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**RECLAMATION**

**Technical Report No. ENV-2020-033**

**Geomorphic Response to Gravel Augmentation  
in the Stanislaus River Downstream of Goodwin  
Dam**

**Bay-Delta Office  
California-Great Basin Region**



**U.S. Department of the Interior  
Bureau of Reclamation  
Technical Service Center  
Sedimentation and River Hydraulics Group  
Denver, Colorado**

**May 2020**

## **Mission Statements**

The Department of the Interior conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

**BUREAU OF RECLAMATION**  
**Technical Service Center, Denver, Colorado**  
**Sedimentation and River Hydraulics Group, 86-68240**

**ENV-2020-033**

**Geomorphic Response to Gravel Augmentation in the  
Stanislaus River Downstream of Goodwin Dam**

*Prepared by:*

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Jianchun Victor Huang, Ph.D., P.E.  
Hydraulic Engineer, Sedimentation and River Hydraulics Group, 86-68240

Date

*Report Reviewed by:*

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Blair Greimann, Ph.D., P.E.  
Hydraulic Engineer, Sedimentation and River Hydraulics Group, 86-68240

Date

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## **Acronyms and Abbreviations**

cfs	cubic feet per second
cgrv	coarse gravel
csnd	coarse sand
D <sub>##</sub>	sediment size at which ##% of sediment grains are fine
DWR	California Department of Water Resource
ft	feet
in	inch
mgrv	medium gravel
mm	millimeter
mm	millimeter
NED	National Elevation Data
RM	river mile
Sc	small cobble
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USRDOM	Upper Sacramento River Daily Operations Model
vcgrv	very coarse gravel
vcsnd	very coarse sand
vfgrv	very fine gravel
vgrv	fine gravel
WSE	water surface elevation
yd <sup>3</sup>	cubic yards
yr	year

## Table of Contents

1. Introduction.....	1
2. Input Data .....	2
2.1. Cross Section Geometry.....	2
2.2. Daily Flows.....	3
2.3. Boundary Conditions.....	7
2.4. Incoming and Lateral Sediment Loads.....	7
2.5. Bed Material.....	11
2.5.1. <i>Bed Material in Historical Gravel Augmentation Simulations</i> .....	11
2.5.2. <i>Bed Material in Future Gravel Augmentation Simulations</i> .....	13
2.6. Other Parameters.....	14
3. Historical Gravel Augmentation Modeling Results .....	15
3.1. Bed Profile.....	15
3.2. Water Surface Elevation at Flow of 8,000 cfs.....	18
3.3. Cumulative Sediment Deposition.....	20
3.4. Bed Material Sediment Size.....	23
3.5. Sensitivity to Sediment Transport Equations.....	24
4. Future Gravel Augmentation Modeling Results .....	27
4.1. Bed Profile.....	27
4.2. Water Surface Elevation during Required Protection Level of 8,000 cfs.....	29
4.3. Cumulative Sediment Deposition.....	33
4.4. Bed Material Sediment Size.....	35
4.5. Results at Old Knight’s Ferry Bridge.....	37
5. Modeling Results of Various Gravel Augmentation Amounts .....	39
6. Summary and Conclusions .....	43
7. References.....	44

## Figures

Figure 1-1. Stanislaus River in the study area .....	1
Figure 2-1. Accumulated flows at Knight’s Ferry downstream of the Goodwin Dam and at Ripon .....	4
Figure 2-2. Annual flow volume downstream of Goodwin dam.....	5
Figure 2-3. Monthly average flow rate downstream of Goodwin Dam at Knight’s Ferry .....	6
Figure 2-4. Annual maximum daily flow rates downstream of Goodwin Dam at Knight’s Ferry .....	6
Figure 2-5. Rating curve for the downstream boundary.....	7
Figure 2-6. Gravel augmentation locations.....	8

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**

Figure 2-7. Bed material finer than along the channel. Regression fits are shown as solid lines and data are given as points. ....12

Figure 3-1. Initial and simulated bed profiles for the historical gravel augmentation scenario and no gravel augmentation scenario. ....16

Figure 3-2. Detailed view of initial and simulated bed profiles in different scenarios.....16

Figure 3-3. Bed profile differences between historical gravel augmentation and no historical gravel augmentation condition.....17

Figure 3-4. Initial and simulated water surface elevations at a flow of 8,000 cfs for with and without historical gravel augmentation.....18

Figure 3-5. Detailed view of initial and simulated water surface elevations at a flow of 8,000 cfs for with and without historical gravel augmentation. ....19

Figure 3-6. Water surface elevation differences at a flow of 8,000 cfs between historical augmentation and no augmentation scenarios. ....20

Figure 3-7. Cumulative sediment deposition volumes in different gravel augmentation scenarios. ....21

Figure 3-8. Cumulative gravel deposition volumes in different gravel augmentation scenarios. ....22

Figure 3-9. Initial and simulated D<sub>50</sub> in conditions with and without gravel augmentation....23

Figure 3-10. Initial and final D<sub>84</sub> in conditions with and without gravel augmentation.....24

Figure 3-11. Water surface elevation difference between historical gravel augmentation and no historical gravel augmentation at a flow of 8,000 cfs using different sediment transport equations. ....25

Figure 3-12. Cumulative gravel deposition volumes simulated with different sediment transport equations. ....26

Figure 4-1. Initial and simulated bed profiles in different scenarios. ....27

Figure 4-2. Detailed view of initial and simulated bed profiles for the augmentation and no-augmentation scenarios.....28

Figure 4-3. Bed profile differences in different scenarios as compared with no gravel augmentation condition.....28

Figure 4-4. Initial and simulated water surface elevations in different scenarios. ....30

Figure 4-5. Detailed view of initial and simulated water surface elevations in different scenarios. ....30

Figure 4-6. Water surface elevation differences between gravel augmentation scenarios and no gravel augmentation scenario. ....31

Figure 4-7. Cumulative sediment deposition volumes in different gravel augmentation scenarios. ....34

Figure 4-8. Cumulative gravel deposition volumes in different gravel augmentation scenarios. ....35

Figure 4-9. Initial and simulated mean sediment sizes in different gravel augmentation scenarios. .....	36
Figure 4-10. Initial and simulated D <sub>84</sub> in different gravel augmentation scenarios.....	36
Figure 4-11. Cross section geometry and water surface elevation at a flow of 8,000 cfs at the Old Knight's Ferry Bridge compared with the current condition.....	38
Figure 4-12. Cross section geometry and water surface elevation at a flow of 8,000 cfs at the Old Knight's Ferry Bridge compared with the no gravel augmentation condition. ....	38
Figure 5-1. Water surface elevation profiles at flow rate of 8,000 cfs after various amounts of gravel augmentation per year.....	40
Figure 5-2. Detailed view of water surface elevation profiles at flow rate of 8,000 cfs after various amounts of gravel augmentation per year. ....	41
Figure 5-3. Water surface elevation changes with various amount of gravel augmentation per year as compared with no gravel augmentation scenario. ....	41
Figure 5-4. Detailed view of water surface elevation changes at a flow of 8,000 cfs with various amount of gravel augmentation per year as compared with no gravel augmentation condition. .....	42

**Tables**

Table 2-1. Gravel Augmentation Amount and Locations.....	8
Table 2-2. Gravel Augmentation GIS Locations and Relative River Miles.....	9
Table 2-3. Gravel Augmentation Amounts in each Simulated Scenarios .....	10
Table 2-4. Injected Gravel Gradation (Source: Reclamation Preformation Work Statement) 10	
Table 2-5. Injected Sediment Gradation .....	11
Table 2-6. Bed material size percentages estimated from Kondolf et al. (.....)	11
Table 2-7. Bed gradations used for historical gravel augmentation simulations.....	13
Table 2-8. Bed gradations estimated from Pebble Counts on November 19, 2019.....	14
Table 2-9. Bed gradations used for future gravel augmentation simulations. ....	14
Table 3-1. Maximum and average channel deposition in each reach for the historical augmentation and no historical gravel augmentation scenarios. ....	18
Table 3-2. Average and Maximum water surface elevation changes in each reach under different scenarios as compared with no gravel augmentation and with initial condition .....	20
Table 3-3. Total sediment and coarse gravel deposition (>16mm) in each reach in different scenarios.....	22
Table 3-4. Maximum water surface elevation difference between historical gravel augmentation and no historical gravel augmentation using different sediment transport equations.....	25
Table 3-5. Gravel deposition (>16mm) in each reach using various sediment transport formulas. .....	26

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**

Table 4-1. Average channel deposition in each reach under different scenarios as compared with no gravel augmentation.....29

Table 4-2. Maximum water surface elevation changes for a flow of 8,000 cfs in each reach for various gravel augmentation scenarios as compared to the no gravel augmentation scenario. ....31

Table 4-3. Average water surface elevation changes for a flow of 8,000 cfs in each reach for various gravel augmentation scenarios as compared to the no gravel augmentation scenario. ....32

Table 4-4. Average water surface elevation changes in each reach for various gravel augmentation scenarios as compared to the current water surface elevation at a flow rate of 8,000 cfs.....33

Table 4-5. Gravel deposition volumes (>16mm) in each reach in different scenarios. ....35

Table 4-2. Sediment loads passing the Old Knight’s Ferry Bridge. ....37

Table 4-2. Initial and final water surface elevations at the Old Knight’s Ferry Bridge and their changes as compared with the current condition and the no gravel augmentation condition. ....39

Table 5-1. Average water surface elevation changes in each reach for various gravel augmentation amounts as compared to the current water surface elevation for a flow of 8,000 cfs.....43

# 1. Introduction

The Sedimentation and River Hydraulics Group of the Technical Service Center was requested by the Bay Delta Office of the California-Great Basin to estimate the geomorphic response to historical and potential future gravel augmentation in the Stanislaus River downstream of the Goodwin Dam. The site map of the study area is shown in Figure 1-1.



Figure 1-1. Stanislaus River in the study area

Stanislaus River is a major tributary of the San Joaquin River. The main stem of the Stanislaus River is 113 miles long and its drainage area is 1,075 square miles. The elevations in the watershed range from less than 15 feet at the confluence with the San Joaquin River to over 10,000 feet in the high Sierra Nevada. Annual precipitation varies from 10 in/yr near the confluence with the San Joaquin River, 18 in/yr in the Stanislaus foothills around Knight's Ferry, and over 50 in/yr in the headwaters (Kondolf et al., 2001). At elevations above 5,000 feet most precipitation falls as snow.

Since the installation of the Goodwin, Tulloch, and New Melones Dams, the habitat has been significantly degraded. Due to the reservoir storage and water diversion, the peak flow rate has been reduced to about 1,500 cfs in many years, with a maximum of 6,300 cfs on January 5<sup>th</sup>, 2006 in the last 20 years. The reduction of peak flows and sediment trapping in the reservoir decreases river dynamics, isolates the river from the floodplains, removes the side channels, resulting a channel that is heavily encroached upon by riparian vegetation. Combined with in-river aggregate mining and the conversion of floodplain into agricultural land, the area of suitable salmonid spawning and rearing habitats has been substantially reduced. As a result, the spring-run Chinook and steelhead have been nearly extirpated from the watershed and fall-run Chinook and steelhead have been substantially impacted and limited only to the lower 60 miles downstream of Goodwin Dam.

The Bureau of Reclamation has been injecting gravel downstream of the Goodwin Dam to increase the salmon spawning habitat area. Gravels added to the river can make up for the deficit caused by the dams and maintain a mobile bed suitable for salmon spawning. Currently, the dams trap nearly all the sediment supplied from the watershed. Compared with the San Joaquin River and its other tributaries, the lower reach downstream of Goodwin Dam provides valuable spawning and rearing habitat for Chinook salmon and steelhead.

Currently New Melones Dam is designed to release flows less than 8,000 cfs during the 100-year flood (Kondolf et al., 2001). For that reason, the US Army Corp of Engineers (USACE) is required to maintain an 8,000 cfs floodway from Goodwin Dam to the San Joaquin River, subject to the condition that local landowners maintain private levees and prevent encroachment on the channel between levees. The objective of this study is to use numerical modelling to estimate the geomorphic response of the gravel augmentation in the Stanislaus River downstream of the Goodwin Dam, and to estimate the impact to water surface elevations during a flow of 8,000 cfs.

SRH-1D (Huang and Greimann, 2007), developed at the Sediment and River Hydraulics Group, Technical Service Center, was used to simulate historical gravel augmentations and seven future gravel augmentation scenarios, where one of those scenarios (Scenario 3) is the preferred gravel augmentation scenario that the Bay-Delta Office of the Bureau of Reclamation has selected. Baseline conditions in the past and in the future with no gravel augmentation were also simulated for comparison. Water surface elevations at the required floodway protection level (8,000 cfs) will be compared before and after the gravel augmentation simulations to estimate the river response resulting from these different actions. The information provided from this study will be used to assist Reclamation with obtaining permit for gravel augmentation to improve salmon spawning habitat.

## **2. Input Data**

SRH-1D (Huang and Greimann, 2007) is a one-dimensional (1D) flow and sediment transport model used to assess river response resulting from management actions. SRH-1D model inputs includes upstream flow and sediment loads, channel geometry, bed material, downstream water surface elevation, along with other model parameters.

All elevations in this report are given in the North American Vertical Datum of 1988 (NAVD88).

### **2.1. Cross Section Geometry**

The cross-section geometry used in the model is a combination of a 2017 USCOE HEC-RAS model and a 2009 Bureau of Reclamation bathymetric survey. The 2017 HEC-RAS model was built using the DWR\_2008 CVFED LiDAR and National Elevation Dataset (NED) 10-meter data. The model includes the entire reach of

Stanislaus River starting from Goodwin Dam to the confluence of San Joaquin River. There is no documentation regarding the source and accuracy of underwater channel geometry, and the underwater channel geometry might be from model calibration.

In this study, the USCOE HEC-RAS model was updated in the following steps:

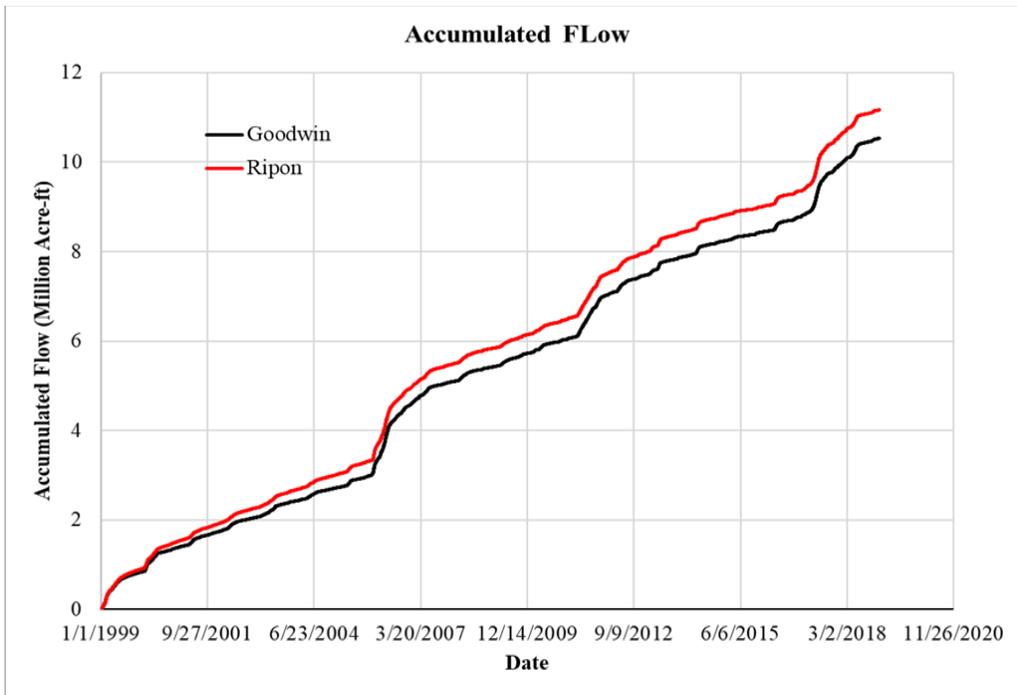
1. The Sedimentation and River Hydraulics Group at Technical Service Center performed the bathymetric survey in 2009. The survey covered a 7-mile reach from RM 56 to RM 49. The channel geometry data (Hilldale, personal communication, 2019) was obtained in the form of Triangulated Irregular Network (TIN) and then interpolated into HEC-RAS cross section geometry with HEC-GeoRAS. The USCOE HEC-RAS cross section data in this reach is replaced by the cross-section data from the bathymetric survey.
2. The original HEC\_RAS geometry in the canyon reach from Goodwin Dam to Knight's Ferry was interpolated from several cross-section geometry; however, the interpolation seemed unrealistic. New interpolation is performed to update the channel geometry in the reach from Goodwin Dam to Knight's Ferry.
3. Fictitious levees were added in downstream reach downstream of Caswell Memorial State Park in the original HEC-RAS model. There levees are removed in this study.

River characteristics are represented by cross sections in a 1D model. A separate program is used to transform the HEC-RAS geometry into SRH-1D format. The numerical model covers a 60-mile reach from downstream of Goodwin Dam (RM 60) to the confluence with San Joaquin (RM 0), represented by 315 cross sections, with an average spacing of 1,006 ft and a maximum spacing of 4,085 ft.

## **2.2. Daily Flows**

Most of the moisture in the Stanislaus Basin comes in the form of snow, with an annual precipitation ranges from 26 inches in a very dry year to 68 inches in a wet year (Arm Corps of Engineers, 1980). The basin is characterized by cool and wet winters, and hot and dry summers. Major storms occur from November through April. Winter storms account for about 80% of the annual precipitation. Below 4,000 feet the precipitation usually falls as rain, which generally continues for 3 or 4 days. Above 4,000 feet, precipitation usually falls as snow. Most of the runoff from the Stanislaus River basin occurs from November through July. Historically the average annual runoff at the New Melones Dam is 1.1 million acre-ft with a maximum runoff of 2.8 million acre-feet in water year 1907 and minimum 0.16 million acre-feet in water year 1977. With dam regulation and water diversion under current operations, the annual runoff downstream of the Goodwin dam is significantly reduced.

