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Matilija Dam Removal 65% Design Subtask 2.2: Detailed Sediment Transport Modeling from Matilija Dam to Downstream to Ventura River Delta

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Cover photo: Matilija Dam, Ventura County, California, April 30, 2013.

I hereby certify that all work described in this report follows accepted engineering practices and was completed under my direction. Sediment transport modeling was conducted by Dr. Yantao Cui and the results are summarized in this report. Future use of the information presented herein should consider the limitations of this analyses including inherent uncertainties associated with sediment transport modeling and the coarse nature of the modeling approach.

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1 INTRODUCTION

Located on Matilija Creek within the Ventura River watershed in southern California, Matilija Dam (cover photo and Figure 1) was 198 ft (60 m) tall upon its completion in 1948, with a storage capacity of 7,018 acre-ft (8.7 million m^3). It was notched twice (in 1965 and 1977) to the current height of 168 ft (51 m) to lessen the risk of dam failure[1]. As a result of both sedimentation and notching, the Matilija Reservoir storage capacity had been reduced to less than 10% of its original design capacity by 2000, completely losing its design functionality for water storage and flood control (e.g. Bureau of Reclamation (BOR) (2006). The stored sediment volume was approximately 6–7 million cubic yards (CY) (4.5–5.4 million m^3) by 2005 (BOR 2006, Stillwater Sciences 2014c), and likely reached 8 million CY (6.1 million m^3) at the time this report is drafted as projected in AECOM and Stillwater Sciences (2015). Because of the diminishing functionality of Matilija Dam, Ventura County decided to pursue dam removal in 1998, and studies of dam removal effects and alternatives began in 2000. Removing Matilija Dam would not only eliminate a public safety liability, but also provide access to valuable steelhead habitat in Matilija Creek and its tributaries. The expanded steelhead habitat could potentially improve the fish population throughout the Ventura River watershed. The release of the stored sediment upon dam removal, however, may impact the extensive infrastructure located along Matilija Creek/Ventura River (Figure 2).

There have been several studies that examined sediment delivery and geomorphology in the Ventura River watershed as well as sediment transport dynamics following proposed Matilija Dam removal under various dam removal alternatives (e.g., Keller and Capelli 1992; BOR 2006; Cluer 2010; Warrick and Mertes 2010; Warrick and Milliman 2018). The most comprehensive of these studies was BOR (2006), which examined a suite of dam removal-related issues such as geology, climate, flood frequency, past projects in the watershed, ground water, sediment accumulation in the reservoir, sediment yield, sediment load in streams, river morphology, and improvement to downstream infrastructure. Proposed downstream infrastructure improvements included potentially constructing a high flow sediment bypass (HFSB) structure at the Robles Diversion Dam to reduce the amount of sediment deposition in the Robles Diversion forebay. The BOR (2006) study also provided hydraulics and sediment transport modeling using HEC-RAS and GSTARS-1D (Yang et al., 2003), respectively. Relying mostly on information provided in BOR (2006), URS and Stillwater Sciences (2014) provided an empirical analysis of fine sediment transport for two potential alternatives that would quickly release the sediment stored in the impoundment during a large storm event (also see Cui et al. 2017 for details). AECOM and Stillwater Sciences (2015) developed a preliminary DREAM-2 model that simulates coarse sediment (gravel and coarse sand) transport dynamics following Matilija Dam removal.

AECOM and Stillwater Sciences are currently working on 65% Design Plans for Matilija Dam Removal (Project). This technical report addresses Subtask 2.2 of the Project and uses analyses and modeling to: a) provide a reasonable estimate of when sediment is likely to fill to the top of Matilija Dam if the dam is left in place; b) provide a reasonable estimate of the sediment load near the mouth of the Ventura River following dam removal that can be used as input for subsequent estuary sediment transport modeling; c) revisit the fine sediment transport analyses of URS and Stillwater Sciences (2014) and Cui et al. (2017) to examine the consequences if the water discharge in Matilija Creek fails to reach the design discharge; and d) refine and finalize the DREAM-2 model developed in the early stages of the study (AECOM and Stillwater Sciences

[1] http://www.matilijadam.org/facts.htm

2015) and apply it to examine coarse sediment transport dynamics following Matilija Dam removal under the uncontrolled orifice option (i.e., open up tunnels near the base of the dam prior to a storm event to initiate sediment erosion). The uncontrolled orifice option is intended to quickly release sediment during a 4-year or higher flow event in Matilija Creek (i.e., to have daily average flow exceeds 1,700 cfs for a minimum of one day, measured at Matilija Creek at Matilija Hot Springs [USGS 11115500]) to shorten the duration of downstream impacts. The DREAM-2 modeling provides insight into sediment transport dynamics following dam removal as compared to the current conditions (i.e., with dam in place), and provides coarse sediment flux calculations near the river mouth that can be used as input for estuary sediment transport modeling. In addition to examinations of sediment transport dynamics, the modeling focuses on capturing the maximum likely sediment deposition in different reaches downstream of Matilija Dam during storms up to 100-year recurrence. The simulated profiles during the 100-year flow events along with profiles for other typical flow events (e.g., 5-year and lower, and between 5- and 100-year events) are then used to modify the HEC-RAS profiles for application to Subtask 2.3 of the Project (hydraulic modeling) as described in Stillwater Sciences 2020.

Note that presentations in this technical report employ a mix of International System of Units (SI units) and traditional imperial units out of necessity: imperial units are more familiar to the readers because of the history of the project, while the modeling is conducted and results are presented in SI units. Efforts have been made to provide values in both unit systems in the text, and important landmarks are added in diagrams wherever possible. A table listing conversion of relevant units between imperial and SI unit systems is also provided toward the end of the document (Appendix A).

Figure 1. Ventura River watershed, California. Matilija Dam is located on Matilija Creek a short distance upstream of USGS 11115500.

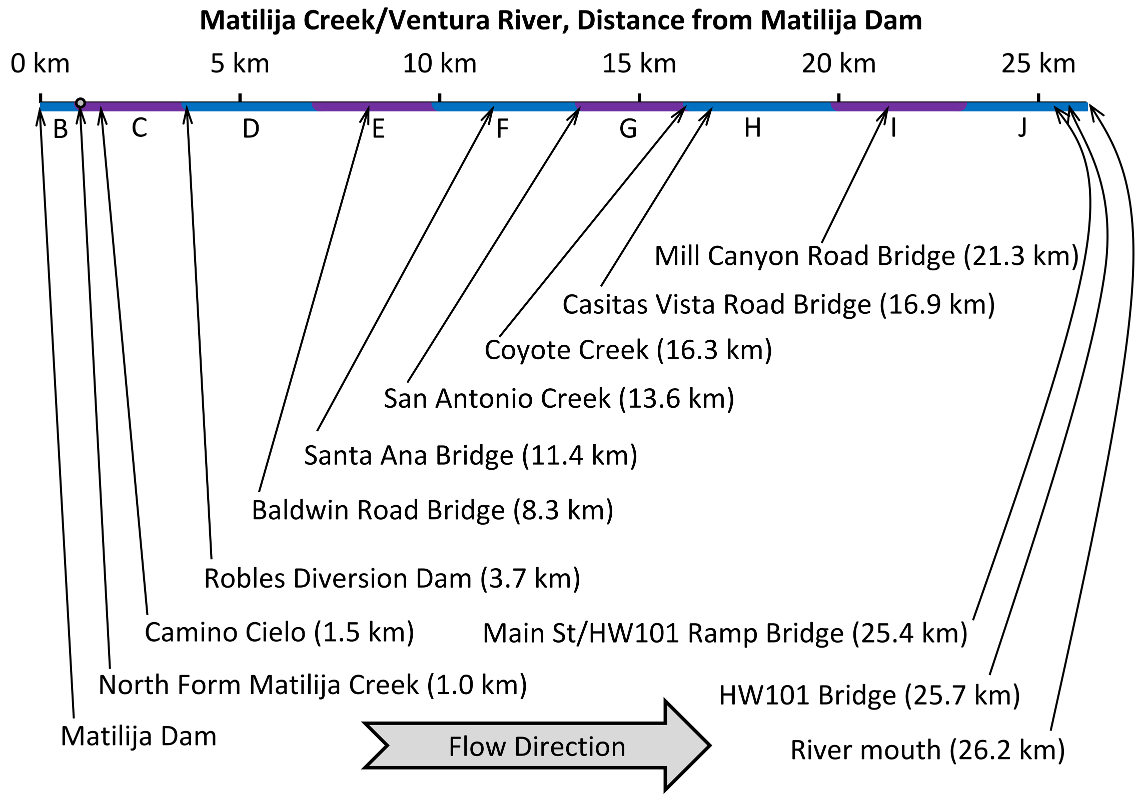


Figure 2. Important infrastructures along the Matilija Creek/Ventura River that can potentially be affected by Matilija Dam removal. Colored segments are subreaches labeled B-J. Subreach A is the reach upstream of Matilija Dam not depicted in this diagram.

2 METHODS OF ANALYSES

2.1 Overview of Methods used for Analyses

The analyses provided in this technical report rely on general principles of geomorphology and physically based modeling to develop reasonable estimates and predictions of sediment transport and deposition that can be used to draw useful conclusions about the downstream effects of dam removal. Below, we outline our approach to predicting the aspects of sediment transport dynamics important to the project discussed above in Section 1.

To estimate the time interval still needed for sediment to fill up to the top of the Matilija Dam, a simple delta progradation model is used that assumes the channel area aggrades uniformly while the delta advances downstream with time, forming parallel profiles at different times. It is further assumed that the channel-to-delta break point maintains a constant elevation (Figure 3). Note that this is a simplified model that averages the process through time, as the main channel within the impoundment swings left and right to gradually fill up the reservoir area with sediment.

More details of this simple model and its application to Slab Creek Reservoir (South Fork American River, California) for delta progradation analysis can be found in Cui et al. (2011).

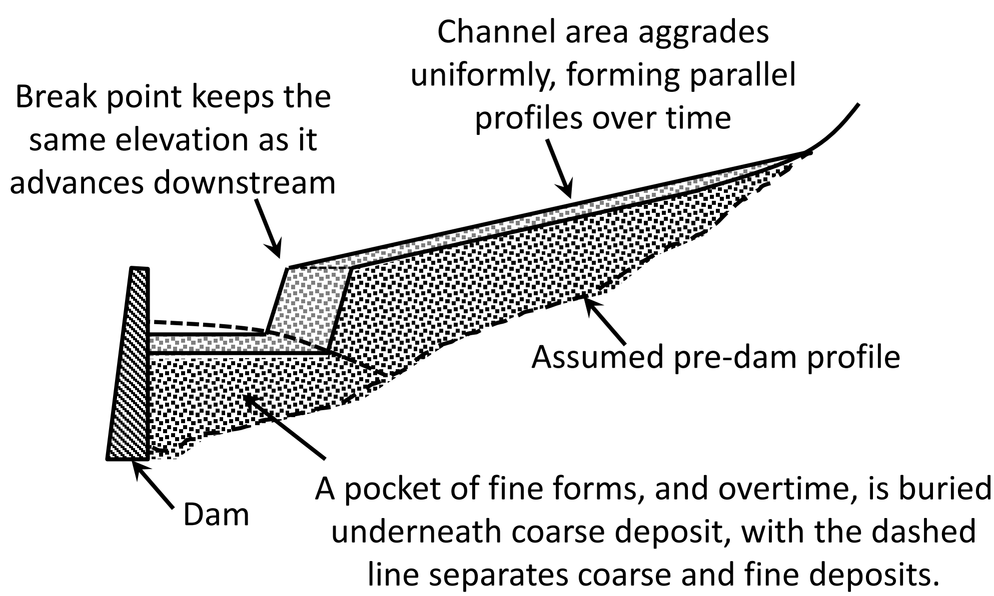


Figure 3. Sketch of a simple delta progradation model in reservoirs with uncontrolled overtop spill to be used for estimate of time needed for sediment to fill up to the top of the dam. Discussions and application of the model can be found in Cui et al. (2011).

There is currently no numerical model that can reliably simulate the detailed processes of erosion of the fine sediment deposits because their release following dam removal is driven by a rapid erosional process (including mass failure) not addressed by traditional sediment transport theory. Previous analysis by URS and Stillwater Sciences (2014) and Cui et al. (2017) applied an empirical approach that reasonably depicts the process, providing rough estimates of suspended sediment concentration during the early stages of dam removal and the approximate duration of impact to downstream water diversion operations. This approach is also used in the present report to examine the possible consequences in case the water discharge in Matilija Creek does not reach the design discharge (i.e., less than a 4-year flood).

Coarse sediment erosion, transport, and deposition following dam removal under current and post-removal conditions are simulated with the DREAM-2 sediment transport model (Cui et al. 2006a,b). As the centerpiece of this study, the DREAM-2 sediment transport model is introduced and discussed in more detail below in Section 2.2.

2.2 DREAM-2 Sediment Transport Model

2.2.1 Overview of the model

DREAM-2 is one of the two Dam Removal Express Assessment Models (DREAM-1 and DREAM-2) developed for sediment transport simulation following dam removal (Cui et al. 2006a,b). DREAM-1 and DREAM-2 and their predecessors and related models (i.e., early versions of the models and models that differ only in sediment transport equations, which were selected based on the composition of sediment deposit), have been used for simulation of sediment pulse movement in rivers with "unnatural" sediment supply ranging from a few thousand tons to over a billion tons and time span of a few days to several decades, including sediment transport following dam removal for many projects. Example case studies include: mining waste disposal in Ok Tedi – Fly River system in Papua New Guinea (Cui and Parker 1999); proposed Soda Springs Dam removal on the North Umpqua River in Oregon (Stillwater Sciences 1999); Marmot Dam removal on the Sandy River, Oregon (Stillwater Sciences 2000, 2012b; Cui and Wilcox 2008; Cui et al. 2014); Saeltzer Dam removal on Clear Creek, California (Stillwater Sciences 2001); landslide sediment evolution in the Navarro River, California (Sutherland et al. 2002, Cui and Parker 2005); Iron Gate, Copco 1, Copco 2, and J.C. Boyle Dam removal on the Klamath River, California and Oregon (Stillwater Sciences 2004; Stillwater Sciences 2008); Simpkins and Bloede Dam removal on the Patapsco River, Maryland (Stillwater Sciences 2010, 2014a, 2014b; Cui et al. 2018); proposed Harvey Diversion Structure removal on Santa Paula Creek, California (Stillwater Sciences 2012a); proposed Freeman Dam removal on the Santa Clara River, California (Stillwater Sciences 2013a); and proposed Englebright Dam and Daguerre Point Dam removal on the Yuba River, California (Stillwater Sciences 2013b). In addition to these practical projects, DREAM-1 and DREAM-2 models were also examined with flume experiments and proved to produce excellent results without or with minimal model calibrations (Cui et al. 2008).

DREAM-2 was designed for simulation of sediment transport dynamics in rivers following dam removal where at least the top layer of the impounded sediment deposit is composed primarily of gravel and coarser sediment. It simulates the transport and deposition of gravel and sand; it is applicable to rivers with any combination of gravel-bedded and bedrock reaches downstream of the dam. For flow parameter calculations, the DREAM-2 model applies a standard backwater equation for low Froude number conditions and quasi-normal approximation (i.e., energy slope is assumed to be identical to local channel gradient) for high Froude number conditions (see Cui and Parker 2005 and Cui et al. 2006a for more details). DREAM-2 applies the surface-based bedload equation of Parker (1990) for calculating transport capacity of gravel and coarser sediment (i.e., particles coarser than 2 mm) and Brownlie's (1982) bed material equation for calculating transport capacity of sand-sized sediment (i.e., particles between 0.0625 and 2 mm). Sediment in the silt and clay range (i.e., particles finer than 0.0625 mm) are treated as wash load that is assumed unable to redeposit onto the channel bed once released into the water column following erosion of the sediment deposits upstream of the dam. Furthermore, the model assumes that the erosion of reservoir deposit is governed by the mobilization of gravel-sized and coarser particles, and thus eroding the deposits down to a given elevation by mobilizing gravel and coarser particles will simultaneously result in the release of all the finer particles (i.e., sand, silt and clay). Because of the large amount of fine sediments accumulated behind Matilija Dam and their violent release following dam removal under the dam removal option studied, however, their transport cannot be reliably simulated with the model and can only be evaluated empirically (Cui et al. 2017). Because of that, the current DREAM-2 model study focuses only on the erosion, transport and deposition of coarse sediment and provides future longitudinal profiles for flood impact evaluations.

More details of the Dam Removal Express Assessment Models can be found in Cui et al. (2006a,b), and comprehensive comparisons of pre-removal modeling and post-removal monitoring can be found in Cui et al. (2014) for DREAM-2 and Cui et al. (2018) for DREAM-1.

2.2.2 Overview of required input parameters

The model requires the following input parameters: a) initial channel profile; b) initial grain-size distributions of the sediment deposits upstream and downstream of the dam to be removed; c) channel cross-sections simplified as rectangles with widths equal to the active channel width during significant flood events; d) daily average water discharge series representing post-removal hydrologic conditions; e) the rate and grain-size distribution of the sediment supply; and f) the downstream base-level control (i.e., either downstream water surface elevation or fixed bed elevation). All the input data used for this study are derived from the information discussed below in Section 3.

Model output includes the evolution of the thickness of sediment deposits in reaches upstream and downstream of the dam, and potentially sediment fluxes of different sizes at selected locations. Output related to fine sediment transport, such as daily-averaged total suspended sediment concentrations along the river, are not provided because of the reason discussed earlier.

2.2.3 Initial Conditions for Modeling: the Application of Zeroing Process Run

To apply DREAM-2, a zeroing process run needs to be conducted to establish the base condition from which dam removal simulation can be conducted. Instead of taking the surveyed longitudinal profile directly as model input, a zeroing process run attempts to simulate the historical processes, producing a simulated current longitudinal profile to serve as the initial condition for dam removal sediment transport modeling. Because a sediment transport model such as DREAM-2 is always an imperfect representation of the simulated system and the processes that transport sediment, it is a certainty that running the model using a surveyed initial condition will result in sediment deposition in some areas and erosion in other areas (hereafter termed "background noise") regardless of whether dam removal is simulated. Because of the existence of background noise, simulated changes in bed elevation are always combinations of the background noise and the signal generated from perturbation to the system (such as dam removal), and it is virtually impossible to separate the two. Starting the simulation from the simulated profile produced through a zeroing process run largely eliminates the background noise, making the simulated results a better representation as the result of the introduction of the perturbation. Procedures similar to a zeroing process run (e.g., "warmup period" in Randle and Bountry 2005, "base test" in Thomas and Chang 2008, "model priming" in Bountry and Randle 2001, and "spin-up" in Ferguson and Church 2009) are widely used in one-dimensional sediment transport modelling, and they all require modifying the surveyed channel cross sections through modelling. Failing to apply such a procedure would most likely produce false predictions at least in some locations (see demonstration in Cui et al. 2008).

A three-step zeroing process run was conducted to produce a simulated current profile to provide the initial profile for dam removal simulation, with each step representing a period of geomorphic significance, as discussed below and summarized in Table 1.

- Step 1: run the model repeatedly, starting from the 2005 surveyed profile, and assume that Matilija Dam, Casitas Dam, and Robles Diversion Dam are not constructed. Under such assumed conditions, bedload from the upper Matilija Creek and Coyote Creek would continue to be supplied to the system instead of being trapped in the reservoirs, and there is also no sediment trapping at the Robles Diversion Dam. The resulting longitudinal profile from this simulation represents the historical quasi-equilibrium condition before these structures were constructed.
- Step 2: continue the model run using discharge record between WY 1948 and 1957, assuming Matilija Dam is constructed and traps all the bedload from the upper Matilija Creek. The resulting longitudinal profile from this simulation represents the condition in 1958 prior to the construction of Casitas Dam and Robles Diversion Dam.
- Step 3: continue the model run using discharge records between WY 1958 and 2017, assuming Casitas Dam and Robles Diversion Dam are constructed in 1958 so that all the bedload from upper Coyote Creek is trapped behind the dam, and Robles Diversion Dam provides a local water surface elevation control point (Appendix B). In addition to the presence of dams and the diversion, there had been gravel removal operation from the Robles Diversion Dam forebay during this period. According to BOR (2006), an estimated 559,000 cubic yards (bulk volume ~427,000 m^3) was removed during the 33-year period between 1966 and 1998. This is equivalent to approximately 335,000 CY (256,000 m^3) of solids assuming a porosity of 0.4 for the removed sediment. Because DREAM-2 cannot directly simulate the sediment removal operation, the sediment supply from the North Fork Matilija Creek was reduced to approximate the sediment removal process.

Table 1. Brief description of zeroing processing run that produced the current condition that served as initial condition for dam removal simulation.

Steps	Period	Geomorphic significance
1	WY 1811–1947	Assumed historical quasi-equilibrium condition
2	WY 1948–1957	Post-Matilija Dam
3	WY 1958–2017	Post-Matilija, Casitas, and Robles Diversion dams, and sediment removal from Robles Diversion Dam forebay

Results of the zeroing process runs are provided and discussed below in Section 4.

3 BACKGROUND INFORMATION RELEVENT TO THIS STUDY

3.1 Geomorphology

The Ventura River watershed has a catchment area of 226 square miles (590 km^2) consisting of steep mountains and foothills, with altitudes ranging from 6,010 feet (1,830 m) to sea level (Walter 2015). There are four primary tributaries contributing to the Ventura River: Matilija Creek with a catchment area of 55 square miles (141 km^2), North Fork Matilija Creek with a catchment area of 16 square miles (41 km^2), San Antonio Creek with a catchment area of 52 square miles (133 km^2), and Coyote Creek with a catchment area of 42 square miles (108 km^2) (BOR 2006) (Figure 1). Most of the rivers in the watershed are gravel-bedded with surface particles ranging from sand sized particles up to large boulders (Figure 4 and Figure 5). The long profile exhibits an upward concave shape (Figure 5) often seen in natural rivers, with the average channel gradient ranging from approximately 0.025 just downstream of Matilija Dam in Matilija Creek to under 0.006 near the Ventura River mouth (Figure 6). The river is narrower in Matilija Creek, roughly 20–30 m (60–100 ft) wide, gradually opens up in the Ventura River to around 300 m (1000 ft), but is restricted and narrowed by levees about 9.3 miles (15 km) downstream of the dam (Figure 7).

The longitudinal profile and geomorphic processes were significantly altered by the construction of Matilija Dam on Matilija Creek in 1948 and the construction of Robles Diversion Dam on the Ventura River and Casitas Dam on Coyote Creek in 1958-1959. Each of these dams traps coarse and fine sediment. Matilija Dam likely has trapped approximately 8 million CY (6.1 million m^3) of coarse and fine sediment in the upstream channel, delta, and reservoir areas (AECOM and Stillwater Sciences 2015). Accumulation is projected to increase over time as long as the dam remains in place (or is overtopped) (Figure 8 and Table 2). Casitas Dam has been trapping all the coarse sediment and likely the majority of fine sediment since its construction in 1958, and sediment deposition in the Robles Diversion Dam forebay has required mechanical sediment removal multiple times (BOR 2006) as a result of sediment deposition.

Table 2. Volume and composition of Matilija Dam impoundment deposits in different areas as of year 2000, derived from data presented in BOR (2006).

Area	Reservoir	Delta	Upstream channel	Entire deposit
Gravel fraction (> 2 mm)	< 1%	13%	78%	20%
Sand fraction (0.0625-2 mm)	17%	54%	16%	34%
Silt fraction (< 0.0625 mm)	83%	33%	6%	46%
Bulk Volume (m^3)	1,600,000	2,100,000	800,000	4,500,000
Deposit Mass (t [metric ton])	1,900,000	2,900,000	1,300,000	6,100,000
Bulk Density (t/m^3)	1.2	1.4	1.6	1.36

Note: 1 m^3 = 1.308 CY; 1 t = 1.102 ton. Upstream channel, delta, and reservoir areas are defined by BOR (2006) as shown in Figure 8.

New LiDAR and bathymetry surveys were conducted in 2017 and 2018, respectively, after the December 2017 Thomas Fire burned a substantial area within the watershed. Comparing the 2000 and 2017 profiles in the upstream channel and delta, however, indicates that there has been minimal change in bed elevation and the two bed profiles are nearly identical. Comparison of historical aerial photographs from 2005 and 2018 shows that the delta front has not advanced appreciably since 2005, implying minimal channel aggradation upstream between 2005 and 2018 (Figure 9).

While the minimal channel aggradation in upstream channel and delta areas over the 14 year period between 2005 and 2018 is somewhat surprising, given that it is expected that sediment accumulation in the impoundment area would continue over time, it is not entirely unexplainable. Rivers in mountainous regions such as the Ventura River watershed often experience episodic sediment input as large pulses in response to catastrophic events such as landslides and debris flows (e.g., Kasai et al. 2001), and it is likely that no such events occurred between the two surveys in the headwaters of Matilija Creek after the 2005 survey, resulting in minimal channel aggradation over the examined period. It can be expected that a period of higher sediment supply is likely to emerge over the next few years to decades due to the 2017 Thomas Fire, making it more susceptible to erosion during large storm events and potentially increasing the probability for landslides and debris flows, as evidenced by the recent observations of rapid delta advancement resulting from the 2018/2019 high flow season (Figure 10).

Comparison of the 2005 survey with a 2018 bathymetry survey conducted by Ventura County Watershed Protection District (VCWPD) and boring logs by Gregg Drilling shows that there has been roughly 135,000–270,000 m^3 (180,000–360,000 CY) of sediment accumulation in the reservoir area over 13 years since the 2005 survey. This accumulation most likely reflects sand and finer sediments eroded after the December 2017 Thomas Fire prior to the 2018/2019 high flow season as fine sediment eroded from the watershed soon after the fire was quickly transported to and deposited in the reservoir area. Much more additional sediment was transported into the delta and reservoir areas during the 2018/2019 high flow season as evidenced in Figure 10

Evidence from the detailed characterization of the impounded sediment in the 2005 survey suggests that the addition of recent fine sediment deposits in the reservoir area is not crucial to the analyses presented in this technical report and can be ignored, because most if not all of these sediments will likely be scoured in future floods prior to dam removal. This conclusion is based on inspection of the detailed 2005 profile (Figure 11), which demonstrates an earlier period of near-complete erosion of fine sediment following their initial deposition. A small “bulge” of fine sediment centered on 108+00 in the 2005 profile was higher than the surrounding of fine sediment level (blue dashed line on Figure 11). This would have been possible only if the fine sediment deposit downstream of 108+00 was once higher and later scoured down to the observed 2005 level. With the expectation that this process will again be repeated, the sediment deposit of the 2005 profile is considered below for analyses.

