Received: 8 November 2017 | Revised: 13 February 2019 | Accepted: 13 February 2019
DOI: 10.1002/rra.3443

RESEARCH ARTICLE

WILEY

Dam effects on bedload transport on the upper Santa Ana River, California, and implications for native fish habitat

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Funding information
U.S. Geological Survey; U.S. Fish and Wildlife Service; San Bernardino Valley Municipal Water District

Abstract

Dams disrupt the flow of water and sediment and thus have the potential to affect the downstream geomorphic characteristics of a river. Though there are some well-known and common geomorphic responses to dams, such as bed armouring, the response downstream from any particular dam is dependent on local conditions. Herein, we investigate the response of the upper Santa Ana River in southern California, USA, to the construction of a large dam at the transition from mountains to valley, using calculations of bedload transport capacity on the mainstem below the dam and for major tributaries. Approximate sediment budgets were constructed for downstream reaches to estimate deposition and erosion rates for sand, gravel, and cobble particle sizes. Our results indicate that the classical response of bed armouring and erosion is likely limited to a short reach immediately below the dam. Farther downstream, though transport capacity is reduced by flow regulation by the dam, the channel reaches are likely to remain depositional but with reduced deposition rates. Persistent deposition, as opposed to erosion, is the result of the replenishment of flow and sediment supply by large downstream tributaries. In addition, the calculations indicate that the composition of the bed is unlikely to change substantially in downstream reaches. A Monte Carlo approach was employed to estimate the uncertainty in the sediment budget predictions. The impacts of the dam on the geomorphic character of the river downstream could have implications for native fish that rely on coarse substrate that supports their food base.

KEYWORDS

bedload transport, deposition and erosion, downstream effects of dams, fish habitat, Santa Ana River

1 | INTRODUCTION

Dams can have substantial effects on the geomorphology and sediment transport characteristics of downstream river reaches. These effects occur primarily because the reservoirs created by dams trap at least some portion of the incoming sediment load and thus release water with less sediment than would occur without the dam. In addition, dams affect the downstream flow hydrograph, typically through a reduction in peak flows and an increase in low and medium flows through temporary storage and release of water in the reservoir.

These dam-induced changes to flow and sediment supply can manifest a variety of downstream geomorphic impacts, depending upon the particular set of circumstances for each dam. Williams and Wolman (1984) conducted an extensive review of the downstream effects of 21 dams, documenting decreased flood peaks, decreased sediment concentrations for long distances downstream, bed erosion and coarsening, changes in channel width, and increased riparian vegetation. These responses, including bed erosion, coarsening, and the development of an armour layer (Vericat, Batalla, & Garcia, 2006), are likely to occur immediately downstream from most dams. However, as one moves farther downstream from a dam, the river response becomes more variable and increasingly dependent on the supply of water and sediment from tributaries. This variability in responses has led to the development of several methodologies and metrics for assessing the downstream impacts of a particular dam. Brandt (2000a, 2000b) reviewed many case studies and developed a classification system comprising nine styles of channel change based on Lane's classical sediment balance concept, as well as a method to predict downstream channel change. Building on this previous work, Grant et al. (2003) and Schmidt and Wilcock (2008) developed metrics for evaluating the downstream effects of dams based on the "sediment budget" concept; that is, the effect of a dam on a particular reach depends on whether that reach experiences a post-dam sediment deficit or surplus. Sediment budgets are an effective method for evaluating the downstream effects of dams because they can account for the effects of downstream tributaries on the sediment balance.

Herein, we evaluate the downstream effects on bedload sediment transport of Seven Oaks Dam on the upper Santa Ana River (SAR), California, USA. In particular, we focus on how the impact of the dam varies downstream as unregulated tributaries replenish the sediment supply to the mainstem. The sediment supply to downstream reaches, particularly of gravel-sized particles, has important implications for the Santa Ana sucker, a federally threatened native fish.

1.1 | Site description

The SAR basin is the largest in southern California, with headwaters in the San Gabriel and San Bernardino Mountains and draining to the Pacific Ocean near Newport Beach, CA (Figure 1). The watershed can be divided into upper and lower sections at the Prado Dam, a reservoir constructed in the 1940s at a natural constriction in the river. The upper Santa Ana watershed consists of the mountain headwaters and the San Bernardino Valley, which can be classified as a sandy, braided-river depositional system (Haner, 1984). The longitudinal profile of the river in the valley exhibits the classical upward-concave shape of depositional basins (Figure 1), with decreasing slope and sediment transport capacity in the downstream direction. The valley is highly urbanized with a population of about 4 million people in the metropolitan area, requiring flood protection for valley residents. In response to flooding concerns, Seven Oaks Dam was constructed in the late 1990s at the approximate location where the river emerges from the mountains into the valley (Figure 1). The dam reduces peak flows downstream and also traps the incoming sediment load, particularly the coarse sizes. These changes in the flow hydrograph and sediment supply have the potential to affect the geomorphology of downstream reaches on the SAR.

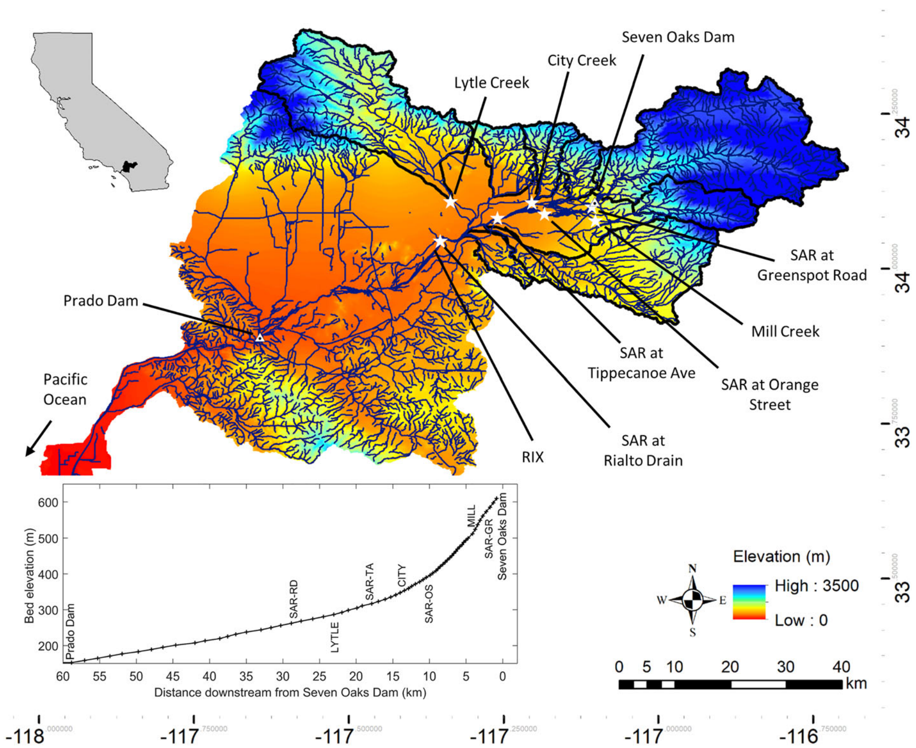

FIGURE 1 Upper Santa Ana River watershed elevation map showing the locations of major dams (Seven Oaks and Prado) and locations of measurement and transport calculation sites. Inset shows longitudinal elevation profile from Seven Oak Dam to Prado Dam (see Table 1 for site names)

Approximately 28 km downstream from Seven Oaks Dam, perennial flow is supported in the mainstem by discharges from two wastewater treatment plants (the mainstem upstream is typically dry during the summer and fall seasons). The majority of perennial flow is provided by the Rapid Infiltration and Extraction plant (RIX), which discharges about 1.2 m^3/s of treated water. The wastewater discharges have established a channel of about 10-m width, which is inset within the much larger flood control channel (about 250-m width). This inset channel supports the only remaining population within the watershed of the Santa Ana sucker (Thompson, Baskin, Swift, Haglund, & Nagel, 2010). An important aspect of the inset channel habitat is the presence of coarse particles (gravel and cobble), which provide the substrate for the sucker food base of diatoms and algae (Burton, Brown, & Belitz, 2005; Thompson et al., 2010).