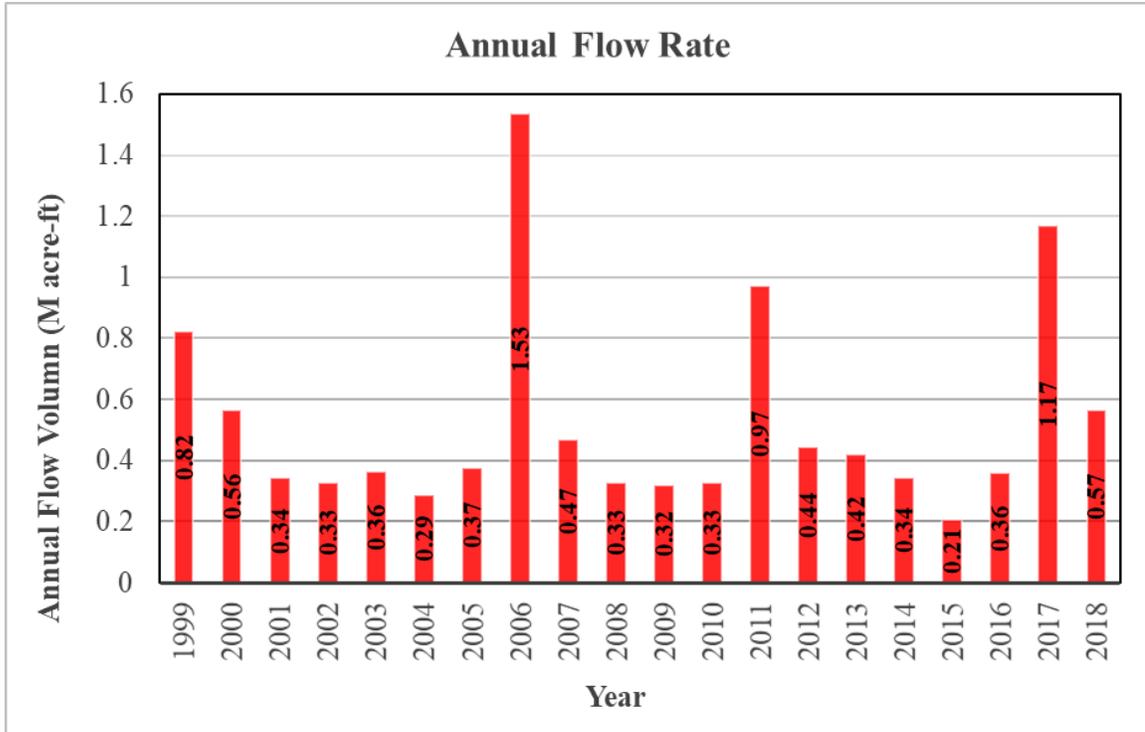
Two stream gages are operated and maintained by the U.S. Geological Survey (USGS) in the study reach: USGS 11302000 Stanislaus R BL Goodwin Dam NR Knight's Ferry CA and USGS 11303000 Stanislaus R A Ripon CA. Figure 2-1 shows the accumulated flows at these two gages. Compared with the flow at Knight's Ferry downstream of the Goodwin dam, the average flow rate is about 6% more at the Ripon gage. Since only flow in the upper steep reach from the Goodwin dam (RM60) to Jacob Meyers Park (RM34.5) can move the injected gravels and the Ripon gage station is located downstream in RM 17.1, the numerical model uses flow at the Stanislaus R BL Goodwin Dam NR Knight's Ferry CA (USGS 11302000) as the upstream boundary condition.



**Figure 2-1. Accumulated flows at Knight's Ferry downstream of the Goodwin Dam and at Ripon**

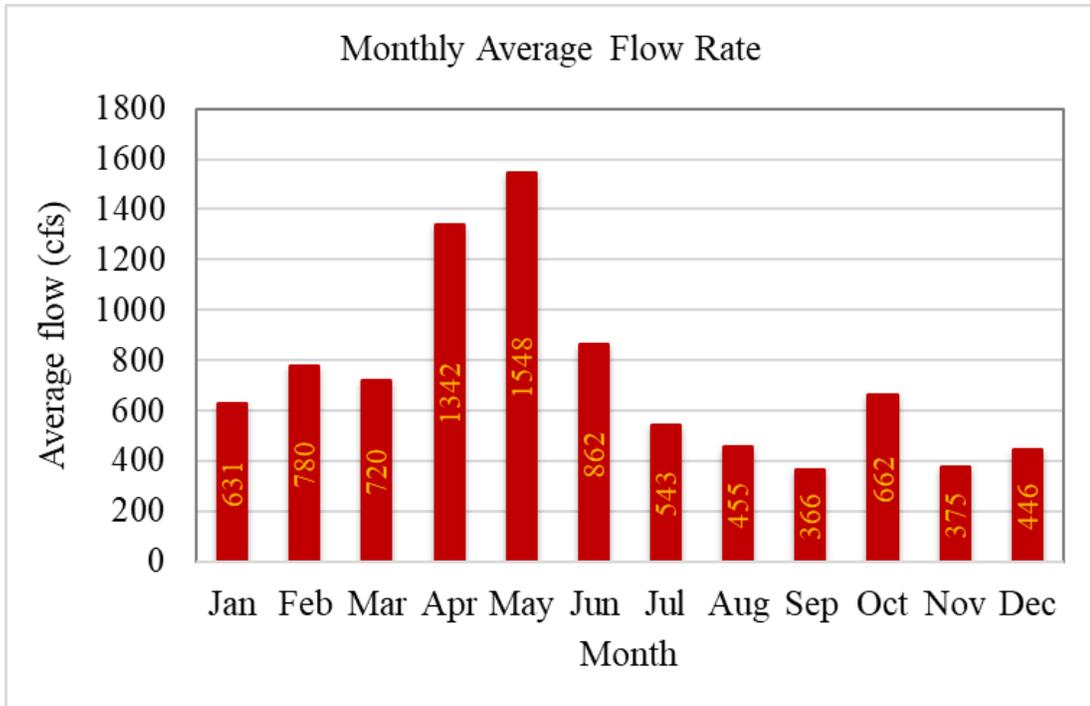
Figure 2-2 shows the annual flows downstream of Goodwin Dam. The records in the last twenty years show that the annual flow rate has been significantly reduced after the installations of the Goodwin, Tulloch, and New Melones Dams and water diversions. The average annual runoff dropped from a historical value of 1.1 million acre-ft to currently 0.54 million acre-ft with a maximum of 1.5 million acre-ft (in 2006), and a minimum of 0.21 million acre-ft (in 2015) in a 20-year record that was used for the numerical model study.

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**



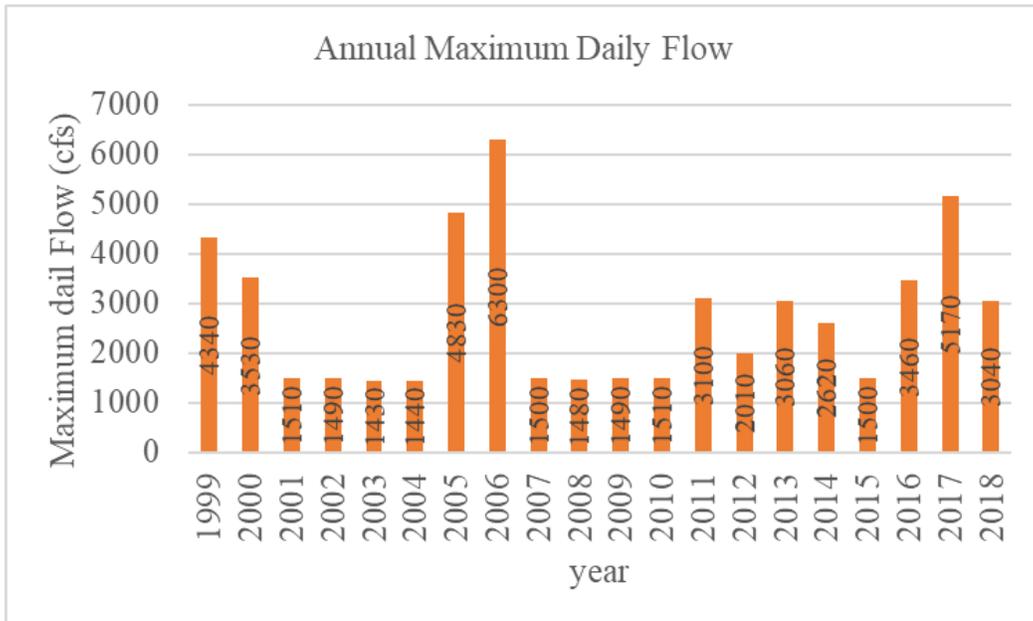
**Figure 2-2. Annual flow volume downstream of Goodwin dam**

Figure 2-3 presents the monthly average flows downstream of the Goodwin dam at Knight's Ferry. After the constructions of the dams, the flow is more evenly distributed in each month with relatively large flows occurring in April (1,340 cfs) and May (1,550 cfs).



**Figure 2-3. Monthly average flow rate downstream of Goodwin Dam at Knight’s Ferry**

Figure 2-4 presents the annual maximum daily flow rates downstream of the Goodwin dam at Knight Ferry. After the constructions of the dams, the maximum daily flow rate is significant reduced. In a 20-year period, the maximum daily average flow rate was 6,300 cfs and it could be as low as 1,430 cfs.

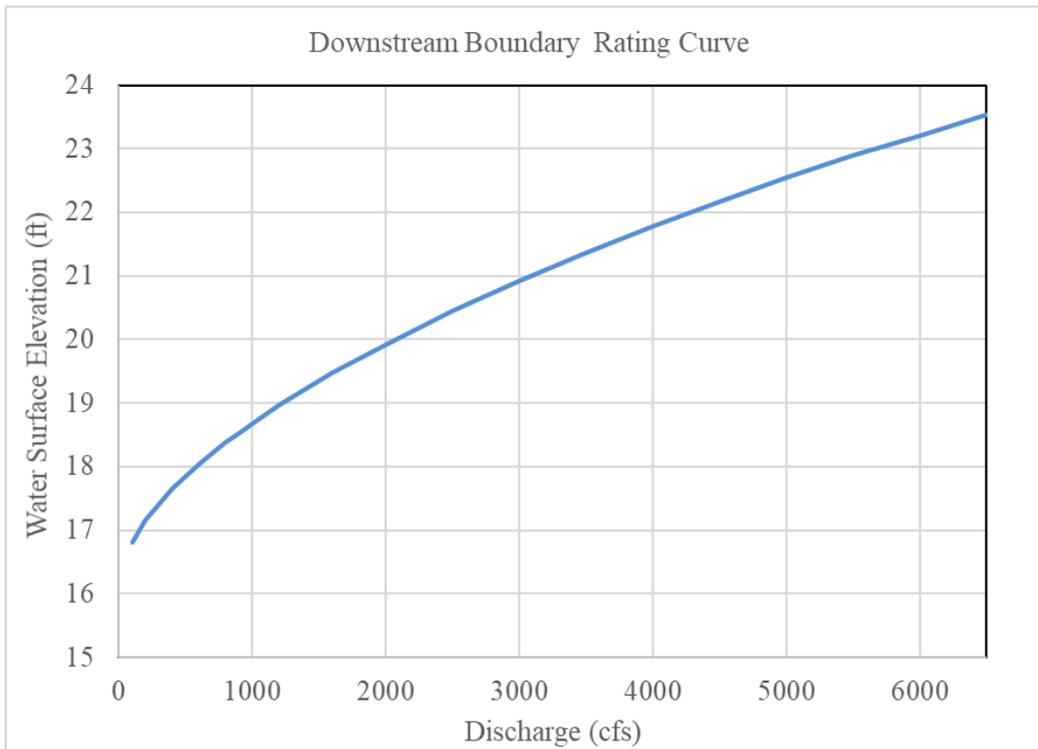


**Figure 2-4. Annual maximum daily flow rates downstream of Goodwin Dam at Knight’s Ferry**

To simulate the historical gravel augmentation from 1994 to 2018, the numerical model uses measured flows during that period at the Stanislaus R BL Goodwin Dam NR Knight's Ferry CA (USGS 11302000) as the upstream boundary conditions. To simulate the future gravel augmentation, the numerical model uses measured flows from 1/1/1999 to 12/31/2018.

### **2.3. Boundary Conditions**

Downstream boundary conditions were determined based on a rating curve of water surface elevation and discharge at the downstream most cross section (RM 0.0). The rating curve was calculated in the HEC-RAS model with a normal depth and channel slope of 0.00026 ft/ft (Figure 2-5).



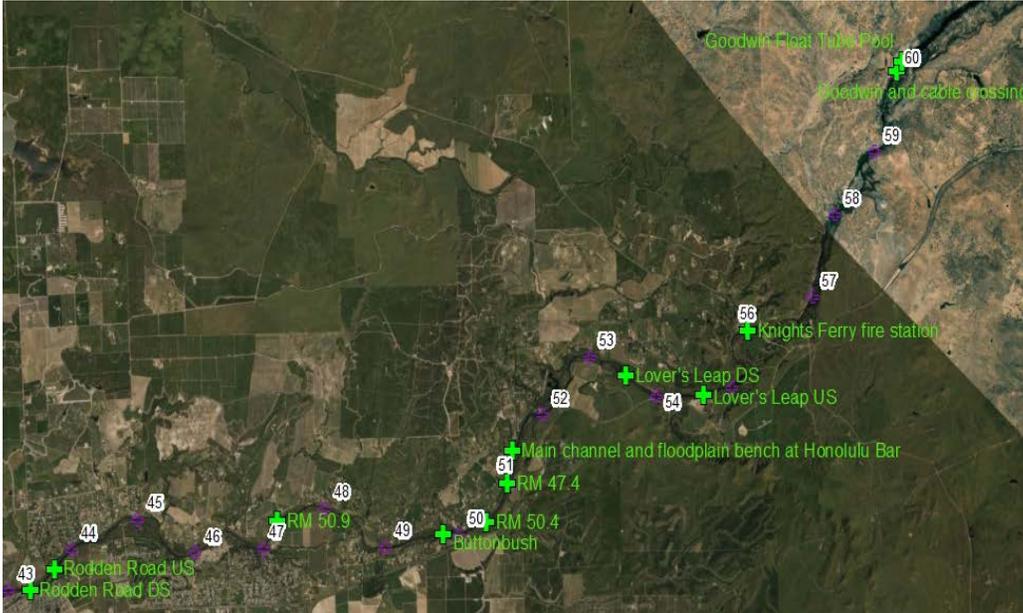
**Figure 2-5. Rating curve for the downstream boundary.**

### **2.4. Incoming and Lateral Sediment Loads**

Since the closures of the Goodwin, Tulloch, and New Melones Dams, nearly all incoming sediment is trapped in the reservoirs. The numerical model assumes that no sediment enters upstream into the simulation reach except for injected gravel.

Since 1994, gravels have been injected in the reach from Goodwin Dam to Oakdale (RM 41). The gravel augmentation locations are shown in Figure 2-6. These locations along with the years and amounts of gravel augmentation are also summarized in Table 2-1 and Table 2-2. No exact dates of gravel augmentations are available, and the model assumes all gravels are input in a single day on July

15 of each year. The locations of “Goodwin Cable Crossing area” and “Goodwin Float Tube Pool” are both near the upstream end of the model and the loads there are input as upstream incoming load. All the others are input as lateral loads. At “Lover’s Leap” and “Rodden Road”, gravels are injected in a reach more than one mile in length, and the model treats the sediment loads there as a non-point source and all the other loads are treated as point source. Over 72,000 cubic yards (~96,400 tons) of gravel have been placed in the river since 1994.



**Figure 2-6. Gravel augmentation locations.**

**Table 2-1. Gravel Augmentation Amount and Locations**

Year	Amount (yd <sup>3</sup> )	Gravel Injection Location
1994	3,070	Stanislaus River at RM 47.4, 50.4, and 50.9
1995	0	
1996	0	
1997	13,181	Goodwin Cable Crossing area
1998	4,444	Goodwin Cable Crossing area
1999	7,647	18 riffles in lower Stanislaus River (Two-Mile Bar to city of Oakdale)
2000	1,432	Goodwin Cable Crossing area
2001	488	Goodwin Float Tube Pool - helicopter
2002	2,353	Goodwin Cable Crossing area
2003	0	
2004	700	Goodwin Float Tube Pool - sluice
2005	1,471	Goodwin Float Tube Pool - helicopter
2006	1,471	Goodwin Cable Crossing area
2007	3,000	Goodwin Cable Crossing area

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**

<b>Year</b>	<b>Amount (yd<sup>3</sup>)</b>	<b>Gravel Injection Location</b>
2007	11,412	Lover's Leap
2008	0	Knight's Ferry fire station
2009	0	
2010	0	
2011	2,941	Goodwin Cable Crossing area
2012	1,765	Goodwin Float Tube Pool - sluice
2012	8,000	Main channel and floodplain bench at Honolulu Bar
2013	0	
2014	0	
2015	4,706	Goodwin and cable crossing
2017	2,838	Buttonbush
2018	1,250	Rodden Road
<b>TOTAL</b>	<b>72,169</b>	

**Table 2-2. Gravel Augmentation GIS Locations and Relative River Miles**

<b>Site Name</b>	<b>Longitude</b>	<b>Latitude</b>	<b>RM</b>
Goodwin and cable crossing	N37°51'34.91"	W120°38'4.43"	60
Goodwin Float Tube Pool	N37°51'40.17"	W120°37'59.98"	60
Knight's Ferry fire station	N37°49'6.91"	W120°40'14.93"	56.184
Lover's Leap Upstream End	N37°48'30.67"	W120°40'53.17"	54.6
Lover's Leap Downstream End	N37°48'42.57"	W120°41'58.51"	53.5
Main channel and floodplain bench at Honolulu Bar	N37°48'1.1"	W120°43'36.1"	51.4
RM 50.9	N37°47'24"	W120°46'55.2"	50.9
RM 50.4	N37°47'20.4"	W120°43'58.8"	50.4
Buttonbush	N37°47'13.86"	W120°44'35.53"	49.8
RM 47.4	N37°47'42"	W120°43'40.8"	47.4
Rodden Road Upstream End	N37°46'59.95"	W120°50'3.96"	43.625
Rodden Road Downstream End	N37°46'48.07"	W120°50'24.43"	43.275

Seven future gravel augmentation scenarios are simulated as shown in Table 2-3. The gravel augmentation efforts will take place in the first 15 years with amounts averaging from 5,000 yd<sup>3</sup> to 12,000 yd<sup>3</sup> per year. A baseline scenario with no gravel augmentation is also simulated and the results will be compared after 20-year simulations.

**Table 2-3. Gravel Augmentation Amounts in each Simulated Scenarios**

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
	yd <sup>3</sup>						
1	20,000	25,000	10,000	40,000	15,000	15,000	12,000
2	20,000	8,000	10,000	10,000	15,000	8,000	12,000
3	10,000	8,000	10,000	10,000	15,000	8,000	12,000
4	8,000	8,000	10,000	10,000	15,000	8,000	12,000
5	8,000	8,000	10,000	10,000	15,000	8,000	12,000
6	8,000	8,000	10,000	10,000	0	8,000	12,000
7	8,000	8,000	10,000	10,000	0	8,000	12,000
8	8,000	25,000	10,000	10,000	0	8,000	12,000
9	8,000	8,000	10,000	10,000	0	8,000	12,000
10	8,000	8,000	10,000	10,000	0	8,000	12,000
11	8,000	8,000	10,000	10,000	0	8,000	12,000
12	8,000	8,000	10,000	10,000	0	8,000	12,000
13	8,000	8,000	10,000	10,000	0	8,000	12,000
14	8,000	8,000	10,000	10,000	0	8,000	12,000
15	8,000	8,000	10,000	10,000	0	8,000	12,000
Max	20,000	25,000	10,000	40,000	15,000	15,000	12,000
Average	9,733	10,267	10,000	12,000	5,000	8,467	12,000
Min	8,000	8,000	10,000	10,000	0	8,000	12,000

The gradation of the injected gravel was taken from the gradation specified in the performance work statement given to the contractors.