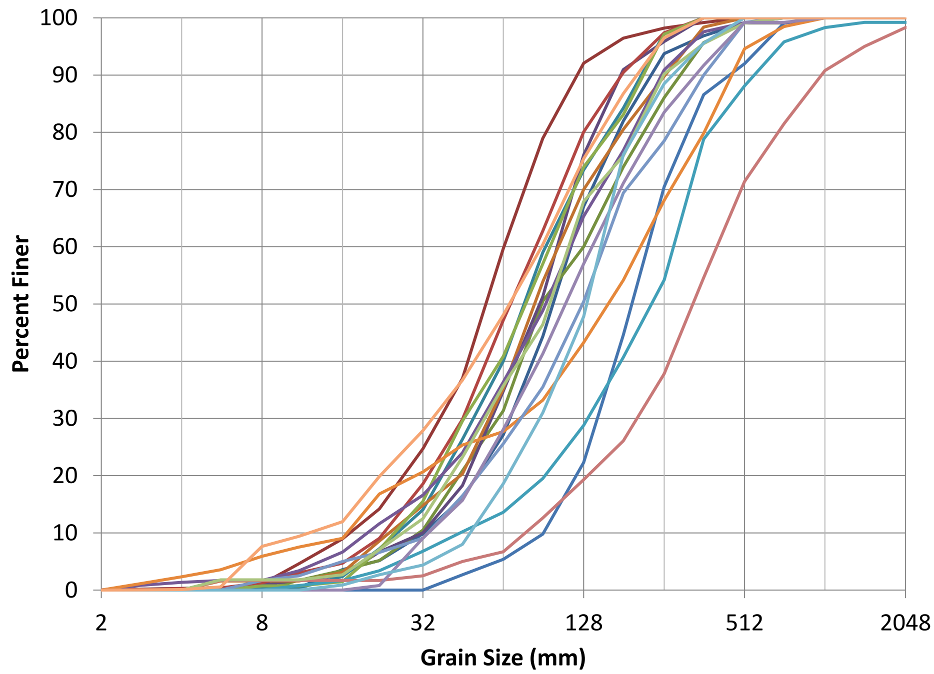


Figure 4. Surface gravel grain-size distributions in Matilija Creek and Ventura River, based on pebble count data collected by BOR (2006). Diagram intends to show the range of grain sizes rather than individual pebble count.

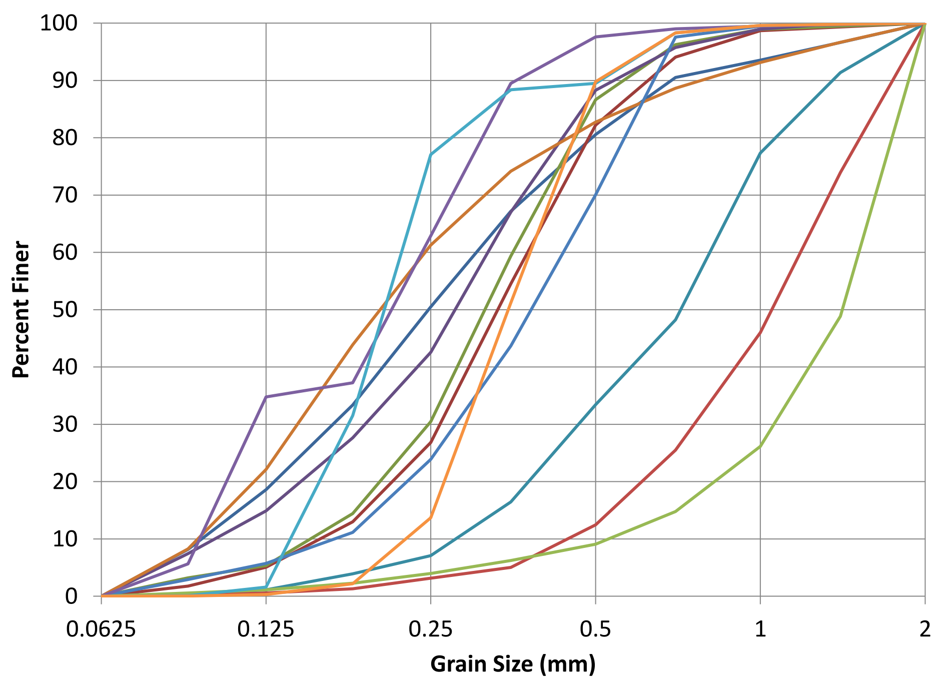


Figure 5. Surface sand grain-size distributions in Matilija Creek and Ventura River, based on pebble count data collected by BOR (2006). Diagram intends to show the range of grain sizes rather than individual pebble count.

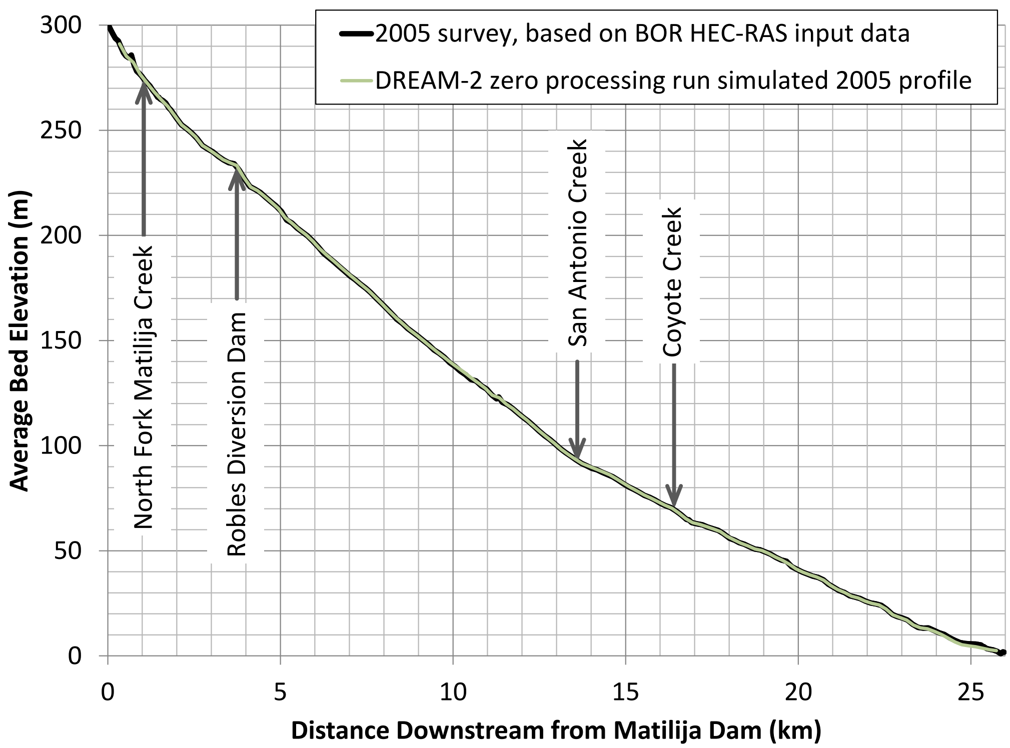


Figure 6. Longitudinal profile of Matilija Creek and Ventura River downstream of Matilija Dam. The 2005 survey was based on data provided in BOR (2006) HEC-RAS model.

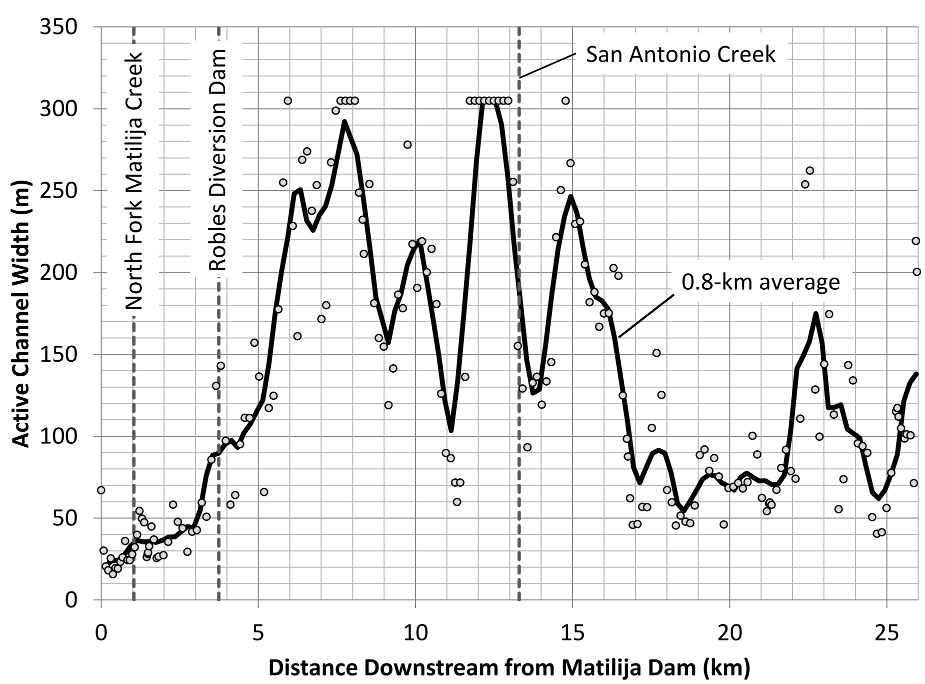


Figure 7. Active channel width of Matilija Creek and the Ventura River downstream of Matilija Dam, in which the symbols are obtained from the BOR (2006) HEC-RAS model, and the line represents the 0.8-km (0.5-mile) moving average.

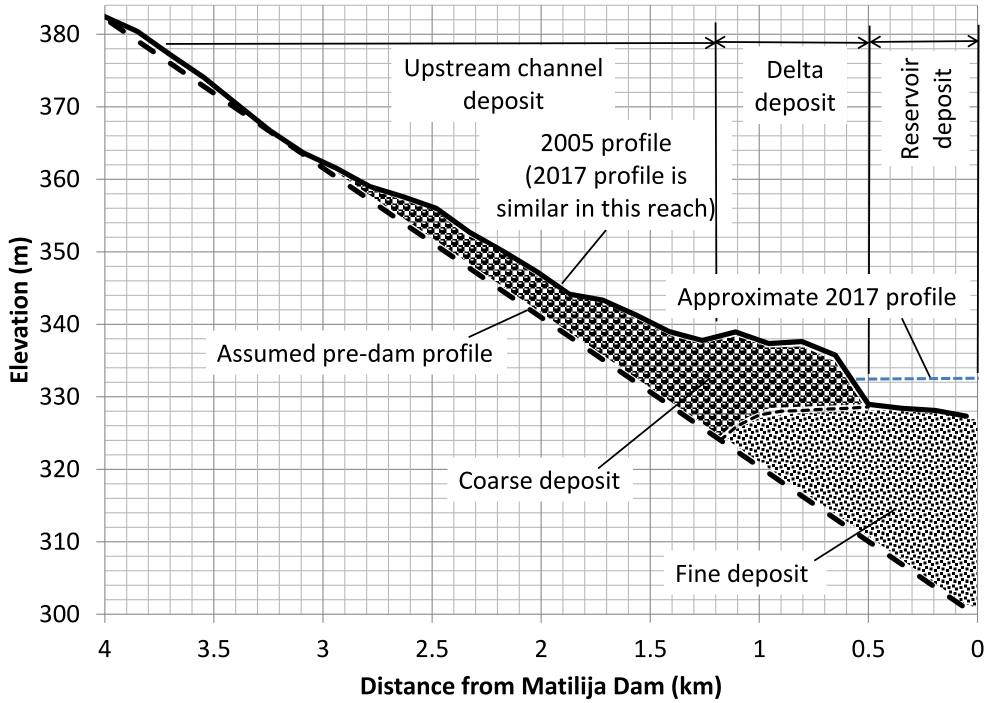


Figure 8. Matilija Creek longitudinal profile upstream of Matilija Dam, illustrating the composition of the sediment deposits in 2000 (BOR 2006). The most recent profile acquired from LiDAR and bathymetry surveys in 2017/2018 is similar to the 2005 profile, except in the reservoir area as approximated by blue dashed line.

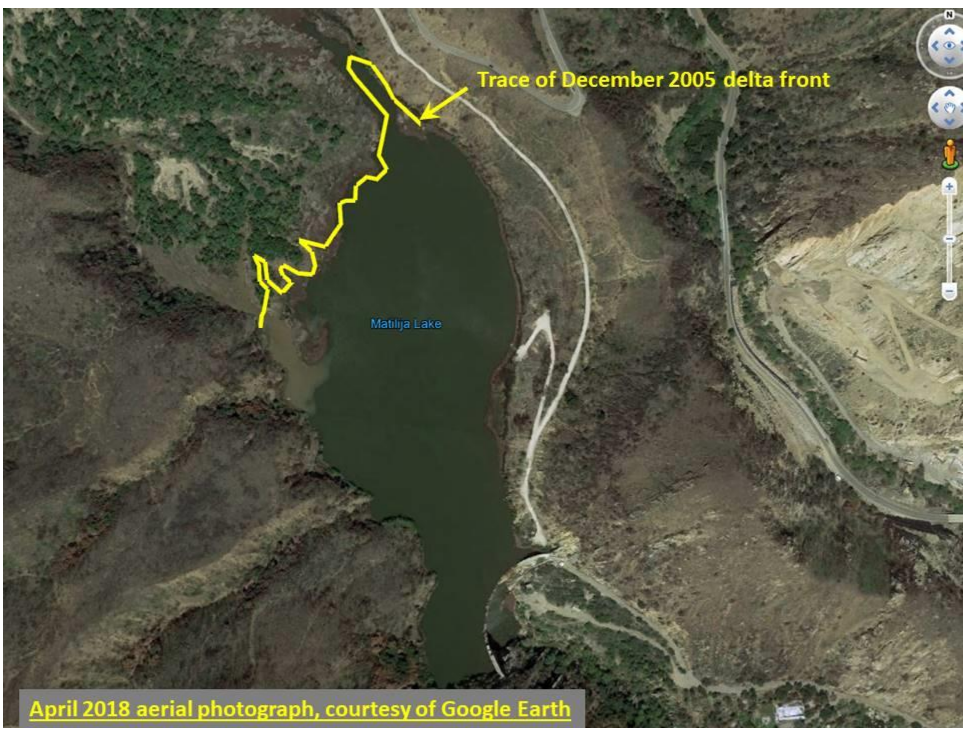
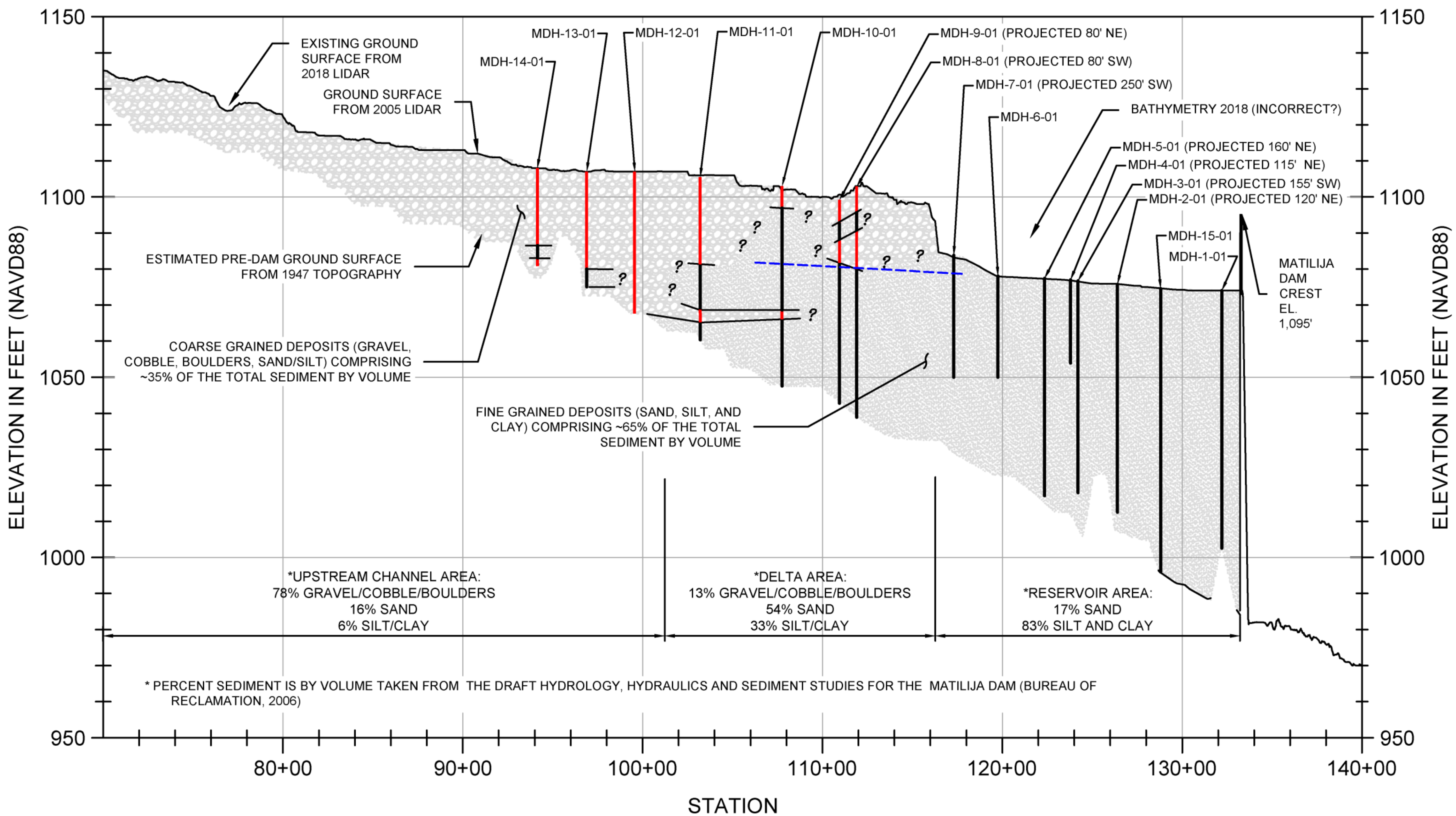


Figure 9. April 2018 aerial photograph, showing the current delta front location and a trace of delta front in December 2005, indicating virtually identical delta front locations.

Figure 10. Photograph of the recent advancement of Matilija Reservoir delta, courtesy of Paul Jenkin, February 24, 2019



NOTES:
1. PROFILE SHOWN WITH 20X HORIZONTAL EXAGGERATION
2. DEPTHS AT WHICH BOREHOLES ENCOUNTER COARSE SEDIMENT DEPOSITS ARE HIGHLIGHTED IN RED

Figure 11. Detailed 2005 Matilija Dam impoundment deposit profile, showing that the fine sediment profile is locally higher (centered on 108+00) than the extension of 2005 level (blue dashed line) under the gravel cap. This requires that the uncapped area was once higher and was subsequently scoured to the 2005 level.

3.2 Matilija Dam Impoundment Deposits

Analyses provided in BOR (2006) indicate that the impounded Matilija Dam sediment deposit has three distinct subreaches, each with its own characteristics regarding its sediment composition (Figure 8). The Reservoir Area deposits are dominated by fine sediments--roughly 83% of the Reservoir Area sediments are silt- and clay-sized particles (i.e., particles finer than 0.0625 mm). The Delta Area is dominated by sand and finer material (54% sand, 33% silt/clay), and is capped by a layer of gravel (Figure 11). The Upstream Channel Area is dominated by coarse sediment, with more than 78% of the sediments are gravel (> 2 mm) and coarser. Overall, BOR (2006) estimated that 46% of the impoundment deposits were silt- and clay-sized material, 34% sand (i.e., 0.0625–2 mm), and 20% gravel and coarser (Table 3 and Figure 12). AECOM and Stillwater (2015) used data from BOR (2006) to derive Table 3 and Figure 12. These data were then used to generate the grain size distributions of the gravel deposits (Table 4 and Figure 13) and the sand deposits (Table 5 and Figure 14) as well as the gravel, sand, and silt/clay fractions in the deposits (Table 6).

Table 3. Grain-size distributions of Matilija Dam impoundment deposits, based on data provided in Table 5.6 in BOR (2006).

Graindiameter (mm)		% Finer			Entire deposit
		Reservoir	Delta	Upstream channel	
512		100	100	100	100
256		100	100	87.9	97.95
128		100	100	75.9	95.92
64		100	99.8	60.9	93.28
32		100	98.4	48.9	90.58
16		99.9	95.1	36.9	86.94
8		99.8	92.5	29.9	84.49
4		99.7	89.9	24.9	82.37
2		99.7	87.3	21.9	80.63
1		99.5	83.7	18.4	78.26
0.5		99	77.5	15	74.56
0.25		97.2	66.5	12	68.19
0.125		92.2	50.8	9	58.45
0.0625		82.8	33.2	6	46.24
0.03125		70.9	21.9	4	36.31
0.015625		57.3	14.5	2	27.62
0.007813		43.1	9.7	1	20.11
0.003906		30.1	5.3	0	13.23
0.001953		18	0	0	6.41
Total volume	**(m^3)**	**1,600,000**	**2,100,000**	**800,000**	**4,500,000**
	(CY)	**2,100,000**	**2,800,000**	**1,000,000**	**5,900,000**

The impoundment grain-size distribution presented in BOR (2006) has been slightly modified here to adjust for likely bias in sediment sampling. This modified grain-size distribution has been adjusted to approach the shape of the grain-size distributions of the pebble counts for use in the modeling, shown in Figure 15 as more “parallel” to the pebble counts. The modification is minor and the actual impact to modeling results is believed to be minimal but likely more realistic.

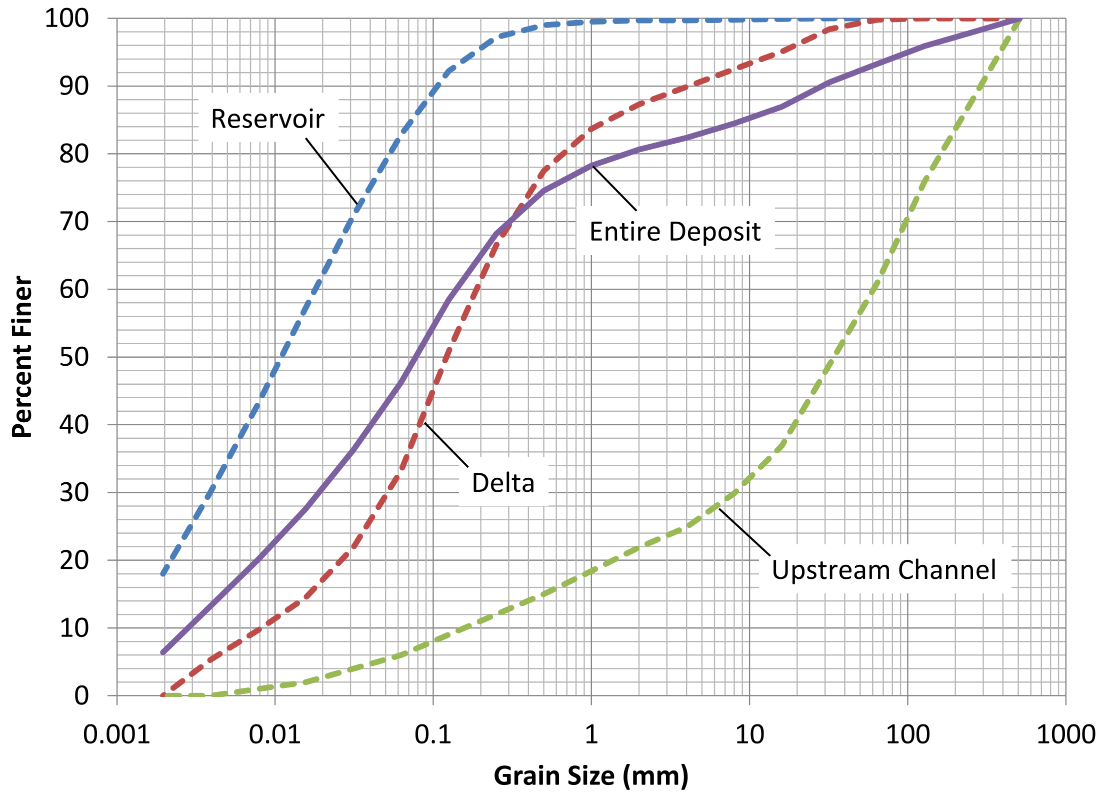


Figure 12. Grain-size distributions of Matilija Dam impoundment deposits, based on data provided in BOR (2006).

Table 4. Grain-size distribution of Matilija Dam impoundment gravel deposits, based on data provided in in BOR (2006).

Grain diameter (mm)	% Finer			Entire deposit
	Reservoir	Delta	Upstream channel	
512	100	100	100.0	100.0
256	100	100	84.5	89.4
128	100	100	69.1	78.9
64	100	98.4	49.9	65.3
32	100	87.4	34.6	51.4
16	66.7	61.4	19.2	32.6
8	33.3	40.9	10.2	19.9
4	0	20.5	3.8	9.0
2	0	0	0	0

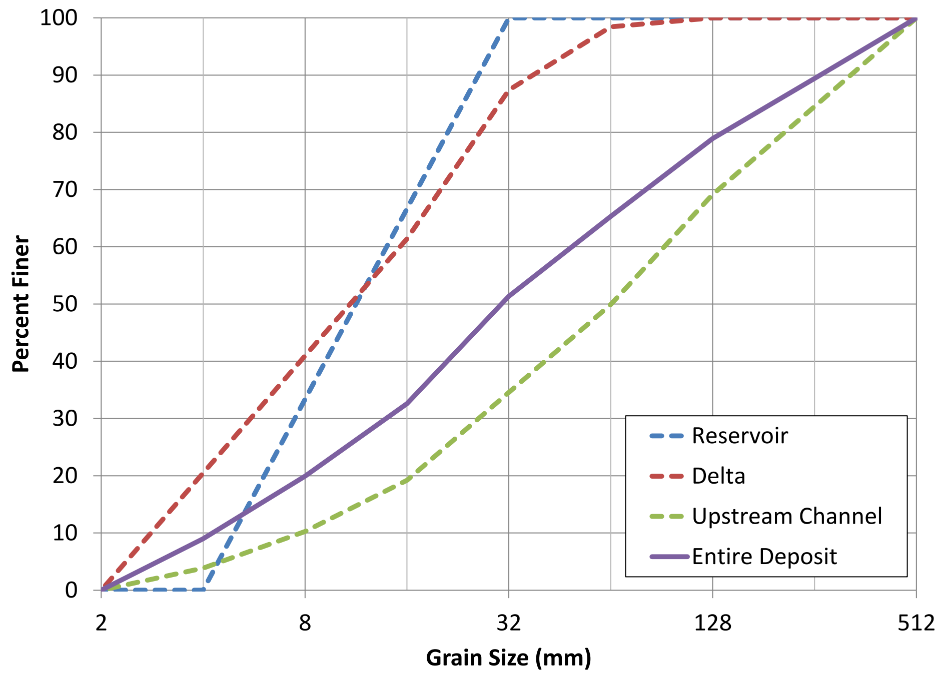


Figure 13. Grain-size distributions of gravel deposits in Matilija Dam impoundment, based on data provided in BOR (2006).