The presence of Seven Oaks Dam has raised concerns within the resource management community regarding its potential reduction of coarse sediment supply to the river reach currently occupied by the sucker. The dam impounds a portion of the watershed within the steep terrain of the San Bernardino Mountains (Figure 1) and thus has cut off some portion of the coarse sediment supply. In addition, the dam has reduced the peak flows that would transport the largest volumes of coarse sediment. However, several large, mostly unregulated tributaries (Mill Creek, City Creek, and Lytle Creek; see Figure 1) enter the mainstem between Seven Oaks Dam and the reach occupied by the sucker. These tributaries have the potential to deliver substantial flows and sediment to the mainstem. Thus, the effects of Seven Oaks Dam on downstream sediment transport and geomorphology must take into consideration the effects of these tributaries.

The primary objective of the analyses reported herein is to evaluate the impacts of Seven Oaks Dam on coarse-sediment bedload transport rates in downstream reaches, with particular focus on the influence of downstream tributaries. In addition, we discuss the implications of our results in relation to coarse substrate in the reach occupied by Santa Ana sucker.

2 | METHODS

The analyses presented herein are based on calculations of bedload transport capacity using channel hydraulic and bed sediment particle size information only. No bedload measurements are available for the SAR, and given the dangerous nature of high flows in this river and its tributaries, bedload measurements are not logistically feasible.

2.1 | Transport capacity calculations

The transport capacity for sand, gravel, and cobble-sized sediment was computed at several locations along the mainstem and for the major tributaries, using the Bedload Assessment for Gravel-Streams (BAGS) software tool (Pitlick, Cui, & Wilcock, 2009). BAGS is a software programme for computing sediment transport capacity, with a range of options available for the methods used. For this study, we applied two of the more popular methods for bedload transport calculations: the Wilcock and Crowe (2003) and Parker (1990) methods. The Wilcock and Crowe (2003) method is particularly attractive for the SAR because it was specifically developed for use with gravel–sand mixtures. Initial test calculations indicated that the primary results and conclusions were similar for the two methods; thus, we report only the Wilcock and Crowe results herein. BAGS computes the sediment transport capacity, on a particle-size-specific basis, based on hydraulic variables and the distribution of particle sizes on the bed. The input variables required for the BAGS calculations are the discharge, channel cross-section, channel bed slope, and bed sediment particle-size distribution (PSD). With this information, BAGS computes the sediment transport capacity for individual particle size bins as defined in the PSD data.

Bedload transport calculations were performed for a range of flows with annual exceedance probabilities of 0.5, 0.2, 0.1, 0.04, 0.02, and 0.01 (corresponding to return intervals of 2, 5, 10, 25, 50, and 100 years). In addition, the effects of Seven Oaks Dam were evaluated using flow estimates with and without the dam in place. The flow values used were those developed by the Corps of Engineers (CoE) in their studies evaluating the effects of Seven Oaks Dam (Corps of Engineers, 1988). The CoE peak flows were developed based on flood-frequency analyses of USGS gage data available at that time. The USGS gage just downstream from Seven Oaks Dam (USGS 11051500) has an annual peak flow record dating to 1897, and the major tributaries such as Mill Creek, City Creek, and Lytle Creek have USGS gages with records dating to the 1920s. For comparison, we updated these flood-frequency estimates using the entire period of record for each gage (Parrett et al., 2011; Veilleux, Cohn, Flynn, Mason, & Hummel, 2014) and computed transport rates for all sites based on the two different sets of flow estimates. The CoE flood-frequency estimates were chosen for presentation herein for two reasons: (a) the differences between transport rates computed from the two sets of flow estimates were well within our uncertainty estimates (described below) and (b) the CoE flood-frequency estimates for the case with Seven Oaks Dam in place are preferable because they are based on reservoir storage and operating rules. Though it is possible to compute flood-frequency for below the dam from the annual peak flows from 1999 to present (the years with the dam in place), this is likely subject to more error than estimates based on reservoir routing, because the period of record is short and the flow is regulated. Appendix A contains the CoE flow information for all sites that was used in the transport calculations.

2.2 | Field methods

Channel cross-sections, bed slopes, and bed sediment PSDs were measured at four mainstem locations and on five tributaries during May 2013. Channel cross-sections and slopes were surveyed using RTK-GPS (slopes were computed from thalweg profiles over a distance of approximately five channel widths at each site). Bed sediment PSDs were determined by taking photographs of the bed at equally spaced increments across the channel. A photograph of a scale was used to determine the size of each pixel (typically ~0.3 mm/pixel) in the photographs. Individual particle sizes were then measured on the photographs and the results accumulated to develop the cross-section averaged PSD. Twenty-five individual particles from each photograph were selected randomly and measured. Particles finer that 2 mm (sand) were accumulated into a single group from the photographs. The number of photographs ranged from 17 to 23 for a given site depending on channel width. To characterize the PSD of particles finer than 2 mm, three grab samples were collected at each site from patches of fine sediment. These samples were sieved for sizes greater than 1 mm (typically less than 10% of the samples); sediment finer than 1 mm was processed for PSD using a Beckman Coulter LS 13 320 Laser Particle Size Analyzer. The results from the photographic analysis and the grab samples were then combined to determine the full PSD from 0.0625 to 1,024 mm.

Two of the tributaries for which measurements were made, Warm Creek and Reche Creek, were not incorporated into the analysis because computed transport rates were much less than those of the other tributaries. Also, San Timeteo Creek, a relatively large tributary draining from the southwest, was excluded from further analyses due to the presence of a series of sediment-trapping debris basins approximately 6 km upstream from its confluence with the SAR. Figure 2 shows the measured channel cross-sections and PSDs for all of these sites (Appendices B and C contain the cross-section and PSD data). Table 1 presents the measured bed slopes, approximate channel widths, and fractions (as percent) of sand, gravel, and cobble in the PSDs for each site.

2.3 | Deposition and erosion (sediment budget) estimates

The computed transport capacities from BAGS were used to estimate erosion and deposition rates in reaches of the mainstem through application of the Exner equation (e.g., Paola & Voller, 2005), which is an expression of conservation of mass of sediment in differential form, as follows:

$$B(1-p)\frac{\partial \eta}{\partial t} = -\frac{\partial Q_s}{\partial x}, \tag{1}$$

where B is channel width, p is porosity, η is bed elevation, Q_s is volumetric sediment transport rate, t is time, and x is longitudinal distance. Equation (1) can be used with the total sediment transport rate to compute the total bed elevation change, or it can be written for individual particle size bins and used to compute the rate of change of a given size fraction on the bed (e.g., Parker, 2008). For our purposes here, Equation (1) can be rearranged into a simple control volume form as follows:

$$D = \frac{Q_{s,\text{in}} - Q_{s,\text{out}}}{B(1-p)\Delta x}, \tag{2}$$

where D represents the deposition (or erosion) rate for a given reach, Δx is the reach length, and $Q_{s,\text{in}}$ and $Q_{s,\text{out}}$ represent sediment transport capacity entering and leaving the reach, respectively. We apply this equation to two reaches of the mainstem (described in a later section) to estimate the total deposition/erosion rate, for a range of flows with and without Seven Oaks Dam. In addition, we apply Equation (2) to the same reaches for three particle size ranges (sand, gravel, and cobble) as follows:

$$D_k = \frac{Q_{sk,\text{in}} - Q_{sk,\text{out}}}{B(1-p)\Delta x}, \tag{3}$$

where the k subscript denotes an individual particle size bin (sand, gravel, or cobble) such that $D = \sum D_k$, $Q_{s,\text{in}} = \sum Q_{sk,\text{in}}$, and Q_s,