**Table 2-4. Injected Gravel Gradation (Source: Reclamation Preformation Work Statement)**

Particle Size (inches)	Percent Passing	Percent Retained
4"	95-100	0-5
2"	75-85	15-25
1"	40-50	50-60
¾"	25-35	65-75
½"	10-20	80-90
¼"	0-5	95-100

The mean gradation for each size class is used and the size fraction is translated into SI units (mm) and logarithmically interpolated for all size classes defined in standard sediment grade scale. The final injected sediment gradation is presented in Table 2-5 and is used in the model.

**Table 2-5. Injected Sediment Gradation**

Class Name	Short Class Name	Lower Limit	Upper Limit	Fraction
		(mm)	(mm)	(%)
Medium Sand	msnd	0.25	0.5	0.0
Coarse Sand	csnd	0.5	1	0.0
Very Coarse Sand	vcsnd	1	2	0.0
Very Fine Gravel	vfgrv	2	4	2.4
Fine Gravel	fgrv	4	8	4.3
Medium Gravel	mgrv	8	16	16.9
Coarse Gravel	cgrv	16	32	33.1
Very Coarse Gravel	vcgrv	32	64	29.2
Small Cobbles	sc	64	128	14.2

## **2.5. Bed Material**

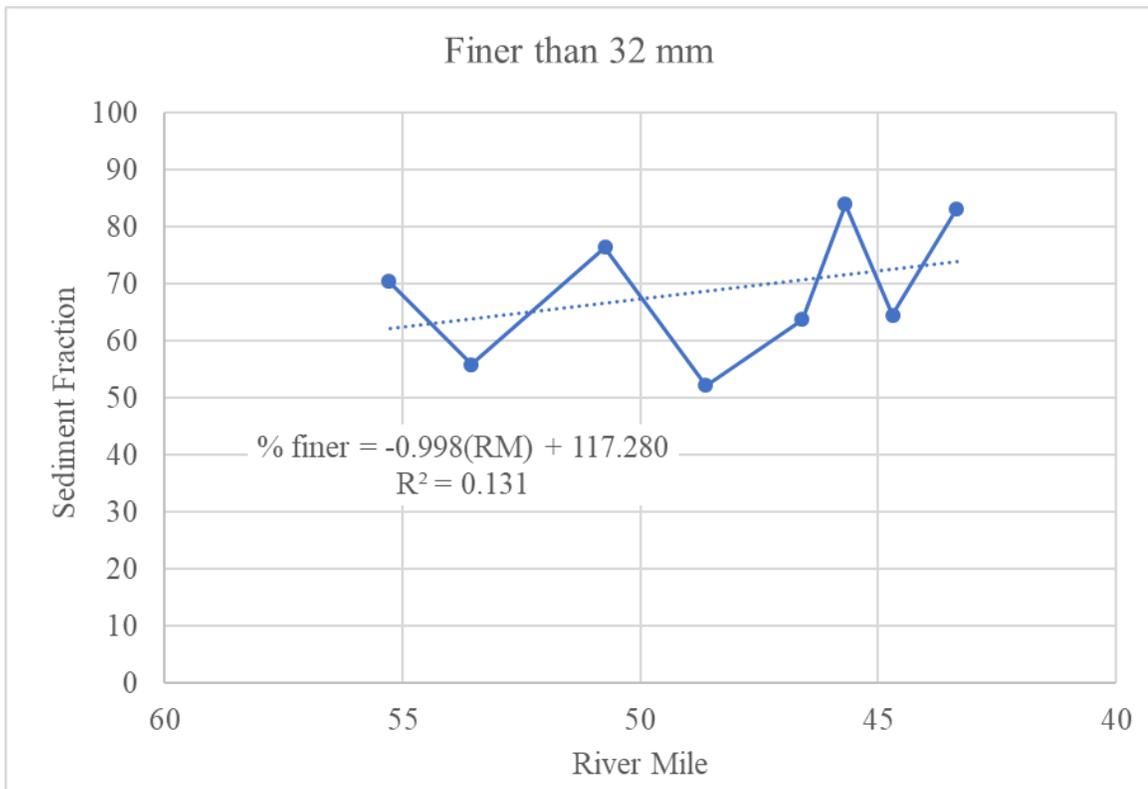
### **2.5.1. Bed Material in Historical Gravel Augmentation Simulations**

The bed material data set used for the historical gravel augmentation simulation is from pebble counts taken in 2000 (Kondolf et al., 2001). Only the summary statistics of the pebble counts were given in the report in the form of D<sub>10</sub>, D<sub>16</sub>, D<sub>25</sub>, D<sub>50</sub>, D<sub>75</sub>, D<sub>84</sub>, and D<sub>90</sub>. The sediment gradations are estimated from the summary statistics. A total of 9 samples pebble counts each at a gravel bar were performed and bed gradations are summarized in Table 2-6 in which the gravel bar names are located in the first column.

**Table 2-6. Bed material size percentages estimated from Kondolf et al. (2001)**

Lower Size (mm)	0.5	1	2	4	8	16	32	64
Upper Size (mm)	1	2	4	8	16	32	64	128
	csnd	vcsnd	vfgrv	fgrv	mgrv	cgrv	vcgrv	sc
R10	4.73	5.27	5.27	16.94	18.50	19.82	16.18	13.28
R20	5.89	4.11	4.11	10.08	15.48	16.19	17.60	26.54
R34	5.13	4.87	4.87	15.63	21.77	24.14	20.48	3.10
R42	0.00	0.00	0.00	9.82	13.17	29.23	29.55	18.23
R56	10.00	6.00	4.77	6.00	15.71	21.23	24.09	12.21
R59	10.00	6.00	4.38	4.38	21.28	37.95	16.00	0.00
R65	4.57	5.43	5.43	6.06	14.32	28.69	29.98	5.53
R69	16.00	9.00	11.36	11.36	17.32	18.13	15.96	0.88
R77	0.00	0.00	0.00	0.00	11.77	21.35	32.33	34.54

The sediment size fractions change along the river and, as an example, the fraction finer than 32 mm is plotted in Figure 2-7. It should be mentioned that the river mile presented for each gravel bar has changed in the current numerical model. The river miles in this study follow the river miles presented in USACE's HEC-RAS model. New river mile for each gravel bar, read from the HEC-RAS cross sections plotted in GIS Map, is used in this model. Even though the sediment size fractions seem scattered, a trend is clear in Figure 2-7. The percent finer than 32 mm becomes higher going downstream (smaller RM), meaning that the bed material becomes finer in the downstream direction. It is determined that the samples might be influenced by local conditions, so sediment gradations are not used directly in this model. Instead linear equations are developed for the size fractions of each class. The bed gradations used for historical simulation are presented in Table 2-7.



**Figure 2-7. Bed material finer than along the channel. Regression fits are shown as solid lines and data are given as points.**

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of  
Goodwin Dam**

**Table 2-7. Bed gradations used for historical gravel augmentation simulations**

Lower Size (mm)	0.5	1	2	4	8	16	32	64
Upper Size (mm)	1	2	4	8	16	32	64	128
RM	csnd	vcsnd	vfgrv	fgrv	mgrv	cgrv	vcgrv	sc
56	2.59	5.92	8.88	24.19	42.05	61.39	79.73	100.00
55	3.19	6.75	9.99	24.59	42.36	62.38	81.12	100.00
54	3.79	7.59	11.11	24.99	42.68	63.38	82.50	100.00
53	4.39	8.43	12.22	25.40	42.99	64.38	83.89	100.00
52	4.99	9.26	13.33	25.80	43.30	65.38	85.28	100.00
51	5.59	10.10	14.45	26.21	43.62	66.38	86.66	100.00
50	6.19	10.93	15.56	26.61	43.93	67.38	88.05	100.00
49	6.79	11.77	16.67	27.01	44.24	68.37	89.44	100.00
48	7.38	12.60	17.78	27.42	44.56	69.37	90.82	100.00
47	7.98	13.44	18.90	27.82	44.87	70.37	92.21	100.00
46	8.58	14.28	20.01	28.22	45.18	71.37	93.60	100.00
45	9.18	15.11	21.12	28.63	45.50	72.37	94.98	100.00
44	9.78	15.95	22.24	29.03	45.81	73.36	96.37	100.00
43	10.38	16.78	23.35	29.43	46.12	74.36	97.76	100.00
42	10.98	17.62	24.46	29.84	46.44	75.36	99.14	100.00
41	11.58	18.46	25.58	30.24	46.75	76.36	100.53	100.00
40	12.18	19.29	26.69	30.65	47.06	77.36	100.00	100.00

**2.5.2. Bed Material in Future Gravel Augmentation Simulations**

The bed material data set used for the future gravel augmentation simulations is from pebble counts taken during a site visit on November 19, 2019. Sample counts were performed at four locations each at a gravel bar. Bed gradations are summarized in Table 2-8. Compared with the samples in 2000, the sediment samples are coarser at three locations: Knight’s Ferry Bridge, Valley Oak, and Oakdale Rec Area, and about the same at Honolulu Bar. The same trend is found in the 2019 samples that the bed material becomes finer as the river goes downstream. Accordingly, linear equations are also developed for the 2019 bed gradations, and the results are presented in Table 2-9.

**Table 2-8. Bed gradations estimated from Pebble Counts on November 19, 2019**

Lower Size (mm)	1	2	4	8	16	32	64
Upper Size (mm)	2	4	8	16	32	64	128
	vcsnd	vfgrv	fgrv	mgrv	cgrv	vcgrv	sc
Knights Ferry Bridge	5.8	2.9	15.4	17.9	19.2	18.3	20.5
Honolulu Bar	9.8	4.3	12.0	17.4	22.6	20.2	13.8
Valley Oak	14.4	5.8	8.1	17.0	26.3	22.3	6.3
Oakdale Rec Area	18.2	7.0	4.9	16.5	29.4	23.9	0.0

**Table 2-9. Bed gradations used for future gravel augmentation simulations.**

Lower Size (mm)	1	2	4	8	16	32	64
Upper Size (mm)	2	4	8	16	32	64	128
RM	vcsnd	vfgrv	fgrv	mgrv	cgrv	vcgrv	sc
56	0.00	0.00	0.45	8.18	23.90	67.57	100.00
55	0.00	0.00	0.64	8.87	27.15	69.89	100.00
54	0.00	0.00	0.82	9.56	30.39	72.21	100.00
53	0.00	0.00	1.01	10.25	33.64	74.53	100.00
52	0.00	0.00	1.20	10.94	36.89	76.85	100.00
51	0.00	0.00	1.39	11.63	40.13	79.17	100.00
50	0.00	0.00	1.58	12.33	43.38	81.50	100.00
49	0.00	0.00	1.76	13.02	46.63	83.82	100.00
48	0.00	0.00	1.95	13.71	49.87	86.14	100.00
47	0.00	0.00	2.14	14.40	53.12	88.46	100.00
46	0.00	0.00	2.33	15.09	56.37	90.78	100.00
45	0.00	0.00	2.51	15.78	59.61	93.10	100.00
44	0.00	0.00	2.70	16.47	62.86	95.42	100.00
43	0.00	0.00	2.89	17.16	66.11	97.74	100.00
42	0.00	0.00	3.08	17.85	69.35	100.00	100.00
41	0.00	0.00	3.27	18.55	72.60	100.00	100.00
40	0.00	0.00	3.45	19.24	75.85	100.00	100.00

## 2.6. Other Parameters

Several parameters are required by the model.

A sensitivity analysis is performed using other sediment transport equations. The active layer thickness of 1 ft is used. Channel and overbank roughness values

(Manning's  $n$  values) are based on previous HEC-RAS numerical simulations. The overbank roughness is set as 0.038 and the channel roughness is set as 0.031. The time step is set as 0.5 hr.

The Parker (1990) gravel transport equation combined with Engelund–Hansen sand formula (Engelund and Hansen, 1972) is used to calculate the sediment transport capacity. From past experience, it is determined that Parker (1990) gravel transport equation combined with Engelund–Hansen (1972) formula better predicts the sediment transport in a gravel river with sand. In the gravel reach, the Parker's equation provides a hiding effect which increases the gravel transport due to sand lubrication and reduces the sand transport due to gravel hiding. If gravel is not present, this equation functions exactly the same as the original Engelund–Hansen equation. This combination works well with larger gravel and cobble sizes and is also able to deal with the sand river in the downstream reach.

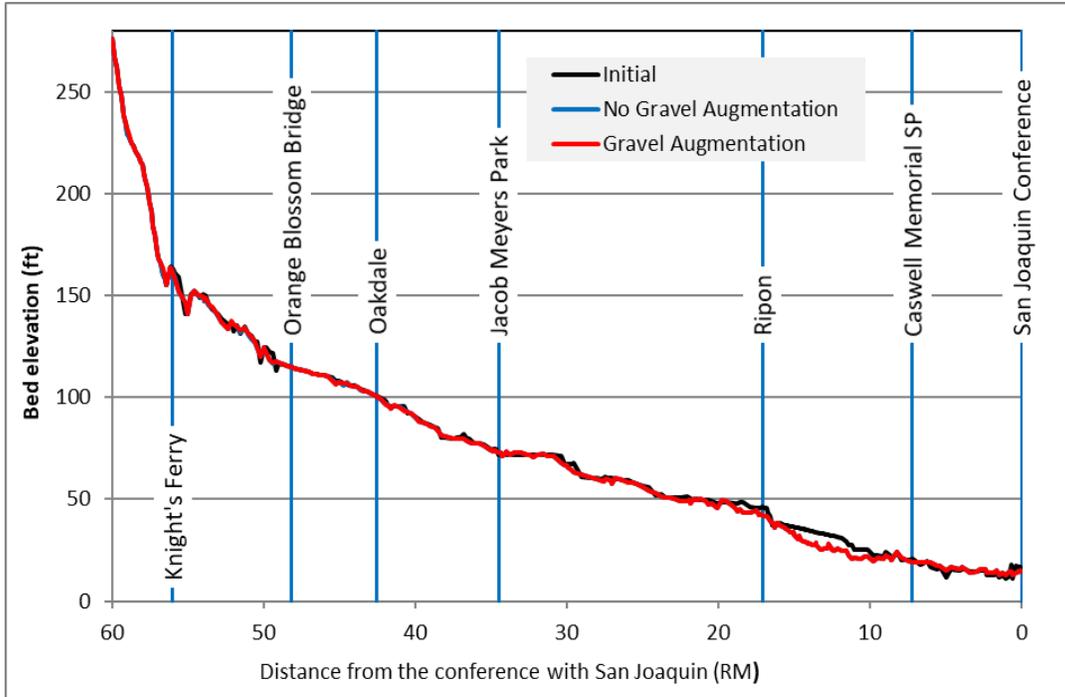
For sensitivity analysis, other sediment transport equations are analyzed including Wilcock's gravel equation (Wilcock and Crowe, 2003) combined with Engelund–Hansen sand formula, Wu et al.'s sand and gravel mixed transport equation (Wu et al., 2000), and Yang's sand and gravel equations (Yang, 1973; Yang, 1984).

### **3. Historical Gravel Augmentation Modeling Results**

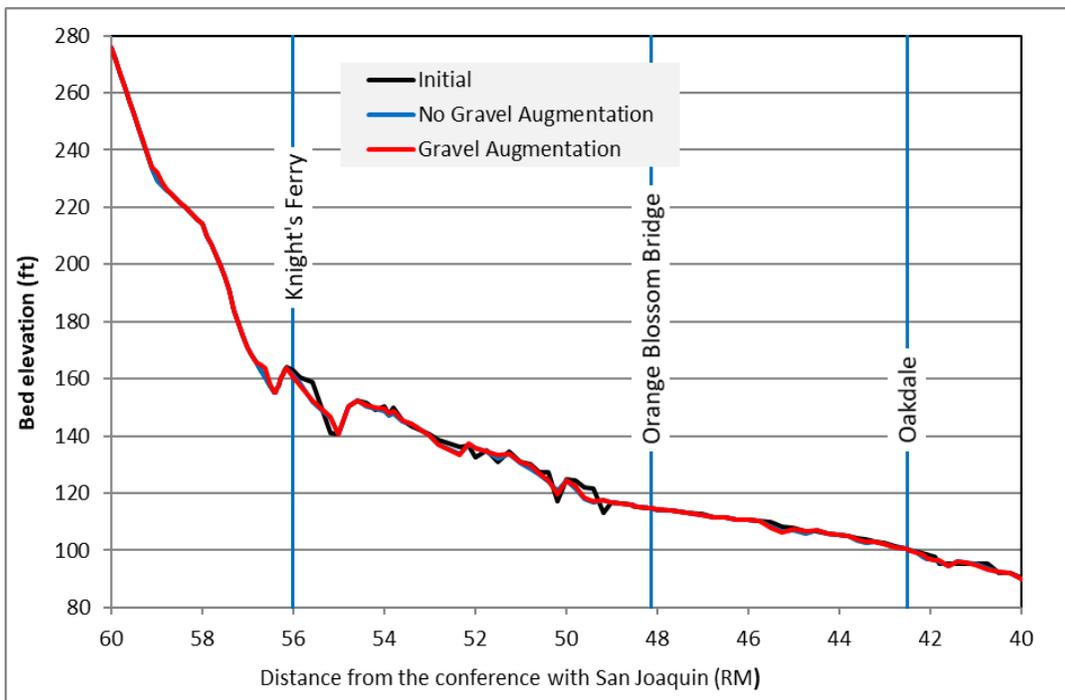
To simulate the effects of historical gravel augmentation, the known amounts of gravel augmentation in Table 2-1 are input into the model from 1994 to 2018. The gravel injected at “Goodwin Cable Crossing area” and “Goodwin Float Tube Pool” are set as upstream incoming sediment loads and all others as lateral sediment loads at the specified locations in Table 2-2. The gravel augmentation is assumed to occur on July 15 of each year. For comparison purposes, a scenario with no gravel augmentation is also simulated as a baseline condition. The model simulates the period from January 1, 1994 to December 31, 2018 with flow rates from historical gage data as discussed in section 2.2.