Table 5. Grain-size distribution of Matilija Dam impoundment sand deposits, based on data provided in BOR (2006).

Grain diameter (mm)	% Finer			Entire deposit
	Reservoir	Delta	Upstream channel	
2	100	100	100	100
1	98.8	93.3	78.0	93.1
0.5	95.9	81.9	56.6	82.3
0.25	85.2	61.6	37.7	63.8
0.125	55.6	32.5	18.9	35.5
0.0625	0	0	0	0

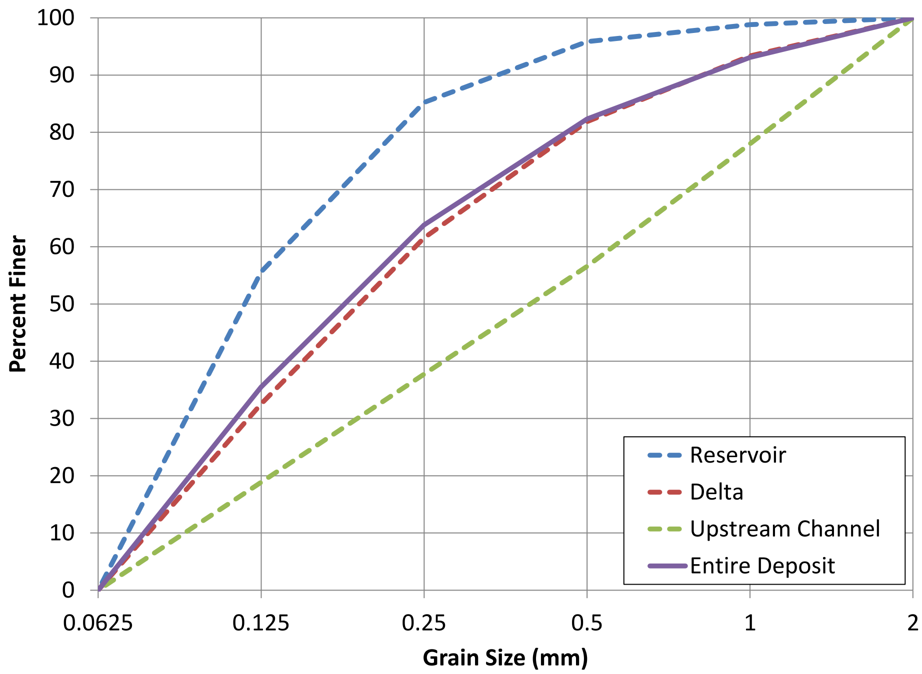


Figure 14. Grain-size distributions of the sand deposits in Matilija Dam impoundment, based on data provided in Section 5.4 in BOR (2006).

Table 6. Gravel, sand, and silt/clay fractions in Matilija Dam impoundment deposits, based on data provided in in BOR (2006).

Sediment	Reservoir	Delta	Upstream channel	Entire deposit
Gravel Fraction	0.00	0.13	0.78	0.19
Sand Fraction	0.17	0.54	0.16	0.34
Silt/clay Fraction	0.83	0.33	0.06	0.46

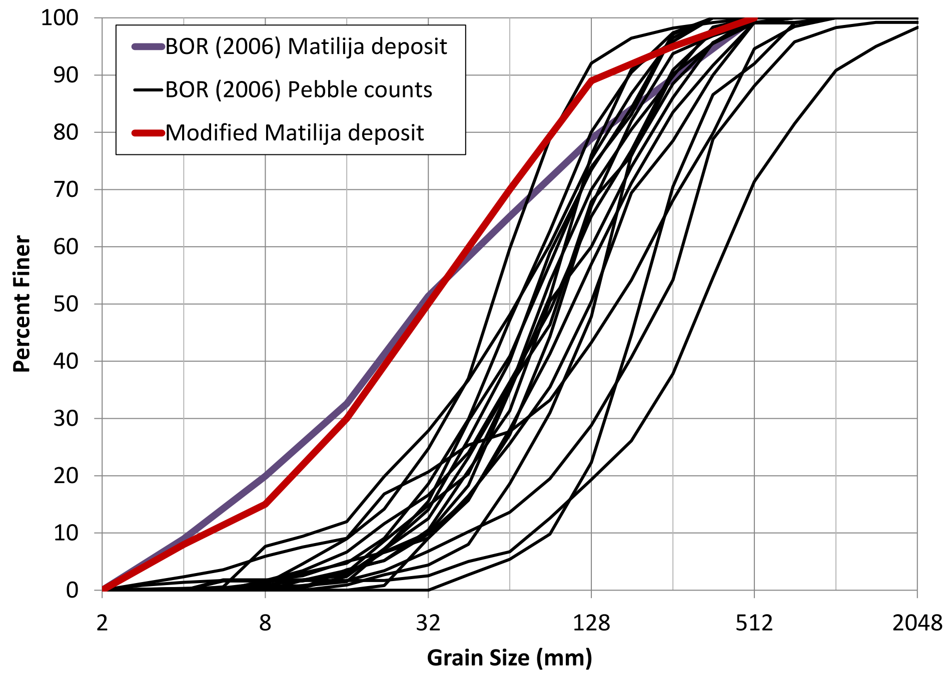


Figure 15. Comparison of modified grain-size distribution of Matilija impoundment gravel deposits with pebble counts obtained in Ventura River downstream of Matilija Dam.

3.3 Long-term Average Rate of Sediment Supply

Using the volume of the impoundment deposits in the three different areas of the Matilija Dam impoundment and the estimated density of sediment deposits provided in BOR (2006) and summarized in Stillwater Sciences (2014c), and assuming 100% trapping efficiency for gravel and sand particles, AECOM and Stillwater Sciences (2015) estimated that the long-term average rates of supply from the Matilija Creek are approximately 16,000 m^3/yr for sand (solid) and 10,000 m^3/yr for gravel (solid), respectively. Using the 3,000 t/km^2/yr sediment production rate for the watershed estimated by Stillwater Sciences (2014c), AECOM and Stillwater Sciences (2015) then estimated that the long-term average total sediment (i.e., gravel, sand, and silt) supply rate in Matilija Creek is approximately 160,000 m^3/yr (solid), from which the long-term silt/clay supply rate was estimated to be approximately 134,000 m^3/yr (solid, $= 160{,}000 - 16{,}000 - 10{,}000$ m^3/yr). AECOM and Stillwater Sciences (2015) extended their estimate to North Fork Matilija Creek and San Antonio Creek using reasonable assumptions (detailed in Table 7). Table 7 also estimates the sediment supply in Coyote Creek, assuming the rate of sediment production in Coyote Creek is identical to that of the upper Matilija Creek. Note that the rate of sediment supply from Coyote Creek is only important when evaluating historical conditions because Casitas Dam currently traps all the sand and gravel, which will continue for the foreseeable future.

The total sediment supply from the four catchments under current conditions includes all the sediment from North Fork Matilija Creek and San Antonio Creek and silt and clay from Matilija Creek, assuming that Matilija Dam will no longer have the capacity to trap silt- and clay-sized sediment over the long term. That is, fine sediments may deposit in the reservoir over a period of time, as observed after the Thomas Fire, but these sediments will be scoured by subsequent high flow events, as discussed above. A small but unknown fraction of the silt- and clay-sized sediment likely passes over Casitas Dam and contributes to the Ventura River when Casitas Dam spills that is not included in our analysis. In total, these assumptions result in 380,000 m^3 (~500,000 CY) annual sediment supply to the Ventura River (**Table 7).** The total sediment delivery would have been 510,650 m^3 (667,900 CY) if Matilija Dam and Casitas Dam had not been constructed, which compares within a factor of 1.2 with the BOR's (2006) estimate of total sediment load delivered to the ocean at equilibrium condition (i.e., no Matilija Dam) of 548,000 cubic yards. Other literature (e.g., Patsch and Griggs 2007) suggest that sediment loads may be significantly lower. However, the value used in this report and analyses was obtained primarily based on the amount of gravel deposited in the Matilija Dam impoundment over the duration of its operation, which is more reliable than values obtained by any other potential methods.

Table 7. Estimated rates of sediment supply from the upper Matilija Creek, North Fork Matilija Creek, San Antonio Creek, and Coyote Creek, in m^3/yr (solid).

	Gravel	Sand	Silt/Clay[a]	Total[b]	Catchment[c] Area (km^2)
Matilija Creek[d]	10,000 [h]	16,000 [h]	134,000	160,000	139.8
North Fork Matilija Creek[e]	2,850	4,570	42,580	50,000	39.9
San Antonio Creek[f]	4,750	7,620	167,630	180,000	157.4
Coyote Creek[g]	7,550 [h]	12,100 [h]	101,000 [h]	121,00	105.5
Total (historical)	**25,150**	**40,290**	**445,210**	**510,650**	**443**
Total (current)	**7,600**	**28,190**	**344,210**	**380,000**	

[a] Silt/clay supply rates estimated as total supply minus gravel and sand supply.
[b] Total sediment supply estimated based on the assumption of 3,000 t/km^2/yr production rate (Stillwater Sciences 2014c).
[c] Drainage area provided by BOR (unpublished document).
[d] Gravel and sand supply rates based on volumes of gravel and sand deposits in Matilija Reservoir in 2005 provided in Stillwater Sciences (2014c).
[e] Gravel and sand supply rates estimated based on the assumption that sediment production rate in the upper Matilija Creek and North Fork Matilija Creek watersheds are identical.
[f] Gravel and sand supply rates estimated based on the assumption that gravel and sand supply from San Antonio Creek and North Fork Matilija Creek have a ratio of 5:3 based on the analysis of BOR (2006), Table 5.16.
[g] Gravel and sand supply rates estimated based on the assumption that sediment production rate in the upper Matilija Creek and Coyote Creek watersheds are identical.
[h] Not currently contributing to the Ventura River.

3.4 Sediment Supply Rating Curves

For modeling purposes, AECOM and Stillwater Sciences (2015) recommended applying a power relation between sediment supply and water discharge in the form of

$$Q_g = a_1 {Q_w}^{b_1}\ ;\ \ Q_s = a_2 {Q_w}^{b_2}\ ;\ \ Q_{si} = a_3 {Q_w}^{b_3} \tag{1a,b,c}$$

in which Q_g, Q_s, and Q_{si} denote gravel, sand, and silt/clay supply rates, respectively; Q_w denotes water discharge; and a_1, b_1, a_2, b_2, a_3 and b_3 are coefficients. Power relation is a common assumption in geomorphic analysis when assessing sediment supply rating curves (e.g., Warrick and Milliman 2003).

Through literature review and analyses of suspended sediment concentration data within the Ventura River watershed provided by BOR (2006), AECOM and Stillwater Sciences (2015) proposed the following exponential coefficients (i.e., b_1, b_2, and b_3) to be used for Equations 1a, 1b, and 1c in Ventura River watershed for modeling purposes:

$$b_1 = 3.0;\ b_2 = 2.4;\ b_3 = 1.7 \qquad \text{(2a,b,c)}$$

Coefficients b_1, b_2, and b_3 determine the shape of the sediment rating curve at each catchment, while coefficients a_1, a_2, and a_3 determine the magnitude of sediment supply, which are calculated automatically in the DREAM-2 model based on the historical discharge record and the long-term average sediment supply rates for gravel, sand and silt (i.e., values provided in Table 7 under historical conditions, reduced to take account for trapping of sediment by reservoirs under current conditions).

Gravel particles break down to smaller particles while being carried downstream by the flow due to collision and the rate of breakdown is usually quantified by volumetric abrasion coefficient, or the fraction of volume lost as a gravel particle to transport a unit distance downstream. Based on surface pebble count data provided by BOR (2006), literature review, and a series of zeroing process runs of DREAM-2 model, AECOM and Stillwater Sciences (2015) estimated that the volumetric abrasion coefficient for the Ventura River gravel cannot exceed approximately 0.1 km^{-1}. AECOM and Stillwater Sciences (2015) further suggested that a value of 0.02 km^{-1} be used for the initial modeling with the understanding that it could be adjusted if better modeling results were achieved. Here in this study the abrasion coefficient was adjusted to 0.05 km^{-1} during the trial runs for zeroing process run, as this value provided slightly better results. The abrasion coefficient of gravel particles varies by three orders of magnitude in natural rivers (e.g., Attal and Lave 2009), and an adjustment between 0.02 and 0.05 km^{-1} is considered normal. A volumetric abrasion coefficient of 0.05 km^{-1} implies that a gravel particle at Matilija Dam would lose approximately 73% of its volume and 35% of its diameter (i.e., a 100-mm particle would reduce to roughly 65 mm) by the time it reaches the Ventura River mouth, approximately 26 km downstream.

3.5 High Flow Sediment Bypass at Robles Diversion Dam

BOR (2006) proposed that a high flow sediment bypass (HFSB) structure needs to be constructed at Robles Diversion Dam prior to dam removal in order to reduce the amount of sediment deposition in the forebay following dam removal. Although the construction of HFSB cannot be directly modeled in DREAM-2, its impact to sediment transport can be indirectly modeled by implementing pre- and post-HFSB water surface–discharge rating curves. These curves are derived in Appendix B based on the experimental data of Mefford et al. (2008).

4 ANALYSES AND MODELING RESULTS

4.1 Time for Sediment to Fill to the Top of the Dam

As discussed earlier, virtually all fine sediments are already passing over the dam over multi-year time scales, and so the coarse sediment delta will need to migrate to the dam face for sediment to completely fill to the top of the dam. Applying the simple delta progradation model discussed in Section 2 to gravel and coarser sediment, and assuming the 2005 fine sediment profile in the reservoir area is the final quasi-equilibrium profile, it is estimated that it will take roughly 50 years from 2005 for the sediment to fill to the top of Matilija Dam (Table 8). Given the assumptions and approximations being made to generate this estimate, a two-fold uncertainty is likely. That is, it may take as few as 25 years or as many as 100 years for the sediment to fill to the top of the dam. Early estimates by BOR (2006) using a different approach found that it would take 38 years, well within the range of the estimate provided here.

Table 8. Estimate of time needed for sediment to fill the Matilija impoundment to the top of the dam.

Parameter	Estimate	Note
a. Upstream channel gradient near delta:	0.0025	Estimated based on 2005 profile
b. Current distance between delta front and the dam (m):	500	Estimated from 2018 aerial photograph
c. Projected terminal channel aggradation:	1.25	= a*b
d. Assumed width of channel aggradation (m):	100	Estimated from 2018 aerial photograph
e. Assumed length of channel aggradation (m):	3,000	Estimated from 2018 aerial photograph
f. Bulk volume of channel aggradation (m^3):	375,000	= c*d*e
g. Estimated reservoir area (m^2):	100,000	Estimated from 2018 aerial photograph
h. Break-point depth (to 2005 bathymetry) (m):	6	Estimated 2005 profile
i. Estimated percent of reservoir area to be filled with gravel and sand at terminal stage:	75%	Rough estimate, mostly professional judgement based on 2018 aerial photograph
j. Bulk volume of coarse sediment deposition in reservoir area (m^3):	450,000	= g*h*i
k. Bulk volume of terminal coarse sediment deposition (m^3):	825,000	= f+j
l. Gravel solid volume of terminal coarse sediment deposition (m^3)	495,000	Assuming 60% of the bulk deposit (k) is gravel, 40% is sand and pores.
m. Estimated Matilija Creek gravel long-term average gravel supply rate (solid, m^3/yr)	10,000	Table 7
n. Number of years needed to fill to the top:	50	= l/m

Note that any attempt trying to improve the estimate is unlikely to provide a more robust answer, given the uncertainties in parameters and the stochastic nature of sediment production, evidenced by the minimal coarse sediment accumulation upstream of Matilija Dam between 2005 and 2018 that had not been expected before the recent survey data became available.

It is also important to acknowledge that significant vegetation was observed in November 2019 growing in the fine sediment within the impoundment adjacent to the dam. If the vegetation stabilizes the fine sediment deposit, it may be much more resistant to erosion by future high flow events. This could result in sediment filling to the top of the dam at a much faster rate than described above due to the increased trapping efficiency of fine sediment caused by the vegetation.

4.2 Summary and Revisit of Analyses for Erosion of Fine Deposits

URS and Stillwater Sciences (2014) and Cui et al. (2017) provided semi-quantitative assessments of fine sediment transport analysis following the removal of Matilija Dam based on both realistic scenarios and worst-case-scenarios. They concluded that suspended sediment concentrations during the initial stage of sediment erosion (termed Phase I erosion) are likely to approach 10^6 mg/L that persists from less than a day to no more than three days for the design daily average flow of 1,700 cfs in Matilija Creek after dam removal. After that the flow becomes confined by the historical channel, the fine sediment deposits is no longer exposed to flow and the channel enters Phase II erosion, with the suspended sediment concentration decreasing more or less exponentially, reaching background level within a few hours to no more than a few days. To ensure that the estimated durations captured the range of potential values, the analyses included many factors of safety including using a smaller suspended sediment concentration and higher erosion volume for calculation (both of which would increase the duration of the impact), and the actual duration of suspended sediment impacts is likely toward the lower bound of the estimate.

Building from those earlier studies, two questions are now explored in the current document:

1. Has additional information been collected or have any advancements in research been developed that could potentially change the conclusions of the early analyses of URS and Stillwater Sciences (2014) and Cui et al. (2017)?
2. What is the likely consequence if water discharge in Matilija Creek does not reach the intended 1,700 cfs daily average design flow after the tunnels near the base of the dam are opened?

To help answer the first question, Gregg Drilling collected coring samples in 2018 in the reservoir area, and attempts were made to quantify the cohesiveness of the sediment deposits. The attempts, however, failed due to a lack of strength of the samples, which confirmed the early assessment that the fine sediment deposits are likely to offer minimal resistance to withstand erosion once the tunnels are open near the base of the dam. To date, there is no additional information or research that suggests contradictory results from that in the URS and Stillwater Sciences (2014) and Cui et al. (2017) analyses.

The key parameter for answering the second question is how the sediment-carrying capacity of a smaller discharge would compare to the 1,700 cfs flow in Matilija Creek. By applying the same method presented in URS and Stillwater Sciences (2014) and Cui et al. (2017), the Phase I suspended sediment concentration still exceeds 10^6 mg/L even if water discharge is only 850 cfs (half of the design discharge of 1,700 cfs). This implies that the duration of Phase I would be twice that of the estimated 1,700 cfs duration, because duration is linearly related to water discharge if erosion volume and sediment concentrations do not change[2]. That is, a

[2] There is likely some minor differences in concentrations between the two flows, but calculations in URS and Stillwater Sciences (2014) indicate that the concentration would exceed 10^6 mg/L under both conditions. However, the duration calculation applied a conservative concentration value well below 10^6

proportionately extended Phase I erosion can be expected if the discharge in Matilija Creek is slightly lower than 1,700 cfs.

Phase II erosion, which follows the primary evacuation of sediment from the channel carried by the released flow (Phase I erosion), is controlled by processes such as slumping and mass wasting driven by gravity and precipitation rather than discharge (Cui et al. 2017). Thus, failing to reach the design discharge of 1,700 cfs in Matilija Creek after dam removal is unlikely to increase the duration of Phase II erosion. In summary, as long as the discharge is only modestly smaller than the design discharge (e.g., no less than half of the design discharge), no significant consequence is expected for fine sediment erosion other than a similarly lengthened period of Phase I erosion.

4.3 Sediment Transport Dynamics Simulated with DREAM-2 Model

4.3.1 Zero processing run results

The study reach is divided into the following 10 subreaches (A through J) to facilitate the discussion of modeling results (Figure 2). Capital letters are chosen to name the subreaches instead of digits to avoid confusion with reach names from previous studies.

- Subreach A: Upstream of Matilija Dam;
- Subreach B: 0–1.05 km downstream of Matilija Dam, where the downstream boundary corresponds to the North Fork Matilija Creek confluence;
- Subreach C: 1.05–3.74 km downstream of Matilija Dam, where the downstream boundary corresponds to Robles Diversion Dam;
- Subreach D: 3.74–7 km downstream of Matilija Dam, where the downstream boundary corresponds to the westward extension of Ferrara Drive in the City of Mira Monte;
- Subreach E: 7–10 km downstream of Matilija Dam, where the downstream boundary approximately corresponds to the border between the communities of Mira Monte and Oak View;
- Subreach F: 10–13.6 km downstream of Matilija Dam, where the downstream boundary corresponds to the San Antonio Creek confluence;
- Subreach G: 13.6–16.3 km downstream of Matilija Dam, where the downstream boundary corresponds to the Coyote Creek confluences;
- Subreach H: 16.3–20 km downstream of Matilija Dam, where the downstream boundary corresponds to the westward extension of Los Cabos Lane in the City of Ventura;
- Subreach I: 20–23 km downstream of Matilija Dam, where the downstream boundary corresponds to roughly the westward extension of West Stanley Avenue in the City of Ventura;
- Subreach J: 23 km downstream of Matilija Dam to the Ventura River mouth.

The subreach delineation (Figure 2) was partly based on geomorphic features (e.g., the selection of dams and river confluences as boundaries) and partly arbitrary (e.g., the selection of whole km numbers as boundaries), with the guidance that each subreach should not exceed 4 km.

mg/L. For these reasons, the same (and conservatively low) concentration for both conditions is used here.

Figure 16 and Figure 17 present the simulated change in bed elevation for the 206-year zero process run (Run 0) discussed above in Section 2. The left and middle plates in Figure 16 show the 136-year simulation of the pre-Matilija Dam quasi-equilibrium condition, where the left plate is the 68-year simulation using the recorded 68-year discharge records between WY 1950 and 2017 (Appendix C) and the middle plate continues the simulation by repeating the same 68-year record. Two observations confirm that the simulated system is indeed in a quasi-equilibrium state: a) there is only minor, short-term sediment deposition and erosion (generally within 0.5 m, or approximately 2 ft) in different reaches, but no cumulative channel aggradation or degradation over time; b) there are similar deposition/erosion patterns between the left and middle plates, indicating that the deposition and erosion are due to variations in flow conditions. Note this particular simulation arranged the discharge record in the order of WY 1958–2017 followed with WY 1950–1957 (and then repeating this entire sequence). Rearranging the discharge order in any other way would not change the general observations above, except that the temporal patterns of sediment deposition and erosion would differ somewhat (e.g., a patch of sediment deposition that occurred in 1832 and 1900 in Figure 16 and Figure 17 might occur in some other year).

The right plate in Figure 16 is the simulation of the post-Matilija Dam years (WY 1948–2017), a period in which Matilija Dam, Casitas Dam, and Robles Diversion Dam were constructed (between 1948 and 1958). Each facility traps fine and coarse sediments to different degrees. The simulation applied the discharge records in these years, except that the records for WY 1948–1949 are substituted with the records of WY 2016–2017 because the processed discharge records for this study start at WY 1950 (Appendix C). Results of the post-Matilija Dam simulation indicate the most significant change in bed elevation occurred after the closure of Casitas Dam and Robles Diversion Dam. This caused up to 1.5 m (~ 5 ft) of aggradation upstream of Robles Diversion Dam (located 6.2 km downstream of Matilija Dam) and up to 1 m (~3 ft) of degradation downstream of Robles Diversion Dam (the right plate in Figure 16). Note that the amount of channel degradation reported in Figure 16 is averaged through the cross section; the actual degradation along the thalweg was probably significantly higher.

The simulated change in average bed elevation in different subreaches in Figure 17 clearly shows the 68-year cyclic response in sediment deposition and erosion in response to the cyclic discharge input. Figure 17 also clearly shows the sediment deposition upstream of Robles Diversion Dam (subreach C) and channel degradation immediately downstream of Robles Diversion Dam (subreach D) following construction of Matilija and Robles Diversion dams, as expected. Other subreaches experienced only relatively minor channel aggradation or degradation.

A comparison between simulated and surveyed 2005 profiles was previously presented in Figure 6, which shows that the two profiles are reasonably similar. The simulated profile is smoother compared with the survey, and the maximum difference between the two profiles is on the order of several feet. For the subsequent model simulations, the simulated 2017 profile is used as the "base" condition for the reasons previously explained, and so any modeled locations and amounts of post-dam-removal sediment deposition and erosion are reported as measurements against this profile.

