dams and debris basins.

BACKGROUND

Coastal watersheds in southern California share several characteristics. As summarized in MOUNT (1995), all of the main rivers are less than 160 km in length, and none have drainage areas that exceed 5,000 km^2. Most of them have steep gradients, high sediment yields, limited baseflow in the major streams, and they flood frequently. The coastal mountain ranges in the region, with several peaks exceeding 3000 m, induce substantial orographic precipitation and occasional catastrophic flooding (COOKE, 1984). For example, during the extreme precipitation events of 1938, rainfall totals in excess of 800 mm were recorded during a one week period in the San Gabriel Mountains behind Los Angeles, and the resulting floods inundated more than 400 km^2 (TROXELL and others, 1942). As a result of these floods, about 15,000,000 m^3 of sediment were impounded by reservoirs and debris basins in Los Angeles County alone (COOKE, 1984). During the floods of 1969, sediment volumes totaling more than 14,000,000 m3 were trapped in the same area in a two-month period (COOKE, 1984).

BARRON (2001) studied the temporal distribution of maximum debris production years in debris basins in the watersheds of the Los Angeles and San Gabriel Rivers. A maximum debris production year (the year when the largest volume of sediment is trapped, and the volume trapped) is recorded for each debris basin maintained by the Los Angeles County Department of Public Works. She found that for almost all of the debris basins in the two watersheds, most maximum debris production years occurred in the late 1930s (especially 1938), or since 1968 (especially in 1969, 1978, 1980, and 1993). Her results mirrored those of INMAN and JENKINS (1999) in their study of southern California river discharges from 1928-1995. As part of their analysis, they characterized periods of above average and below average precipitation using the cumulative residuals of stream flow and sediment flux for twenty rivers in the region. Their results indicated a wet (above average precipitation) climate from at least the mid-1930s until 1944, and perhaps back to the beginning of their time series in 1928. Dry conditions (below average precipitation) then prevailed until 1969. The subsequent wet climate persisted through at least 1998. The identification of these climate variations is important for the interpretation of time-dependent sedimentation data. For example, any records beginning after 1969 are likely to indicate sedimentation rates that exceed longer-term averages that include a dry climate period. In the discussion of sedimentation records below, the terms "normal" and "long-term" are both used to denote conditions that include at least most of one complete wet and dry cycle.

BROWNLIE and TAYLOR (1981) published the first comprehensive effort to calculate sediment delivery to the southern California coastline and to compare those results with estimates of what sediment flux might have been under natural conditions. Their investigation considered the eleven largest drainage basins in southern California, from Ventura County through San Diego County (Figure 1). Most of their estimates of natural sediment flux were derived from stream flow measurements at USGS gauging stations near the coast, with discharge corrected for the effects of reservoir storage and percolation losses along the channel, and from measurements of suspended sediment concentrations at those same stations. Additional sedimentation data were gathered for some watersheds using reservoir deposition data. Where gaps existed in the sediment data, sediment rating curves were developed. The methods were those developed by PORTERFIELD (1972). This approach is most applicable when sediment production in a drainage basins has not changed appreciably through time. For watersheds where the land use had changed substantially, BROWNLIE and TAYLOR (1981) used other data. In particular, for the watersheds of the Los Angeles River, and San Gabriel River, they used repeat survey data of deltaic deposits at the river mouths to estimate sediment volumes. For these two watersheds, it was estimated that human impacts had reduced sediment delivery to about 1/3 of that occurring under natural conditions, with most of this effect attributed to dams. For less developed watersheds, they estimated sediment yield reductions up to almost 100% (for the San Dieguito River).

Figure 1. The eight watersheds and five counties discussed in this study.

FLICK (1993) also assessed reduction in sediment load in southern California coastal streams, relying mainly on the BROWNLIE and TAYLOR (1981) data. He refined some aspects of the analysis, but his findings were not substantially different from the earlier report. INMAN and JENKINS (1999) estimated sediment discharge from twenty coastal streams in southern and central California using USGS data. Their goal was to describe the effects of precipitation variability on sediment flux. They did not estimate sediment flux for natural conditions. None of these earlier studies relied extensively upon sedimentation data from the reservoirs and basins where the impoundment is taking place. Because these data exist for most major structures in California, they represent an important tool for assessing the overall impact on potential sediment delivery to the coastal zone.