#### **3.1. Bed Profile**

Figure 3-1 shows the initial and simulated bed profiles with and without historical gravel augmentation. From this figure it is difficult to distinguish the difference between the two conditions. A detailed view of the reach from Goodwin Dam to RM 40 is shown in Figure 3-2, which shows that the bed profile was slightly elevated in the reach from Goodwin Dam to Knight's Ferry Bridge and in the reach from Knight's Ferry Bridge to Orange Blossom Bridge. The model shows that deposition was primarily in the pools or in the areas where the channel slope decreases significantly.



**Figure 3-1. Initial and simulated bed profiles for the historical gravel augmentation scenario and no gravel augmentation scenario.**

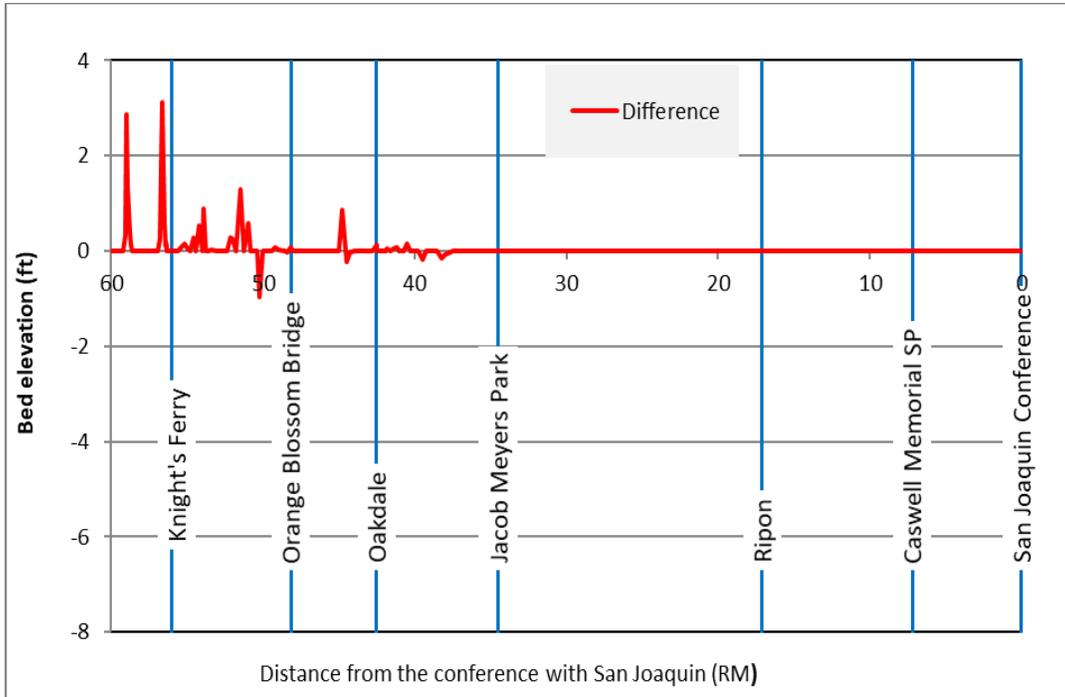


**Figure 3-2. Detailed view of initial and simulated bed profiles in different scenarios.**

Figure 3-3 shows the bed profile differences between the historical gravel augmentation and the condition of no historical gravel augmentation. Only locations where overall deposition occurred in the historical gravel augmentation

### Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam

scenario are presented in Figure 3-3; thus, the erosion just below Knight's Ferry is not shown in this figure. The numerical model shows that most sediment deposition occurred in the upstream reach from Goodwin Dam to Oakdale. The deposition was primarily in the pools.



**Figure 3-3. Bed profile differences between historical gravel augmentation and no historical gravel augmentation condition.**

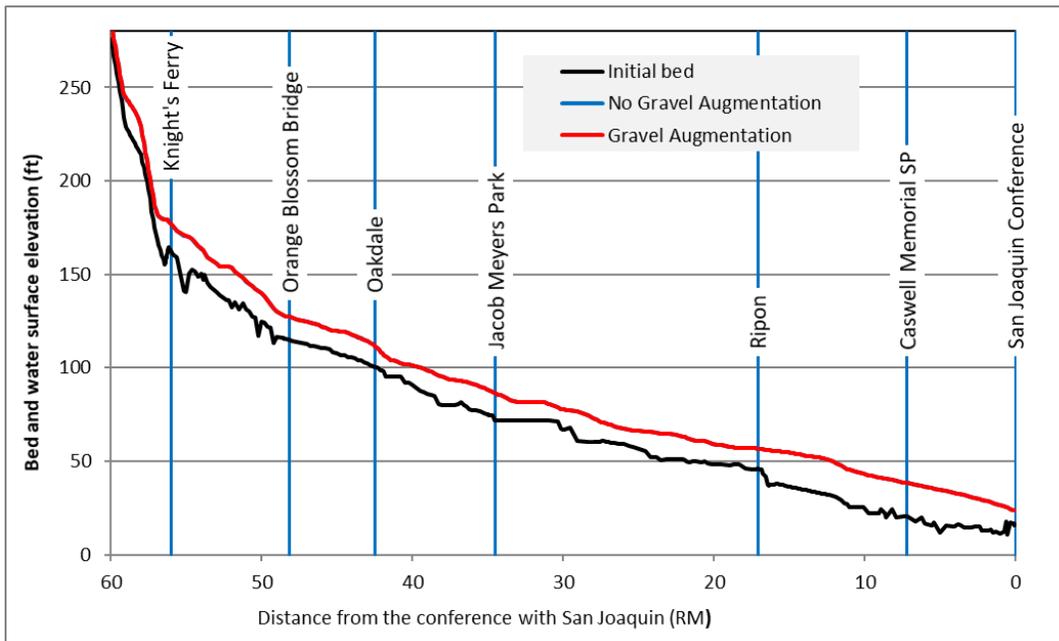
Table 3-1 shows the average and maximum channel elevation changes with and without gravel augmentation. The numerical model predicts that with gravel augmentation there was an average of 0.2 ft sediment deposition in the reach from Goodwin Dam to Knight's Ferry and 0.3 ft erosion in the reach from Knight's Ferry to Orange Blossom Bridge. The numerical model also estimates that there was about an of 0.1 ft sediment erosion in the reach from Goodwin Dam to Knight's Ferry and 0.5 ft erosion in the reach from Knight's Ferry to Orange Blossom Bridge without gravel augmentation. The maximum bed changes are also presented in the table. The maximum bed elevations changes are likely over-predicted due to limitations of 1D numerical models to fill in the pools with sediment artificially. A riffle-pool sequence usually develops in streams carrying gravel or coarser sediments that the 1D model cannot simulate. The elevation difference between the two conditions with and without gravel augmentation are more useful.

**Table 3-1. Maximum and average channel deposition in each reach for the historical augmentation and no historical gravel augmentation scenarios.**

Reach	Goodwin Dam to Knight's Ferry	Knight's Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
Average Change (ft)				
No Gravel Augmentation	-0.1	-0.5	-0.3	-0.5
With Gravel Augmentation	0.2	-0.3	-0.2	-0.5
Maximum Change (ft)				
No Gravel Augmentation	0.0	5.5	0.7	1.4
With Gravel Augmentation	3.1	5.7	0.4	1.2

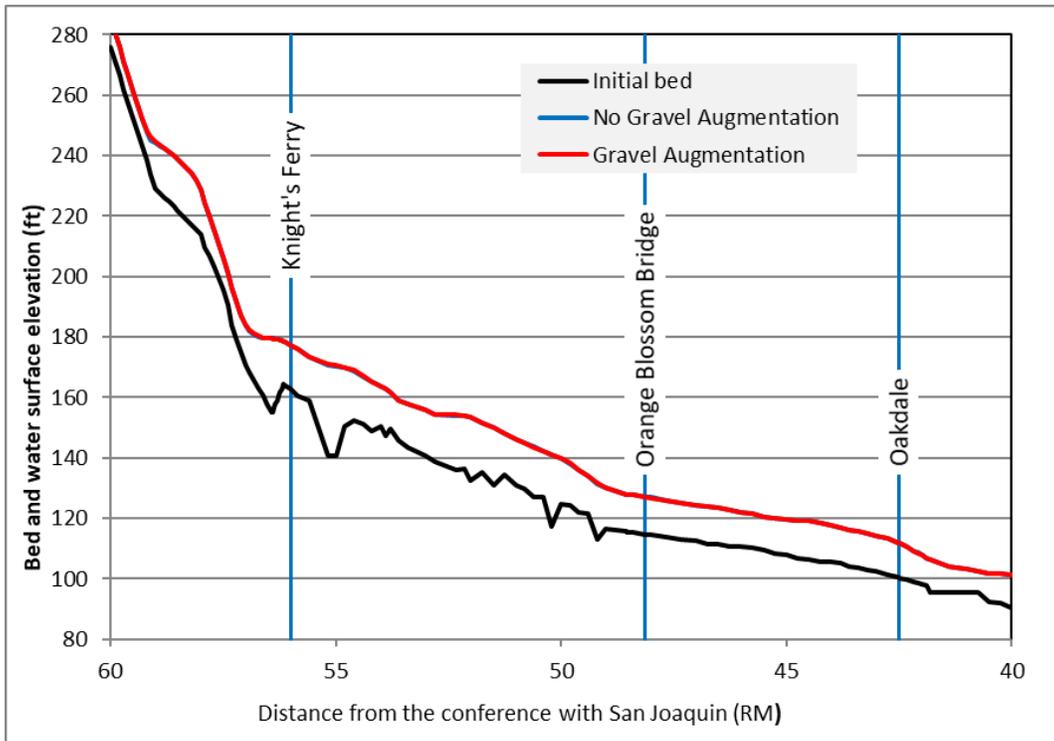
### 3.2. Water Surface Elevation at Flow of 8,000 cfs

Figure 3-4 shows the initial and simulated water surface elevation profiles at a flow of 8,000 cfs with and without gravel augmentation. From this figure it is difficult to distinguish difference between the two conditions because the differences are less than the line width. A detailed view of the figure shows the reach from Goodwin Dam to RM 40 is shown in Figure 3-5, which shows that the bed profile was slightly elevated in the reach from Goodwin Dam to Knight's Ferry Bridge and in the reach from Orange Blossom Bridge, but only in the area where the bed slope decreases.



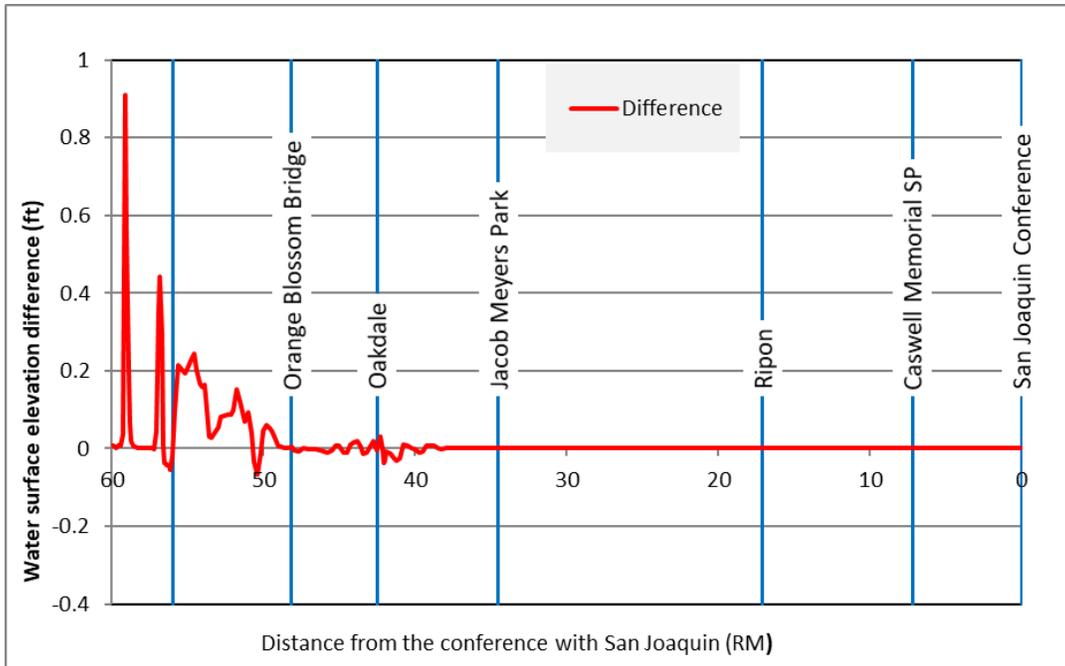
**Figure 3-4. Initial and simulated water surface elevations at a flow of 8,000 cfs for with and without historical gravel augmentation.**

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**



**Figure 3-5. Detailed view of initial and simulated water surface elevations at a flow of 8,000 cfs for with and without historical gravel augmentation.**

Figure 3-6 and Table 3-2 show the water surface profile differences between with the historical gravel augmentation scenario and the without historical gravel augmentation scenario. Figure 3-6 filters the locations where the water surface elevations decreases due to sediment erosion, as it is not essential to the flood inundation level. The numerical model shows that the water surface elevation changes mostly in the reach from Goodwin Dam to Knight's Ferry Bridge with a maximum increase of 0.9 ft. In the reach from Knight's Ferry to Orange Blossom Bridge, the change was reduced to a maximum of 0.2 ft. Downstream of Orange Blossom Bridge, the gravel augmentation did not significantly increase the water surface elevation.



**Figure 3-6. Water surface elevation differences at a flow of 8,000 cfs between historical augmentation and no augmentation scenarios.**

**Table 3-2. Average and Maximum water surface elevation changes in each reach under different scenarios as compared with no gravel augmentation and with initial condition**

Reach	Goodwin Dam to Knight's Ferry	Knight's Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
	(ft)	(ft)	(ft)	(ft)
Average WSE change relative to No Augmentation	0.1	0.1	0.0	0.0
Average WSE change relative to initial WSE	-0.1	-0.1	-0.1	-0.2
Maximum WSE change relative to No Augmentation	0.9	0.2	0.0	0.0
Maximum WSE change relative to initial WSE	0.9	1.0	-0.1	0.2

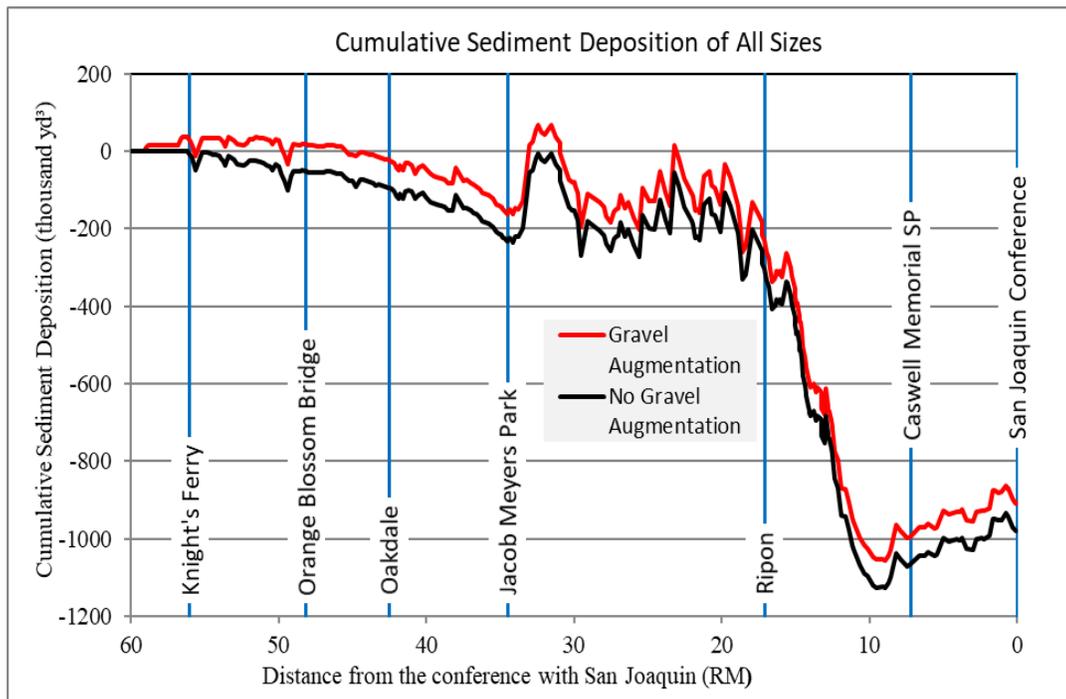
### **3.3. Cumulative Sediment Deposition**

Figure 3-7 shows the Stanislaus River has likely experienced continuous erosion downstream from Goodwin Dam without gravel augmentation. The numerical

## Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam

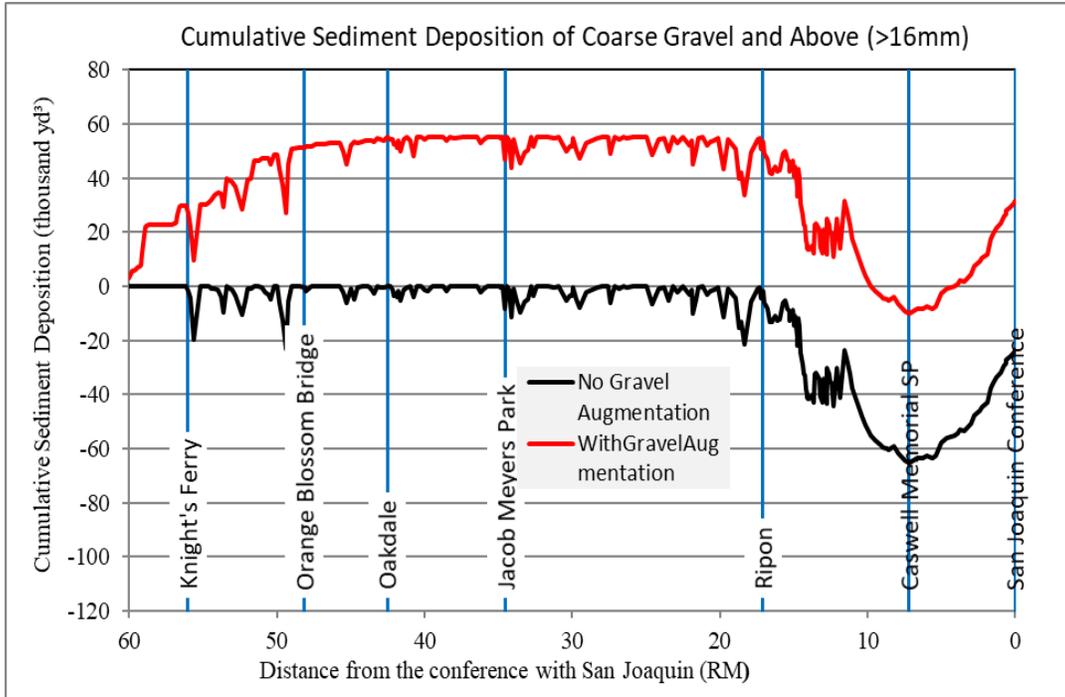
model assumes that bed rock in the canyon upstream of the historic Knight's Ferry Bridge will prevent channel erosion, but in the reach from the Knight's Ferry Bridge to Jacob Meyers Park, about 230 thousand yd<sup>3</sup> of sediment was estimated to be eroded without gravel augmentation. There was some deposition expected just downstream of Jacob Meyer's Park, and then further downstream the river was estimated to erode from Rippon to Caswell Memorial. There is considerable uncertainty in the results downstream of Jacob Meyers Park because only one bed material sample is currently available near the confluence with the San Joaquin River. Bed gradations from samples downstream of the Jacob Meyers Park could improve our confidence in the model results.