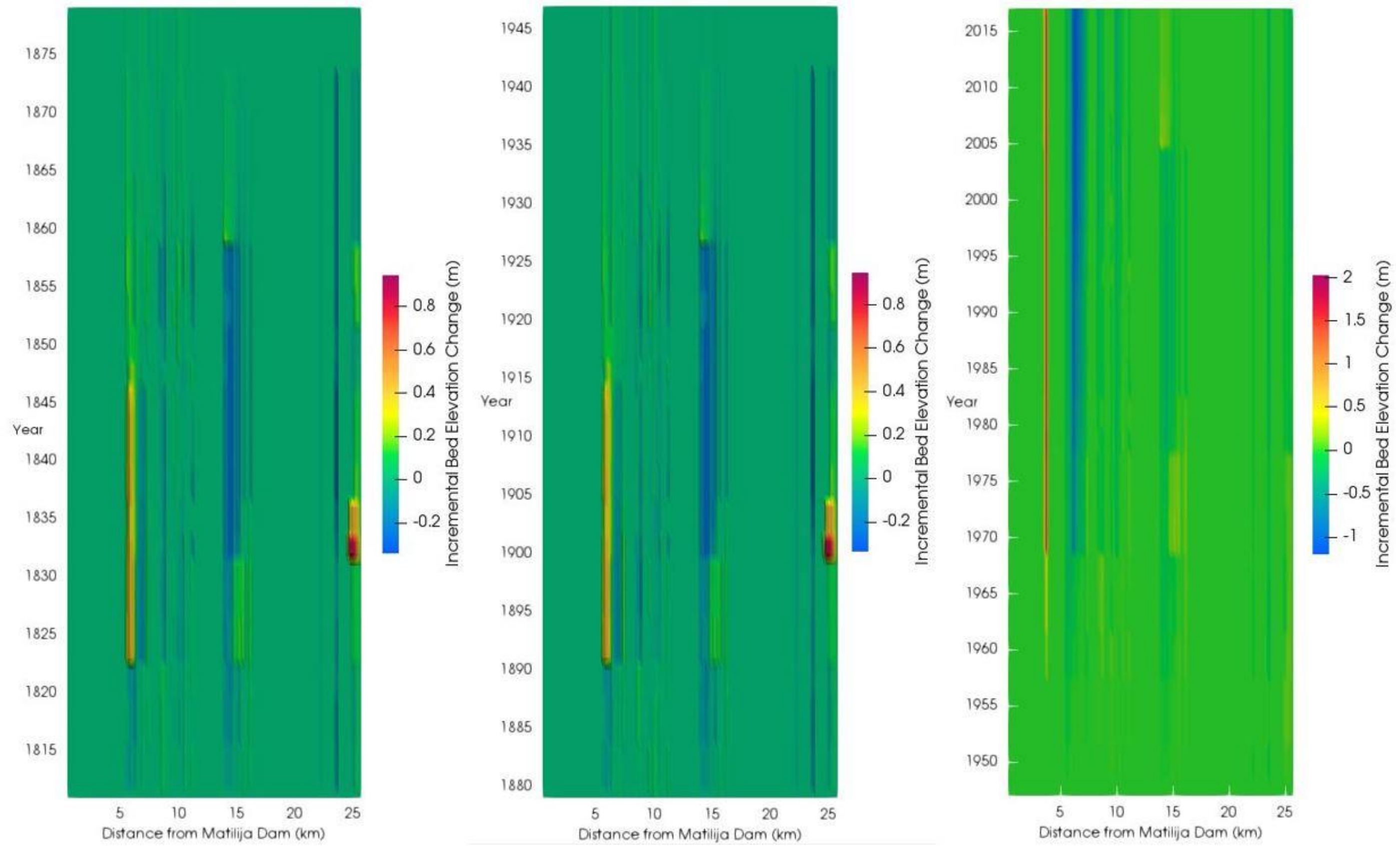


Figure 16. Simulated change in bed elevation for the zeroing process run (Run 0). A 204-year run was first conducted to acquire a historical equilibrium profile (not presented). Using this quasi-equilibrium profile as initial condition, a 206-year run was conducted to simulate the bed elevation change between 1811 and 2017. Years 1811 through 1947 (left and middle plates) represent continued simulation of the assumed historical quasi-equilibrium condition prior to Matilija Dam construction, which applied a 68-year discharge record for the simulation of 1911–1979 (left plate), then the same record was repeated for 1879–1947. The similarity in erosion and deposition patterns between the left and middle plates indicate that the system was indeed in a quasi-equilibrium state. Year 1947 through 2017 (right plate; note change in scale) represents the period of major in-river human disturbance that includes the construction of Matilija Dam, Casitas Dam, and Robles Diversion Dam, and sediment removal from Robles Diversion Dam forebay. Values of change in bed elevation prior to 1947 are relative to 1811, and after 1947 are relative to 1947.

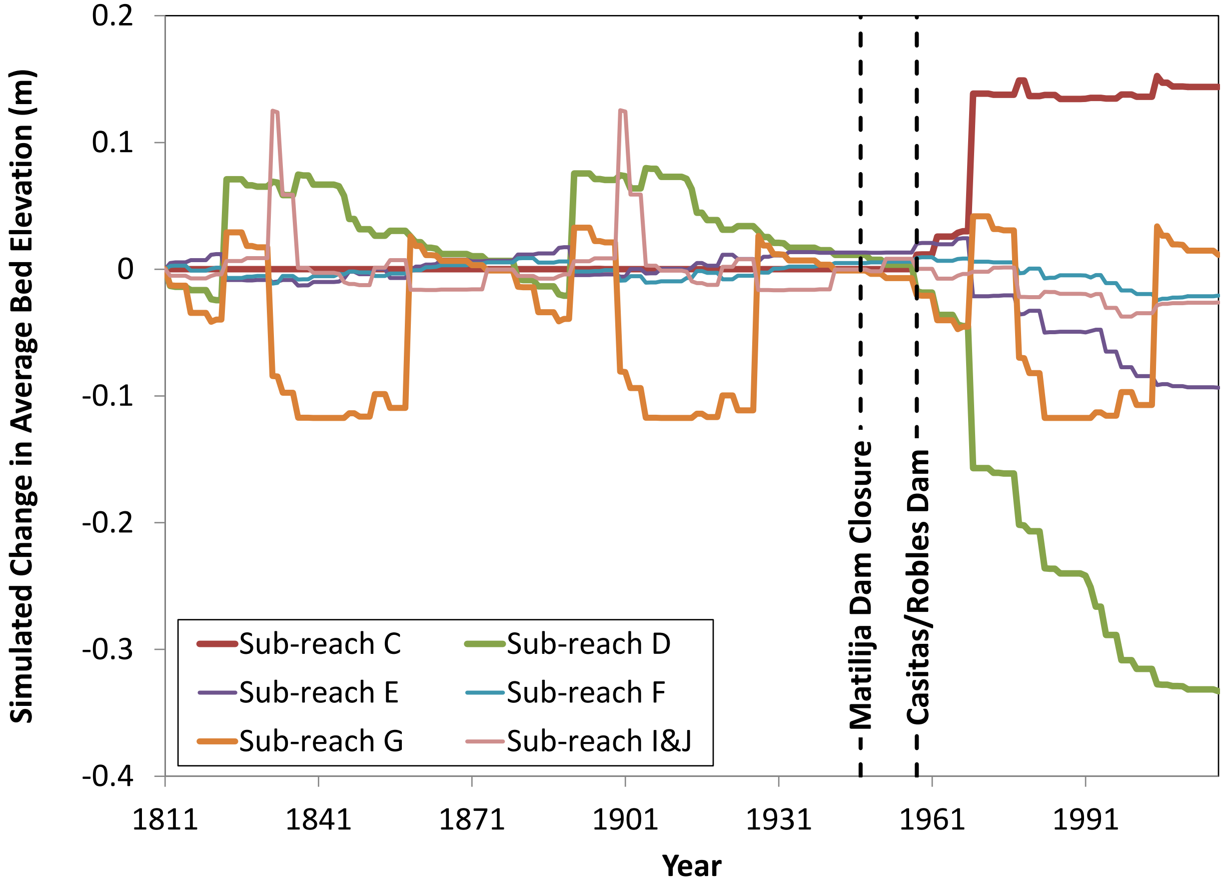


Figure 17. Simulated change in average bed elevation six subreaches of the Ventura River for the zeroing process run (Run 0). Figure legend shows distance from Matilija Dam; Robles Diversion Dam is located at 3.74 km downstream of Matilija Dam; Subreach 0-1.05 km downstream of Matilija Dam not presented because the simulation reported no change in bed elevation. Major changes are evident in Reach C (upstream of Robles Diversion), Reach D (downstream of Robles Diversion). Reach G (between San Antonio Creek and Coyote Creek) is seen to have periodic sediment deposition and erosion driven by periodic discharge input, which are likely enhanced by tributary sediment supply.

4.3.2 Future conditions with and without dam removal

4.3.2.1 Overview of DREAM-2 runs

A total of ten runs (Runs 1a, 1b, 1c, 1d, 1e, 2a, 2b, 2c, 2d, and 2e) were conducted to simulate sediment transport dynamics in the Ventura River, among which five (Runs 1a, 1b, 1c, 1d, and 1e) are simulations under the current condition, assuming Matilija Dam is not removed and continues to trap all the coarse sediment coming from Upper Matilija Creek over the duration of the simulation. The remaining runs (i.e., Runs 2a, 2b, 2c, 2d, and 2e) simulate the period following dam removal. The five alternative model runs for the two scenarios begin the sequence of flows at different points in the discharge record to explore whether flow sequencing influences the downstream patterns of sediment erosion and deposition. Each simulation lasted for 204 years, or three cycles of the 68-year discharge records. The purpose of running the model for multiple cycles of discharge record is to clearly demonstrate that some of the sediment deposition and erosion in the river are at least partially due to changes in hydrology as opposed to permanent trends.

As discussed earlier in Section 4.1, 204 years will likely be more than sufficient for the sediment to fill to the top of the dam if no removal occurs, and so coarse sediment would pass over the dam to reestablish sediment transport continuity between the upstream and downstream of the dam. For modeling purposes, however, Runs 1a through 1e assume that the dam will continue to trap coarse sediment through the entire duration of the run, so that the general trend can be more easily distinguished from changes in response to variations in hydrology.

The hydrologic sequences, the first significant flow, and the maximum daily average discharge within the first year of simulation in Matilija Creek for each model run are summarized below in Table 9. The design discharge on a daily averaged basis is 1,700 cfs in Matilija Creek provided by URS and Stillwater Sciences (2014), and dam removal is presumed to occur only if a storm event large enough to generate a flow higher than the design discharge in Matilija Creek is forecasted.

Table 9. Summary of hydrologic sequences for the five runs that simulate sediment transport dynamics under the current conditions and following dam removal.

Runs	Sequence of discharge records	Matilija Creek daily average discharge (cfs)		Approximate recurrence interval (yr) [c]
		First significant flow [a]	First year maximum [b]	
1a, 2a	WY 1992–2017, WY 1950–1991	3,906	3,906	10.2
1b, 2b	WY 1969–2017, WY 1950–1968	3,620	8,340	96 [d]
1c, 2c	WY 1958–2017, WY 1950–1957	1,260	2,390	4.4 [e]
1d, 2d	WY 2017, WY 1950–2016	2,120	2,120	4.2
1e, 2e	WY 1991–2017, WY 1950–1990	1,720	1,720	3.7

[a] The first significant flow is what the Matilija Creek will experience within a few days after the start of the run (and within a few days after dam removal for Runs 2a through 2e);
[b] First year maximum discharge occurs at least a couple of weeks after the occurrence of the design discharge;
[c] Based on first year maximum discharge;
[d] The first significant flow for Runs 1b/2b is equivalent to approximately an 8-year recurrence flow;
[e] The first significant flow for Run 1c/2c is equivalent to approximately a 3-year recurrence flow.

Of the five choices of dam removal dates, Run a (i.e., both Run 1a and 2a) examines the case of a 10-year flow soon after dam removal, while Runs d and e examine the case of approximately 4-

year events soon after dam removal. Run b assumes dam removal occurs during WY 1969, which had the largest flow event in the recorded history with a discharge very close to a 100-year event. The first significant high flow event for Run b, however, is approximately a 10-year event. A smaller but significant event preceding an extreme event is normal and dam removal immediately before a 100-year event is considered not likely. Run c has a slightly higher than 4-year events, but its first significant event following dam removal is only 1,260 cfs. Run c serves as an examination for the consequences if the first discharge following dam removal fails to reach the forecast level.

The discussions below are organized by the 10 subreaches delineated above. For brevity, only modeling results from selected runs are presented, comparing sediment deposition patterns throughout the run for future conditions without dam removal (e.g., Figure 18 for Run 1a) and with dam removal (e.g., Figure 19 for Run 2a), reach-averaged changes in bed elevation (e.g., Figure 20 for Run 1a and Figure 21 for Run 2a), and maximum thickness of sediment deposition from all runs without dam removal and with dam removal (Figure 22, Figure 23 and Figure 24). For dam removal runs, local bed profiles in the impoundment area and a short distance downstream of Matilija Dam are examined to help understand how quickly the impoundment area may recover to become similar to natural conditions (e.g., Figure 25 for Run 2e and Figure 26 for Run 2c).

The full set of modeling results, including those not presented in this section, is provided in Appendix D.

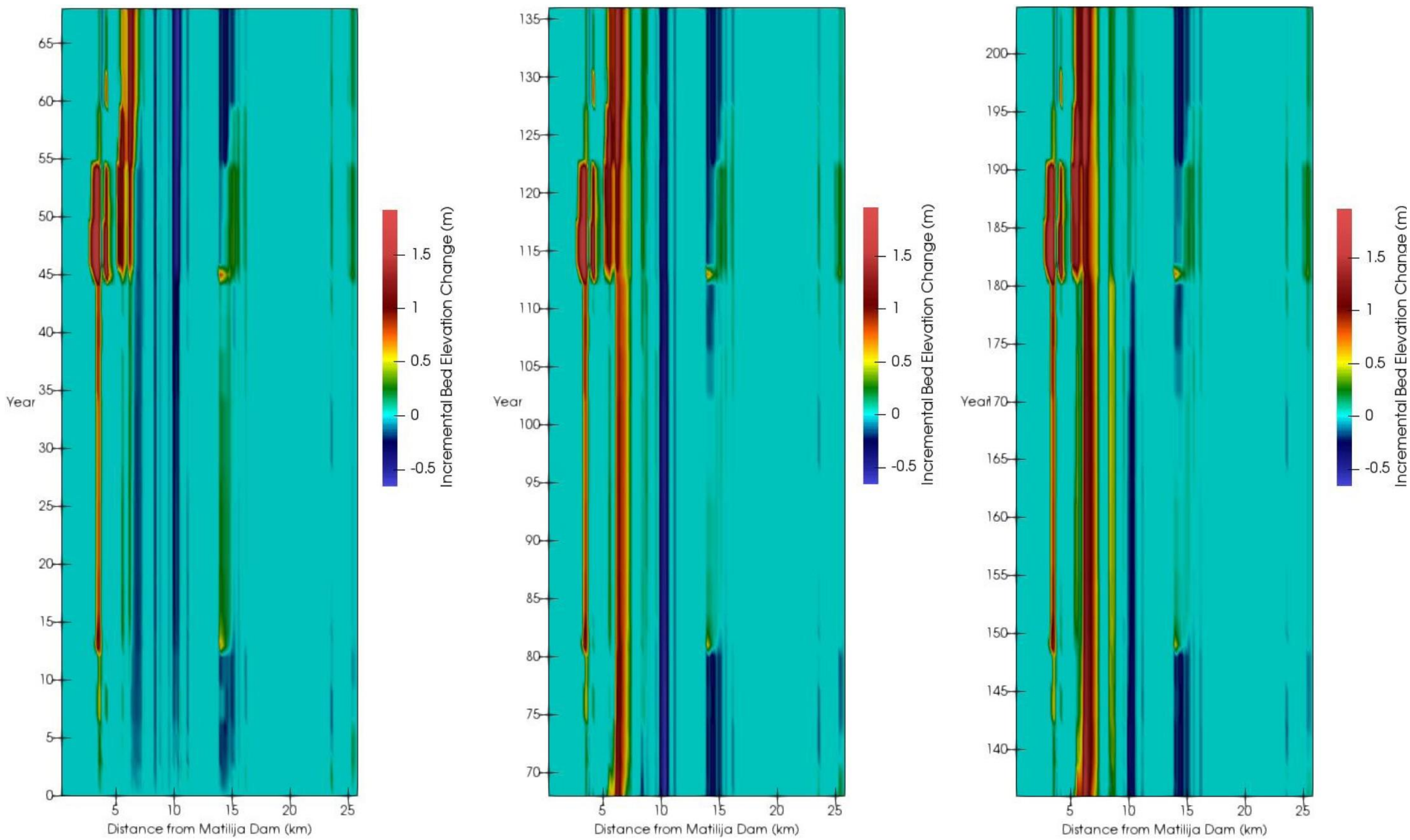


Figure 18. Simulated change in bed elevation, Run 1a. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous; each plate presents 68 years of results).

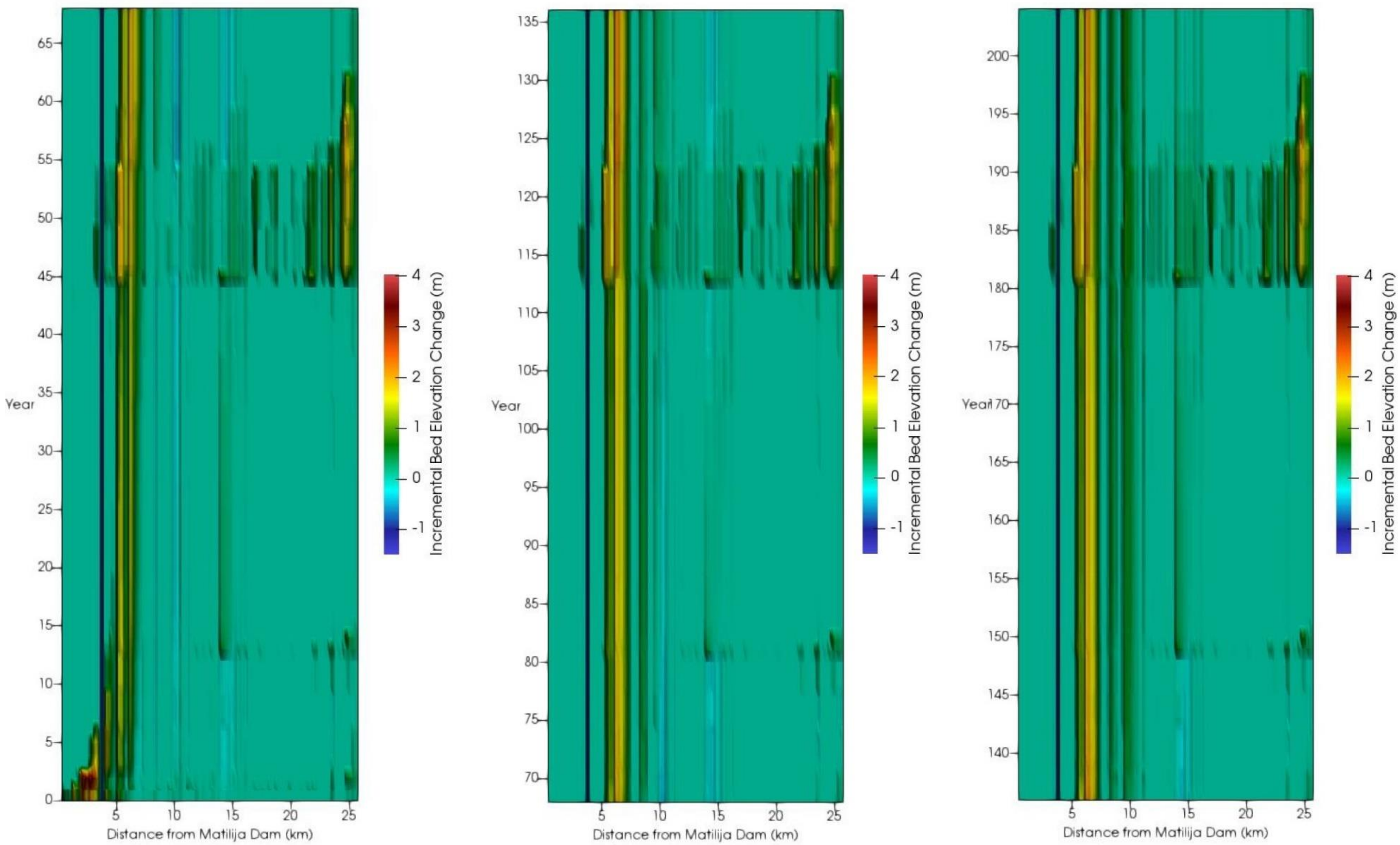


Figure 19. Simulated change in bed elevation, Run 2a. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous; each plate presents 68 years of results).

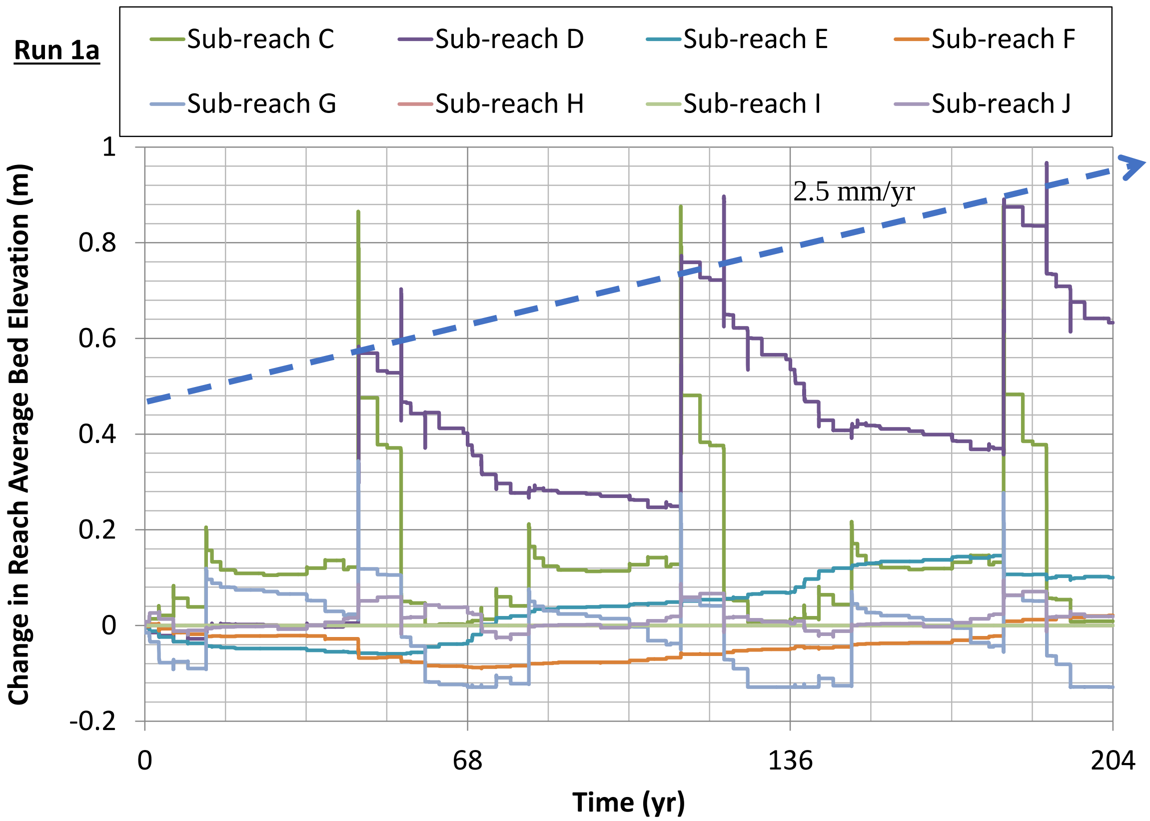


Figure 20. Simulated change in reach averaged bed elevation in subreaches C-J for Run 1a. Periodic sediment deposition/erosion are predicted to occur in subreaches upstream of Robles Diversion Dam (subreach C, 1.05–3.74 km downstream of Matilija Dam) and downstream of Robles Diversion Dam (subreach D, 3.74–7 km downstream of Matilija Dam). Part of the sediment deposition in the subreach downstream of Robles Diversion Dam seems to be permanent (as indicated in the dashed trend line with arrow that connects elevations with identical hydrological conditions). Other subreaches also experience periodic sediment deposition and erosion, but the magnitude of such deposition and erosion are seen to be relatively small and believe to be within the range of natural conditions. Subreach A is not simulated; subreach B has minimal sediment deposition/erosion.

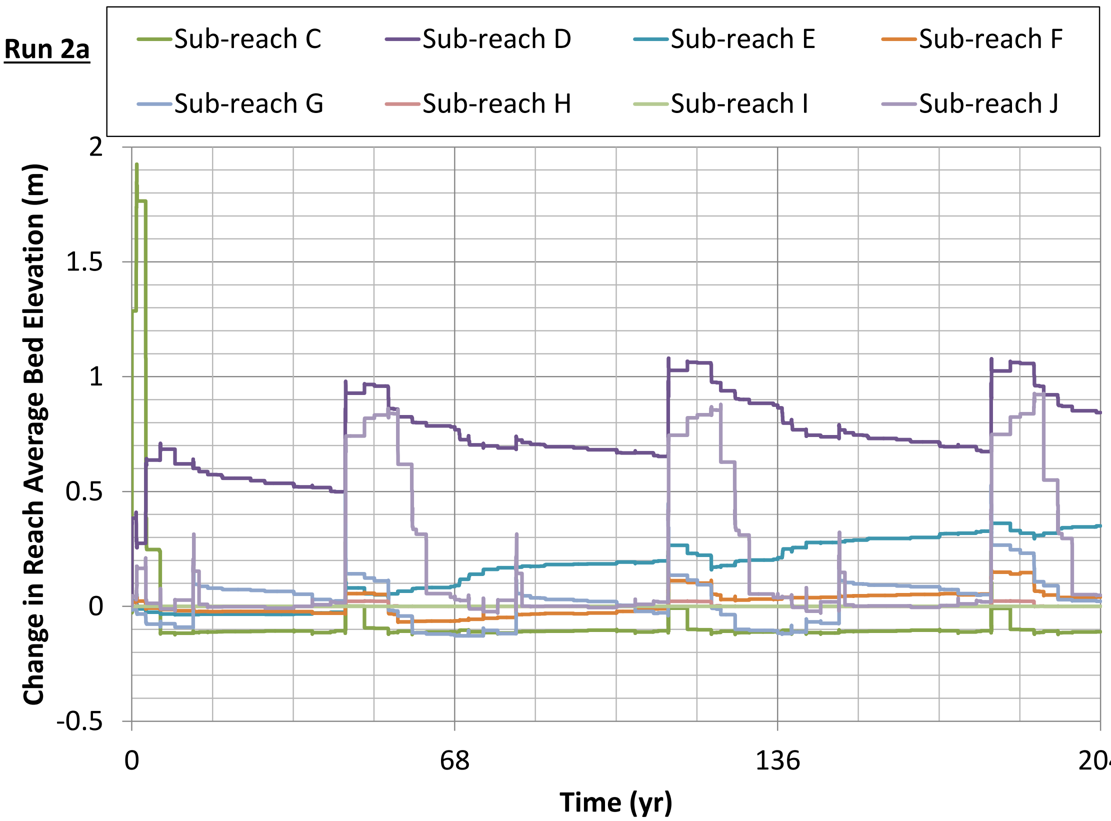


Figure 21. Simulated change in reach averaged bed elevation, Run 2a. Comparing with the corresponding case without dam removal (i.e., Run 1a), less sediment deposition is predicted upstream of Robles Diversion Dam (subreach C, 1.05–3.74 km downstream of Matilija Dam) except during the first few years following dam removal, but more is predicted downstream of Robles Diversion Dam (subreach D, 3.74–7 km downstream of Matilija Dam) and near the river mouth (subreach J, 23 km downstream of Matilija Dam to river mouth). There is also increased sediment deposition in subreach E (7–10 km downstream of Matilija Dam) over time, although the increase is likely within the discernable resolution of the model for the next 50 years. Subreaches A and B are presented because they do not show up well in the scale presented and are presented in other formats.