For this study, sedimentation data were gathered for eight watersheds in southern California associated with the following rivers: the Santa Ynez, Ventura, Santa Clara, Los Angeles, San Gabriel, Santa Ana, San Dieguito, and San Diego (Figure 1). Several smaller watersheds, for example Ballona Creek in Los Angeles, or watersheds where there has been minimal human impact, e.g., Calleguas Creek in Ventura County, are not considered herein.

WATERSHED SEDIMENTATION

Sedimentation data were obtained from published sources or from responsible agencies where possible. For deposition behind dams, the primary data source is Sediment Deposition in U.S. Reservoirs, compiled by the SUBCOMMITTEE on SEDIMENTATION (1992) of the U.S. Department of Interior. These data were used to characterize deposition for 17 of the 28 dams evaluated in this study. The publication reports average sedimentation rates for selected reservoirs in units of acre-feet per square mile of net drainage area per year, based upon repeat surveys of basin capacity. Net drainage area refers to the potential sediment production area of the drainage basin, excluding the reservoir area and areas controlled by upstream structures. The sedimentation data were converted, time averaged using the length of record, and rounded to the nearest 1000 m^3 yr^{-1}. The length of record spans the time from the completion of the structure, or the earliest capacity survey, to the most recent survey. In most cases this duration exceeds the period for which sediment surveys are available. Therefore the sediment accumulation rates presented here are conservative estimates of actual rates. Data for the other 11 dams were obtained from several sources, mainly local water or flood control districts, and standardized to the nearest 1000 m^3 yr^{-1}.

Sedimentation data for debris basins were obtained from either the SUBCOMMITTEE on SEDIMENTATION (1992), or from a county flood control district. For exampe, the Los Angeles County Flood Control District (part of the Los Angeles County Department of Public Works), has maintained extensive records on their 116 debris basins. Details of these records can be found in BARRON (2001). Original sedimentation data were converted and rounded to the nearest 1000 m^3 yr^{-1}. Debris basins that have been recently constructed (i.e., last decade), or where sedimentation rates are small, were omitted for this study.

Santa Ynez River Watershed

The watershed of the Santa Ynez River has an area of 2335 km^2, most of which is in Santa Barbara County. According to CARA (1997), there are about 2,500 km of natural waterways in the basin, many of which are intermittent or ephemeral, and the average annual precipitation is 577 mm. The Santa Ynez River is about 100 km long, with an average gradient of 0.003. More than 30% of the watershed has slopes greater than 15% (CARA, 1997). The basin occupies a fold in poorly consolidated Cenozoic sedimentary formations, mainly marine sandstones and shales, and the river itself follows the Santa Ynez fault for much of its course (NORRIS and WEBB, 1990).

In this watershed, sedimentation data were found for two dams, Bradbury and Gibraltar, and two debris basins, Caliente and Mono (Figure 2). The data were obtained from an internal report of the Cachuma Operation and Maintenance Board (WIGNOT, 2001). The report presented deposition in the two debris basins as a single value. Therefore sedimentation rates (Table 1) were calculated using 1936 as a baseline, as it is the earliest completion date for the pair (they were finished within a year of each other). The average sedimentation rate for this watershed is about 735,000 m^3 yr^{-1}, with the two dams accounting for about 97% of the total deposition. The length of record for these four structures averages about 65 years, long enough to include most of two cycles of wet and dry climate as defined by INMAN and JENKINS (1999). The average for the watershed should, therefore, be a reasonable representation of long-term sedimentation rates.

Ventura River Watershed

The watershed of the Ventura River has an area of 705 km2, and it is contained entirely within the County of Ventura. There are approximately 750 km of mainly intermittent or ephemeral waterways (CARA, 1997), while the Ventura River is about 48 km long with an average gradient of 0.033. More than 40% of the watershed has slopes exceeding 15% (CARA, 1997), and the average annual precipitation is 652 mm. The upper reaches of the

Figure 2. The watersheds of the Santa Ynez River, Ventura River, and Santa Clara River, and the dams and debris basins discussed in this study.

Table 1. Sedimentation data for dams and debris basins in the watersheds of the Santa Ynez River, the Ventura River, and the Santa Clara River. Data sources are indicated in text.