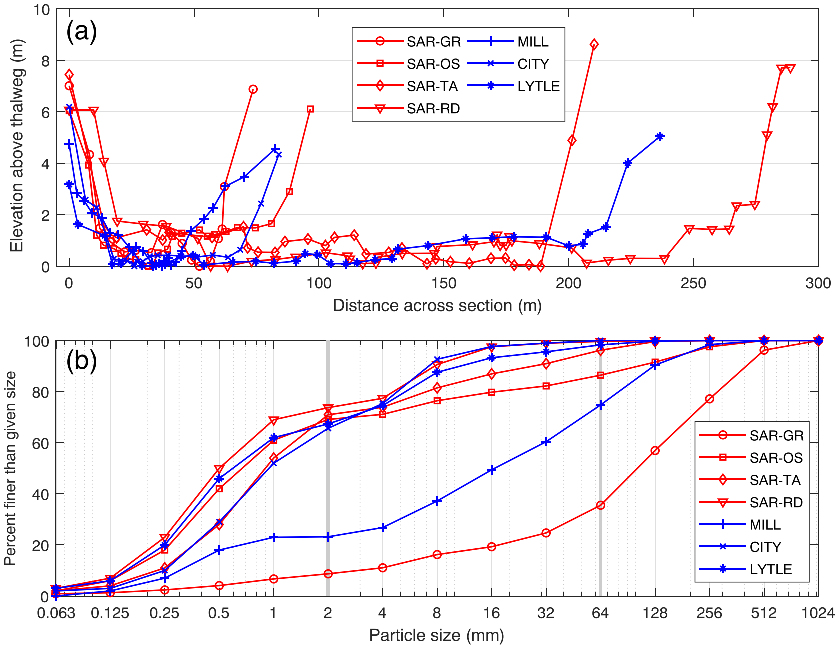

FIGURE 2 Measured channel cross-sections (a) and particle size distributions (b) at all sites

TABLE 1 Site names, locations, and characteristics of channel hydraulics and bed sediment particle size distributions

Site name	Latitude (north)	Longitude (west)	Bed slope (m/m)	Channel width (m)	Percent sand	Percent gravel	Percent cobble
Santa Ana River near Greenspot Road (SAR-GR)	34°6′1.67″	117°6′23.26″	0.025	70	9	27	64
Santa Ana River near Orange Street (SAR-OS)	34°5′19.20″	117°10′58.05″	0.013	90	69	17	14
Santa Ana River near Tippecanoe Avenue (SAR-TA)	34°4′55.09″	117°15′32.17″	0.0067	200	71	25	4
Santa Ana River above Rialto Drain (SAR-RD)	34°2′44.20″	117°21′4.52″	0.0031	270	74	26	0
Mill Creek near Greenspot Road (MILL)	34°4′39.91″	117°6′1.28″	0.036	70	23	52	25
City Creek near 5th Street (CITY)	34°6′25.44″	117°12′11.24″	0.0072	80	66	34	0
Lytle Creek near Hwy 66 (LYTLE)	34°6′30.85″	117°20′4.41″	0.0064	230	67	31	2

$_{out} = \sum Q_{sk,out}$. These estimates were then used to compute the fraction of deposition or erosion due to each size bin:

$$F_k = \frac{D_k}{D}. \tag{4}$$

Deposition and erosion rates were computed based on the transport capacity calculations for two reaches of the mainstem using Equations (2)–(4). Reach 1 extends from the SAR–Mill Creek confluence to Tippecanoe Avenue (Figure 1) and includes the tributaries Mill Creek and City Creek. The reach length is 13 km, and the average channel width is about 150 m. Reach 2 extends from Tippecanoe Avenue to the confluence with Rialto Drain (Figure 1) and includes the tributary Lytle Creek. The reach length is 11 km, and the average channel width is about 250 m. For both reaches, we used a porosity of 0.35 in Equations (2) and (3), which is a typical value for coarse sand and gravel particle sizes (Wu & Wang, 2006). It is important to note that the deposition and erosion rates computed herein are reach averages such that local effects (such as erosion at structures and channel constrictions) may not be captured and reflected.

2.4 | Uncertainty analysis

There are many potential sources of error in sediment transport capacity calculations, and the cumulative level of uncertainty resulting from these errors is difficult to quantify. Sources of error in the calculations include peak flow estimates; channel cross-section location selection; the assumption of a steady, uniform flow for computing bed shear stress; bed sediment PSD measurements; and sediment transport equations. Previous compilations of comparisons between measured bedload transport rates with those predicted from transport equations demonstrate errors of an order of magnitude or greater (Gomez and Church, 1989, Barry, Buffington, & King, 2004). Although this is likely due to many factors, including measurement errors and the stochastic nature of sediment transport, it illustrates the difficulty in making precise calculations of sediment transport rates. Because it is impossible to quantify the error precisely, our approach was to specify a reasonable range of uncertainty in the transport calculations and compute how this uncertainty propagates into the deposition and erosion estimates. This is similar to the approach of assigning uncertainty estimates for sediment transport measurements and then propagating this uncertainty into sediment budgets, which is common practice.

To estimate the bedload transport uncertainty, we employed a Monte Carlo-type analysis. First, we specified two possible uncertainty levels on the transport rates computed from BAGS: ±50% and ±100%. For each calculated value of bedload transport capacity at a given site, we then generated a distribution of 10,000 possible values by randomly sampling from a normal distribution with the specified uncertainty. In this sampling, the mean was specified as the calculated transport rate, and the uncertainty values were specified as 95% confidence intervals. Thus, the distribution standard deviation was approximately 25% of the mean for the ±50% case and 50% of the mean for the ±100% case, because for a normal distribution, the 95% confidence interval bounds are approximately 2 standard deviations. These distributions of 10,000 transport rates were then used in Equation (2) for $Q_{s,in}$ and $Q_{s,out}$ to compute distributions of deposition/erosion rates. Because each site was sampled randomly and independently from other sites, this procedure thus encompasses the widest possible range of error scenarios.

3 | RESULTS AND DISCUSSION

3.1 | Transport capacity

The results of the BAGS transport capacity calculations for the mainstem sites are summarized in Figures 3–5 for sand, gravel, and cobble size ranges and for flows with and without Seven Oaks Dam. Several observations are apparent. For the without Seven Oaks Dam scenario, there is a general trend for the transport capacity of gravel and cobble to decrease in the downstream direction. This is an expected result for a system of rapidly decreasing slope (Figure 1, Table 1) like the upper SAR and is indicative of a depositional system. This trend is the mechanism leading to downstream fining of the bed sediment (Table 1). One notable exception to this trend is seen in the sand transport results at the most upstream site (SAR near Greenspot Road [SAR-GR]), where computed sand transport rates tend to be lower than those of the downstream sites. This may be due to winnowing of sand from the bed immediately below Seven Oaks Dam (which was constructed between 1993 and 2000) such that our recent measurements (2013)