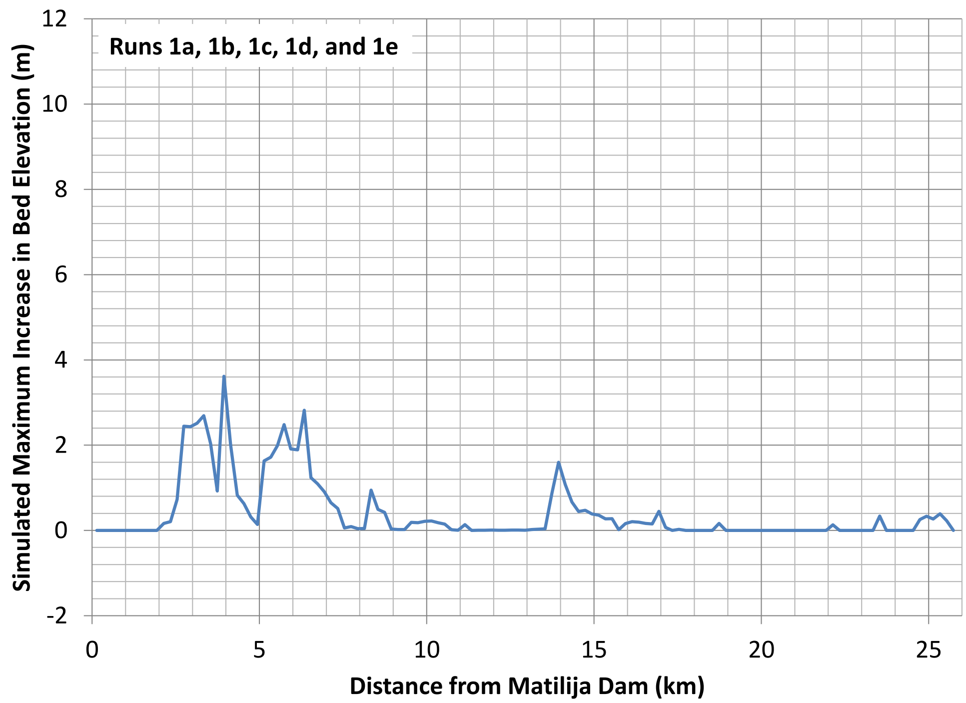


Figure 22. Simulated maximum increase in bed elevation under the no dam removal scenario, assuming Matilija Dam traps coarse sediment throughout the run. Profile shows the maximum aggradation across all current condition runs (Runs 1a, 1b, 1c, 1d, and 1e) at each location.

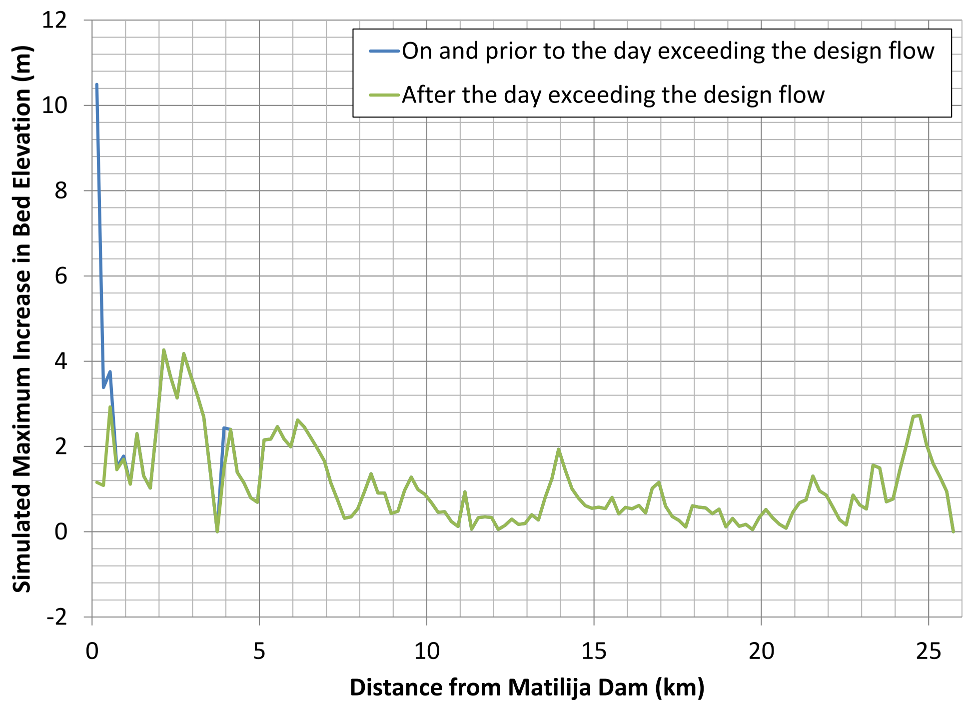


Figure 23. Simulated maximum increase in bed elevation following dam removal from all dam removal runs (Runs 2a, 2b, 2c, 2d, and 2e).

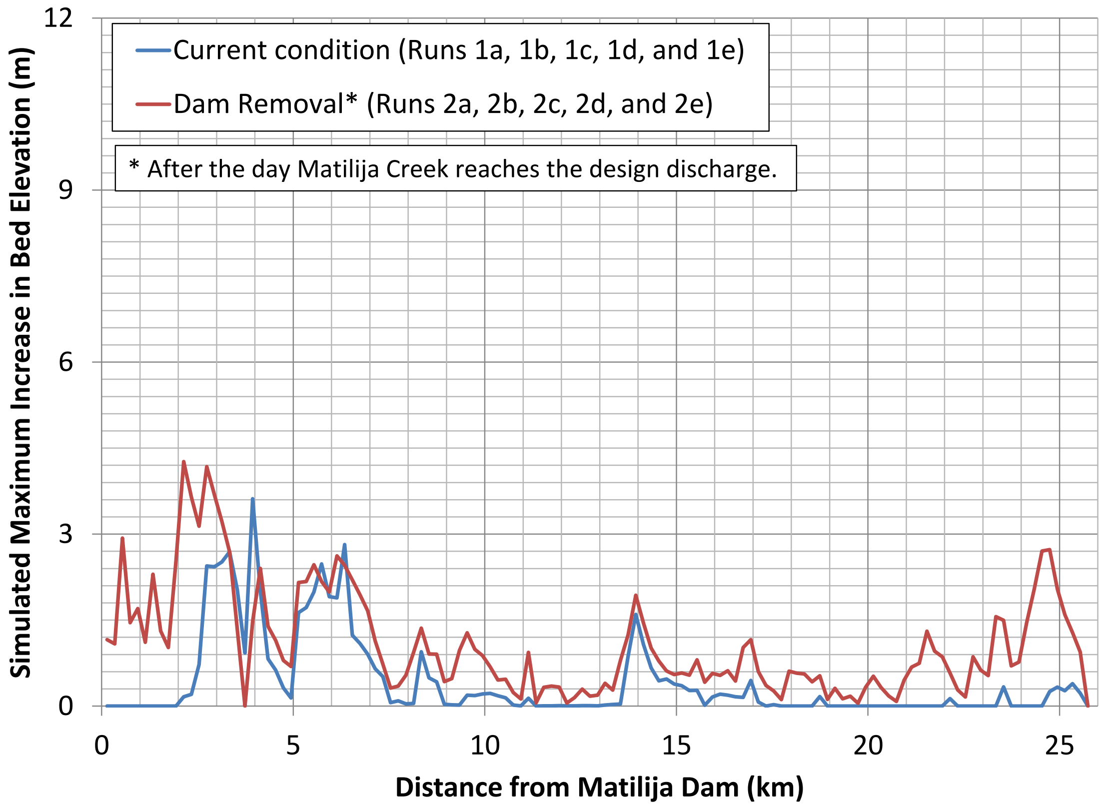


Figure 24. Comparison of simulated maximum increase in bed elevation from all runs under current condition (Runs 1a, 1b, 1c, 1d, and 1e) and following dam removal (Runs 2a, 2b, 2c, 2d, and 2e).

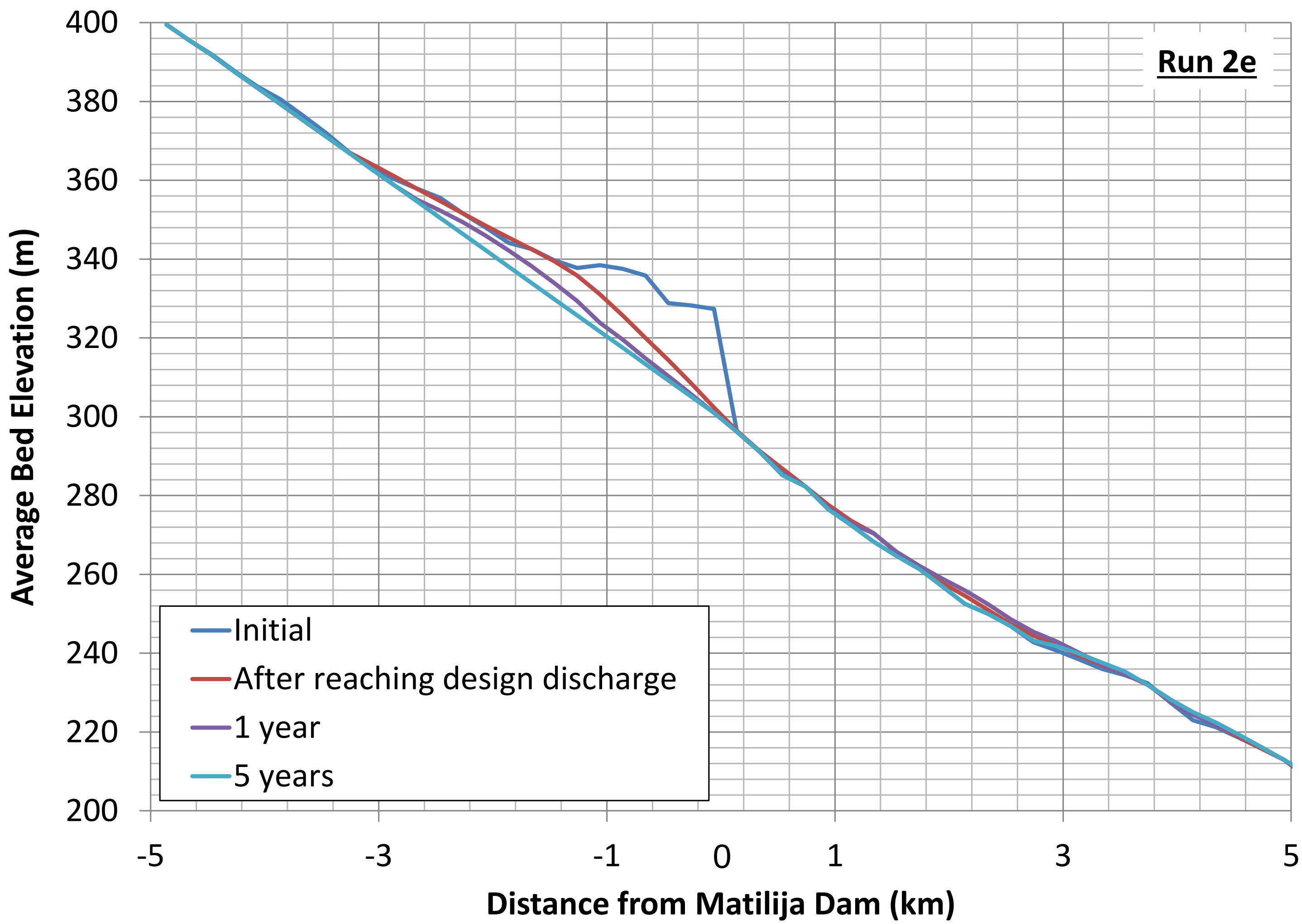


Figure 25. Simulated bed elevation near Matilija Dam, Run 2e. The daily average discharge on the day it reached design discharge was 1,720 cfs, corresponding to a 3.7-year recurrence interval event.

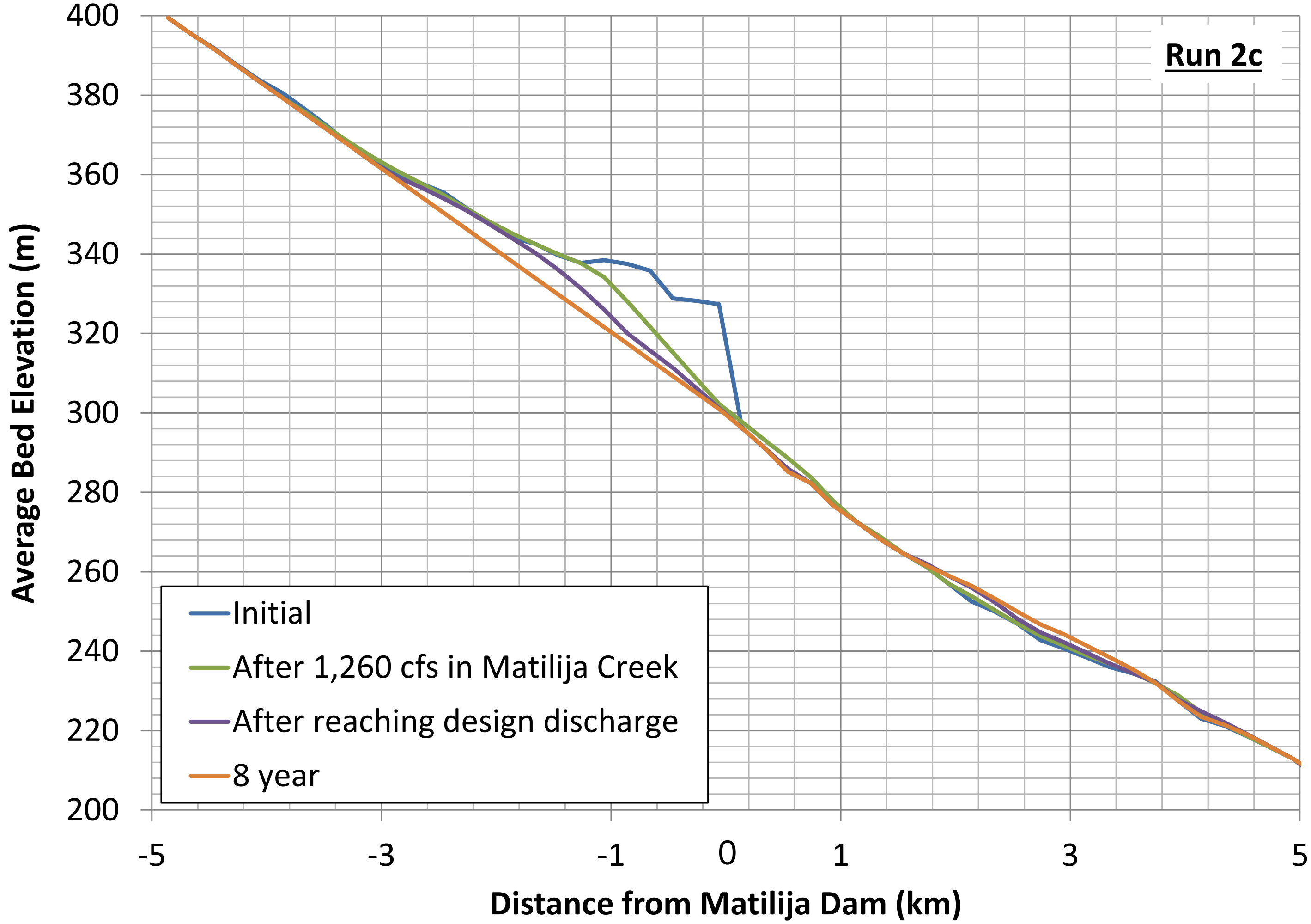


Figure 26. Simulated bed elevation near Matilija Dam, Run 2c. The first significant event after dam removal is 1,260 cfs in Matilija Creek, which is smaller than the design discharge of 1,700 cfs. The daily average discharge on the day that flows first reach design discharge was 2,390 cfs, corresponding to a 4.4-year recurrence interval event.

4.3.2.2 Subreach A (upstream of the dam)

The future condition upstream of the dam without dam removal was analyzed above in in Section 4.1, and no DREAM-2 simulation was conducted. A brief summary of the Section 4.1 analyses is provided below:

- Fine sediment (silt, clay and most sand particles) will continue to pass over the dam if looked at over a multi-year time scale, although short-term fine sediment accumulation such as observed after the Thomas Fire will occur;
- Coarse sediment (gravel and some sand) will continue to accumulate in the impoundment, advancing the delta front and aggrading the channel area and delta over time;
- A quarter of a century to a century may be needed for sediment to fill to the top of the dam, based on a simple delta progradation model for coarse sediment.

Under the preferred dam-removal scenario that opens up large tunnels near the base of the dam prior to a large storm event for sediment transport (the uncontrolled orifice option), both the early analysis by URS and Stillwater Sciences (2014; see also Cui et al. 2017) and the subsequent DREAM-2 modeling reported here indicate that coarse and fine impoundment deposits will be eroded quickly, with removal of much of the reservoir deposits within a day when Matilija Creek exceeds the design flow of 1,700 cfs. Run 2e, for example, shows that a significant amount of sediment has been eroded after Matilija Creek reached a daily average discharge of 1,720 cfs (Figure 25). The average channel gradient in the impoundment area after Matilija Creek slightly exceeded the design discharge shown in Figure 25 is less than 3%, which is comparable to the natural channel gradient just downstream of the dam. As expected, higher discharge would result in more rapid erosion and a gentler channel gradient in the impoundment area as shown in the results for other runs in Appendix D.

It is also useful to note that the above observations remain true even if the pre-removal weather forecasting overpredicted the post-removal discharge, and Matilija River slightly misses the design discharge as demonstrated in Run 2c (Figure 26), where the first significant flow event after dam removal is 1,260 cfs, or approximately 26% smaller than the design discharge of 1,700 cfs. After the 1,260 cfs flow, the maximum upstream channel gradient is only slightly higher than 3% (Figure 26), which is still comparable to the natural channel gradient of Matilija Creek just downstream of the dam. After the 1,260 cfs flow, the subsequent high flow of 2,390 cfs two month later continues to erode sediment downstream, further flattening the channel gradient.

The predicted rapid erosion of impoundment deposits is reasonable compared to the observations in Sandy River, Oregon following the removal of Marmot Dam, where upstream fish passage for adult salmon was observed three days after dam removal following the passing of a 2,200 cfs daily average flow (Cui et al. 2014). The Marmot Dam removal is similar to Matilija Dam removal in that both rivers have high channel gradient with almost identical gravel grain-size distributions in the impoundments (AECOM and Stillwater Sciences 2015). In addition, Marmot Dam removal sediment erosion occurred during a large storm event by design, which is similar to the design for Matilija Dam removal.

4.3.2.3 Subreach B (0–1.05 km downstream of the dam)

No appreciable sediment deposition and erosion are predicted in Subreach B if Matilija Dam is not removed and continues to trap coarse sediment (Figure 22). This result is expected because Subreach B is a steep, confined canyon reach dominated by bedrock and large boulders. The bedrock and large boulders prevent channel degradation while the steep channel gradient prevents sediment deposition, particularly in the absence of coarse sediment.

Following dam removal, Subreach B experiences a significant amount of sediment deposition (more than 10 m, or roughly 33 ft) immediately downstream of the dam, but it lasts only the first day (Figure 23). The majority of the deposited sediment in subreach B will be scoured after the day Matilija Creek discharge exceeds the design flow of 1,700 cfs, and no discernable deposition and erosion is expected thereafter.

4.3.2.4 Subreach C (1.05–3.74 km downstream of the dam)

Under the assumption of no future sediment management in the Robles Diversion Dam forebay, subreach C will experience periodic sediment deposition and erosion if the dam remains in place as demonstrated by the results for Run 1a (Figure 18 and Figure 20) and other runs (Appendix D). This is expected because sediment would accumulate in the forebay when sediment supply from North Fork Matilija Creek is high, and the accumulated sediment would be eroded when high flows are not coupled to high sediment supply. If, however, sediment removal continues in the Robles Diversion Dam forebay, subreach C will function as a sediment trap, with sediment supplied from North Fork Matilija Creek depositing in the topographic depression created by sediment removal in the forebay.

Following the removal of Matilija Dam and with the construction of the proposed HFSB at Robles Diversion Dam, subreach C will experience a period of high sediment deposition following dam removal that lasts for a few years to more than 20 years, depending on hydrologic conditions as demonstrated by the results for Run 2a (Figure 21 and Figure 19) and other runs (Appendix D). After this initial period, however, most of the sediment deposited shortly after dam removal will be eroded, and the amount of sediment deposition in the forebay becomes significantly smaller compared to that under the current conditions without dam removal (e.g., comparing Run 2a in Figure 21 with Run 1a in Figure 20). This is because the construction of the HFSB will lower the water surface control at Robles Diversion during high flow events when sediment supply from the upstream is high, hence allowing the sediment to pass through the structure more easily and reduce the amount of sediment deposition in the forebay. This result suggests that a relatively limited campaign of sediment removal from the forebay after the first few high flow seasons following dam removal could potentially be effective if the initial sediment deposition is indeed a problem for water diversion operation.

It should be noted, however, that these results are not independent validation of the effectiveness of the HFSB, because the modeling presented here applied the water surface level—discharge rating curve derived from the early experimental results of Mefford et al. (2008). That is, the modeling results at Robles Diversion Dam forebay are dependent on the findings of Mefford (2008). However, the proposed HFSB should significantly reduce the water surface level in the forebay during high flow events if operated appropriately, and thus should significantly reduce the amount of sediment deposition in the forebay.

Sedimentation has been a historical, ongoing management issue for water diversion at Robles Diversion Dam, and reduced sediment deposition with the construction of the HFSB following dam removal should provide improvement. Nevertheless, reduced sediment deposition in the forebay does not automatically translate into a trouble-free operation for water diversion, because local sediment deposition can often cause operation problems, which cannot be addressed by DREAM-2 or any one-dimensional numerical modeling. The Robles Diversion Dam facility was constructed within the historically active channel bed and banks of the mainstem Ventura River

(Cluer 2010), and channel evolution may have shifted the high flow path to the opposite bank from the diversion intake (Figure 27), making the intake vulnerable to local sedimentation regardless of the amount of sediment deposition in the forebay. In addition, accumulation of woody debris and other vegetation during high flow events may also cause additional operational difficulties.

Figure 27. Photograph of Robles Diversion Dam (courtesy of Paul Jenkin), February 24, 2019, showing the high flow of the river may have shifted to the bank opposite from the diversion intake, with flow being drawn to the intake/spillway only because of the presence of the diversion dam.

HFSB was not conducted due to budget constraints and because the consequence of dam removal without improvement to the Robles Diversion facility is clear: under the current water diversion approach, the large amount of sediment release following dam removal will quickly deposit in the forebay, completely overwhelming the intake facility and most likely resulting in a shut-down of the diversion operation. Once the flow recedes, the diverter will have to mechanically remove the sediment deposited in the forebay in order to resume water diversion. However, this will only create a sink for the sediment to quickly fill once the transport flows resume. Thus, proposing no improvements at the Robles Diversion Dam is clearly an extremely high-risk alternative. Other than the proposed HFSB, potential improvement to the diversion operation at Robles Diversion Dam that could be considered include sluicing facilities that reduce sediment deposition near the intake area as well as flow diverters (such as spur dikes) that could alter the flow patterns to push the high flow toward the right bank.

4.3.2.5 Subreach D (3.74–7 km downstream of the dam)

With Matilija Dam remaining in place, subreach D experiences both periodic and permanent channel aggradation, as demonstrated by results from Run 1a in Figure 18 and Figure 20, and from other runs in Appendix D, with maximum reach-average sediment deposition on the order of 0.8 m (~ 3 ft). The predicted maximum sediment deposition on a cross-section averaged basis is 2.6 m (~ 9 ft) (Figure 22), and local sediment deposition is likely to be much higher. Channel aggradation in subreach D under the current conditions is also predicted by BOR (2006).

Following the construction of Matilija Dam and Robles Diversion Dam, subreach D experienced channel degradation, because the two dams trapped coarse sediment upstream. Sediment removal from the Robles Diversion Dam forebay further reduced the amount of coarse sediment that passes through the Robles Diversion Dam spillway and increased the amount of channel degradation in subreach D. With the supply from North Fork Matilija Creek and with the assumption that there is no future sediment removal in Robles Diversion Dam forebay, sediment accumulation upstream of Robles Diversion Dam would eventually reach quasi-equilibrium. After this point, coarse sediment would begin to pass through the dam's spillway to reach subreach D, hence the predicted sediment deposition and channel aggradation.

Following Matilija Dam removal, subreach D experiences similar pattern and magnitude of sediment deposition. Relative to the current condition periodic sediment deposition arrives sooner and the subsequent amount of sediment erosion is smaller, resulting in higher permanent channel aggradation (Figure 21 and Appendix D).