Watershed	**Sediment Production Area (km^2)**	**Years of Record**	**Sedimentation Rate (m^3 yr^{-1})**
Santa Ynez River			
Dams			
Bradbury	1080.0	1953-2000	449,000
Gibraltar	554.3	1920-2001	265,000
Total Both Dams			714,000
Debris Basins			
(1) Caliente and (2) Mono	--	1936-2001	21,000
	Total Santa Ynez River Watershed		735,000
Ventura River			
Dams			
Matilija	142.4	1947-1999	155,000
Debris Basins			
(3) San Antonio	10.4	1964-2000	4000
(4) Stewart Canyon	5.1	1963-2000	4000
Total Both Debris Basins	Total Both Debris Basins		8000
	Total Ventura River Watershed		163,000
Santa Clara River			
Dams			
Santa Felicia	1091.4	1996	390,000
Debris Basins			
(5) Adams	7.4	1994-2000	9000
(6) Fagan Canyon	7.4	1994-2000	6000
(7) Jepson Wash	3.4	1961-2000	7000
(8) Real Wash	0.6	1964-2000	5000
(9) Warring Canyon	2.8	1952-2000	5000
Total All Debris Basin			32,000
	Total Santa Clara River Watershed		422,000

basin are eroded into well-consolidated shales, sandstone, and conglomerates, and the lower reaches are cut into poorly consolidated sandstones, gravels, siltstones, conglomerates and shales (BROWNLIE AND TAYLOR, 1981).

Sedimentation data (Table 1), provided by the County of Ventura Department of Public Works (VCFCD, 2001), were obtained for Matilija Dam and two debris basins, San Antonio and Stewart Canyon (Figure 2). The average sedimentation rate for this watershed is about 163,000 m^3 yr^{-1}. The length of record for these structures averages about 42 years. Matilija Dam, with a 52-year record, includes only about half of the last dry climate and causes almost all of the recorded sedimentation (about 95%). It is likely that the sedimentation rate for the Ventura River watershed is biased because of the dominance of wet climate conditions during the period of record.

Santa Clara River Watershed

The watershed of the Santa Clara River has an area of 4178 km^2 and it is contained in the Counties of Ventura and Los Angeles. There are approximately 4200 km of mainly intermittent or ephemeral waterways in the system (CARA, 1997), and the average annual precipitation is 493 mm. The Santa Clara River is 110 km long with an average gradient of 0.011. About 36% of the watershed has slopes with gradients exceeding 15% (CARA, 1997). The basin of the Santa Clara River is controlled by a fault-bounded syncline with igneous and metamorphic bedrock in the upper basin and Cenozoic clastic sediments (marine and non-marine) in the lower basin.

Sedimentation data were obtained for Santa Felicia Dam (KENTOSH, 1997) and five debris basins (Figure 2), Adams, Fagan Canyon, Jepson Wash, Real Wash, and Warring Canyon (VCFCD, 2001). The average sedimentation rate behind these structures totals about 422,000 m^3 yr^{-1} (Table 1). Approximately 92% of this volume is impounded behind the Santa Felicia Dam, where the length of record is 41 years. This period includes only part of the last major dry climate, and the entire current wet climate. Average record for the debris basins is also relatively short, approximately 27 years, and it includes very little of the last dry climate. Thus, the estimated average sedimentation rate is probably greater than the long-term average.

Los Angeles River Watershed

The watershed of the Los Angeles River has an area of 2163 km^2, and it is contained almost entirely in Los Angeles County. There are approximately 1280 km of waterways, most of them intermittent or ephemeral (CARA, 1997). Almost all of these waterways, including most of the Los Angeles River, are channelized. The Los Angeles River itself is 90 km long with an average gradient of 0.004. More than 20% of the watershed's area has slopes in excess of 15% (CARA, 1997), and the average annual precipitation is 510 mm. Most of the discharge in the system originates in the San Gabriel Mountains that form the northern rim of the watershed. The exposed rocks in the San Gabriel Range are mainly Mesozoic granites (NORRIS and WEBB, 1990). Over much of its course, the river traverses the Los Angeles Basin across alluvial deposits that are more than 5000 m deep in places (NORRIS and WEBB, 1990).