Historical gravel augmentation reduced the channel erosion and resulted in about 2,000 yd<sup>3</sup> of deposition in the reach from Goodwin Dam to Orange Blossom Bridge and reduced the erosion volume to 160,000 yd<sup>3</sup> from Goodwin Dam to Jacob Meyers Park. Downstream of Jacob Meyers Park the results are essentially the same between the with and without historical gravel augmentation scenarios.



**Figure 3-7. Cumulative sediment deposition volumes in different gravel augmentation scenarios.**

Figure 3-8 shows the cumulative deposition of the size of coarse gravel and greater (>16 mm). Numerical model shows that the gravel injected most likely stayed in the reach from Goodwin Dam to Oakdale.



**Figure 3-8. Cumulative gravel deposition volumes in different gravel augmentation scenarios.**

Table 3-3 shows the total sediment deposition and the deposition for sediment in the coarse gravel and larger size classes (diameter > 16 mm) in each reach. About 27 thousand yd<sup>3</sup> of sediment has been deposited in the reach from Goodwin Dam to Knight’s Ferry Bridge and about 9 thousand yd<sup>3</sup> of sediment has been eroded in the reach from Knight’s Ferry Bridge to Orange Blossom Bridge. About 24 thousand yd<sup>3</sup> of injected gravel has been deposited in the reach from Goodwin Dam to Knight’s Ferry Bridge and the same amount in the reach from Knight’s Ferry Bridge to Orange Blossom Bridge.

**Table 3-3. Total sediment and coarse gravel deposition (>16mm) in each reach in different scenarios**

Reach	Goodwin Dam to Knight’s Ferry	Knight’s Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
<b>Total Deposition (yd<sup>3</sup>)</b>				
No Gravel Augmentation	-8,000	-42,000	-43,000	-140,000
With Gravel Augmentation	27,000	-9,000	-40,000	-139,000
<b>Gravel (&gt;16mm) Deposition (yd<sup>3</sup>)</b>				
No Gravel Augmentation	-2,000	1,000	300	-8,000
With Gravel Augmentation	24,000	24,000	4,000	-8,000

### 3.4. Bed Material Sediment Size

Figure 3-9 and Figure 3-10 shows the  $D_{50}$  (median bed material sediment size) and  $D_{84}$  (84% of sediment grains are finer), respectively. The numerical model estimated that with gravel augmentation  $D_{50}$  and  $D_{85}$  would increase as compared with initial bed gradation at most locations. There is little difference between the grain sizes with and without gravel augmentation. This is primarily because they both assumed the same starting gradations, which are similar to the gradations of the augmented gravel. There were no observed grain sizes prior to the onset of gravel augmentation.

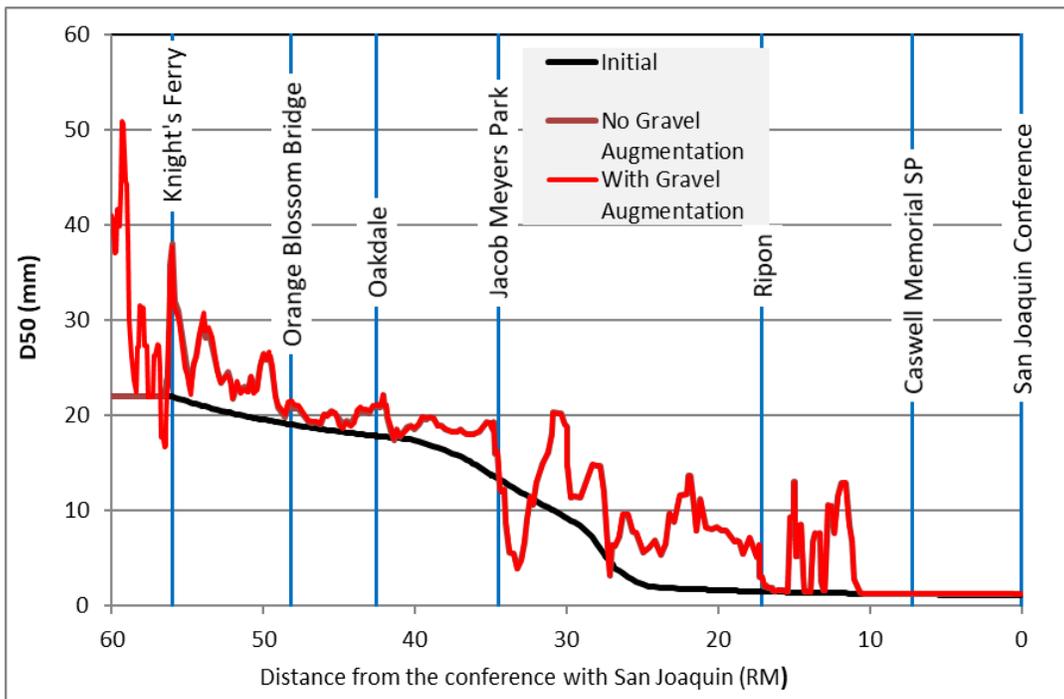
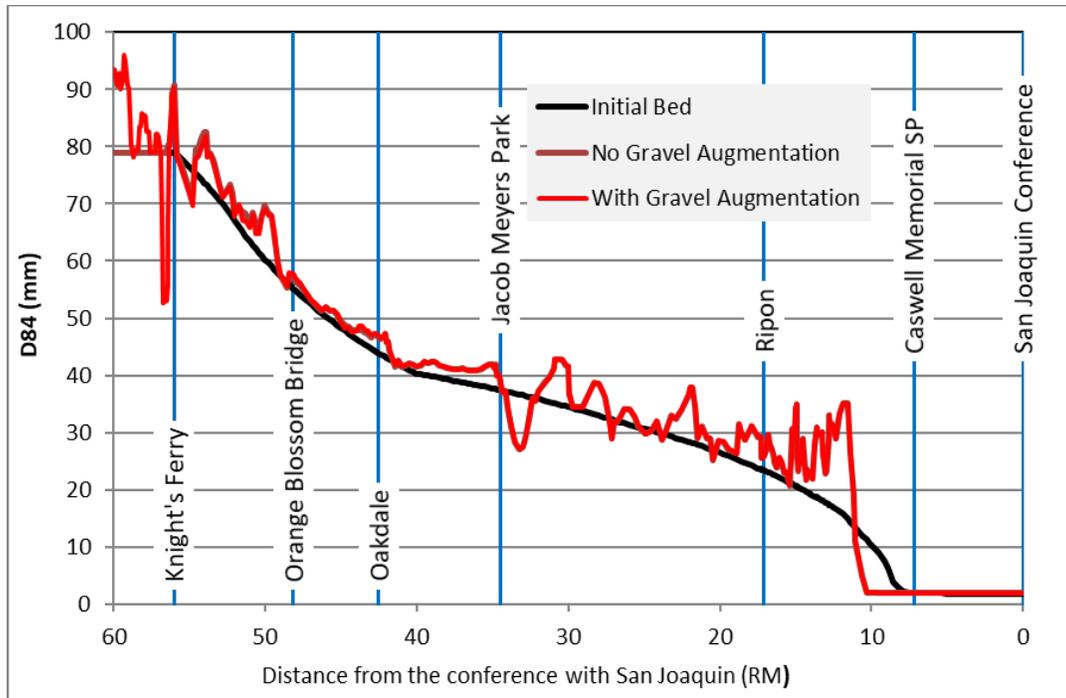


Figure 3-9. Initial and simulated  $D_{50}$  in conditions with and without gravel augmentation.



**Figure 3-10. Initial and final D84 in conditions with and without gravel augmentation.**

### **3.5. Sensitivity to Sediment Transport Equations**

From past experience, it was determined that Parker gravel transport equation (1990) combined with the Engelund–Hansen Formula (1972) better predicts the sediment transport especially in the transition zone from gravel to sand. In the gravel reach the Parker’s equation is used; in the sand reach Engelund–Hansen equation is used; and in the transition reach, this method also provides a hiding effect which increases the gravel transport due to sand lubrication and reduces the sand transport due to gravel hiding.

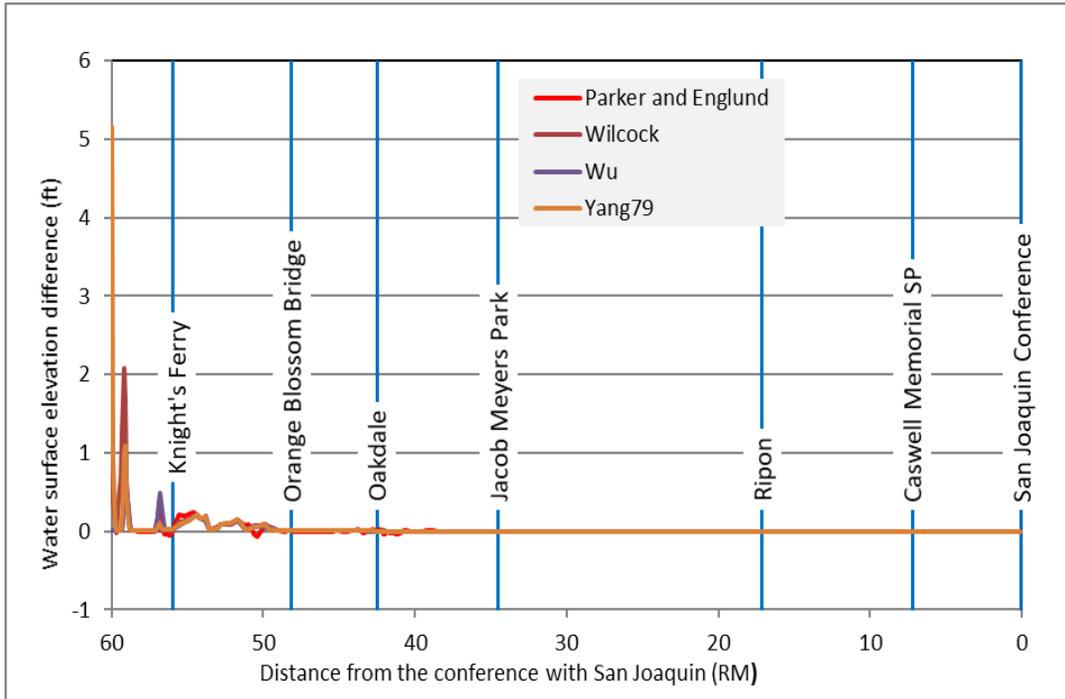
For sensitivity analysis, other sediment transport equations are analyzed including Wilcock’s gravel equation (Wilcock and Crowe, 2003) combined with Engelund–Hansen sand formula, Wu et al’s sand and gravel mixed transport equation (Wu et al., 2000), and Yang’s sand and gravel equations (Yang, 1973; Yang, 1984). Water surface elevations at 8,000 cfs are compared between conditions with and without gravel augmentation using the same sediment transport equation.

Figure 3-11 shows the water surface elevation changes along the river. All sediment transport equations predicted increased water surface elevation only in the reach from Goodwin Dam to Orange Blossom Bridge, and negligible change downstream of Orange Blossom Bridge.

Table 3-4 shows the maximum water surface elevation changes in each reach. In the reach from Goodwin Dam to Knight’s Ferry the maximum water surface elevation change ranges from 0.7 ft to 5.2 ft. In the reach from Knight’s Ferry

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**

Bridge to Orange Blossom Bridge, all equations predict maximum change of 0.2 ft.

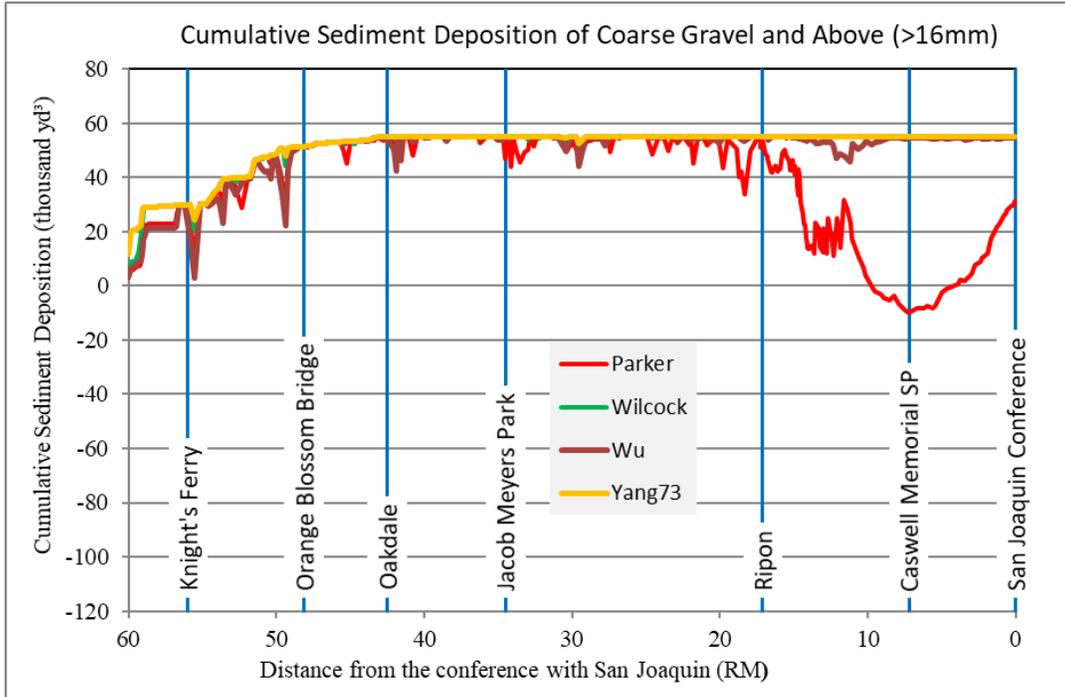


**Figure 3-11. Water surface elevation difference between historical gravel augmentation and no historical gravel augmentation at a flow of 8,000 cfs using different sediment transport equations.**

**Table 3-4. Maximum water surface elevation difference between historical gravel augmentation and no historical gravel augmentation using different sediment transport equations**

Reach	Change in WSE (ft)			
	Goodwin Dam to Knight's Ferry	Knight's Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
Parker with Engelund and Hansen	0.9	0.2	0.0	0.0
Wilcock with Engelund and Hansen	2.1	0.2	0.0	0.0
Wu	0.7	0.2	0.0	0.0
Yang	5.2	0.2	0.0	0.0

Figure 3-12 shows cumulative sediment deposition using different sediment transport equations. Numerical models show that all four equations produce similar gravel (>16 mm) deposition from Goodwin Dam to Ripon. The only difference is that only Parker's gravel transport equation combined with Engelund–Hansen formula produces gravel erosion downstream of Ripon.



**Figure 3-12. Cumulative gravel deposition volumes simulated with different sediment transport equations.**

Table 3-5 shows the deposition of coarse gravel and greater (>16 mm) in each reach using different sediment transport equations. The deposition ranges from 18,000 to 24,000 yd<sup>3</sup> in the reach from Goodwin Dam to Knight’s Ferry, 21,000 to 28,000 yd<sup>3</sup> in the reach from Knight’s Ferry to Orange Blossom Bridge, and 2,000 to 4,000 yd<sup>3</sup> from Orange Blossom Bridge to Oakdale. Depending on the equation used, either erosion or deposition is predicted in the reach from Oakdale to Jacob.

**Table 3-5. Gravel deposition (> 16mm) in each reach using various sediment transport formulas.**

Reach	Volume deposition (yd <sup>3</sup> )			
	Goodwin Dam to Knight’s Ferry	Knight’s Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
Parker with Engelund and Hansen	24,000	24,000	4,000	-8,000
Wilcock with Engelund and Hansen	26,000	21,000	4,000	4
Wu	19,000	28,000	2,000	1,000
Yang73	18,000	21,000	4,000	4

## 4. Future Gravel Augmentation Modeling Results

Seven future gravel augmentation scenarios are simulated with gravel augmentation taking place in the first 15 years, except Scenario 5 with only 5 years of augmentation. The numerical model is run a total of 20 years with no gravel augmentation in the last 5 years, or 15 years in Scenario 5. The sediment results will be used to evaluate the impacts associated with each scenario and determine their effect on water surface elevations during a flow of 8,000 cfs.

### 4.1. Bed Profile

Figure 4-1 shows the initial and simulated bed profiles for the seven gravel augmentation scenarios and for the no gravel augmentation scenario. The numerical model predicts that there is sediment deposition for all seven gravel augmentation scenarios in the reach from Goodwin Dam to Knight's Ferry Bridge. A detailed view of the reach from Goodwin Dam to RM 40 is shown in Figure 4-2. The model shows that the deposition are mostly in the pools in the reach from Goodwin Dam to Knight's Ferry Bridge, or in the area where the channel slope decreases.