4.3.2.6 Subreaches E, F, G, H, and I (7–23 km downstream of the dam)

Subreaches E through I are discussed together in this section because modeling results indicate there are minimal long term impacts in the future under both current conditions and following dam removal with two exceptions (Figure 20, Figure 21, and Appendix D):

a) Subreach E (7–10 km downstream of Matilija Dam) aggrades slowly over time following dam removal. This is reasonable because subreach E is immediately downstream of the aggrading reach of subreach D, and thus smaller and delayed channel aggradation is expected. The predicted reach-averaged channel aggradation within the next 50 years following dam removal for subreach E is less than 0.15 m (~ 0.5 ft) on a reach averaged basis, and even smaller if the dam remains in place (Figure 20 and Appendix D).

b) Short-term local sediment deposition up to 2 m (~ 7 ft) at approximately 14 km downstream of Matilija Dam occurs periodically (Figure 18, Figure 19, Figure 22, and Figure 23). This location is just downstream of the San Antonio Creek confluence, where the river exits a reach with bank restrictions and significantly expands its active channel width. The results are potentially reasonable at least qualitatively, as it is understood that large sediment deposition can occur downstream of major tributaries either when the water surface in the main stem river is high, creating a backwater effect in the tributary, allowing the sediment coming from the tributary stream to accumulate locally, or when there is a high flow in the tributary that contributes large quantities of sediment while the flow in the mainstem river is low, allowing the sediment contributed from the tributary to accumulate locally. For example, Stillwater Sciences (2013) observed a large sand dune (estimated to be taller than 2 m) deposited in Gordon Creek, a small tributary (< 45 km^2 catchment) of the Sandy River, Oregon just upstream of its confluence with the Sandy River during a field visit, which almost completely disappeared when it was revisited a few months later. Dam removal simulation in the Yuba River also produced large amount of short-term sediment deposition in the Yuba-Feather River confluence under certain hydrological conditions (Stillwater Sciences 2013). The other possible cause of simulated large quantities of sediment deposition is that the river experiences a sudden expansion of active channel width, and it is known that DREAM-2 model over predicts sediment deposition in such locations as documented in Cui et al. (2011) and shown in Figure 28. To further understand which factor contributed more to the sediment deposition, three sets of sensitivity runs were conducted, two of which varied sediment transport input parameters from San Antonio Creek and one arbitrarily changed the location of sudden channel expansion. Results of the sensitivity analyses indicate that San Antonio Creek sediment transport input parameters contributed little to the sediment deposition, and sudden expansion of channel width was the primary contributing factor. Considering the over-prediction from previous similar studies discussed above, it is highly likely that the amount of sediment deposition in this location was over predicted. In Section 4.3.2.8 below, a method is provided to filter out the over predictions and apply the simulated results in a more meaningful way.

Other than the periodic sediment deposition discussed above, the lack of modeled impacts to subreaches E through I is reasonable as these subreaches are more than 7 km away from the dam. The removal of Marmot Dam on the Sandy River, Oregon, for example, resulted in sediment deposition within only the upper 2 km downstream of the dam while the prediction indicated potential deposition for up to 10 km. Given the many similarities between the two dam removal cases and the attenuation of sediment transport due to the sediment trapping at Robles Diversion Dam, the lack of impact in subreaches E through I is understandable.

4.3.2.7 Subreach J (23 km downstream of the dam to river mouth)

Modeling results indicated minimal long-term change in subreach J in the future under the current condition with Matilija Dam in place (Figure 22). Following dam removal, periodic local sediment deposition of up to 0.9 m (~ 3 ft) is predicted under certain hydrological conditions (Figure 19, Figure 21, Figure 23, Figure 24, and Appendix D). It should be noted that subreach J is near the downstream boundary of the simulation, a location where modeling results are less reliable than in other subreaches because they are more dependent on the assumptions applied as the downstream boundary condition of DREAM-2. DREAM-2 uses a normal depth downstream boundary condition. A discrepancy between modeled deposition and actual deposition near the downstream extent of modeling was evident at the Sandy River mouth following Marmot Dam removal where sediment deposition was predicted by DREAM-2, and no such deposition was observed following dam removal (Cui et al. 2014).

However, it is reasonable to expect that there is likely to be more short- and long-term sediment deposition in subreach J due to the substantially increased sediment supply and potentially much coarser bedload sediment particles following dam removal. Due to tidal influence, subreach J is more dynamic than the other reaches due to its susceptibility to sediment deposition and erosion as varying hydrologic and tidal condition interact. Therefore, the predicted periodic and long-term sediment deposition in subreach J of the Ventura River predicted by DREAM-2 is included in the post-dam removal channel profiles used for flood evaluation.

4.3.2.8 Interpretation of modeling results throughout the study reach

It is important to note that the simulated changes in bed elevation presented above are all in reference to the assumed initial modeling condition which was created through a zeroing process run (Section 4.3.1). As such, the simulated absolute values of deposition and erosion are not meaningful without comparative interpretations based on the modeling approach as explained below.

Of the two sets of modeling results, Runs 1a through 1e represent the future condition with Matilija Dam continuing to trap coarse sediment. DREAM-2 modeling results showed a fairly small increase in aggradation downstream of Robles Diversion Dam during the first 68 years following dam removal, which in principle is in agreement with the BOR (2006) study that showed up to 4 ft of channel aggradation within this reach. For example, Run 1a showed less than 0.2 m of channel aggradation during the first 68 years following dam removal as indicated with the dashed trend line with arrow in Figure 20. This slow rate of aggradation is well within the potential error of the modeling and much smaller than the temporary deposition and erosion due to changes in hydrologic conditions. Thus, future conditions with Matilija Dam continuing to trap coarse sediment during the next several decades can be considered to be in a quasi-equilibrium state and can therefore be used as the reference condition to evaluate sediment deposition resulting from dam removal.

Figure 29 below shows the simulated maximum sediment deposition following dam removal relative to the simulated maximum sediment deposition under current conditions. The amount of deposition shown in Figure 29 represents the potential impact of dam removal, resulting from both the release of a portion of the impounded sediment within Matilija Reservoir and the re-establishment of sediment transport continuity once the dam is removed. Immediately following dam removal there is huge amount of sediment deposition of up to 4 m within Reach B immediately downstream of the dam. However, this deposition is short-lived and the bed is expected to return to near pre-project condition after the day Matilija Creek exceeds the design flow. Understandably, Robles Diversion Dam forebay (Reach C) also traps a substantial amount of sediment (up to 4 m), but over the long term the amount of sediment deposition in this reach will be smaller than the current condition due to the construction of the HFSB as discussed earlier. Between Robles Diversion Dam and the estuary, the amount of sediment deposition is generally limited to within 1 m (~ 3ft) except some isolated locations, where the spikes in sediment deposition are potentially an artifact due to model inaccuracy at locations of sudden channel expansion. The areas with sudden channel expansions that have high potential to over-predict sediment deposition include: 1) the 2 km reach downstream from Robles Diversion Dam (approximately 4 – 6 km downstream of Matilija Dam); 2) the 1.5 km reach upstream of Baldwin Road Bridge (approximately 6.5 – 8 km downstream from Matilija Dam); and 3) the short reach near Sunset School in Oak View (roughly 12 km downstream from Matilija Dam). In the estuary within approximately 1 mile (1.6 km) of the ocean the predicted maximum amount of sediment deposition spikes to up to 3 m (~10 ft), which may not be accurate because model accuracy diminishes near its downstream boundary.

Over time, the impact from the release of the impounded sediment will diminish, and the long-lasting impact will be entirely from the re-established coarse sediment supply. To better understand the impact from re-establishment of coarse sediment supply, Figure 30 presents the average channel aggradation/degradation during the second 68-yr hydrological cycle for Runs 2a through 2e relative to the current condition. It was assumed that the release of impoundment sediment to the river has vanished by year 69 following dam removal. The amount of sediment deposition and erosion presented in Figure 30 can be considered as the quasi-equilibrium state generated by dam removal as a result of renewed sediment supply. Results in Figure 30 is consistent with early discussions that the amount of sediment deposition in Robles Diversion forebay will eventually be reduced due to the construction of HFSB, and Reach D just downstream of Robles Diversion Dam will gradually aggrade to compensate for the degradation that occurred during the years of Robles Diversion Dam operation. Again, results near the estuary that shows more than 2 m of aggradation may not be accurate because model accuracy diminishes near its downstream boundary.

Despite the many uncertainties involved, modeling results are expected to be significantly more reliable when interpreted in a comparative way above, as already recognized and practiced in situations similar to the Matilija Dam removal project (e.g., Cui & Wilcox 2008; Cui et al. 2011).

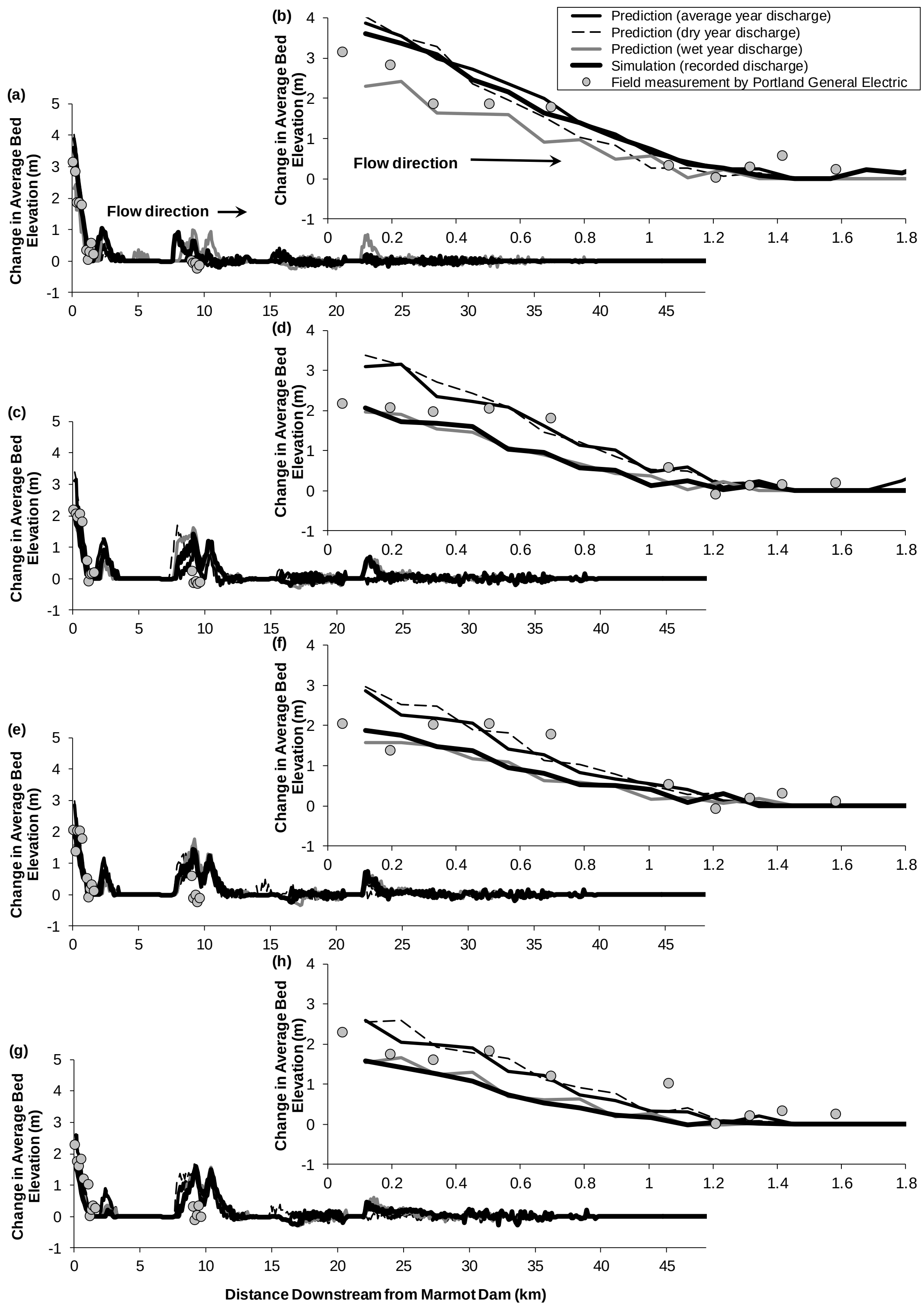


Figure 28. Comparison of simulated and observed sediment deposition in the Sandy River, Oregon following Marmot Dam removal, showing the over prediction of sediment deposition 7–11 km downstream of the dam where the channel suddenly expands as the river exit the Sandy River Gorge (Cui et al. 2014).

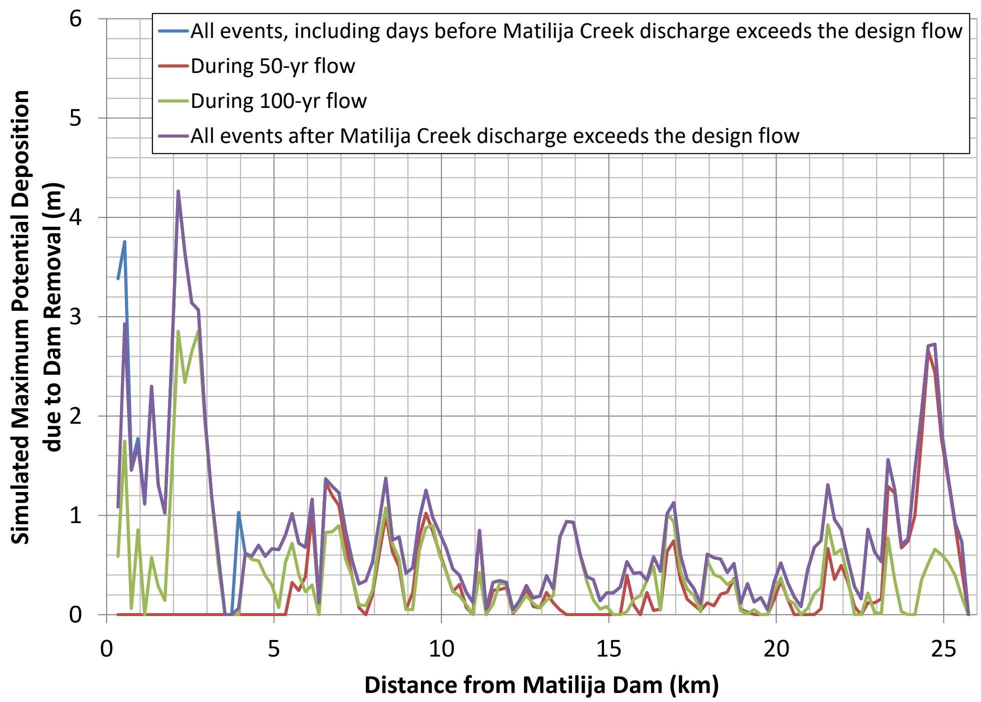


Figure 29. Simulated maximum sediment deposition following dam removal relative to the maximum deposition under current conditions.

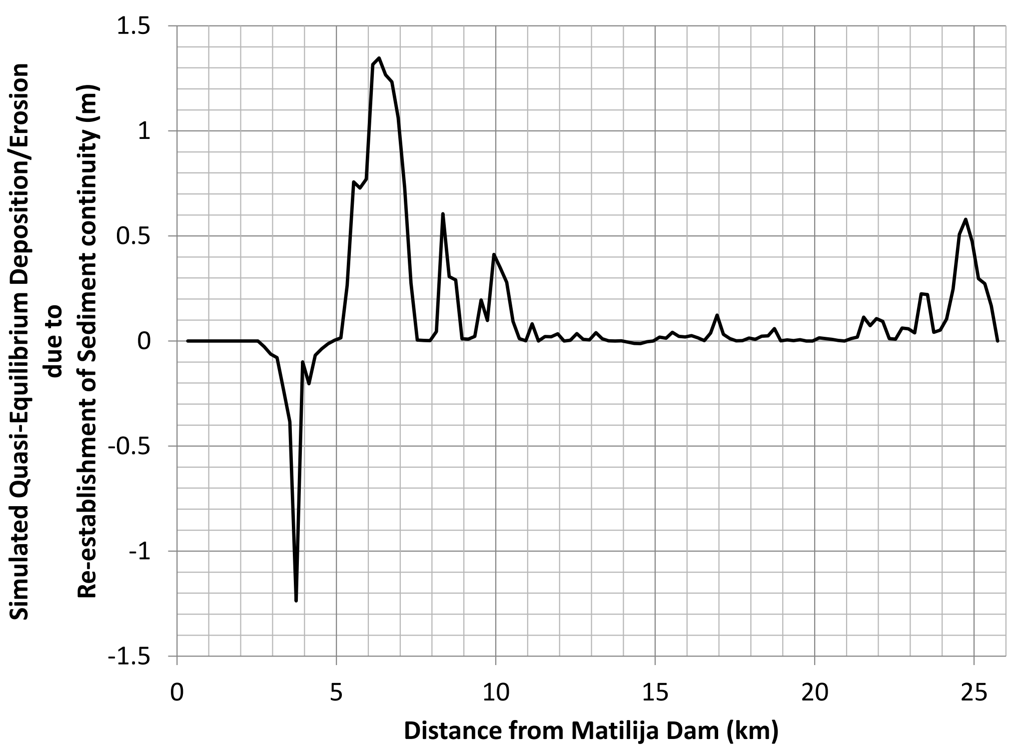


Figure 30. Average sediment erosion/deposition during the 2nd 68-yr hydrological cycle compared to the current condition, representing the impact of re-establishment of sediment supply at Matilija Dam site following dam removal.

5 PROFILES FOR HEC-RAS MODELING

DREAM-2 simulation does not provide water surface profiles, and flood evaluations are being conducted with HEC-RAS model simulation in Subtask 2.3 of the current study (reported in Stillwater Sciences 2020). Because the DREAM-2 model simplifies channel cross sections into rectangles while the HEC-RAS model uses full topographic cross sections, channel aggradation predicted by the DREAM-2 model must be translated into an equivalent area of aggradation within the actual cross-sectional topography in order to conduct HEC-RAS simulation.

As discussed above in Section 4.3.2.8, the river channel is not likely to change substantially in the near future if the Matilija Dam is left in place. Therefore, only profiles for future conditions with dam removal were exported from DREAM-2 to be modeled in HEC-RAS. The water surface elevations (WSE's) resulting from these future conditions profiles will be compared to the existing (surveyed) conditions from BOR (2006).

The translation from DREAM-2 to HEC-RAS is carried out by increasing the bed elevation of HEC-RAS cross sections by the thickness of sediment deposition predicted by DREAM-2 relative to current condition (i.e., results shown in Figure 29 and Figure 30). For cross sections upstream of Robles Diversion Dam, the amount of deposition is extended to the floodplain area to ensure the results will be more conservative, as long as the cross section elevation is below the highest bank station (demonstrated in Figure 31). Downstream of Robles Diversion Dam, the amount of sediment deposition is minor and unlikely be occurring in floodplain area, and thus, deposition is allowed only within the main channel area (i.e., between the two red dots shown on Figure 31). Note the translation above is conservative in nature only for the reach upstream of Robles Diversion Dam. The aggraded cross sections produced as described above are for HEC-RAS modeling purpose only and should not be assumed to represent the true pattern of sediment aggradation in the future.

A total of five post-dam-removal channel profiles shown in Figure 29 and Figure 30 were produced for hydraulic modeling using HEC-RAS.

1. The maximum sediment deposition during the day of the January 1969 flood simulated with Runs 2a through 2e relative to that from Runs 1a through 1e (labeled as "*During 100-year flow*" in Figure 29 legend)[3]. This profile will be used for 100-year event HEC-RAS simulation in Task 2.3 of this Project to evaluate maximum flood risks associated with sediment deposition expected in the future with dam removal.
2. The maximum sediment deposition during the March 1, 1983 event simulated with Runs 2a through 2e relative to that from Runs 1a through 1e (labeled as "*During 50-year flow*" in Figure 29 legend): This profile will be used for 50-year event HEC-RAS simulation in Task 2.3 of this Project.
3. The maximum sediment deposition after the day Matilija Creek daily average discharge first exceeded the design flow of 1,700 cfs following dam removal, simulated with Runs 2a

[3] Maximum sediment deposition simulated with Runs 2a through 2e relative to that from Runs 1a through 1e means to subtract the maximum sediment deposition simulated with Runs 1a through 1e from the maximum sediment deposition simulated with Runs 2a through 2e. This represents the net increase in sediment deposition following dam removal. The net increase in sediment deposition due to dam removal under all hydrological scenarios is represented by the difference between the red line and blue line in Figure 24.

through 2e relative to that from Runs 1a through 1e (labeled as "*All events after Matilija Creek discharge exceeds the design flow*" in Figure 29 legend): This profile applies to all events with magnitude from 10-year to 25-year recurrence interval. Simulation of the 5-year and smaller events should be applied to the profile 4 described below.

4. The maximum sediment deposition throughout the run simulated with Runs 2a through 2e relative to that from Runs 1a through 1e (labeled as "*All events, including days before Matilija Creek discharge exceeds the design flow*" in Figure 29 legend): This profile is different from profile 3 discussed above because there is extensive sediment deposition in subreach B during the first day that the flow in Matilija Creek exceeds the design flow of 1,700 cfs. This profile applies only for HEC-RAS simulation for 5-year or smaller events, because the large sediment deposits in subreach B that is predicted to occur during the first day following dam removal would have been eroded when the flow becomes higher than a 5-year event, making the application of profile 3 appropriate.
5. Quasi-equilibrium sediment deposition presented in Figure 30: This profile represents conditions within the project area after all impounded sediment is released from behind Matilija Dam been transported out of the system. This profile represents the impact due to the re-establishment of sediment continuity due to the removal of Matilija Dam. It also represents the ultimate quasi-equilibrium profile once Matilija impoundment is filled with sediment and sediment continuity is reestablished at the dam site if the dam is not removed.

HEC-RAS modeling results are presented in the technical report prepared for Subtask 2.3 of the Project (Stillwater Sciences 2020).

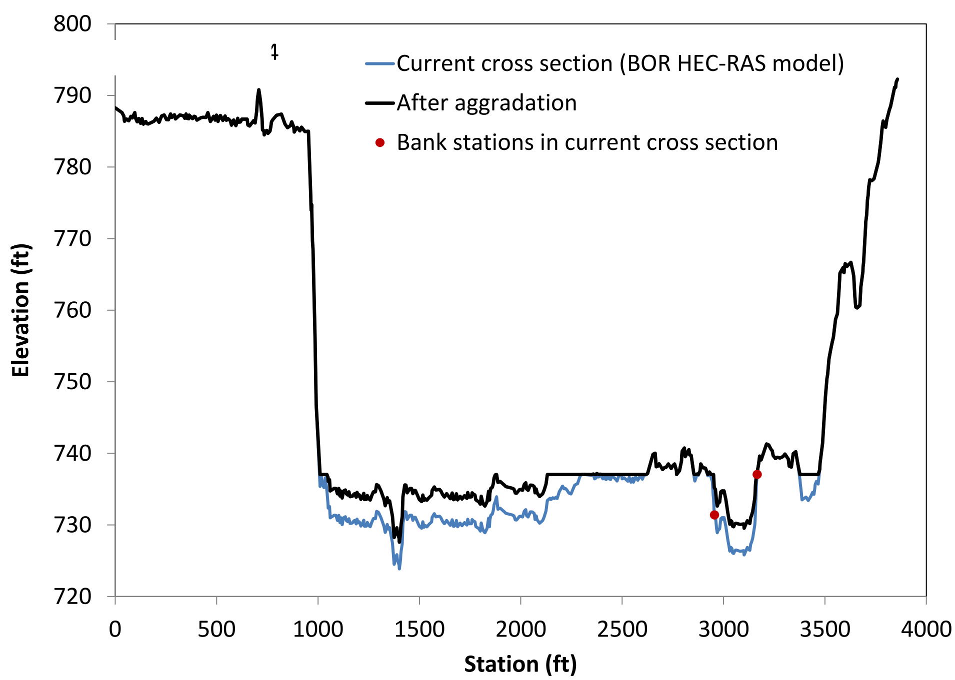


Figure 31. A demonstration of how channel aggradation predicted by DREAM-2 is transferred to HEC-RAS cross sections. The channel is allowed to aggrade uniformly unless the elevation after aggradation exceeds the highest bank station (the red dot on the right side), at which point the aggraded channel takes the elevation of the highest bank station (e.g., the flat line between approximately Station 2,200 and 2,700 ft).

6 RATE OF SEDIMENT DELIVERY TO THE ESTUARY

Sediment delivery rates to the estuary are provided to the estuary modeling team. They are not discussed here because the raw data offers no additional insight to the focus of the present analysis, namely the general patterns and magnitude of sediment deposition/erosion in the future with and without dam removal.

7 SUMMARY OF MAJOR FINDINGS AND RECOMMENDATIONS

The following conclusions and recommendations are provided based on DREAM-2 modeling and other analyses.

1. Under current conditions, the majority of the fine sediment produced in the upper Matilija watershed is most likely passing over the dam, although temporary fine sediment accumulation in the reservoir area does occur.
2. All of the coarse sediment (gravel and coarser) is currently trapped in the impoundment area, advancing the delta front and aggrading the upstream channel. The rate of channel aggradation and delta front progradation is dependent on sediment production in the upper watershed, which is likely episodic with long periods of low sediment production punctuated by brief periods of high production. If the dam is not removed, coarse sediment will fill to the top of the dam within a few to many decades, at which time delivery of coarse sediment to the downstream reaches will resume, perhaps with different sediment delivery dynamics for the coarsest fractions of sediment compared to dam removal because of the significantly wider floodplain with dam in place.
3. Under current conditions with the dam in place, minimal change to the system is expected in the next few decades: the Robles Diversion forebay area will stay as a sediment sink if the practice of mechanical sediment removal is to continue, or become highly dynamic, with periodic sediment deposition followed by erosion as hydrologic conditions fluctuate if mechanical sediment removal is no longer implemented. A short reach downstream of Robles Diversion Dam (subreach D) will likely experience some gradual channel aggradation as coarse sediments begin to pass Robles Diversion Dam, but this trend is very slow and is not expected to produce a meaningful impact within the next few decades.
4. Erosion of the reservoir deposits will be rapid following the opening of the tunnels near the base of Matilija Dam under the preferred dam-removal alternative, with the upstream deposits likely reaching a relatively low slope within a day after the daily average discharge in Matilija Creek exceeds the design flow of 1,700 cfs. The channel gradient in the former impoundment area will lower to <3%, which is comparable to natural conditions up- and downstream of the dam. Even if the daily average discharge only reaches 1,260 cfs (i.e., failing to achieve the design discharge of 1,700 cfs), the channel gradient in the impoundment will still decrease but to slightly higher than 3%, which is still comparable to natural conditions.
5. As inferred in URS and Stillwater Sciences (2014), fine sediment erosion will be rapid following the opening of the tunnels. The erosion is likely a two-phase process: Phase I erosion is the direct erosion into the fine-grained reservoir deposits by the flow, achieving high suspended sediment concentration (likely on the order of 10^6 mg/L) that lasts for a few hours to no more than three days; Phase II erosion is the somewhat slower mass failure of over-steepened channel banks into the flow, with suspended sediment concentration decreasing approximately exponentially that lasts for no more than a few days. If the daily

average discharge in Matilija Creek is reasonably high but fails to reach the design discharge of 1,700 cfs, a Phase I concentration of order 10^6 mg/L is still very likely. If that occurs, however, the Phase I duration will likely be proportionally longer. For example, if daily average discharge is only half of the design discharge of 1,700 cfs, then Phase I duration would likely be twice as long as in the case the discharge is 1,700 cfs. Failing to reach the design discharge of 1,700 cfs is unlikely to affect Phase II duration, only the time needed to begin this phase.