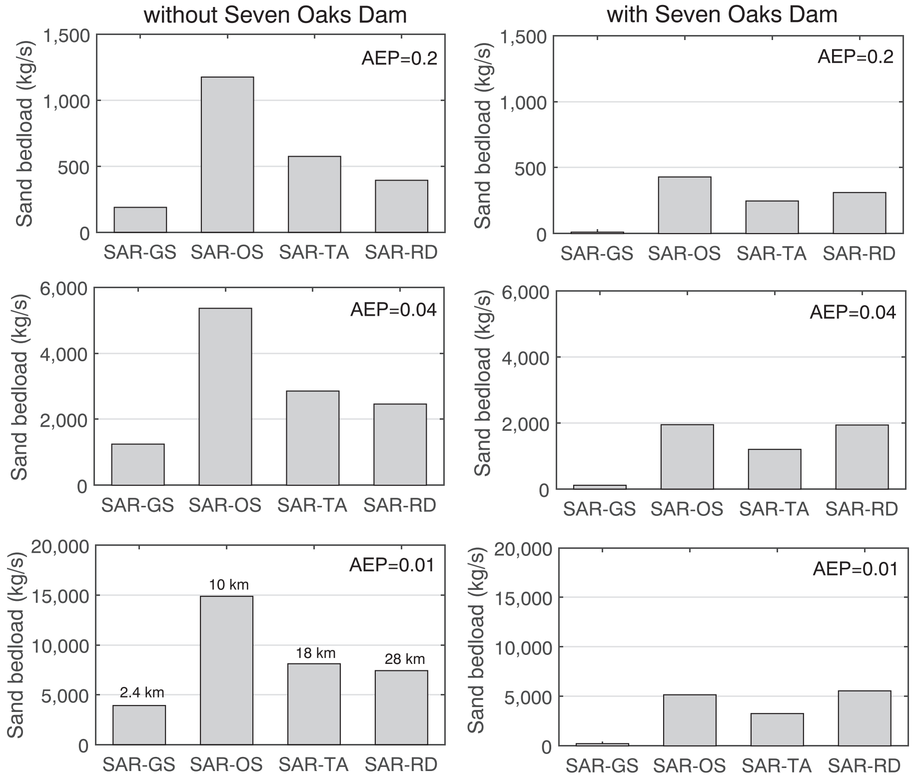

FIGURE 3 Calculated sand (<2 mm) bedload transport rates at the mainstem sites for three annual exceedance probabilities (AEPs). Left column is without Seven Oaks Dam, right column is with Seven Oaks Dam. Distances in the lower left panel refer to the distance downstream from Seven Oaks Dam of each site

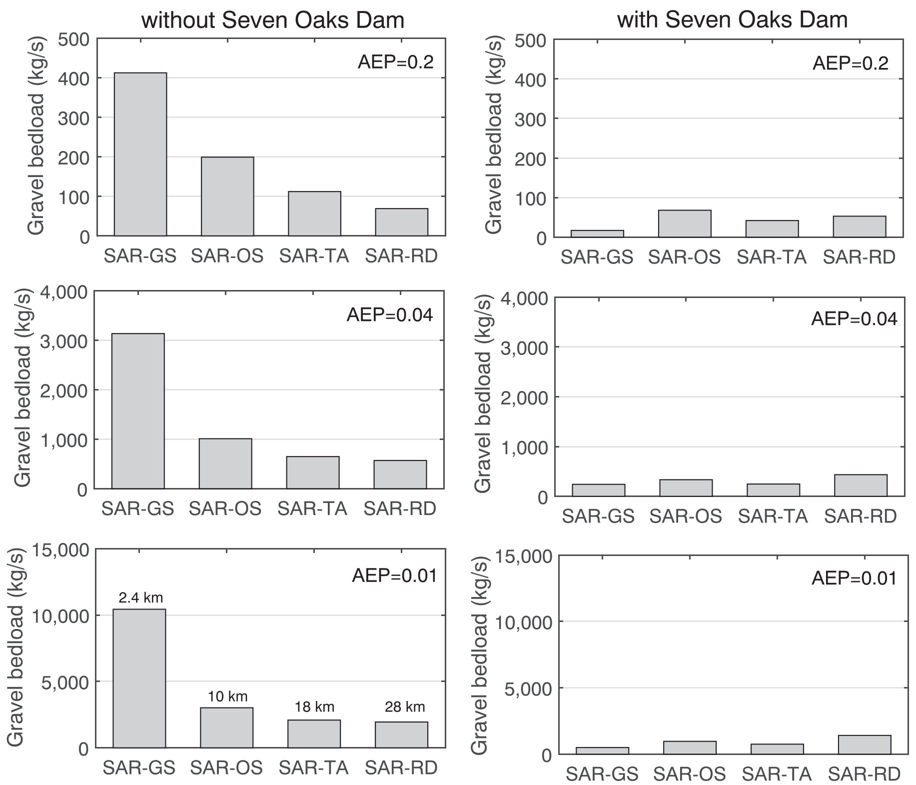

FIGURE 4 Calculated gravel (2–64 mm) bedload transport rates at the mainstem sites for three annual exceedance probabilities (AEPs). Left column is without Seven Oaks Dam, right column is with Seven Oaks Dam. Distances in the lower left panel refer to the distance downstream from Seven Oaks Dam of each site

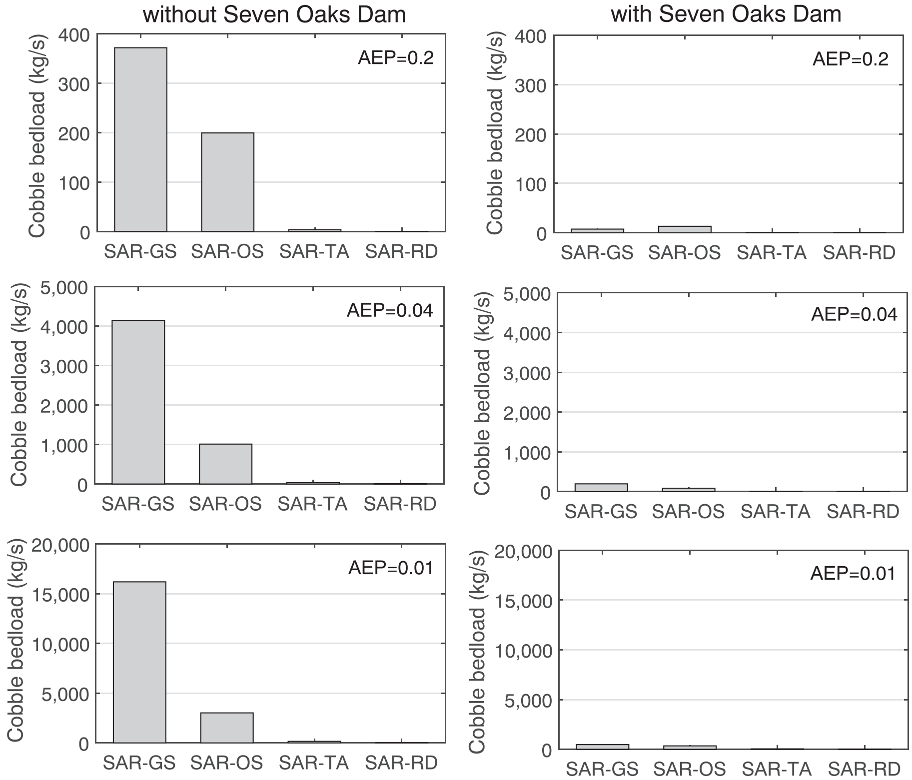

FIGURE 5 Calculated cobble (>64 mm) bedload transport rates at the mainstem sites for three annual exceedance probabilities (AEPs). Left column is without Seven Oaks Dam, right column is with Seven Oaks Dam. Distances in the lower left panel refer to the distance downstream from Seven Oaks Dam of each site

of bed sediment PSD do not accurately reflect the "without Seven Oaks Dam" PSD, in particular for the finer sizes.