The Los Angeles River watershed contains a large number of dams and debris basins (Figure 3). Sedimentation data for seven dams, Big Tujunga, Devil's Gate, Eaton Wash, Hansen, Pacoima, Sawpit, and Sepulveda, were obtained from SUBCOMMITTEE on SEDIMENTATION (1992), and BOHLANDER (2001) provided data for more than 70 debris basins, including nine large ones: Aliso, Halls, La Tuna, Limekiln, Pickens, Santa Anita, Sawpit,

Figure 3. The Los Angeles River watershed and the dams and debris basins discussed in this study.

Table 2. Sedimentation data for dams and debris basins in the Los Angeles River watershed. Data sources are indicated in text.

Structure	Sediment Production Area (km^2)	Years of Record	Sedimentation Rate (m^3 yr^1)
Dams			
Big Tujunga	212.9	1931-1982	178,000
Devil's Gate	82.1	1916-1982	93,000
Eaton Wash	24.3	1936-1983	41,000
Hansen	378.1	1940-1983	330,000
Pacoima	73.0	1929-1983	78,000
Sawpit	8.5	1923-1982	12,000
Sepulveda	367.8	1941-1980	negligible
Total All Dams			732,000
Debris Basins			
(1) Aliso	7.2	1970-2000	8000
(2) Halls	2.1	1935-2000	7000
(3) La Tuna	13.8	1955-2000	11,000
(4) Limekiln	9.6	1963-2000	8000
(5) Pickens	3.9	1935-2000	9000
(6) Santa Anita	4.4	1959-2000	15,000
(7) Sawpit	7.3	1954-2000	12,000
(8) Sierra Madre Villa	3.8	1957-2000	14,000
(9) Verdugo	24.3	1935-2000	10,000
59 Others	--		100,000
Total All Debris Basins			194,000
	Total Los Angeles River Watershed		926,000

Sierra Madre Villa, and Verdugo (Table 2). Data for very new or very small debris basins are omitted. The average sedimentation rate behind the listed dams and debris basins is approximately 926,000 m^3 yr^{-1}. Hansen Dam impounds more than 1/3 of this total. The extensive system of debris basins traps about 21% of the total. Sedimentation behind the Sepulveda Dam is negligible it is downstream of Hansen Dam, and the latter catches the sediment discharge. Records for most of the dams begin early enough to include at least part of the wet climatic period that ended in 1944. However, the last reported surveys occurred in the early 1980’s, during the first third of the present wet climate. The records for most of the larger debris basins extend back only to the middle of the last dry period, but, other than Aliso, include all of the present wet climatic period. The average sedimentation rate for the period of record is probably a reasonable approximation of normal conditions.

San Gabriel River Watershed

The area of the San Gabriel River watershed is 1837 km2, and it is contained in Los Angeles and Orange Counties. The drainage network comprises about 1320 km of waterways, most of which are intermittent or ephemeral (CARA, 1997), and the average annual precipitation is 564 mm. The San Gabriel River is about 90 km long with an average gradient of 0.007. Slopes steeper than 15% occupy 33% of the watershed (CARA, 1997). The upper reaches of the river, including its East and West Forks, follow the San Gabriel Fault for about 40 km (NORRIS and WEBB, 1990). The lower reaches of the river cross the alluvial deposits of the San Gabriel Valley and the Los Angeles Basin. The major source of sediments is the San Gabriel Mountains, dominated by granitic rocks (NORRIS and WEBB, 1990).

Nine dams in the San Gabriel River watershed have sedimentation rate data reported by the SUBCOMMITTEE on SEDIMENTATION (1992): Big Dalton, Cogswell, Live Oak, Puddingstone, San Dimas, San Gabriel, Santa Fe, Thompson Creek, and Whittier Narrows (Figure 4). BOHLANDER (2001) presents data for 11 large or old debris basins, including Big Dalton and Little Dalton (Figure 4). The average sedimentation rate behind these