6. Following the opening of the tunnels, large amounts of sediment will be deposited immediately downstream of the dam in subreach B, with the highest deposition on the order of more than 10 m (~33 ft) following dam removal. This deposit, however, is transitory with most of it being scoured after daily-average Matilija Creek flow exceeds the design discharge of 1,700 cfs. Despite the short duration, the Camino Cielo Bridge is expected to be completely overwhelmed by sediment if it is not removed or replaced prior to dam removal.
7. A large volume of sediment will be deposited in subreach C, immediately upstream of Robles Diversion, following Matilija Dam removal. This deposit will last between a few years and a few decades if not mechanically removed. Once this sediment is removed or naturally scoured downstream during appropriate high flow events, however, the amount of subsequent sediment deposition in this reach becomes smaller compared to the current condition due to the assumed construction of the high flow sediment bypass (HFSB), which lowers the water surface elevation at Robles Diversion Dam during floods. This result should not be viewed as an independent validation of the early findings (e.g., Mefford et al. 2008), however, because DREAM-2 simulation results are dependent on the water surface level and discharge data reported in Mefford et al. (2008). These results suggest that some maintenance sediment removal from Robles Diversion Dam forebay area will be needed following the first few years of dam removal if the accumulated sediment causes problems for water diversion operation.
8. Periodic sediment deposition and permanent channel aggradation will occur in subreach D downstream of Robles Diversion Dam following Matilija Dam removal. The simulated maximum combined periodic sediment deposition and permanent channel aggradation is comparable in magnitude to that simulated for future conditions without dam removal, but the permanent channel aggradation is locally higher than without dam removal by no more than 1 meter (~ 3ft). In addition, channel aggradation in subreach D following dam removal occurs sooner than under current conditions without dam removal.
9. Downstream of subreach D, the predicted magnitude of sediment deposition following dam removal is only slightly higher than predicted for the current condition without dam removal, except a short reach upstream of the river mouth where the results are particularly unreliable due to model sensitivity to the assumed boundary conditions.

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Appendices

Appendix A

Conversion Between SI and Imperial Units

Imperial to SI	**SI to Imperial**
1 ft = 0.3048 m	1 m = 3.28 ft
1 mile = 1.609 km	1 km = 0.621 km
1 square mile = 2.59 km^2	1 km^2 = 0.386 square mile
1 acre = 4407 m^2	1 m^2 = 0.000247 acre
1 acre-ft = 1233 m^3	1 m^3 = 0.000811 acre-ft
1 cubic yard = 0.705 m^3	1 m^3 =1.308 cubic yard
1 cfs = 0.0283 m^3/s	1 m^3/s = 35.3 cfs
1 ton = 0.907 t (metric ton)	1 t (metric ton) = 1.102 ton

Appendix B

Water Surface Level – Water Discharge Rating Curves at Robles Diversion Dam

Water surface level – water discharge rating curves at Robles Diversion Dam with and without the proposed HFSB structure are developed based on the physical model study data provided in Mefford et al. (2008).

Mefford et al. (2008) conducted two runs under the current conditions without the proposed HFSB (i.e., runs SS6000 and SS14000), using the existing service spillway to control the pool level of the forebay for Casitas Municipal Water District's (CMWD) water diversion operation (showing in Figure B-1 as solid triangles). For water diversion purposes, the existing service spillway is managed in an attempt to maintain a constant forebay pool level of approximately 767 ft (233.78 m) before the flow exceeds the spillway capacity. Althouth Mefford et al. (2008) indicated that the spillway capacity is on the order of 6,000 cfs (169.9 m^3/s), trial fittings (discussed below) of the data presented in Figure B-1 shows that the capacity is most likely lower than that, and a value of 4,000 cfs (113.3 m^3/s) provided a much better match. The trial fittings here are conducted by assuming a discharge-water head relation in the form of $Q - Q_0 \sim (H - H_0)^{3/2}$ based on principles of open channel hydraulics, where Q denotes water discharge, Q_0 denotes spillway capacity, H denotes water surface level, and H_0 denotes water surface level prior to the flow exceeding the spillway capacity. For modeling purposes, a spillway capacity of 4,000 cfs (113.3 m^3/s) is assumed to achieve a better fit, resulting in the following rating curve under the current conditions:

$$Current\ Condition: W.S.ele = \begin{cases} 767.0 \quad Q \leq 4000 \\ 767.0 + 0.01(Q - 4000)^{2/3} \end{cases} \tag{3}$$

in which length scale is in ft while discharge is in cfs. Similarly, using the two setsof experimental data for the case with the proposed High Flow Bypass Structure constructed near the right bank (i.e., runs HFT-R6000 and HFT-R14000) results in the following relation:

$$With\ HFB: W.S.ele = \begin{cases} 766.2 \quad Q \leq 6000 \\ 766.2 + 0.0023(Q - 6000)^{2/3} \end{cases} \tag{4}$$

Both relations are presented in Figure B-1, which we reiterate are for sediment modeling purposes only. The general accuracy of the two equations shown in Figure B-1 should be adequate for sediment transport modelling.

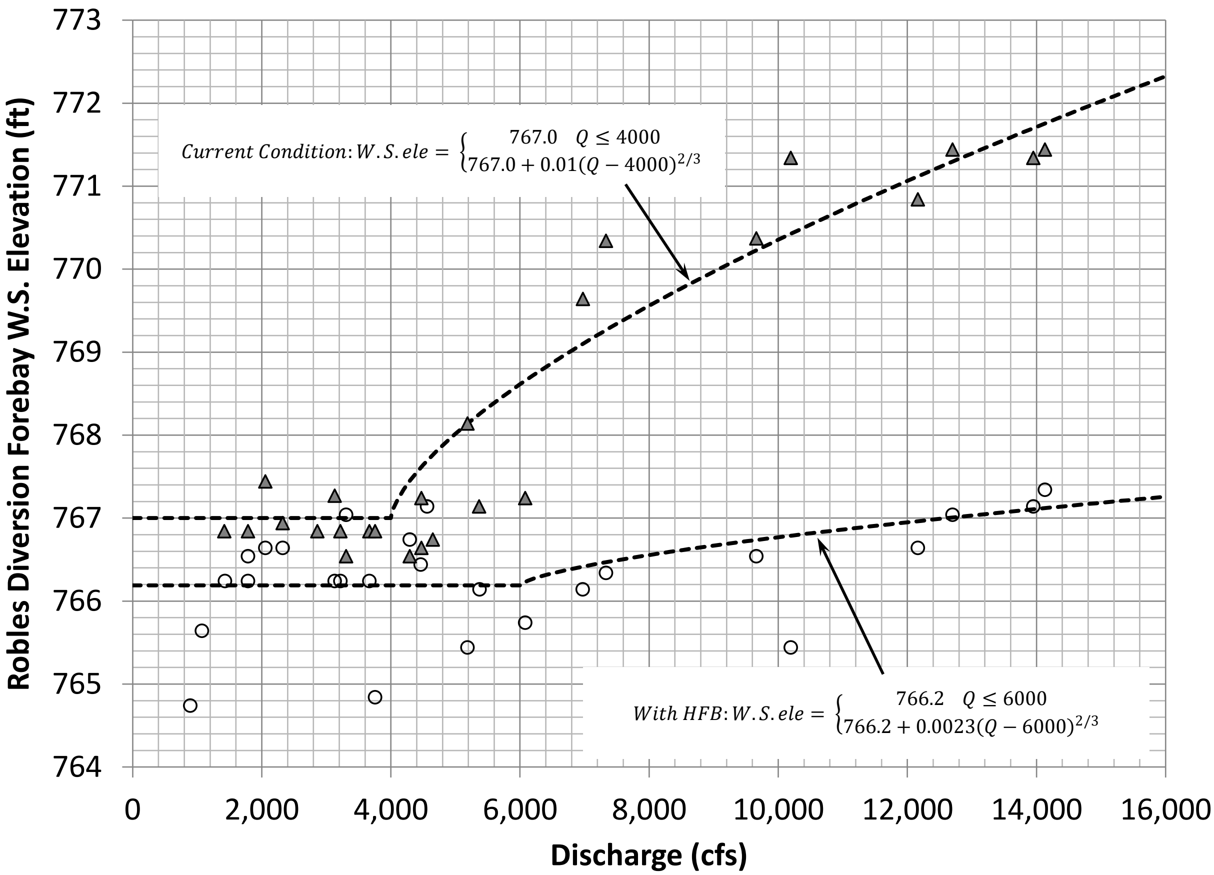

Figure B-1. Robles Diversion forebay water surface level – water discharge relations. Data are obtained from the scaled model experimental results in Mefford et al. (2008). Solid triangles are for the current condition, and open circles are after construction of the proposed modification with High Flow Bypass Structure located near the right bank next to the existing service spillway.

Appendix C

Selection of Water Discharge Records for DREAM-2 Simulation

C.1 Selection of Daily Average Discharge Records for Model Input

Sediment transport modeling following dam removal examines the erosion, transport and deposition of coarse sediment. This modeling utilizes the DREAM-2 sediment transport model that uses continuous daily average discharge records along the river as input to represent hydrologic conditions.

Upon examination of the available gaging records (Table C-1) and watershed map (Figure C-1), we decided to apply the following daily average discharge data for different reaches of the Ventura River for sediment transport modeling.

Table C-1. Stream gages in the Ventura River Watershed potentially useful for modeling purposes.

Description	USGS gate #	Drainage area (mi^2)	Period of record[a] (reasons of no record)	Data source
Matilija Creek at Reservoir Near Matilija Hot Springs	11114500	50.7	1948–1969 (destroyed)	USGS
Matilija Creek Near Res Near Matilija Hot Springs	11114495	47.8	2002–present	USGS
Matilija Creek at Matilija Hot Springs	11115500	54.7	1927–present	USGS, CMWD, and VCWPD
North Fork Matilija Creek at Matilija Hot Springs	11116000	15.6	1928–present	USGS and VCWPD
Ventura River near Ojai	11116500	70.7	1911–1984 (not maintained)	USGS
Ventura River near Meiners Oak	11116550	76.4	1959–present	USGS and CMWD
Robles Division Canal	--	--	1958–present	CMWD
San Antonio Creek near Ojai	11117000	33.7	1927–1932 (unknown)	USGS
San Antonio Creek at Casitas Springs	11117500	51.2	1949–present	USGS and VCWPD
Coyote Creek near Ventura	11118000	41.2	1927–1982	USGS
Ventura River near Ventura	11118500	188	1929–present	USGS
Ventura River near Ventura + Div.	11118501	188	1929–2007	USGS

[a] Calendar years

C.2 Matilija Creek

The discharge series in Matilija Creek relies on the record at Matilija Creek at Matilija Hot Springs located downstream of Matilija Dam (shown in Figure C-1 as USGS 11115500), available for water year [WY] 1928–present, with data collection by USGS [WY 1928–1988], CMWD [WY 1988–2007], and VCWPD [2007–present]).

C.3 Ventura River Between North Fork Matilija Creek and San Antonio Creek Confluences

The discharge series in this reach uses the discharge series in Matilija Creek (discussed above), plus the discharge series in North Fork Matilija Creek recorded at USGS 11116000 (North Fork Matilija Creek at Matilija Hot Springs, available WY 1929–present, with data collection by USGS [WY 1929–1988] and CMWD [WY 1989–present]). We have validated this approach with the discharge record at USGS 11116550 (Ventura River near Meiners Oaks, available WY 1959–present, with data collection by USGS [WY 1959 - 1988] and CMWD [WY 1989–present]) and found that it is a reasonable approach to extend the discharge record to the present day (Figure C-1). Applying the combined discharge from Matilija Creek and North Fork Matilija Creek instead of directly applying the discharge record at USGS 11116550 allows us to have a longer discharge series for modeling.

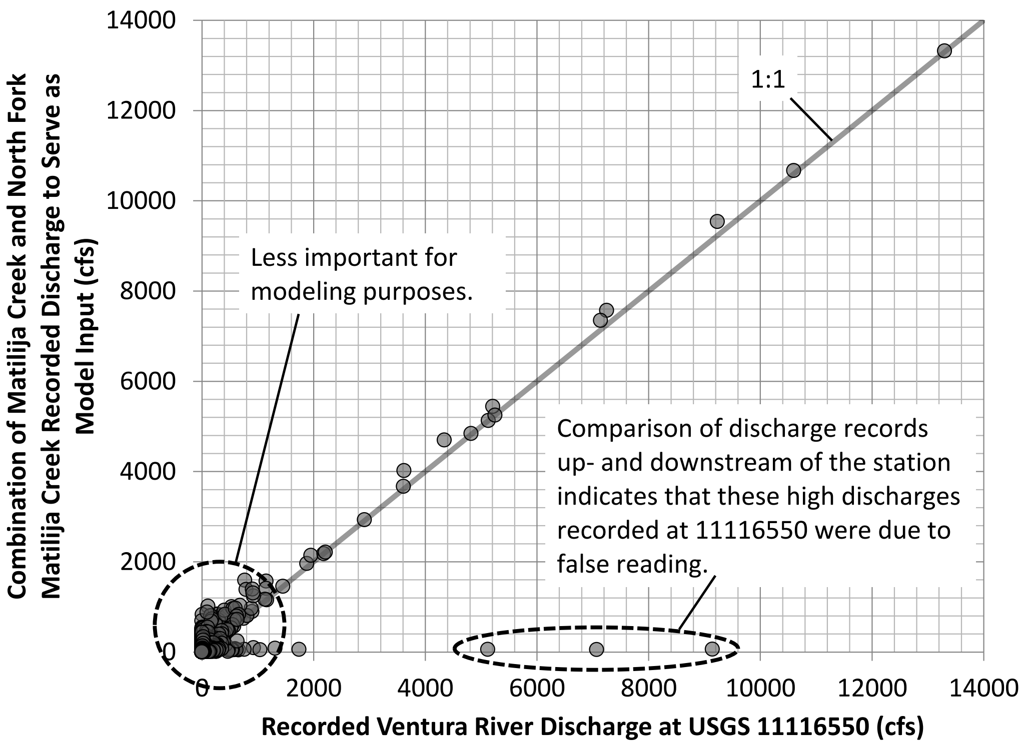

Figure C-1. Comparison of daily average discharge record at USGS 11116550 (Ventura River near Meiners Oaks) with the sum of recorded discharge in Matilija Creek and North Fork Matilija Creek for the period of WY 1959 – 1983.

C.4 Ventura River Between the San Antonio Creek and Coyote Creek Confluences

The flow series in this reach is represented with the discharge in the Ventura River just upstream of San Antonio Creek discussed above, plus the discharge at USGS 11117500 (San Antonio Creek at Casitas Springs, available 1950–present, with data collection by USGS [WY 1950–1983] and VCWPD [WY 1984–present]), located on San Antonio Creek just upstream of its confluence with Ventura River.

C.5 Ventura River Downstream of the Coyote Creek Confluence

The flow series in this reach is represented by the discharge record at USGS 11118500 (Ventura River near Ventura, available WY 1930–present) located on the Ventura River just downstream of the Coyote Creek confluence.

The above recorded series provide us with continuous series of daily flow for all the study reaches between WY 1950 and 2017, a total of 68 years of continuous record.

C.6 Approximate Recurrence Intervals

The dam removal plan calls for opening the orifices prior to a high flow event with daily average discharge in Matilija Creek higher than 1700 cfs, which roughly corresponds to a 4-year event. Table C-2 below summarizes the approximate recurrence intervals of the water years used for model simulation.

Table C-2. Approximate recurrent intervals of the water years used for sediment transport simulation. Rankings are based on discharge record in Matilija Creek between WY 1928 and 2018. Shaded years are selected to represent the year of dam removal for simulation.

WY	Max daily average flow	Exceedance probability	Recurrence interval	WY	Max daily average flow	Exceedance probability	Recurrence interval
1969	8340	1.1%	92.0	1971	436	52.2%	1.9
1983	7740	2.2%	46.0	1965	404	53.3%	1.9
1978	7020	3.3%	30.7	1972	337	56.5%	1.8
1998	5960	4.3%	23.0	2003	261	57.6%	1.7
1995	5580	5.4%	18.4	1997	253	59.8%	1.7
2001	5542	6.5%	15.3	1982	245	60.9%	1.6
2005	4369	8.7%	11.5	1981	237	62.0%	1.6
1992	3906	9.8%	10.2	1985	190	64.1%	1.6
1962	3890	10.9%	9.2	1996	184	65.2%	1.5
2008	2940	14.1%	7.1	1994	168	66.3%	1.5
1966	2900	15.2%	6.6	1987	122	68.5%	1.5
2006	2796	16.3%	6.1	1954	95	69.6%	1.4
1973	2690	17.4%	5.8	1977	80	70.7%	1.4
1986	2660	18.5%	5.4	1968	76	72.8%	1.4
1980	2560	19.6%	5.1	2009	73.6	73.9%	1.4
2011	2500	20.7%	4.8	1963	60	75.0%	1.3
1993	2410	21.7%	4.6	1989	56	77.2%	1.3
1958	2390	22.8%	4.4	1951	52	78.3%	1.3
2017	2120	23.9%	4.2	1956	50	79.3%	1.3
1991	1720	27.2%	3.7	1960	44	81.5%	1.2
1952	1370	29.3%	3.4	2015	39	82.6%	1.2
1975	1110	33.7%	3.0	1999	36	83.7%	1.2
1959	778	35.9%	2.8	1950	34	84.8%	1.2

WY	Max daily average flow	Exceedance probability	Recurrence interval	WY	Max daily average flow	Exceedance probability	Recurrence interval
1967	707	38.0%	2.6	1957	33	85.9%	1.2
1988	681	39.1%	2.6	2002	30	87.0%	1.2
2010	656	40.2%	2.5	1953	26	89.1%	1.1
1979	653	41.3%	2.4	2012	24	90.2%	1.1
1984	597	42.4%	2.4	1964	13	91.3%	1.1
1976	483	44.6%	2.2	1990	11	93.5%	1.1
2004	476	45.7%	2.2	2016	8.8	94.6%	1.1
1970	469	46.7%	2.1	2007	8.5	95.7%	1.0
1974	448	47.8%	2.1	2013	8.3	96.7%	1.0
2000	444	50.0%	2.0	1955	7.3	97.8%	1.0
2014	443	51.1%	2.0	1961	4.9	98.9%	1.0

Appendix D

DREAM-2 Results

This appendix provides results of the DREAM-2 simulation, including those previously presented in the main document for the interest of readers. No additional discussions are provided to these results, but the titles and legends are expanded as much as necessary to point out the main interest points of the diagrams. Readers should reference Section 4.3 for details and implications of the modeling results.

D.1 Future Condition, No Dam Removal, Coarse Sediment Trapping Throughout the Run

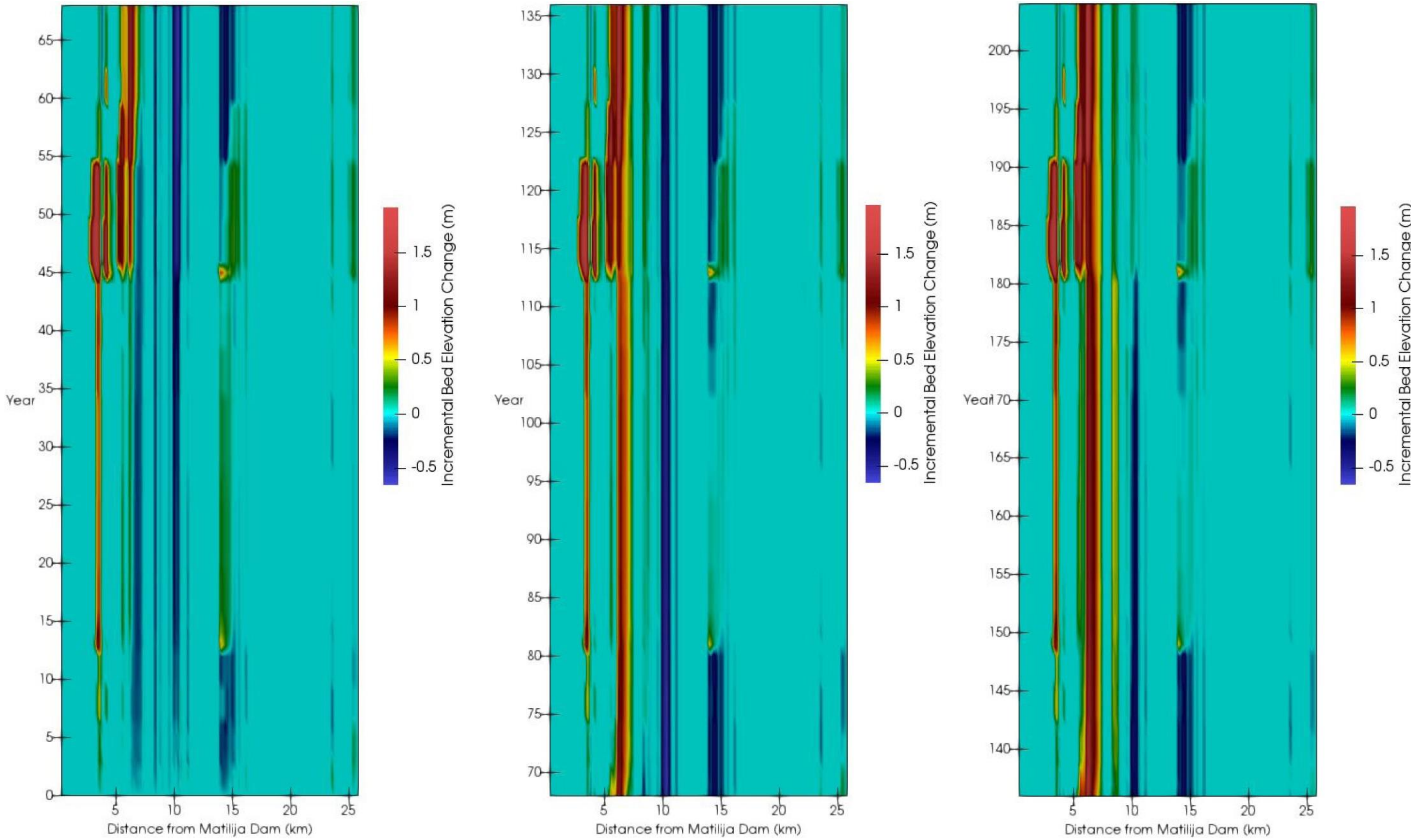

Figure D-1. Simulated change in bed elevation, Run 1a. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

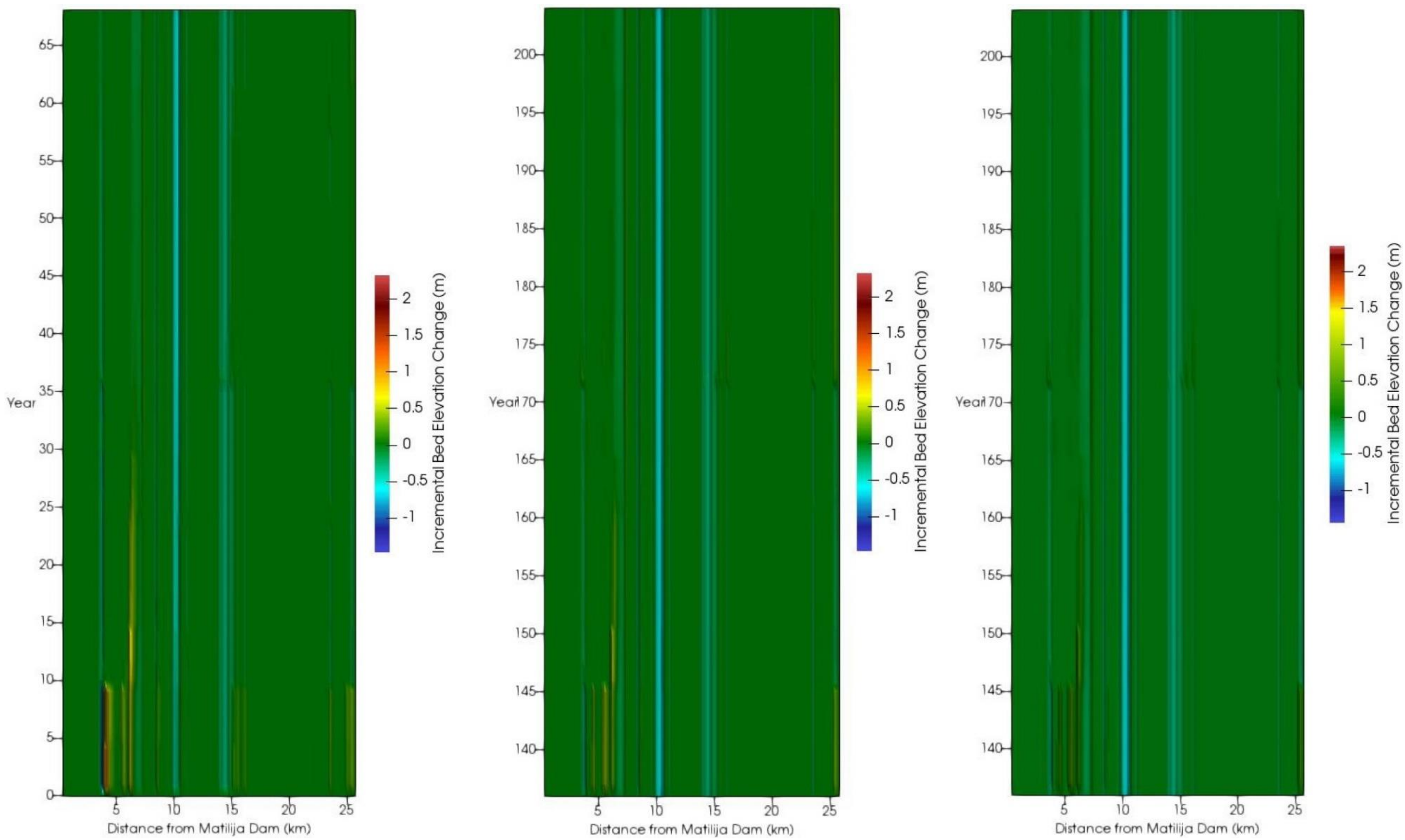

Figure D-2. Simulated change in bed elevation, Run 1b. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