The mainstem bedload transport results exhibit a trend of downstream-decreasing sediment transport capacity that has been substantially affected by flow regulation at Seven Oaks Dam (Figures 3–5). This is the result of reduced peak flows, which is most prevalent at the upstream sites (Appendix A). Calculated transport capacity is reduced by Seven Oaks Dam flow regulation at all sites for sand, gravel, and cobble sizes for all flow annual exceedance probabilities analysed. The magnitude of the decrease in transport capacity varies based on distance downstream from the dam because of the addition of flow from downstream tributaries. To evaluate the magnitude of the reduction, we computed the percent reduction in transport capacity at each site for each flow level. Because the percent reduction tended to be quite consistent across all flows, we computed the average value over all flows. These results indicate that transport capacity has been reduced by about 90% at the most upstream site (SAR-GR), which is immediately downstream from the dam (2.4 km) and upstream of any major tributaries. At the next two downstream sites (SAR near Orange Street and SAR near Tippecanoe Avenue, 10 km and 18 km downstream from the dam, respectively), transport capacity has been reduced by about 60–70%; the tributaries Mill Creek and City Creek enter the mainstem in this reach. At the most downstream site (SAR above Rialto Drain, 28 km downstream from the dam), which is downstream from the tributary Lytle Creek, calculated transport capacity is reduced by about 20–30%. At all sites, the percent reduction in transport capacity is correlated with particle size; that is, the capacity to transport cobble is reduced the most, followed by gravel, followed by sand. This reflects the nonlinear relations among flow, transport, and particle size. Overall, these results provide a good illustration of the well-known phenomenon of decreasing dam influence with increasing distance downstream (Schmidt & Wilcock, 2008; Williams & Wolman, 1984); in the case of the upper SAR, this pattern owes to substantial flows and sediment supply from downstream tributaries.

The transport capacity results for the tributaries (Figure 6), Mill Creek, City Creek, and Lytle Creek, indicate that Mill Creek is the largest source of coarse sediment to the mainstem SAR. The high sediment supply rates for Mill Creek, particularly for gravel and cobble, owe to its steep slope, availability of coarse bed sediment (Table 1), and relatively high peak flows (Appendix A). The bedload transport results for Lytle Creek also indicate that it is a substantial source of sediment to the mainstem, though its sediment supply is substantially finer than that of Mill Creek. The calculations indicate that Lytle Creek delivers a comparable amount of sand as Mill Creek but substantially less gravel and cobble. But gravel transport rates for Lytle Creek are comparable with gravel transport rates on the downstream mainstem sites, and thus it appears to be an important gravel supply to the mainstem. Computed transport rates for City Creek were much lower than those of Mill Creek and Lytle Creek,

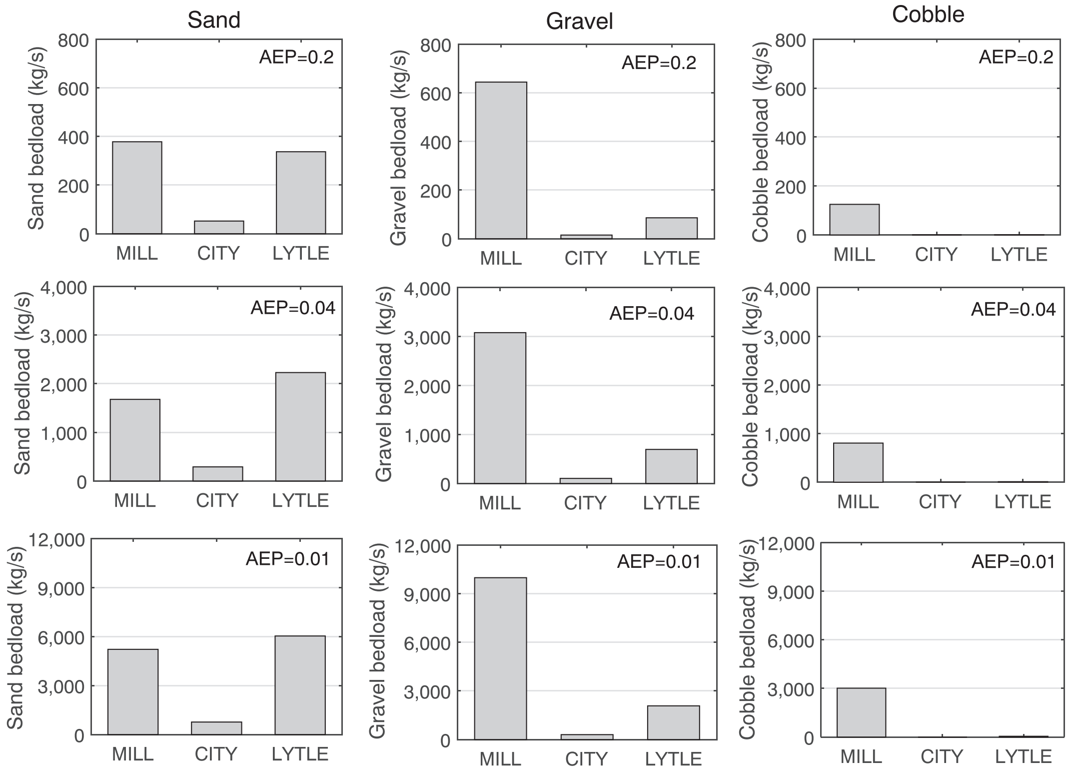

FIGURE 6 Calculated sand (left column), gravel (centre column), and cobble (right column) transport capacity at the three tributary sites

as well as the mainstem sites; hence, City Creek does not appear to be an important sediment source.

3.2 | Deposition and erosion rates

The results of the sediment budgets for Reaches 1 and 2 are shown in Figure 7 and indicate that almost all calculations suggest deposition as opposed to erosion (see uncertainty analysis [Section 3.3]). Several observations are apparent from the results. First, total deposition rates increased systematically with flow for both reaches. Second, deposition rates were greater in Reach 1 than in Reach 2 for gravel and cobble sizes by a factor of about four on average. This is due to the larger divergence in slope and transport capacity in Reach 1, as well as the influence of Mill Creek. The effect of Seven Oaks Dam is to consistently reduce deposition rates for all flows evaluated (the one exception to this is for sand sizes in Reach 1). In Reach 1, the percent reduction in total deposition rates increased with increasing flow, from a 14% decrease for AE0.2 to a 60% decrease for AE0.01. For Reach 2, the percent reduction was consistent across all flows and averaged 42%.

The reductions in deposition rate are ultimately a result of decreases in the upstream sediment supply to a given reach. In addition to the reduction of deposition rates, the source of the sediment available for deposition becomes skewed towards the major tributaries. The results for Reach 1 illustrate this behaviour: For AE0.04 (as an example), the calculated upstream supply without Seven Oaks Dam was about 8,500 kg/s (SAR-GR) plus 5,600 kg/s (Mill Creek near Greenspot Road), and the calculated export (SAR near Tippecanoe Avenue) was about 3,500 kg/s. With Seven Oaks Dam, the upstream supply from SAR-GR was reduced to 600 kg/s (plus Mill Creek near Greenspot Road, which remains unchanged), and the calculated export (SAR-TA) was reduced to 1,500 kg/s. The deposition rate is driven by the difference between upstream supply and export (in minus out); for this case, in minus out was 10,600 kg/s without the dam and 4,700 kg/s with the dam (56% reduction in deposition rate). In addition, the sediment available for deposition post-dam is almost all from Mill Creek, whereas pre-dam, the upstream supply was comparable between Mill Creek and the SAR above Seven Oaks Dam.