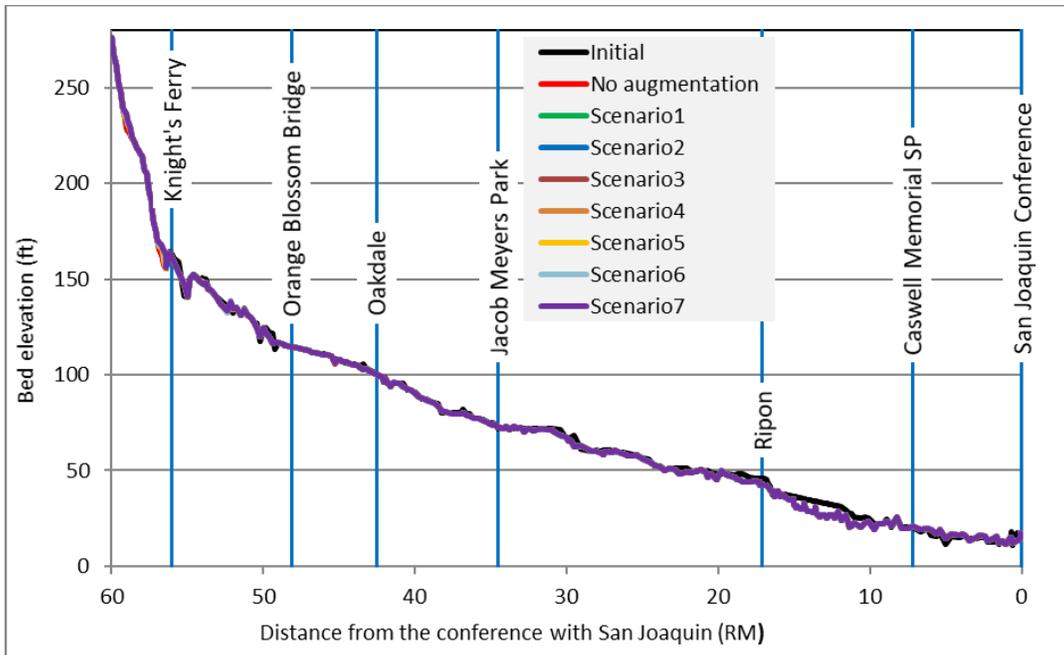
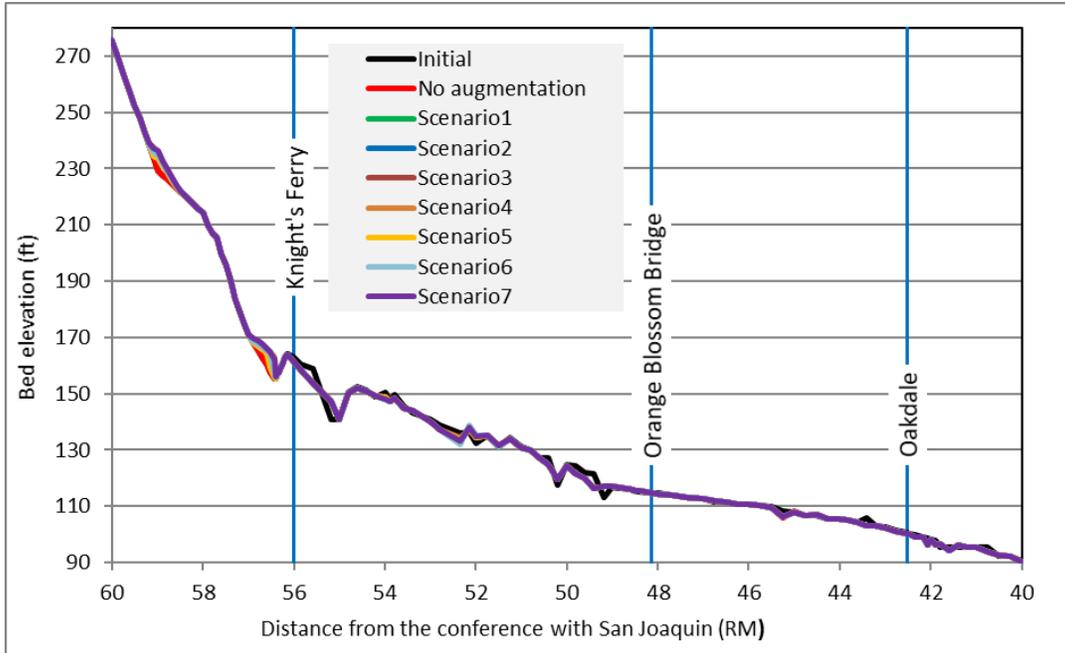
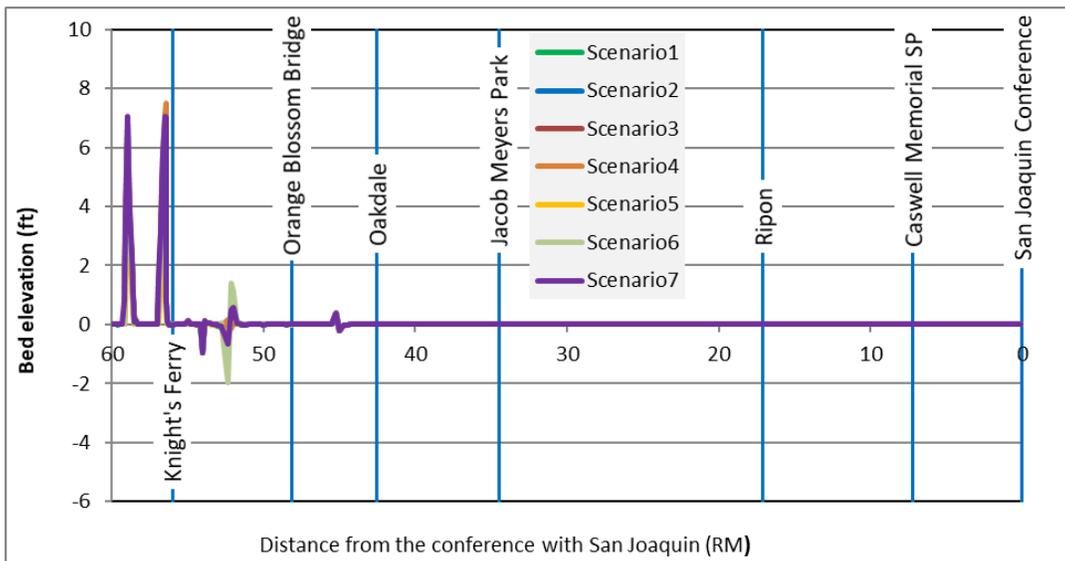


Figure 4-1. Initial and simulated bed profiles in different scenarios.



**Figure 4-2. Detailed view of initial and simulated bed profiles for the augmentation and no-augmentation scenarios.**

Figure 4-3 shows the difference between the sediment bed profile predicted for the gravel augmentation scenarios as compared with the no gravel augmentation scenario. The numerical model predicts that the most sediment deposition will occur in the reach from Goodwin Dam to the Knight’s Ferry Bridge.



**Figure 4-3. Bed profile differences in different scenarios as compared with no gravel augmentation condition.**

Table 4-1 shows the average channel elevation changes in each reach under different scenarios. The differences are calculated as compared with the numerical simulation with no gravel augmentation. In the reach from Goodwin

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of  
Goodwin Dam**

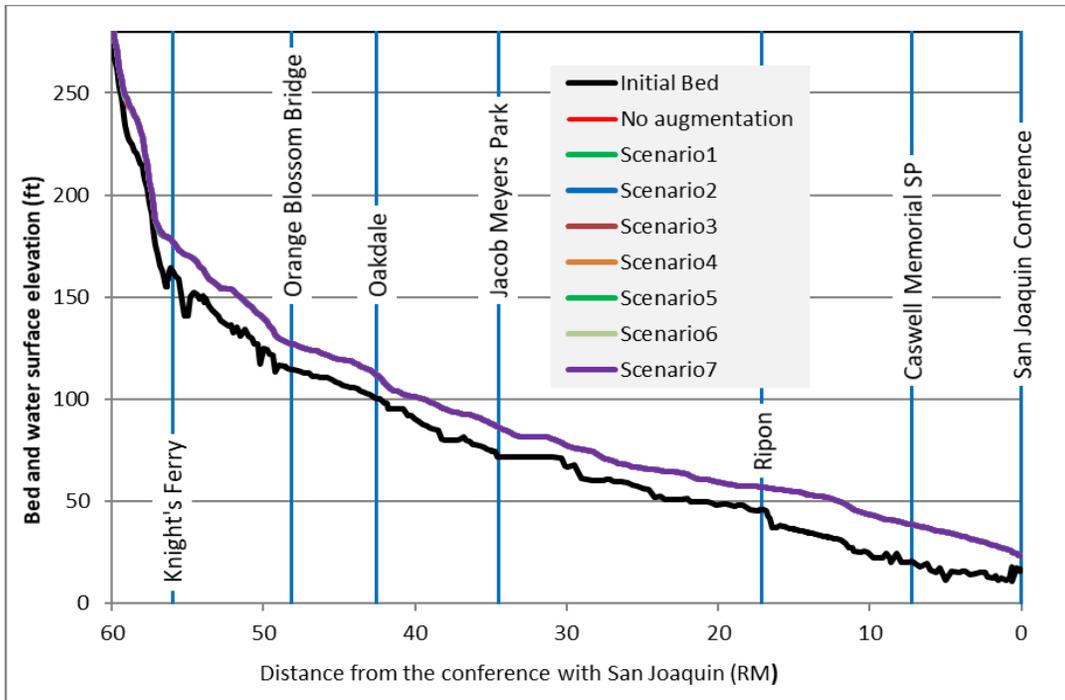
Dam to Knight’s Ferry Bridge, the bed change ranges from 0.5 ft in Scenario 5 to 1.1 ft in Scenarios 4 and 7. No bed change is found in reaches downstream of Knight’s Ferry Bridge.

**Table 4-1. Average channel deposition in each reach under different scenarios as compared with no gravel augmentation**

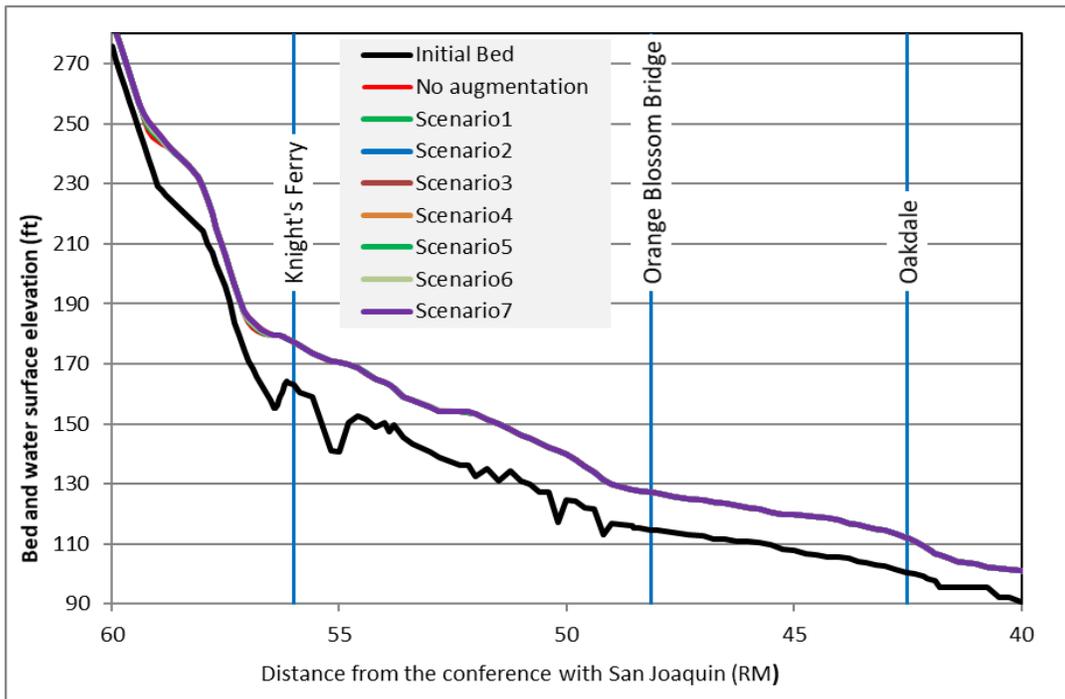
Reach	Goodwin Dam to Knight’s Ferry	Knight’s Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
	Change (ft)	Change (ft)	Change (ft)	Change (ft)
Scenario1	0.9	0.0	0.0	0.0
Scenario2	1.0	0.0	0.0	0.0
Scenario3	1.0	0.0	0.0	0.0
Scenario4	1.1	0.0	0.0	0.0
Scenario5	0.5	0.0	0.0	0.0
Scenario6	0.8	0.0	0.0	0.0
Scenario7	1.1	0.0	0.0	0.0

**4.2. Water Surface Elevation during Required Protection Level of 8,000 cfs**

Figure 4-4 shows the water surface elevation profiles at 8,000 cfs at the end of the 20-yr simulation for the seven gravel augmentation scenarios and for the no gravel augmentation scenario. From this figure it is difficult to determine the water surface elevation difference between these scenarios. A detailed view (Figure 4-5) shows that the water surface profile was slightly elevated in the reach from Goodwin Dam to Knight’s Ferry Bridge, but only in the area when the bed slope decreases.



**Figure 4-4. Initial and simulated water surface elevations in different scenarios.**

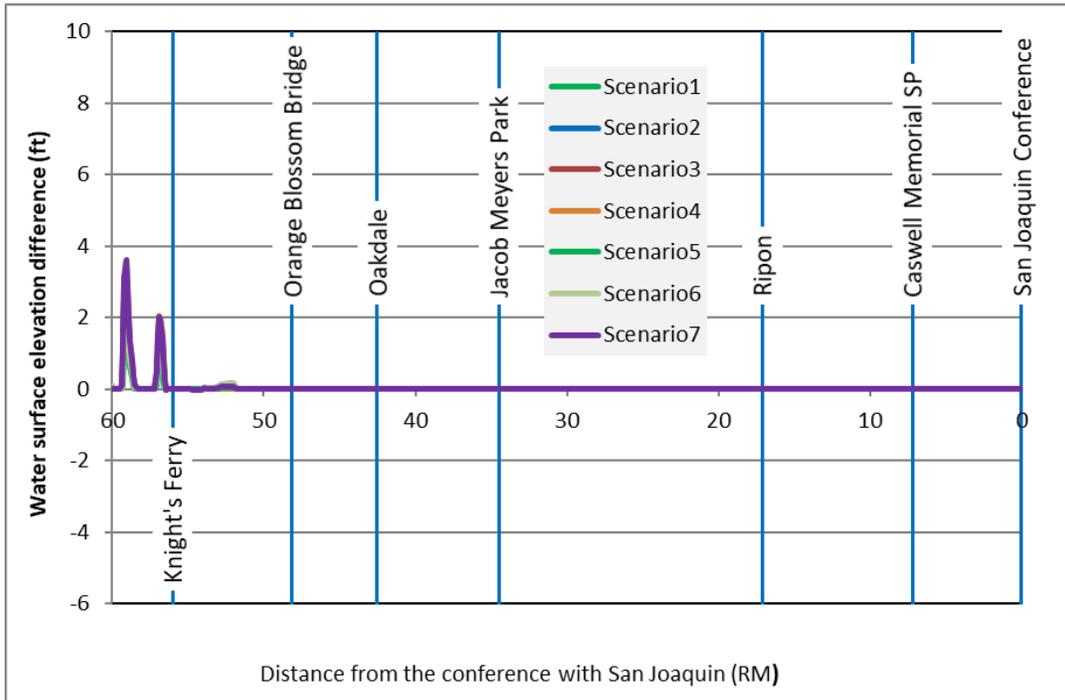


**Figure 4-5. Detailed view of initial and simulated water surface elevations in different scenarios.**

Figure 4-6 and Table 4-2 show the water surface profile differences between gravel augmentation scenarios and that with no gravel augmentation. Figure 4-6 filters the locations where the water surface elevations decrease due to sediment

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**

erosion, as the conveyance is expected to increase in these reaches. The numerical model predicts that the water surface elevations will increase mostly in the reach from Goodwin Dam to Knight’s Ferry Bridge with a maximum of 3.6 ft increase in Scenario 4 and Scenario 7 relative to current conditions. In the reach from Knight’s Ferry Bridge to Orange Blossom, water surface elevation will increase up to 0.2 ft. No water surface elevation change will occur downstream of Orange Blossom Bridge.



**Figure 4-6. Water surface elevation differences between gravel augmentation scenarios and no gravel augmentation scenario.**

**Table 4-2. Maximum water surface elevation changes for a flow of 8,000 cfs in each reach for various gravel augmentation scenarios as compared to the no gravel augmentation scenario.**

Reach	Maximum Increase in Water Surface Elevation (ft)			
	Goodwin Dam to Knight’s Ferry	Knight’s Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
	Change (ft)	Change (ft)	Change (ft)	Change (ft)
Scenario1	3.0	0.1	0.0	0.0
Scenario2	3.3	0.0	0.0	0.0
Scenario3	3.2	0.0	0.0	0.0
Scenario4	3.6	0.0	0.0	0.0
Scenario5	1.9	0.0	0.0	0.0
Scenario6	2.7	0.2	0.0	0.0
Scenario7	3.6	0.1	0.0	0.0

Table 4-3 show the average water surface profile differences between gravel augmentation scenarios and the no gravel augmentation scenario. The numerical model predicts that the average water surface elevations will increase mostly in the reach from Goodwin Dam to Knight’s Ferry Bridge with a maximum of 0.5 ft average increase in Scenario 4 and Scenario 7 relative to no gravel augmentation condition. In the reach from Knight’s Ferry Bridge to Orange Blossom, water surface elevation will increase up to 0.02 ft. No water surface elevation change will occur downstream of Orange Blossom Bridge.

**Table 4-3. Average water surface elevation changes for a flow of 8,000 cfs in each reach for various gravel augmentation scenarios as compared to the no gravel augmentation scenario.**

Reach	Average Increase in Water Surface Elevation (ft)			
	Goodwin Dam to Knight’s Ferry	Knight’s Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
	Change (ft)	Change (ft)	Change (ft)	Change (ft)
Scenario1	0.4	0.01	0.0	0.0
Scenario2	0.4	0.01	0.0	0.0
Scenario3	0.4	0.00	0.0	0.0
Scenario4	0.5	0.00	0.0	0.0
Scenario5	0.2	0.00	0.0	0.0
Scenario6	0.3	0.02	0.0	0.0
Scenario7	0.5	0.01	0.0	0.0

Table 4-4 show the average water surface profile differences between gravel augmentation scenarios and the current water surface profile at 8,000 cfs. The numerical model predicts that the average water surface elevations will increase mostly in the reach from Goodwin Dam to Knight’s Ferry Bridge with a maximum of 0.4 ft increase in Scenario 7 relative to current condition. In the reach from Knight’s Ferry Bridge to Orange Blossom, water surface elevation will decrease 0.2 ft in all scenarios. In the reaches from Orange Blossom Bridge to Oakdale and from Oakdale to Jacob the water surface elevation will decrease in an average of 0.1 ft in all scenarios.