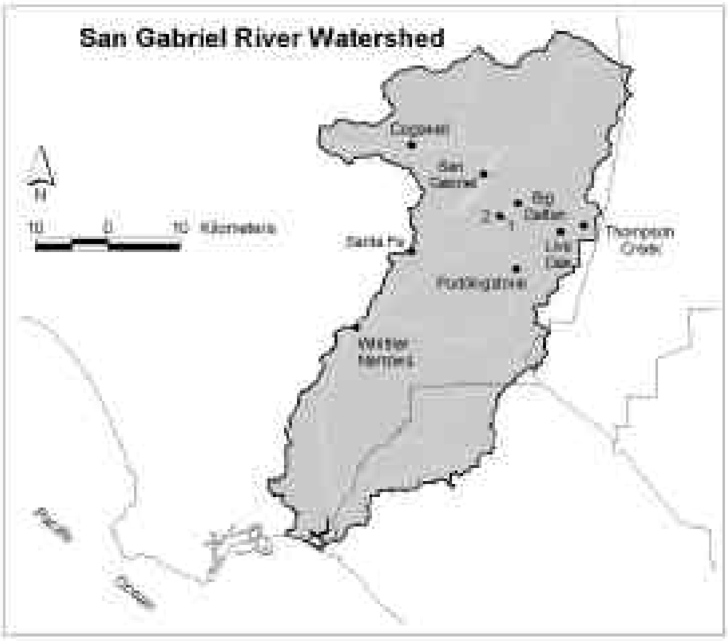

Figure 4. The San Gabriel River watershed and the dams and debris basins discussed in this study.

Table 3. Sedimentation data for dams and debris basins in the San Gabriel River watershed. Data sources are indicated in text.

Structure	Sediment Production Area (km^2)	Years of Record	Sedimentation Rate (m^3 yr^1)
Dams			
Big Dalton	11.5	1930-1981	13,000
Cogswell	99.8	1935-1981	99,000
Live Oak	5.9	1919-1983	4000
Puddingstone	82.2	1928-1980	38,000
San Dimas	41.2	1922-1980	54,000
San Gabriel	519.7	1937-1983	60,000
Santa Fe	52.6	1943-1982	155,000
Thompson Creek	9.0	1916-1981	7000
Whittier Narrows	1434.9	1957-1977	126,000
Total All Dams			556,000
Debris Basins			
(1) Big Dalton	19.0	1960-2000	16,000
(2) Little Dalton	21.7	1959-2000	17,000
10 Others			12,000
Total All Debris Basins			45,000
	Total San Gabriel River Watershed		601,000

structures is about 601,000 m³ yr⁻¹ (Table 3). The dams in this watershed impound about 93% of the total sediment catch per year. Data for most of the dams include substantial portions of two wet and dry climate periods, although none of the records include more than the first third of the present wet period. Most debris basin data extend from the present back to the middle of the 1944-1969 dry climate. Note also that the 20-year record for the Whittier Narrows Dam may be misleadingly high because it includes the 1969 flood data. Overall, it is believed that the resulting sedimentation rate obtained for the San Gabriel watershed is a reasonable long-term estimate.

Santa Ana River Watershed

The watershed of the Santa Ana River has an area of 4381 km2 and it is contained mainly in Orange, Riverside, and San Bernardino Counties. It is the largest coastal drainage basin in southern California, and it includes about 3250 km of waterways, mainly intermittent or ephemeral streams (CARA, 1997). The Santa Ana River is 160 km long and has an average gradient of 0.007. Twenty-six percent of the drainage basin has slopes exceeding 15% (CARA, 1997), and the average annual precipitation is 519 mm. Most of the drainage in this watershed originates in the San Gabriel and San Bernardino Mountains that rim the northern and eastern edges of the basin. Exposed rocks in the watershed include gneisses and schists, granitic rocks, and marine sedimentary sequences (BROWNLIE and TAYLOR, 1981).

For the Santa Ana River watershed (Figure 5), data were obtained for four dams, and no debris basins. Data for Carbon Canyon Dam are from USACOELAD (1990) and for San Antonio Dam, from USACOELAD (1991). Data for Mathews Dam are from METROPOLITAN WATER DISTRICT (2001), and for Prado Dam SUBCOMMITTEE on SEDIMENTATION (1992). The average sedimentation rate behind these structures is about 1,091,000 m³ yr⁻¹ (Table 4). Mathews Dam traps negligible volumes of sediment because it receives almost all of its water supply from the Colorado River Aqueduct. The records for Carbon Canyon Dam and San Antonio Dam are both relatively short, and more importantly, include the 1969 flood data. Thus these records indicate deposition rates that are significantly larger than would be found with a longer term record. Prado Dam impounds about 80% of the sediments trapped by the four dams. Its sedimentation record spans the last dry interval and the first part of the current wet period.