The results for the individual particle size bins (sand, gravel, and cobble) illustrate differences between the two reaches. Reach 1 is dominated by deposition of gravel and cobble in comparison with sand; gravel and cobble sizes accounted for about 90% of calculated deposition rates in Reach 1. However, as noted previously, this could be the result of underprediction of sand transport at site SAR-GR due to winnowing of the bed at this site since dam construction. That said, the results still demonstrate substantial deposition of gravel and cobble in this reach. With respect to the effects of Seven Oaks Dam in Reach 1, Figure 7 shows that the greatest impact is on deposition of cobble sizes. The reduction in cobble deposition was consistent across flows and averaged 74%; gravel deposition reduction was also relatively consistent across flows and averaged 38%.

In contrast to Reach 1, Reach 2 is dominated by deposition of sand and gravel in comparison with cobble (Figure 7); sand and gravel sizes

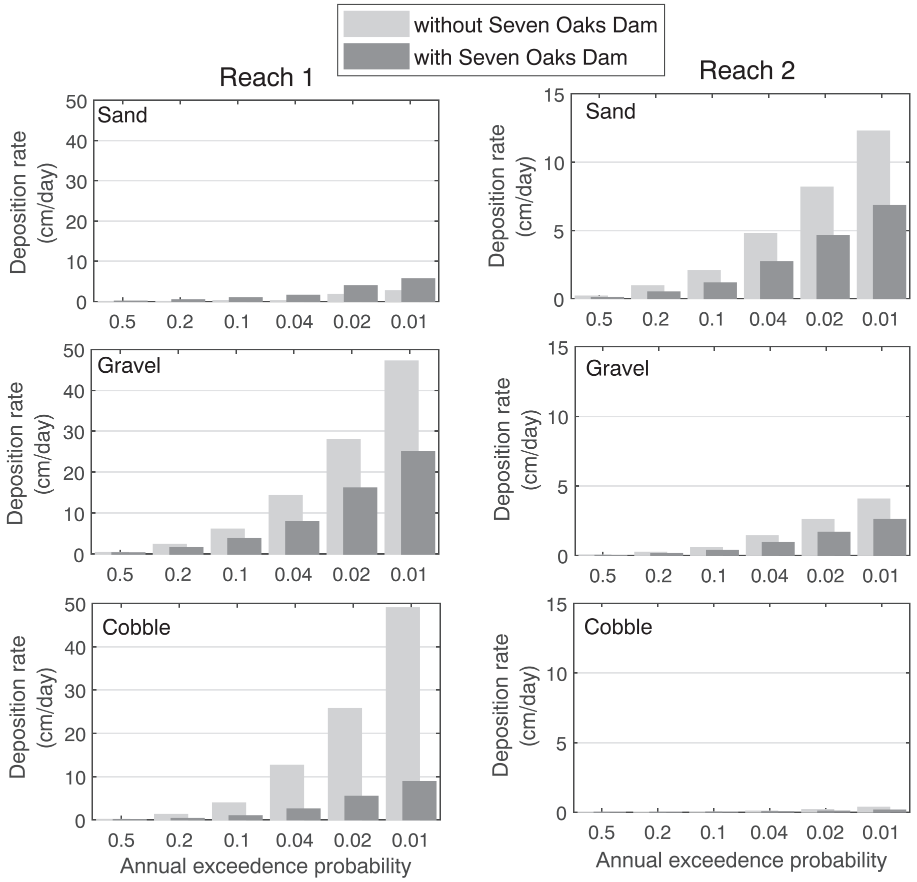

FIGURE 7 Computed deposition rates for Reach 1 (left column) and Reach 2 (right column) for sand (top row), gravel (middle row), and cobble (bottom row) with and without Seven Oaks Dam. The *y*-axis is consistent for all panels for each reach for comparison purposes

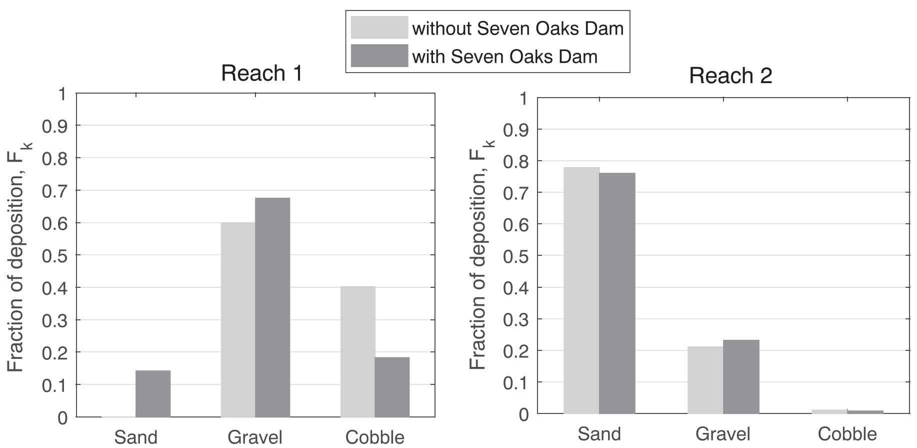

FIGURE 8 Fraction of deposition due to a give particle size range, computed from Equation (4), for both reaches with and without Seven Oaks Dam

accounted for about 98% of calculated deposition rates in Reach 2. This is reflected in the prevalence of sand and gravel in our bed sediment measurements in this reach (Table 1). With respect to the influence of Seven Oaks Dam, the reduction in deposition rate is relatively consistent for all flows and across particle size ranges: The average percent reductions are 44%, 36%, and 57% for sand, gravel, and cobble, respectively.

Figure 8 summarizes the results obtained from Equation (4), which was used to compute the proportion of deposition in each reach due to the individual size fractions. The computed fractions were relatively consistent across the flow levels, thus the results shown are averaged over all flows. These results reinforce those shown in Figure 7; namely, that in Reach 1 deposition is dominated by gravel and cobble, whereas in Reach 2, deposition is dominated by sand and gravel. The

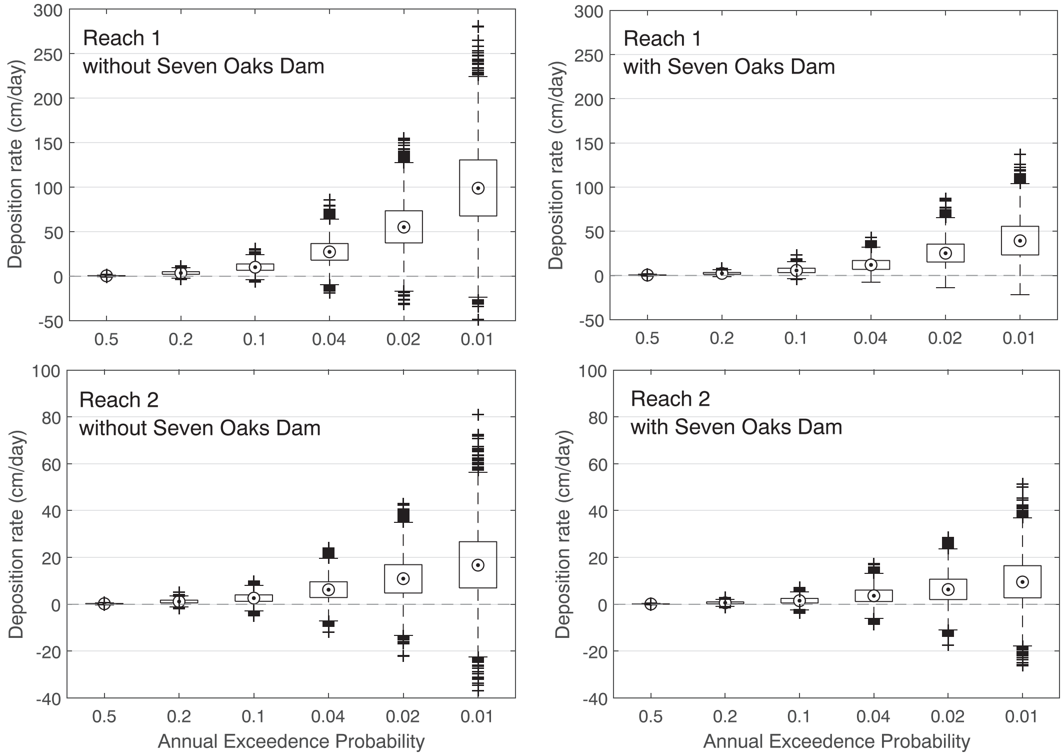

FIGURE 9 Distributions of deposition rates from Monte Carlo analysis for the case with 95% confidence intervals of ±100% on transport rates