**Table 4-4. Average water surface elevation changes in each reach for various gravel augmentation scenarios as compared to the current water surface elevation at a flow rate of 8,000 cfs.**

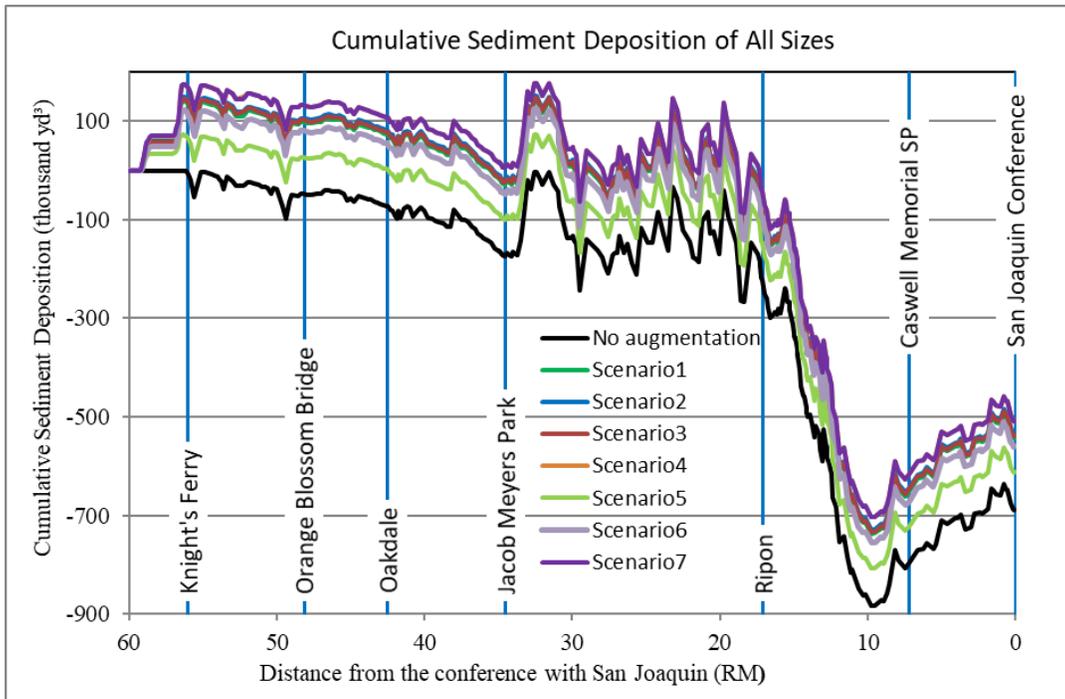
Reach	Average Increase in Water Surface Elevation (ft) as compared with current condition			
	Goodwin Dam to Knight's Ferry	Knight's Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
	Change (ft)	Change (ft)	Change (ft)	Change (ft)
Scenario1	0.2	-0.2	-0.1	-0.1
Scenario2	0.3	-0.2	-0.1	-0.1
Scenario3	0.3	-0.2	-0.1	-0.1
Scenario4	0.3	-0.2	-0.1	-0.1
Scenario5	0.0	-0.2	-0.1	-0.1
Scenario6	0.2	-0.2	-0.1	-0.1
Scenario7	0.4	-0.2	-0.1	-0.1

### **4.3. Cumulative Sediment Deposition**

Figure 4-7 shows cumulative sediment deposition for the seven gravel augmentation scenarios and for the no gravel augmentation scenario. The cumulative sediment disposition plot can be used to identify areas of erosion and deposition as well the magnitude of that erosion or deposition. If the line is increasing in the left to right direction, then deposition is predicted. If the line is decreasing in the left to right direction, then erosion is predicted. Deposition is predicted for all the gravel augmentation scenarios in the reach between Goodwin Dam and Knight's Ferry Bridge. However, erosion is predicted to occur for all gravel augmentation scenarios between Knight's Ferry Bridge and Jacob Meyers Park. The erosion is due to the fact that less gravel makes than the bed material the river transports out of the reach.

Numerical model shows if there is no gravel augmentation, a total of 180,000 yd<sup>3</sup> of sediment will be eroded from the bed in the reach from Goodwin Dam to Jacob Meyers Park. With gravel augmentation, the reach between Goodwin Dam and Jacob Meyers Park will experience erosion of 100,000 yd<sup>3</sup> in Scenario 5 to deposition of 5,000 yd<sup>3</sup> in Scenario 7.

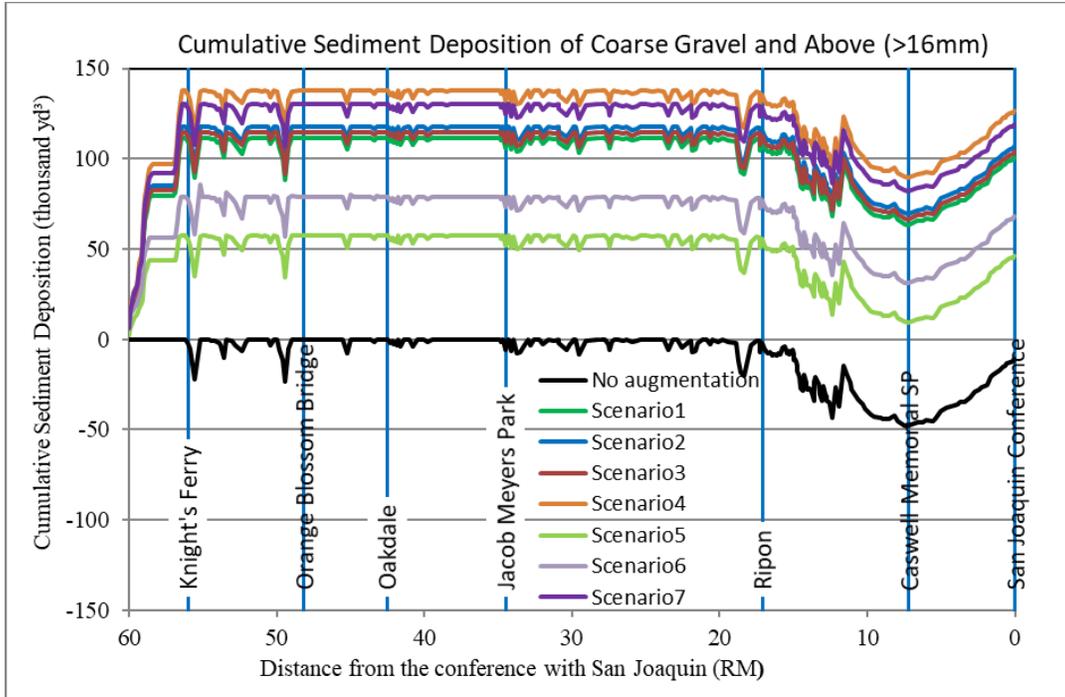
The model predicts significant erosion just downstream of Jacob Meyers Park for all scenarios. It is likely that the river bathymetry is incorrect in this location because the river slope is zero for a significant distance. Because project impacts do not appear to extend below Oakdale, bathymetry improvement below Jacob Meyers Park was not deemed necessary.



**Figure 4-7. Cumulative sediment deposition volumes in different gravel augmentation scenarios.**

Figure 4-8 shows the cumulative deposition of the size of coarse gravel and greater (>16 mm). The numerical model predicts that the gravel injected will most likely remain in the reach from Goodwin Dam to Knight's Ferry.

**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**



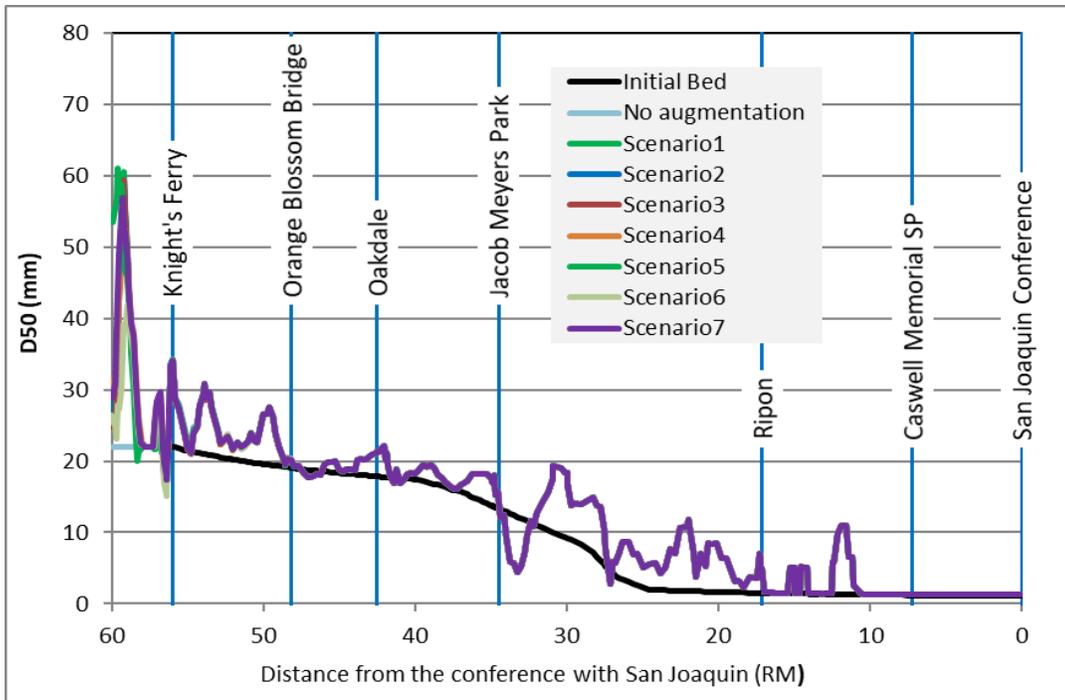
**Figure 4-8. Cumulative gravel deposition volumes in different gravel augmentation scenarios.**

**Table 4-5. Gravel deposition volumes (>16mm) in each reach in different scenarios.**

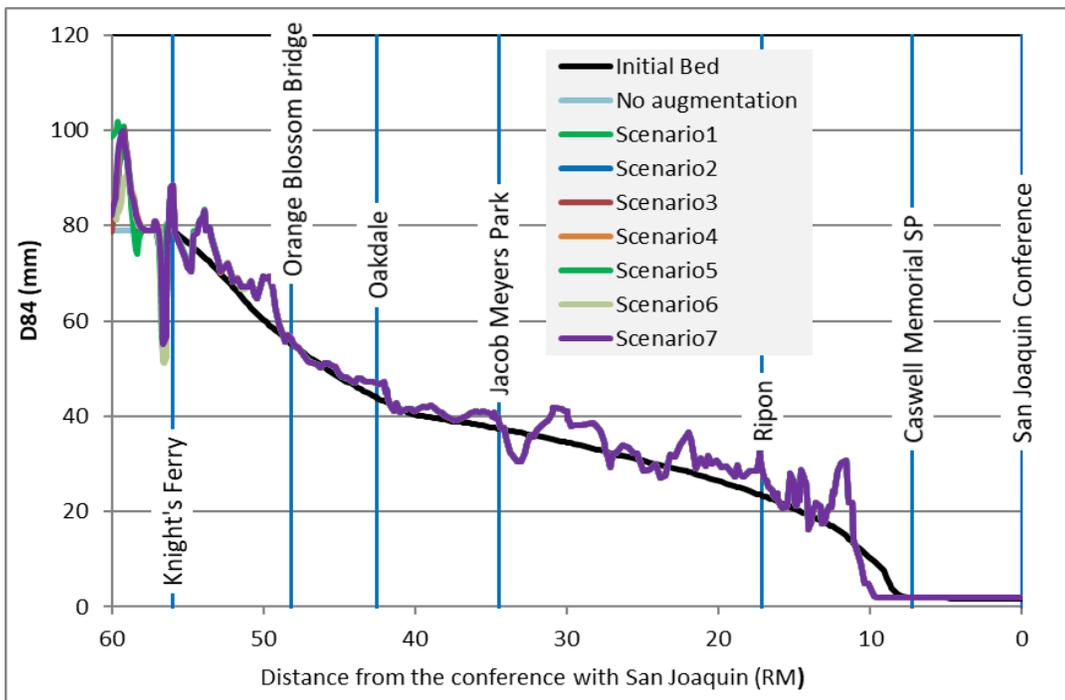
Reach	Goodwin Dam to Knight's Ferry (yd <sup>3</sup> )	Knight's Ferry to Orange Blossom Bridge (yd <sup>3</sup> )	Orange Blossom Bridge to Oakdale (yd <sup>3</sup> )	Oakdale to Jacob (yd <sup>3</sup> )
No Sed	-1,754	1,754	0	-5,669
Scenario1	103,495	1,759	0	-5,669
Scenario2	109,347	1,759	0	-5,669
Scenario3	106,350	1,756	0	-5,669
Scenario4	127,635	1,759	0	-5,669
Scenario5	53,050	1,756	0	-5,669
Scenario6	71,388	1,740	0	-5,669
Scenario7	121,910	1,759	0	-5,669

**4.4. Bed Material Sediment Size**

Figure 4-9 and Figure 4-10 show the D<sub>50</sub> (median bed material sediment size) and D<sub>84</sub> (84% of sediment grains are finer), respectively. The numerical model predicts that with gravel augmentation, the D<sub>50</sub> and D<sub>84</sub> would increase as compared with initial bed gradation at most locations. There is little difference between the augmentation and the no augmentation scenarios.



**Figure 4-9. Initial and simulated mean sediment sizes in different gravel augmentation scenarios.**



**Figure 4-10. Initial and simulated  $D_{84}$  in different gravel augmentation scenarios.**

### **4.5. Results at Old Knight’s Ferry Bridge**

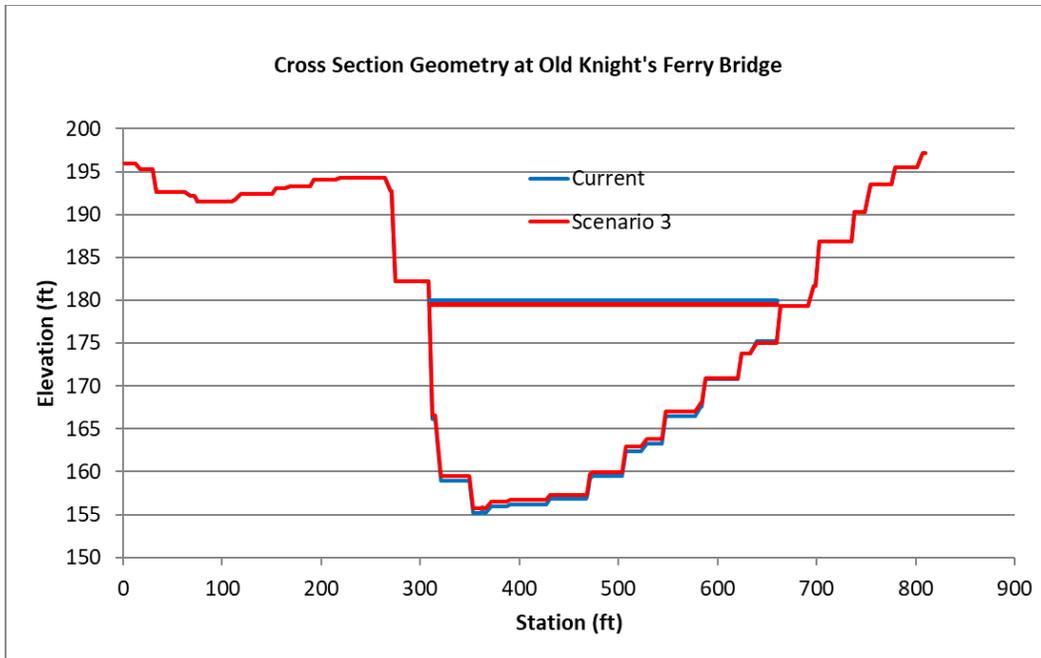
The old Knight’s Ferry Bridge is a historic covered bridge built in 1863. It is one of the best-preserved 19th-century wood-iron Howe truss bridges still existing today. It was designated as a U.S. National Historic Landmark in 2012.

Table 4-2 shows the sediment loads passing the bridge over the 20-year model simulation. Model results indicate that most of the gravel injected will remain in the canyon reach and be transported to the bridge cross section. In Scenario 3, about 6,106 yd<sup>3</sup> of sediment will pass the bridge, of which only 3 are coarse gravel and above (>16 mm). The numerical model assumes that bed rock controls the reach from Goodwin Dam to the cross section just upstream of the old Knight’s Ferry Bridge. In case of no gravel augmentation, the channel would be eroded in the canyon reach where sediment is available. It should be mentioned that the amount of sediment in Table 4-2 represents the sediment passing the bridge, not that deposited at the bridge. The sediment passing the bridge would slightly relieve the downstream sediment erosion that is predicted to occur.

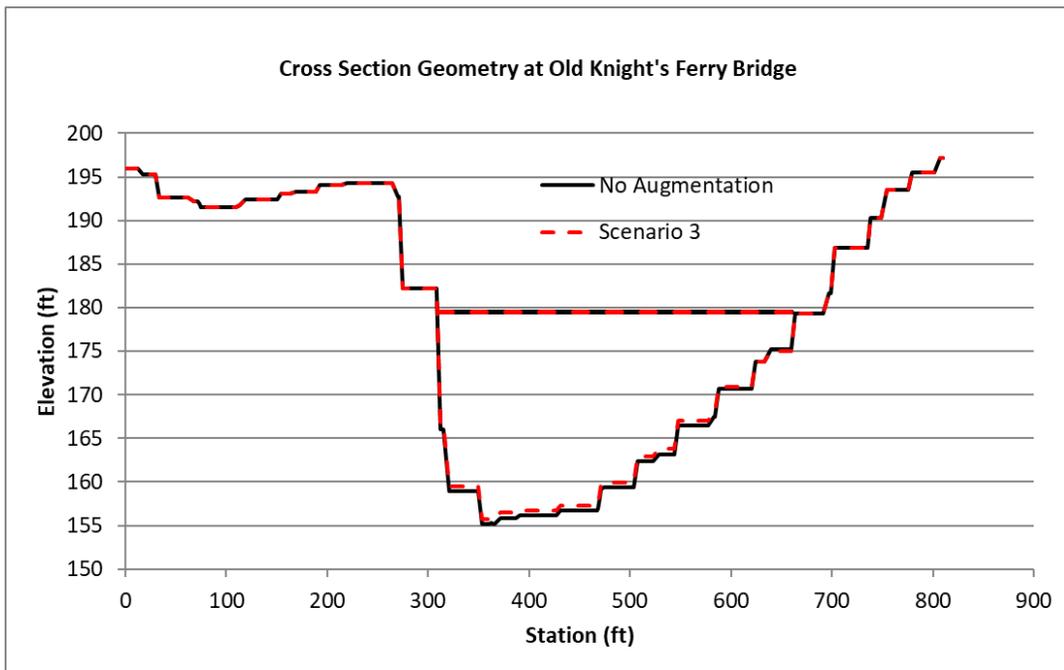
**Table 4-6. Sediment loads passing the Old Knight’s Ferry Bridge.**

	All Sediment Sizes	Coarse Gravel and Above (>16 mm)
	Yd <sup>3</sup>	Yd <sup>3</sup>
No Sed	67	0
Scenario1	6,156	7
Scenario2	6,033	6
Scenario3	6,106	3
Scenario4	6,607	13
Scenario5	3,071	5
Scenario6	5,716	3
Scenario7	6,170	6

Figure 4-11, and Figure 4-12 present the channel cross section at the old Knight’s Ferry Bridge. The numerical model shows that about 0.41 ft of sediment will be deposited at the bridge in no gravel argumentation condition and about 0.45 ft of sediment will be deposited in Scenario 3. It should be mentioned that a 1D numerical model is unable to capture the detailed hydraulics that occur within pool and riffle sequences of gravel bed rivers, and the model usually artificially fills pools in a 1D model. Natural pool forms at at the old Knight’s Ferry Bridge where the river is constricted within a bedrock canyon that is narrow and deep. It is expected that sediment would pass this old Knight’s Ferry Bridge and this sediment deposition at the bridge location values represent an upper limit of deposition.