Figure 5. The watersheds of the Santa Ana River, San Dieguito River, and San Diego River, and the dams discussed in this study.

Table 4. Sedimentation data for dams and debris basins in the watersheds of the Santa Ana River, the San Dieguito River, and the San Diego River. Data sources are indicated in text.

Structure	Sediment Production Area (km^2)	Years of Record	Sedimentation Rate (m^3 yr^1)
Santa Ana River Dams			
Carbon Canyon	50.0	1961-1969	61,000
Mathews	103.6	1918-2001	negligible
Prado	5775.7	1941-1979	875,000
San Antonio	287.5	1956-1971	155,000
	Total Santa Ana River Watershed		1,091,000
San Dieguito River Dams			
Hodges	784.8	1918-1994	121,000
Sutherland	139.9	1954-1988	8000
	Total San Dieguito River Watershed		129,000
San Diego River Dams			
El Capitan	492.1	1956-1998	124,000
San Vicente	191.9	1943-1998	31,000
	Total San Diego River Watershed		155,000

San Dieguito River Watershed

The watershed of the San Dieguito River occupies 896 km^2 and is located within San Diego County (BROWNLIE and TAYLOR, 1981). The San Dieguito River is about 90 km long, with an average gradient of 0.018. The average annual precipitation is assumed to be the same as that for the San Diego watershed, 446 mm (CARA, 1997). Most of the exposed rocks in this drainage basin are granitic, formed as part of the southern California batholith, although there are exposures of marine sediments in the lower reaches of the system (BROWNLIE and TAYLOR, 1981).

Sedimentation data were obtained for two dams in the San Dieguito River watershed, Hodges Dam and Sutherland Dam (Figure 5). Data for both dams were provided by STONE (2001), with the note that data for Sutherland Dam are provisional. The average sedimentation rate behind these structures is about 129,000 m^3 yr^{-1} (Table 4), with most of the storage (94%) occurring behind Hodges Dam. The record for Lake Hodges is one of the longest in southern California and spans several wet and dry climate periods. The resulting estimate of sedimentation rates is considered, therefore, a good approximation of normal conditions.

San Diego River Watershed

The watershed of the San Diego River has an area of 1119 km^2 and it is contained in the County of San Diego. Most of the streams in the system are intermittent or ephemeral waterways. The San Diego River is about 85 km long with an average gradient of 0.014. The average annual precipitation is 446 mm (CARA, 1997). The geology of the San Diego River watershed is essentially the same as that of the San Dieguito, most of the exposed rocks are granitic, part of the southern California batholith, with exposures of marine sediments in the lower reaches of the system (BROWNLIE and TAYLOR, 1981).

Sedimentation data were provided by STONE (2001) for two dams in the San Diego River watershed: El Capitan and San Vicente (Figure 5). The average sedimentation rate behind these structures is about 155,000 m^3 yr^{-1} (Table 4), with most of the storage (80%) occurring behind El Capitan Dam. Note, however, that the results of the most recent (1998) survey are provisional. The San Vicente Dam data covers a complete dry climate period, and the present wet period. However, this dam accounts for a minority of sediment impoundment in the watershed. The record for El Capitan Dam includes only about one-half of the last dry period, and most of the present wet climate. Therefore the average annual sedimentation rate obtained for this drainage basin is probably biased toward the high side.

DISCUSSION

The results of this study can be compared to previous studies of coastal sediment supply in southern California. To accomplish this, data from BROWNLIE and TAYLOR (1981) and INMAN and JENKINS (1999) are combined. The former are used to represent "natural" (or baseline) conditions, while both sets of data are used to represent actual conditions. There are two exceptions. First, BROWNLIE and TAYLOR (1981) did not consider the Santa Ynez watershed, so the estimate of baseline conditions is derived from the data of JOHNSON (1959) modified to account for its record occurring during a dry climate record and to include the influence of discharge during the floods of 1969 (presumed to be a 30-year recurrence interval event). Second, INMAN and JENKINS (1999) did not model the San Dieguito watershed. The INMAN and JENKINS (1999) results do not necessarily represent current sedimentation rates, as they calculated long-term averages without any consideration of the impacts of human activity. Therefore human impacts are already factored into their calculations. The differences between natural and current sediment delivery rates found in those studies should approximate each other, and they should approximate the annual impoundment rates found in this study. The results are presented in Table 5.