results for Reach 1 suggest that the bed in this reach is likely to become finer due to Seven Oaks Dam; this is because the upstream supply to Reach 1 becomes finer with the dam in place due to a reduction of cobble transport into this reach. Conventional wisdom is that the bed of a river will coarsen immediately downstream from a dam due to winnowing of finer sizes, and this is certainly the case on the upper SAR in the reach from Seven Oaks Dam to its confluence with Mill Creek. However, our calculations indicate that this coarsening is likely to be restricted to this upper reach and that downstream from Mill Creek (Reach 1), the bed is likely to become slightly finer (Figure 8). Results for Reach 2 indicate that Seven Oaks Dam is not likely to substantially affect the composition of the bed in this reach. On a fractional basis (i.e., relative to other size fractions), gravel deposition is predicted to slightly increase, and sand deposition is predicted to slightly decrease due to Seven Oaks Dam; however, the calculations suggest that these changes will be small.

3.3 | Uncertainty analysis

The results of the Monte Carlo simulations are presented in Figure 9 as box-and-whisker plots. Each box-and-whisker represents the distributions resulting from the 10,000 simulations. Only the results for ±100% uncertainty on transport capacity are shown in Figure 9; the results for the ±50% uncertainty are visually similar, and the differences are quantified below. The deposition rates shown in Figure 9 are for all particle sizes combined. The Monte Carlo results demonstrate the wide range in deposition rates that are predicted when accounting for uncertainty in the transport capacity calculations.

One of the primary findings from the transport calculations is the prediction that both reaches are depositional for the scenarios with and without Seven Oaks Dam. However, Figure 9 indicates that when uncertainty is included in the transport calculations, some of the simulations do result in negative deposition rates (i.e., erosion in the reach). In general, the probability of an erosion prediction is relatively low but also dependent on the reach, the level of uncertainty specified, and the presence of Seven Oaks Dam. For example, for the ±50% uncertainty level, the probability of an erosion prediction in Reach 1 without Seven Oaks Dam ranged from 0% to 0.35% (depending on flow), and with Seven Oaks Dam, it ranged from 0.05% to 0.2%. For Reach 1 with ±100% uncertainty, these probability ranges increase to 1.3–8.8% and 4.6–7.6%, respectively. Thus for Reach 1, where deposition rates are predicted to be higher overall than those of Reach 2, there is a high probability (>90%) of a deposition prediction for all scenarios evaluated.

For Reach 2, the probability of an erosion prediction is higher than in Reach 1, because deposition rates in Reach 2 are lower overall than in Reach 1. For the ±50% uncertainty level, the probability of an erosion prediction in Reach 2 without Seven Oaks Dam ranged from 0.12% to 1.2% (depending on flow), and with Seven Oaks Dam, it ranged from 0.51% to 3.8%. For Reach 2 with ±100% uncertainty, these probability ranges increased to 5.9–12.3% and 9.8–17.3%, respectively. Thus, there is a relatively small probability that the presence of Seven Oaks Dam could change Reach 2 from depositional to erosional. That said, the probability of a deposition prediction in Reach 2 with Seven Oaks Dam is still approximately 80–90% for the higher uncertainty level.

4 | SUMMARY AND CONCLUSIONS

The upper SAR is characterized by rapidly downstream-decreasing slope and downstream fining of bed sediment, which are both indicative of a depositional environment. Indeed, the study area analysed here encompasses the transition from the San Bernardino Mountains to the San Bernardino Valley. Construction of Seven Oaks Dam in the late 1990s has disrupted this environment due to reduced peak flows and reduced sediment supply. In this paper, we analysed the potential effects of Seven Oaks Dam on transport and deposition rates in downstream reaches.

Our results indicate that reduced peak flows, due to the presence of Seven Oaks dam, result in reduced transport capacity in the downstream channel. The reductions in transport capacity are greatest immediately downstream from the dam and become less pronounced further downstream as tributaries deliver flow and sediment to the mainstem. This is mostly consistent with the classical response for river reaches downstream from dams. Reductions in transport capacity and upstream sediment supply have the potential to change a river reach from depositional to erosional, depending on sediment supply from tributaries in the reach. For the upper SAR, the reach between Seven Oaks Dam and the Mill Creek confluence has almost certainly experienced this change, because the sediment supply to this reach is now effectively zero. Downstream from Mill Creek, however, our calculations indicate that this reach will remain depositional but with reduced deposition rates. This is due to substantial flow and sediment supply from Mill Creek. This trend is also supported by our calculations further downstream where Lytle Creek provides another substantial flow and sediment source. Thus, although our calculation results suggest a substantial effect of Seven Oaks Dam on downstream transport and deposition rates, they also suggest that the overall geomorphic environment (depositional basin) is likely to remain unchanged. This is the result of sediment supply from Mill Creek and Lytle Creek; without this supply, our calculations suggest that the river would become erosional for both of the reaches studied.

These results have important implications for Santa Ana sucker in the upper SAR, which are dependent on coarse substrate to support its food base. The Santa Ana sucker currently reside in a small “inset” channel within the mainstem SAR in the vicinity of Rialto Drain, where perennial flow is supported by wastewater discharge plants. In this reach, coarse sediment (gravel and cobble) provides the substrate that supports the food source and channel complexity favoured by native fish. Thus, the potential for Seven Oaks Dam to reduce the supply of coarse sediment to this reach has been a concern. Our results indicate that although Seven Oaks Dam does indeed decrease coarse sediment supply and deposition rates in the reach currently occupied by native fish, there remains substantial sediment supply from Mill Creek, Lytle Creek, and the bed of the mainstem upstream. Mill Creek and Lytle Creek are important sediment-supplying tributaries to this reach of the SAR, such that any future developments on these tributaries should be rigorously evaluated with respect to potential effects on the mainstem sediment balance. In addition, our results indicate that the reach occupied by native fish is likely to remain depositional with respect to gravel and cobble but at slightly reduced rates as compared with the scenario without Seven Oaks Dam. Finally, our calculations suggest that the composition of the bed in the reach occupied by native fish is not likely to change substantially, because the reductions in transport and deposition rates are consistent among sand, gravel, and cobble sizes. Therefore, we conclude that the presence of Seven Oaks Dam, although having a substantial effect on peak flows, downstream transport capacity, and deposition rates, is unlikely to affect the availability of coarse substrate in the reach occupied by native fish.