**Figure 4-11. Cross section geometry and water surface elevation at a flow of 8,000 cfs at the Old Knight’s Ferry Bridge compared with the current condition.**



**Figure 4-12. Cross section geometry and water surface elevation at a flow of 8,000 cfs at the Old Knight’s Ferry Bridge compared with the no gravel augmentation condition.**

Table 4-2 shows the water surface elevation changes at Old Knight’s Ferry Bridge. Numerical models indicate that the future water surface elevation will be lowered by about 0.45 ft in Scenario 3, as compared with the current channel

geometry at a flow of 8,000 cfs. The water surface lowers at the bridge because channel erosion is predicted to occur downstream of the Old Knight’s Ferry Bridge, lowering the water surface elevations downstream as well as at the bridge.

When compared with the no gravel augmentation scenario, almost no water surface elevation change is found between Scenario 3 and other scenarios. The water surface elevation is controlled by downstream channel profile instead of local cross section changes at the pool. The water surface elevation decrease at the bridge is mostly due to the channel erosion downstream of the Knight’s Ferry Bridge.

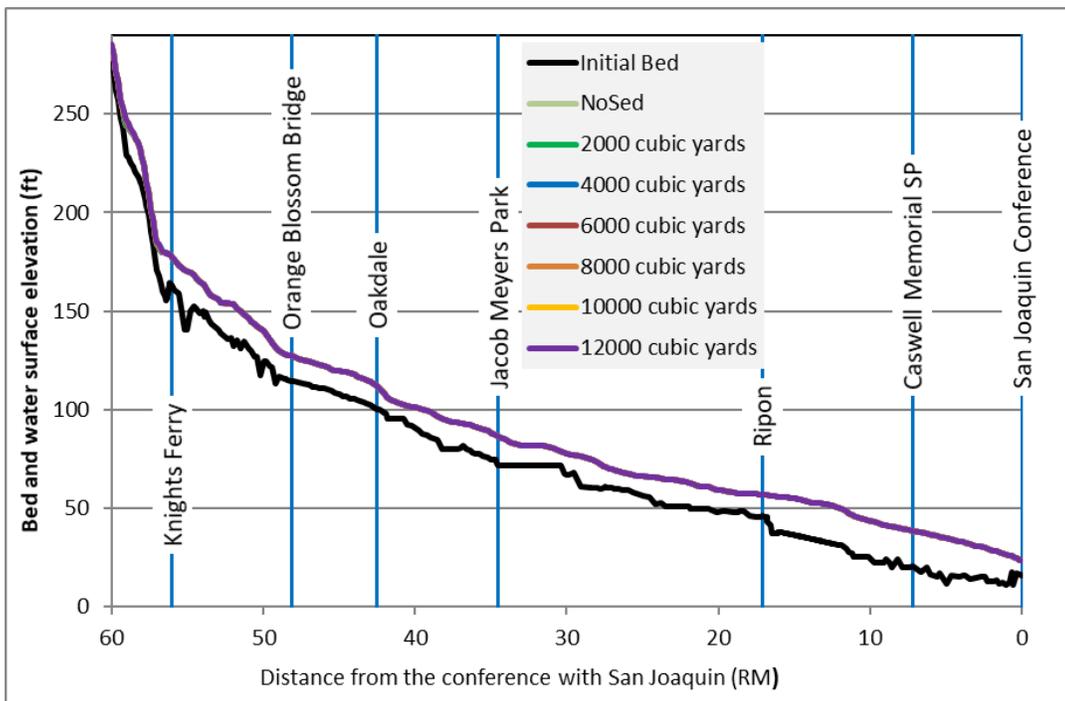
**Table 4-7. Initial and final water surface elevations at the Old Knight’s Ferry Bridge and their changes as compared with the current condition and the no gravel augmentation condition.**

	Water Surface Elevation (ft)	Water Surface Elevation Difference Compared with Current Condition (ft)	Water Surface Elevation Difference Compared with No Augmentation (ft)
Initial	179.96	N/A	N/A
No Sed	179.50	-0.46	N/A
Scenario1	179.51	-0.45	0.003
Scenario2	179.51	-0.45	0.000
Scenario3	179.51	-0.45	0.001
Scenario4	179.51	-0.45	-0.001
Scenario5	179.50	-0.46	-0.002
Scenario6	179.51	-0.45	0.003
Scenario7	179.51	-0.45	-0.001

## **5. Modeling Results of Various Gravel Augmentation Amounts**

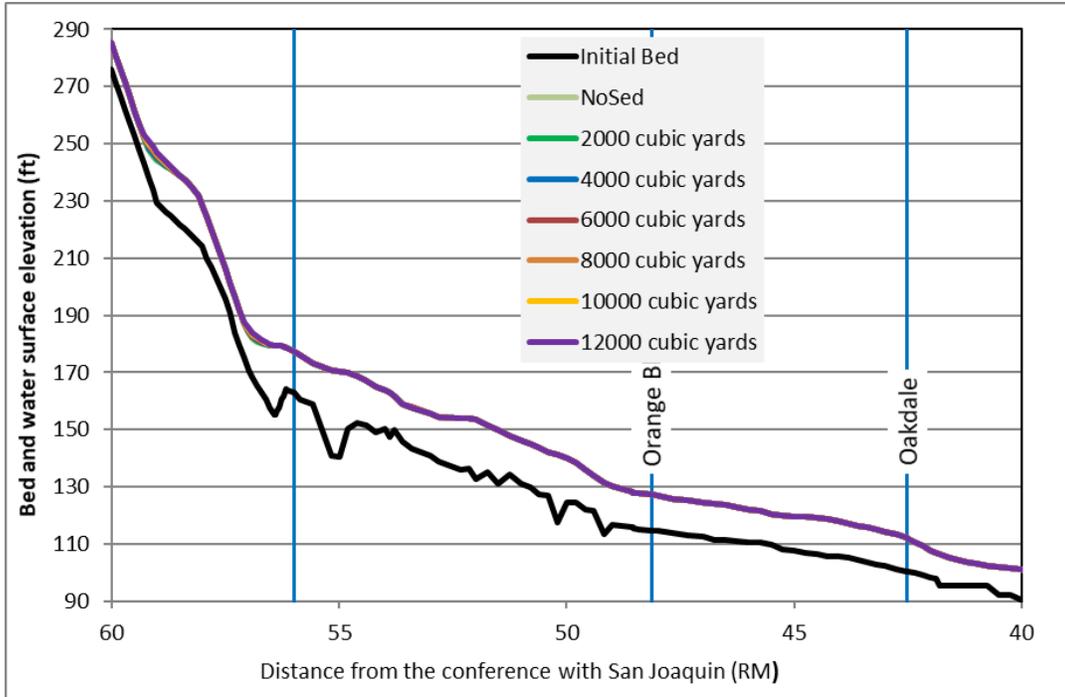
To more clearly quantify the impact of various gravel augmentation amounts on the water surface elevations, gravel augmentation scenarios are simulated with constant rates of gravel augmentation. Several scenarios are simulated with the gravel augmentation rate varied between 2,000 yd<sup>3</sup> to 12,000 yd<sup>3</sup>/yr, in increments of 2,000 yd<sup>3</sup>. The rate is kept constant for the first 15 years of simulation then there are 5 years additional years of simulation with no gravel augmentation. Figure 5-1 and Figure 5-2 show computed water surface elevation profiles at a flow of 8,000 cfs at the end of the simulation of the various scenarios. For comparison, the condition without gravel augmentation is also simulated. The water surface elevation profiles of the gravel augmentation scenarios are slightly elevated in the reach from Goodwin Dam to Knight’s Ferry Bridge.

Figure 5-3 and Figure 5-4 show the water surface elevation changes as compared with the condition without gravel augmentation. Since the numerical model does not allow channel erosion in the reach from old Knight's Ferry Bridge, it is expected that the water surface elevation in the condition without gravel augmentation is similar with the current water surface elevation at 8,000 cfs. The model shows that the water surface elevation changes only in the reach from Goodwin Dam to Knight's Ferry Bridge at two locations where the slope decreases. The maximum water surface elevation increases from 0.8 ft at 2,000 yd<sup>3</sup>/year to 3.6 ft at 12,000 yd<sup>3</sup>/year. Downstream from Knights Ferry Bridge, water surface elevation change is negligible. There are only six cross sections in the reach from Goodwin Dam to the Knight's Ferry Bridge and all the other cross sections in the numerical model were interpolated. For this reason, the maximum water surface elevation increases will occur at places where the channel slope decreases, but the exact locations of these maximum water surface elevation increases from this numerical model are not reliable. It is much more likely that deposition will be spread out more uniformly than the model predicts. However, the average deposition is considered more accurate.

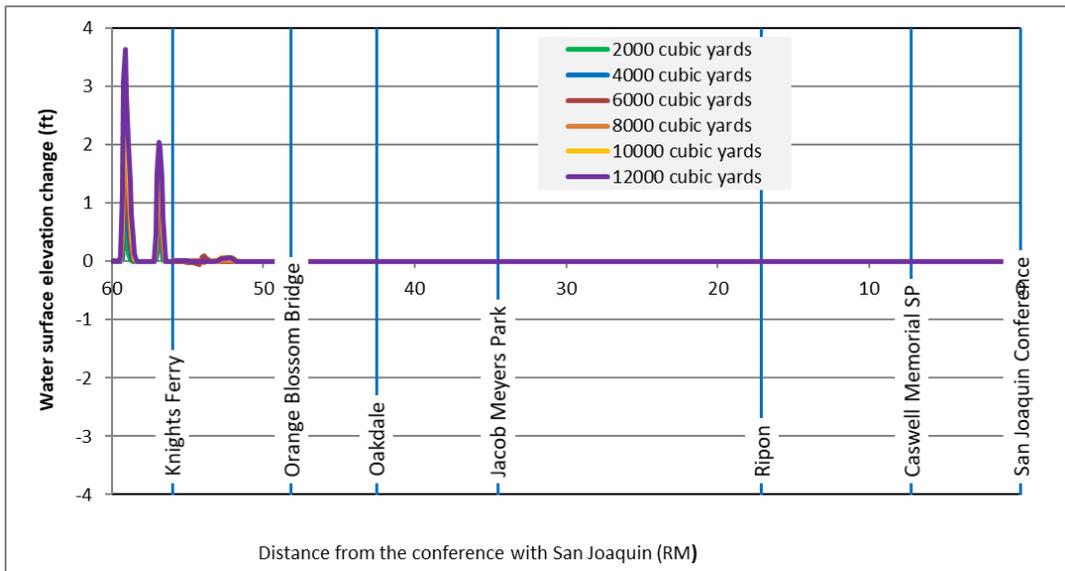


**Figure 5-1. Water surface elevation profiles at flow rate of 8,000 cfs after various amounts of gravel augmentation per year.**

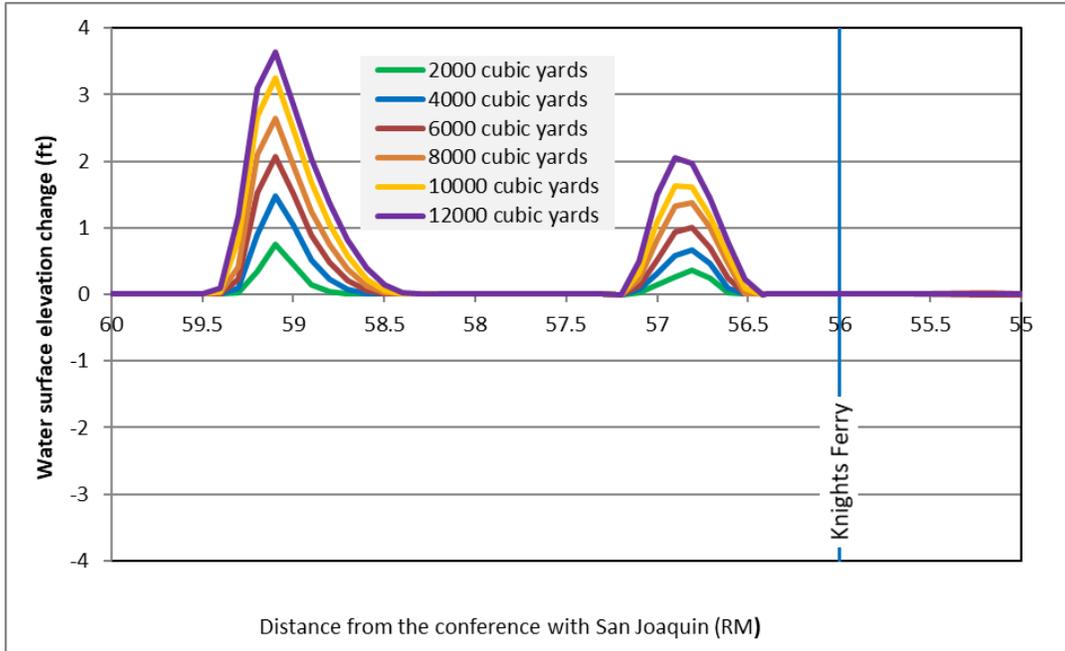
**Geomorphic Response to Gravel Augmentation in the Stanislaus River Downstream of Goodwin Dam**



**Figure 5-2. Detailed view of water surface elevation profiles at flow rate of 8,000 cfs after various amounts of gravel augmentation per year.**



**Figure 5-3. Water surface elevation changes with various amount of gravel augmentation per year as compared with no gravel augmentation scenario.**



**Figure 5-4. Detailed view of water surface elevation changes at a flow of 8,000 cfs with various amount of gravel augmentation per year as compared with no gravel augmentation condition.**

Table 5-1 show the average water surface profile differences between gravel augmentation scenarios and the current water surface profile at 8,000 cfs. The numerical model predicts that in the reach from Goodwin Dam to Knight’s Ferry Bridge the average water surface elevations will vary from a decrease of 0.1 ft in for the 2,000 yd<sup>3</sup> annual gravel injection scenario to an increase of 0.4 ft for the 12,000 yd<sup>3</sup> annual gravel injection scenario. In the reach from Knight’s Ferry Bridge to Orange Blossom, water surface elevation will decrease 0.2 ft in all conditions. In the reaches from Orange Blossom Bridge to Oakdale and from Oakdale to Jacob, the water surface elevation will decrease in an average of 0.1 ft in all conditions. Kondolf et al. (2001) estimated channel incision of about 0.5 to 1.0 meter (1.6 to 3.3 ft) , lateral bank erosion or both from the extensive exposure of tree root crowns in the reach between Knights Ferry and the Highway 120 Bridge at Oakdale. It is estimated that erosion will continue downstream of the Knights Ferry bridge.

**Table 5-1. Average water surface elevation changes in each reach for various gravel augmentation amounts as compared to the current water surface elevation for a flow of 8,000 cfs.**

Reach	Average Increase in Water Surface Elevation (ft)			
	Goodwin Dam to Knight's Ferry	Knight's Ferry to Orange Blossom Bridge	Orange Blossom Bridge to Oakdale	Oakdale to Jacob
	Change (ft)	Change (ft)	Change (ft)	Change (ft)
2,000 yd <sup>3</sup>	-0.1	-0.2	-0.1	-0.1
4,000 yd <sup>3</sup>	0.0	-0.2	-0.1	-0.1
6,000 yd <sup>3</sup>	0.1	-0.2	-0.1	-0.1
8,000 yd <sup>3</sup>	0.2	-0.2	-0.1	-0.1
10,000 yd <sup>3</sup>	0.3	-0.2	-0.1	-0.1
12,000 yd <sup>3</sup>	0.4	-0.2	-0.1	-0.1

## 6. Summary and Conclusions

A one-dimensional flow and sediment transport model (SRH-1D) has been used to study geomorphic response to historical and potential future gravel augmentation. This numerical model simulated the historical gravel augmentation from 1994 to 2018 and the seven gravel augmentation scenarios, of which Scenario 3 is the one for which the Bay-Delta Office of the Reclamation is seeking a permit. The major conclusions from this study are:

1. Historical gravel augmentation from 1994 to 2018 helped reduce channel degradation in the reach from Knight's Ferry Bridge to Jacob Meyers; however, it may have increased the water surface elevation during required protection level of 8,000 cfs by about 0.9 ft in the reach from Goodwin Dam to Knight's Ferry Bridge and 0.2 ft in the reach from Knight's Ferry Bridge to Orange Blossom Bridge. The water surface elevation increase occurs in a short reach where the channel slope decreases.
2. Without gravel augmentation, the river will continue to experience degradation in the reach from Knight's Ferry Bridge to Jacob Meyers. In a 20-year period, 180,000 yd<sup>3</sup> of sediment will be eroded from this reach.
3. Seven scenarios of future gravel augmentations are simulated. Most of the augmented gravel remains in the reach from Goodwin Dam to Knight's Ferry Bridge. Even with gravel augmentation at Goodwin Dam, erosion is expected in the river channel from Knight's Ferry Bridge to Jacob Meyers Park. The water surface elevations at a flow of 8,000 cfs were computed for each scenario, and the maximum increase of all scenarios was up to 3.6 ft in the reach from Goodwin Dam to Knight's Ferry Bridge, up to 0.2 ft from Knight's Ferry Bridge to Orange Blossom Bridge, and negligible change downstream of Orange Blossom Bridge.
4. The gravel argumentation Scenario 3 is the preferred scenario for which that Bay-Delta Office of the Reclamation is seeking permit renewal. In

this scenario, the maximum water surface elevation increase at a flow of 8,000 cfs is predicted to be 3.2 ft in the reach from Goodwin Dam to Knight's Ferry Bridge as compared to the no gravel augmentation scenario, and the average increase in the same reach will be 0.4 ft. When compared with the current river bathymetry, the average water surface elevation increase in this canyon reach will be 0.3 ft. Downstream of the Knight's Ferry Bridge, the water surface elevation will decrease in Scenario 3 of gravel augmentation.

5. Most of the gravel injected in Scenario 3 will remain in the reach from Goodwin Dam to Knight's Ferry Bridge. Based upon the 20-year simulation of Scenario 3, about 6,033 yd<sup>3</sup> of sediment will pass the Old Knight's Ferry Bridge, of which only 3 yd<sup>3</sup> are coarse gravel and larger (>16 mm). The water surface elevation at 8,000 cfs at the Old Knight's Ferry Bridge will be reduced by about 0.5 ft in Scenario 3, due to downstream channel erosion.

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