This comparison shows that the sediment impoundment rate found in this study exceeds the reduction in sediment supply indicated by the results of BROWNLIE and TAYLOR (1981) and INMAN and JENKINS (1999) for all watersheds but that of the Ventura River. These results can be viewed from several perspectives. First, it might be presumed that the impoundment rates calculated here do not account for all of the human impacts liable to reduce sediment delivery to the coast. Thus the predicted differences between natural and actual conditions should exceed the impoundment rates. For example, the data reported here do not include results from all retention structures. There will also be reductions in sediment supply caused by the urbanization of the lower regions of flood plains. There should also be reductions in sediment supply caused by substantial reductions in stream discharge as a result of water supply diversions. On the other hand, it is likely that some fraction of the sediment trapped behind the dams and within the debris basins would have gone into storage on flood plains, especially during extreme runoff events.

The discrepancy between the different approaches may also result from errors in establishing estimates for "normal" sediment delivery rates. This is certainly the case for the BROWNLIE and TAYLOR (1981) estimates for the Los Angeles and San Gabriel River watersheds. These estimates are based on repeated surveys of deltaic deposits that occurred after several structures had been built in those watersheds and the records must include the impacts of those structures.

For the northern watersheds, INMAN and JENKINS (1999) estimate sediment delivery rates that are significantly greater than those of BROWNLIE and TAYLOR (1981). This may occur because the analysis of the former includes almost two decades of data from the current wet climate that are missing from the records of BROWNLIE and TAYLOR (1981). A closer examination of the discrepancies between the methods discussed here is beyond the scope of this study, but is worthy of further consideration.

Table 5. Summary sedimentation data for the eight watersheds. Qn is the "natural" sedimentation rate estimated by BROWNLIE and TAYLOR (1981). Qabt is the BROWNLIE and TAYLOR estimate of actual sediment delivery rates. Qaij is the INMAN and JENKINS (1999) estimate of actual sediment delivery rates. Impoundment rate is from this study.

Watershed	**Qn (m^3 yr^{-1})**	**Qabt (m^3 yr^{-1})**	**Qn-Qabt (m^3 yr^{-1})**	**Qaij (m^3 yr^{-1})**	**Qn-Qaij (m^3 yr^{-1})**	**Impoundment Rate (m^3 yr^{-1})**
Santa Ynez	2,160,000	--	--	1,483,000	677,000	735,000
Ventura	584,000	276,000	308,000	573,000	11,000	163,000
Santa Clara	2,340,000	2,094,000	246,000	2,657,000	--	422,000
Los Angeles	934,000	311,000	623,000	163,000	771,000	926,000
San Gabriel	300,000	100,000	200,000	36,000	264,000	601,000
Santa Ana	1,038,000	350,000	688,000	335,000	703,000	1,091,000
San Dieguito	49,000	10,000	39,000	--	--	129,000
San Diego	69,000	16,000	53,000	7,000	62,000	155,000

CONCLUSIONS

The analysis of deposition caused by dams and debris basins for eight watersheds in southern California indicates that the structures impound a total of about 4,222,000 m^3 of sediment per year. This represents a potential sediment loss to the coastal system of about 8 m3 y-1 per meter of the 550 km shoreline in the five southern counties. Relatively little is known about what proportion of these sediments is suitable for beach sand. There are general estimates of sand content of about 40-50% (e.g., BROWNLIE and TAYLOR, 1981). Assuming a 40% sand content indicates that potential losses of beach sand may exceed 3 m^3 yr^{-1} per meter of the southern California coast. Alternatively, the annual impoundment rate may represent a loss of about 1,700,000 m^3 yr^{-1} of sand. This is equivalent to the loss of a slice of beach 100 m wide, 10 m deep, and 1.7 km long each year.

There is little doubt that human impacts on fluvial sediment supply can have profound implications for coastal sediment budgets. Assessment of the magnitude of such impacts is often difficult and uncertain. However there is little doubt that in the case of sediment impoundment by dams and debris basins in southern California the impact is substantial. Even if the analysis reported here is subject to large errors in estimation (e.g., +/- 50%), the resulting impact is large enough to warrant the attention of coastal managers.

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