ACKNOWLEDGEMENTS

This study was funded by the San Bernardino Valley Municipal Water District and U.S. Fish and Wildlife Service. We are grateful for helpful suggestions from USGS reviewers, USFWS staff, and anonymous journal reviewers that improved the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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How to cite this article: Wright SA, Minear JT. Dam effects on bedload transport on the upper Santa Ana River, California, and implications for native fish habitat. *River Res Applic*. 2019;35:632–645. https://doi.org/10.1002/rra.3443

APPENDIX A

FLOWS (IN M^3/S) USED IN THE SEDIMENT TRANSPORT CALCULATIONS

AEP	0.5	0.2	0.1	0.04	0.02	0.01
With Seven Oaks Dam						
SAR-GR	11	14	14	82	108	142
SAR-OS	22	58	122	263	439	708
SAR-TA	23	74	153	340	566	906
SAR-RD	40	215	510	1,274	2,265	3,681
Without Seven Oaks Dam						
SAR-GR	31	122	249	580	963	1,642
SAR-OS	40	159	331	736	1,274	2,123
SAR-TA	40	164	354	793	1,359	2,265
SAR-RD	45	269	651	1,614	2,888	4,955
Tributaries						
MILL	8	37	82	156	311	481
CITY	1	16	31	76	127	198
LYTLE	14	102	255	651	1,161	1,784

[a]Abbreviations: AEP, annual exceedance probability; CITY, City Creek near 5th Street; LYTLE, Lytle Creek near Hwy 66; MILL, Mill Creek near Greenspot Road; SAR, Santa Ana River; SAR-GR, SAR near Greenspot Road; SAR-OS, SAR near Orange Street; SAR-RD, SAR above Rialto Drain; SAR-TA, SAR near Tippecanoe Avenue.

APPENDIX B

CHANNEL CROSS SECTIONS

SAR-GR		SAR-OS		SAR-TA		SAR-RD		MILL		CITY		LYTLE	
x[a] (m)	y[b] (m)	x (m)	y (m)	x (m)	y (m)	x (m)	y (m)	x (m)	y (m)	x (m)	y (m)	x (m)	y (m)
0.0	7.01	0.0	6.04	0.0	7.44	0.0	6.07	0.0	4.75	0.0	6.19	0.0	3.18
8.1	4.34	7.8	3.93	14.5	1.33	9.8	6.07	3.0	2.83	6.5	2.58	3.4	1.62
12.2	1.47	11.0	1.20	19.0	1.11	13.9	4.09	5.9	2.55	11.0	2.28	14.2	1.18
16.5	0.95	13.8	0.82	19.0	1.11	19.2	1.76	9.2	2.06	17.9	0.28	17.3	0.08
22.2	0.55	17.8	0.68	31.0	1.41	29.6	1.64	13.1	1.87	20.7	0.22	20.6	0.10
26.5	0.61	20.7	0.51	37.4	1.02	38.9	1.55	16.2	1.30	23.4	0.20	25.4	0.58
33.0	0.53	22.5	0.29	39.9	1.32	51.5	1.08	19.7	1.23	25.7	0.10	29.2	0.02
37.4	1.62	26.7	0.26	57.2	1.12	56.6	0.01	24.1	0.73	26.1	0.00	33.7	0.00
40.8	1.31	31.7	0.00	69.8	1.53	63.4	0.00	26.8	0.74	27.2	0.17	38.3	0.09
45.2	0.88	33.5	0.06	71.4	0.71	73.0	0.20	29.7	0.58	29.5	0.19	44.8	0.37
49.0	0.24	35.6	0.52	75.6	0.54	82.6	0.26	33.0	0.14	32.3	0.39	49.7	0.42
52.2	0.00	39.4	0.66	82.4	0.53	90.6	0.36	34.6	0.04	35.4	0.42	54.0	0.05
56.5	0.19	41.2	1.16	86.4	0.96	102.8	0.52	36.0	0.11	39.6	0.43	65.4	0.16
59.7	1.07	45.1	1.28	95.6	1.06	111.4	0.41	37.0	0.00	44.6	0.40	74.7	0.19
61.2	1.44	52.2	1.41	102.6	0.80	112.3	0.29	38.0	0.20	51.2	0.36	81.9	0.12
62.1	3.09	55.3	1.17	106.2	1.12	117.5	0.10	39.9	0.32	57.5	0.44	90.9	0.20
73.6	6.88	58.3	1.23	114.1	1.21	122.8	0.12	40.9	0.03	63.6	0.35	94.6	0.49
		62.8	1.35	118.8	0.47	123.7	0.35	42.6	0.15	68.5	0.64	99.4	0.45
		67.3	1.50	127.9	0.53	133.3	0.49	45.0	0.61	76.8	2.43	104.7	0.10
		74.5	1.49	133.2	0.70	146.2	0.50	48.8	1.38	83.9	4.34	110.7	0.09
		81.0	1.65	143.2	0.09	147.3	0.76	53.9	1.83			115.1	0.14
		88.2	2.90	146.8	0.29	161.5	0.84	57.7	2.27			122.5	0.25
		96.5	6.11	152.6	0.17	170.0	0.95	62.6	3.10			129.3	0.30
				160.2	0.11	171.3	1.22	70.1	3.47			131.6	0.66
				168.9	0.31	172.5	0.82	82.6	4.57			143.5	0.80
				174.7	0.32	174.9	0.82					158.7	1.06
				178.2	0.04	176.2	1.16					169.4	1.11
				184.1	0.06	177.2	0.99					177.9	1.14
				188.7	0.00	188.2	0.89					190.9	1.13
				201.3	4.89	201.2	0.71					200.0	0.79
				210.2	8.62	207.2	0.13					205.7	0.86
						215.8	0.24					207.7	1.26
						224.6	0.31					214.8	1.52
						238.3	0.30					223.6	4.01
						248.2	1.47					236.4	5.04
						257.4	1.43						
						264.2	1.45						
						267.2	2.35						
						274.5	2.41						
						279.4	5.11						
						281.6	6.20						
						285.1	7.70						

(Continued)

SAR-GR		SAR-OS		SAR-TA		SAR-RD		MILL		CITY		LYTLE	
x[a] (m)	*y*[b] (m)	*x* (m)	*y* (m)	*x* (m)	*y* (m)	*x* (m)	*y* (m)	*x* (m)	*y* (m)	*x* (m)	*y* (m)	*x* (m)	*y* (m)
						288.7	7.72						

Abbreviations: CITY, City Creek near 5th Street; LYTLE, Lytle Creek near Hwy 66; MILL, Mill Creek near Greenspot Road; SAR, Santa Ana River; SAR-GR, SAR near Greenspot Road; SAR-OS, SAR near Orange Street; SAR-RD, SAR above Rialto Drain; SAR-TA, SAR near Tippecanoe Avenue.

[a]Distance across section.

[b]Elevation above thalweg.

APPENDIX C

PARTICLE SIZE DISTRIBUTIONS

Particle diameter (mm)	Percent finer than indicated particle diameter (%)						
	SAR-GR	SAR-OS	SAR-TA	SAR-RD	MILL	CITY	LYTLE
0.063	1	2	2	3	0	2	3
0.125	1	6	4	7	2	3	6
0.25	2	18	11	23	7	10	20
0.5	4	42	28	50	18	29	46
1	7	61	54	69	23	52	62
2	9	69	71	74	23	66	67
4	11	71	74	77	27	75	75
8	16	76	81	91	37	93	88
16	19	80	87	98	49	98	93
32	25	82	91	99	60	99	96
64	36	86	96	100	75	100	98
128	57	92	100	100	90	100	100
256	77	98	100	100	98	100	100
512	96	100	100	100	100	100	100
1,024	100	100	100	100	100	100	100

[a]Abbreviations: CITY, City Creek near 5th Street; LYTLE, Lytle Creek near Hwy 66; MILL, Mill Creek near Greenspot Road; SAR, Santa Ana River; SAR-GR, SAR near Greenspot Road; SAR-OS, SAR near Orange Street; SAR-RD, SAR above Rialto Drain; SAR-TA, SAR near Tippecanoe Avenue.