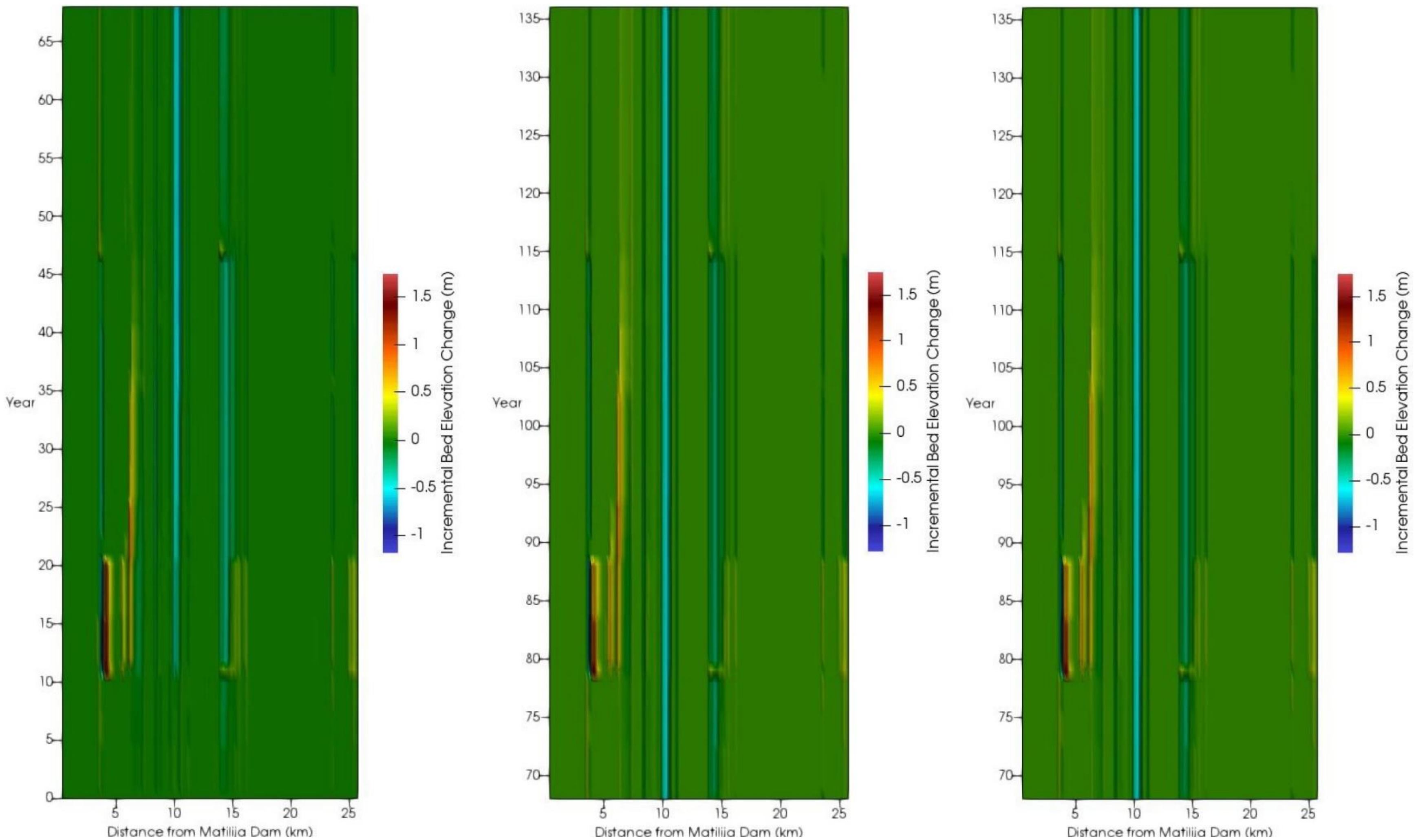

Figure D-3. Simulated change in bed elevation, Run 1c. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

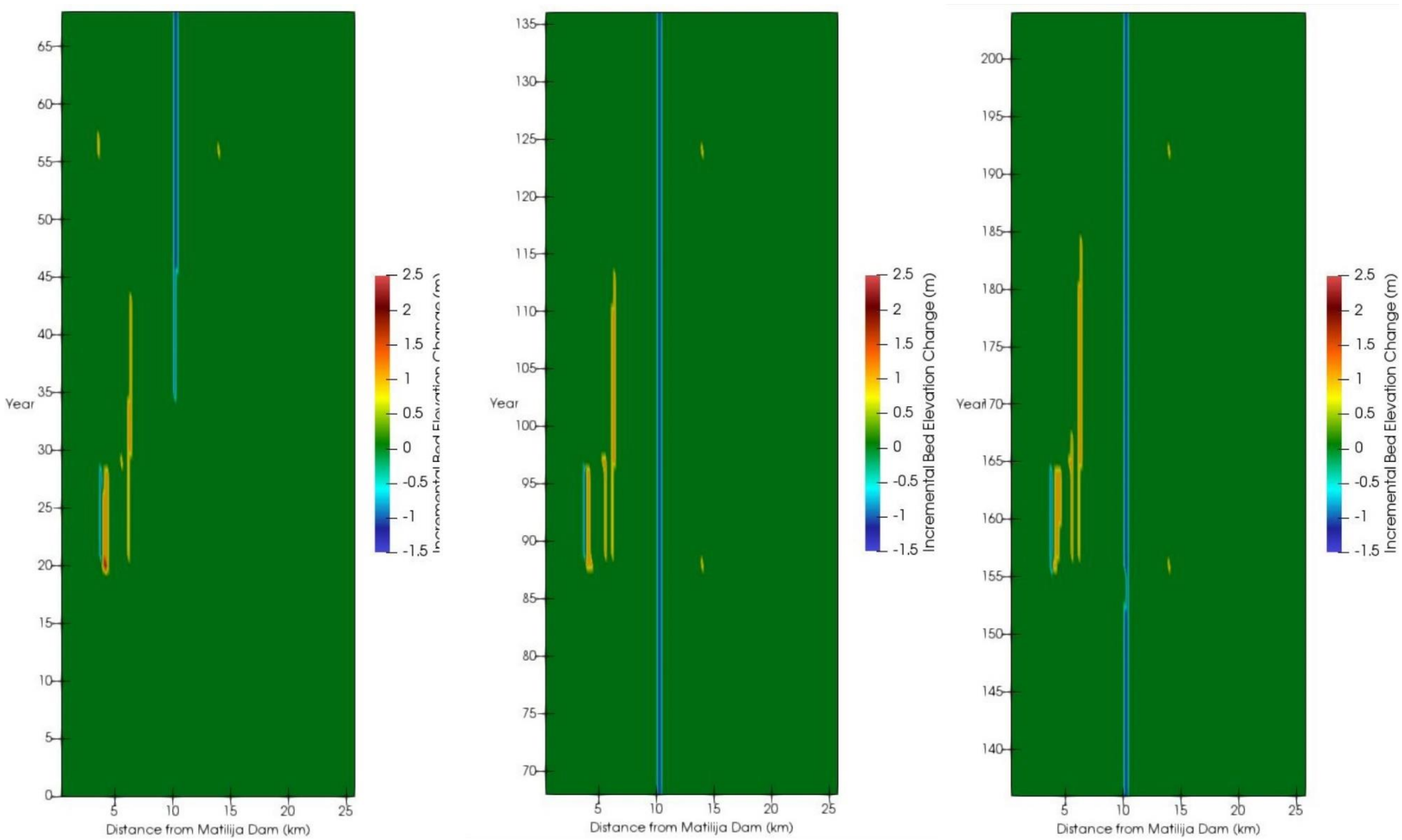

Figure D-4. Simulated change in bed elevation, Run 1d. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

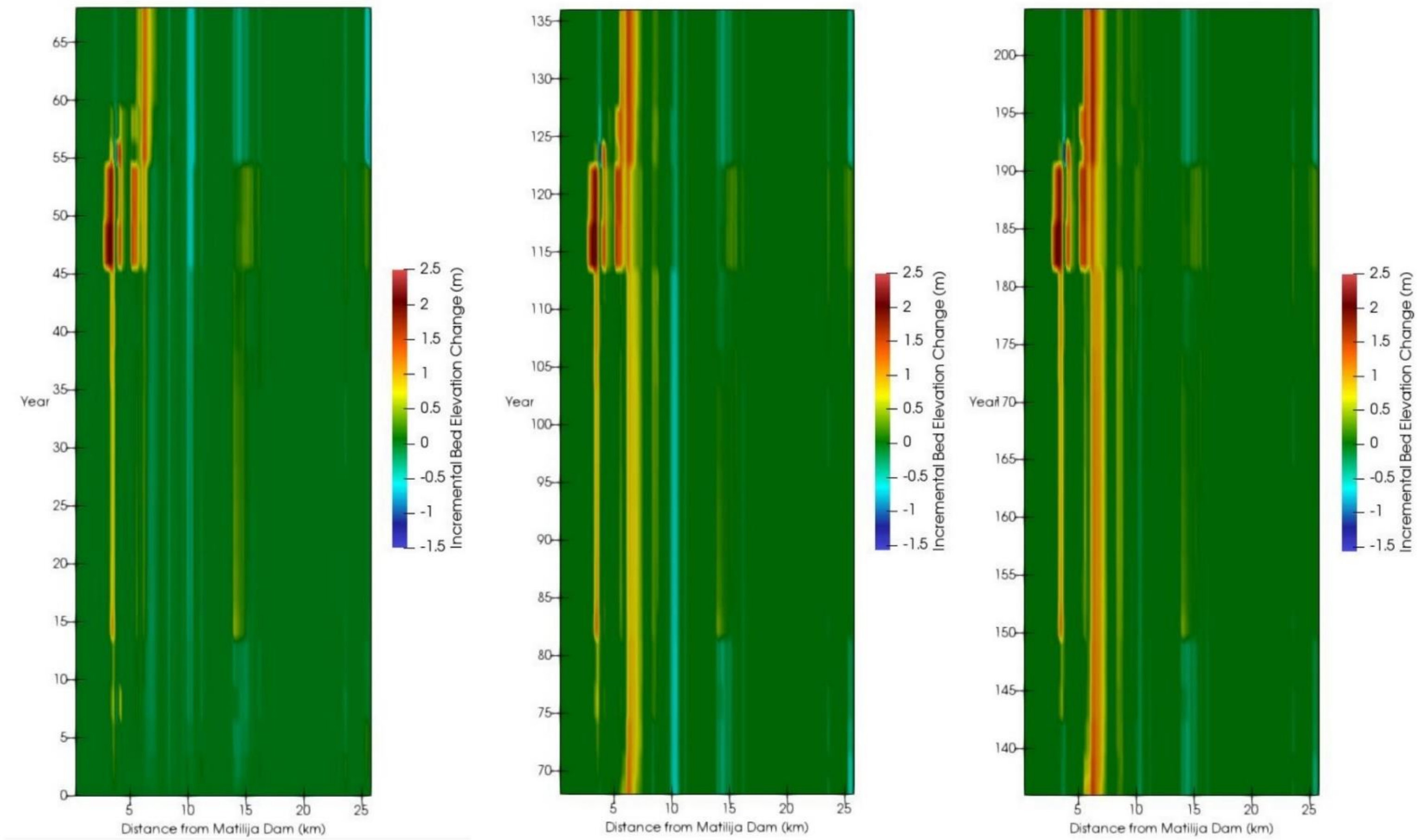

Figure D-5. Simulated change in bed elevation, Run 1e. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

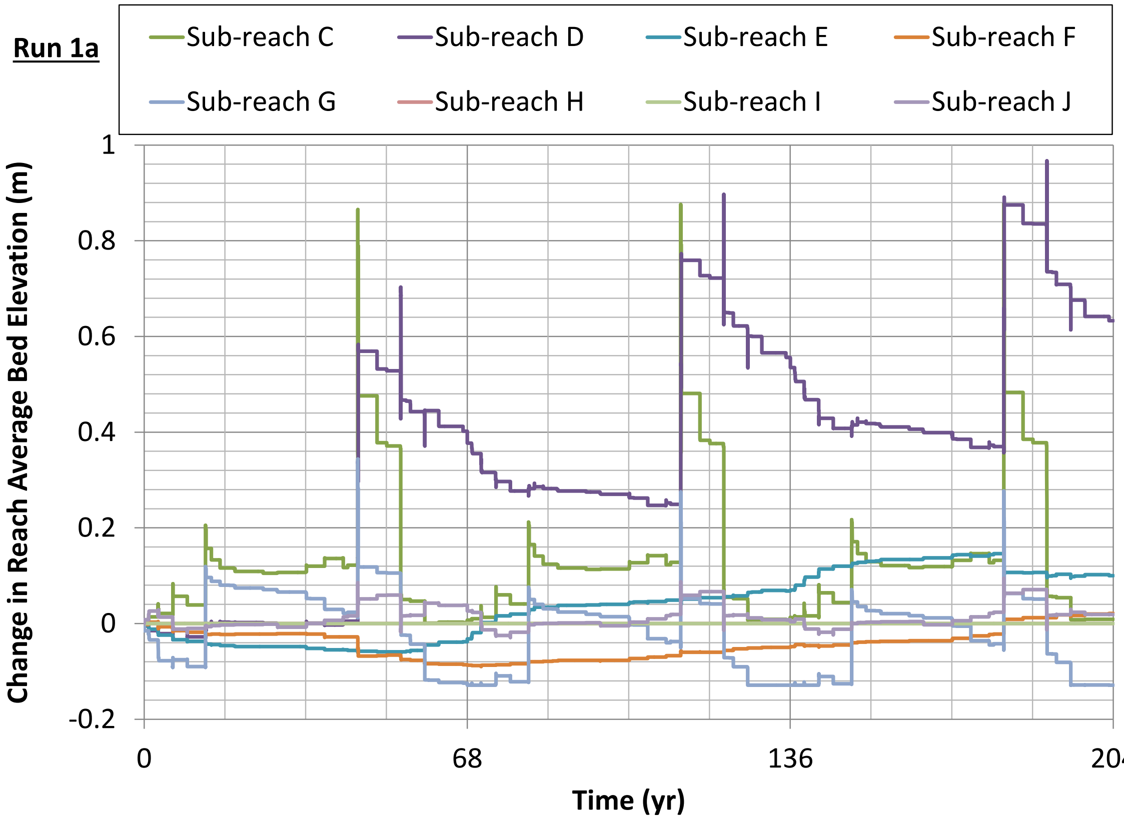

Figure D-6. Simulated change in reach averaged bed elevation in subreaches C-J for Run 1a. Periodic sediment deposition/erosion are predicted to occur in subreaches upstream of Robles Diversion Dam (subreach C, 1.05–3.74 km downstream of Matilija Dam) and downstream of Robles Diversion Dam (subreach D, 3.74–7 km downstream of Matilija Dam). Part of the sediment deposition in the subreach downstream of Robles Diversion Dam seems to be permanent. Other subreaches also experience periodic sediment deposition and erosion, but the magnitude of such deposition and erosion are seen to be relatively small and believe to be within the range of natural conditions. Subreach A is not simulated; subreach B has minimal sediment deposition/erosion.

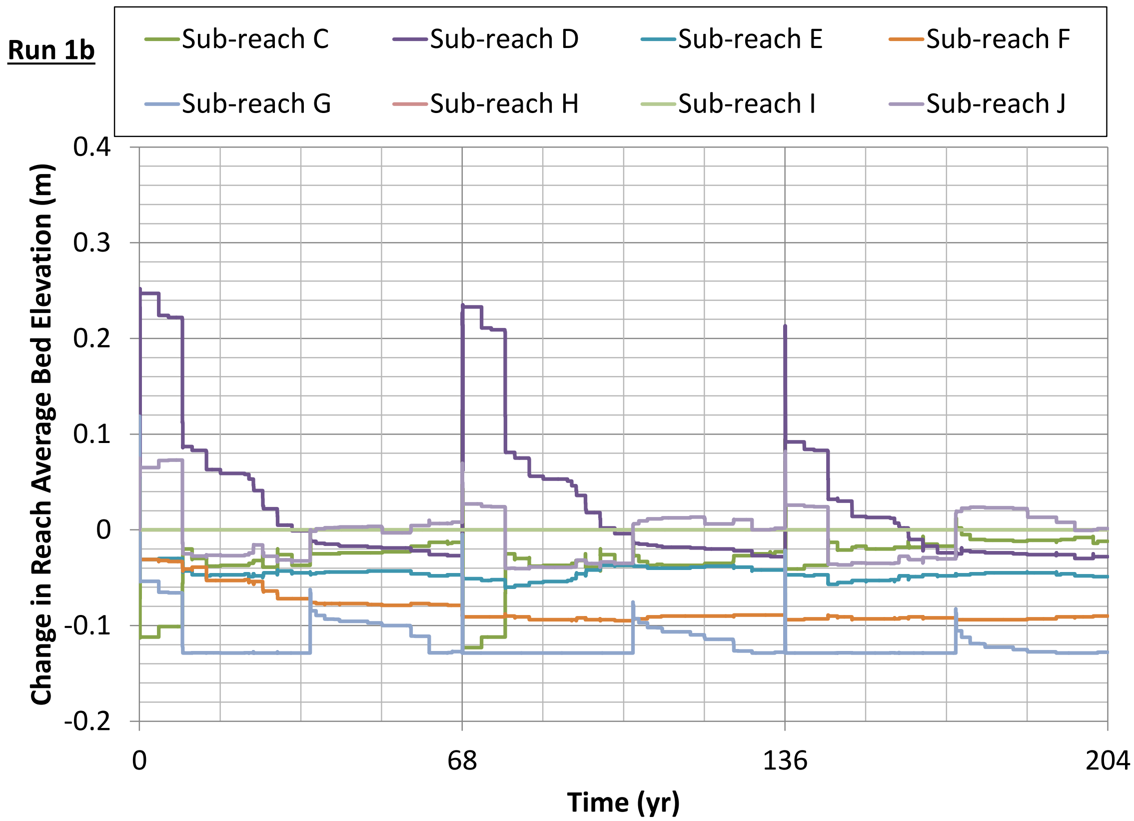

Figure D-7. Simulated change in reach averaged bed elevation for eight subreaches, Run 1b. Periodic sediment deposition/erosion are predicted to occur in subreaches upstream of Robles Diversion Dam (subreach C, 1.05–3.74 km downstream of Matilija Dam) and downstream of Robles Diversion Dam (subreach D, 3.74–7 km downstream of Matilija Dam). Part of the sediment deposition in the subreach downstream of Robles Diversion Dam seems to be permanent. Other subreaches also experience periodic sediment deposition and erosion, but the magnitude of such deposition and erosion are seen to be relatively small and believe to be within the range of natural conditions. Subreach A is not simulated; subreach B has minimal sediment deposition/erosion.

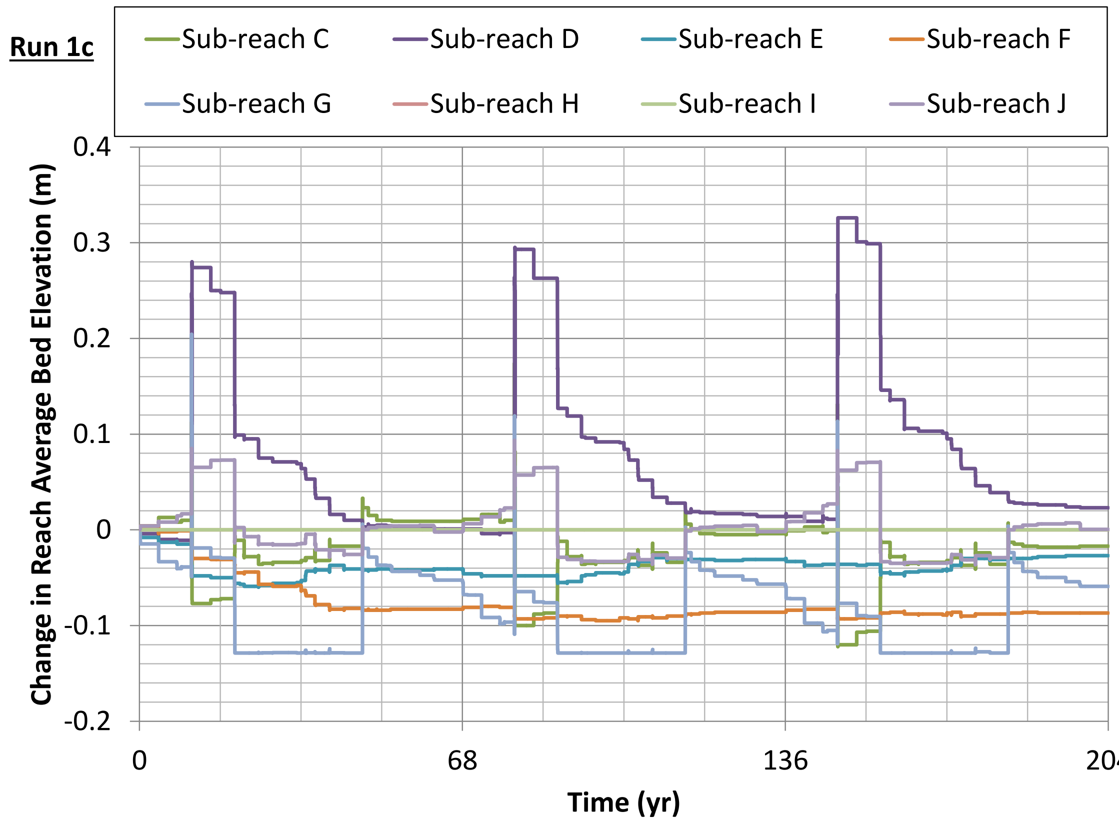

Figure D-8. Simulated change in reach averaged bed elevation for eight subreaches, Run 1c. Periodic sediment deposition/erosion are predicted to occur in subreaches upstream of Robles Diversion Dam (subreach C, 1.05-3.74 km downstream of Matilija Dam) and downstream of Robles Diversion Dam (subreach D, 3.74–7 km downstream of Matilija Dam). Part of the sediment deposition in the subreach downstream of Robles Diversion Dam seems to be permanent. Other subreaches also experience periodic sediment deposition and erosion, but the magnitude of such deposition and erosion are seen to be relatively small and believe to be within the range of natural conditions. Subreach A is not simulated; subreach B has minimal sediment deposition/erosion.

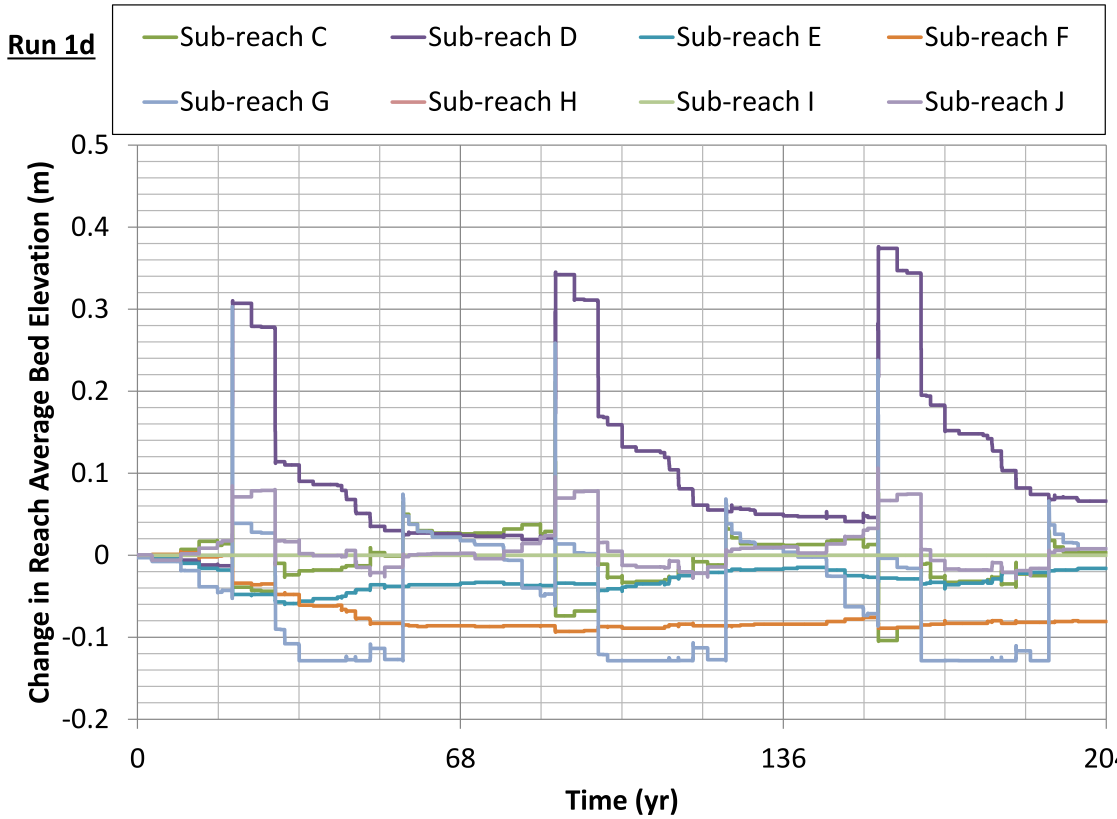

Figure D-9. Simulated change in reach averaged bed elevation for eight subreaches, Run 1d. Periodic sediment deposition/erosion are predicted to occur in subreaches upstream of Robles Diversion Dam (subreach C, 1.05–3.74 km downstream of Matilija Dam) and downstream of Robles Diversion Dam (subreach D, 3.74–7 km downstream of Matilija Dam). Part of the sediment deposition in the subreach downstream of Robles Diversion Dam seems to be permanent. Other subreaches also experience periodic sediment deposition and erosion, but the magnitude of such deposition and erosion are seen to be relatively small and believe to be within the range of natural conditions. Subreach A is not simulated; subreach B has minimal sediment deposition/erosion.

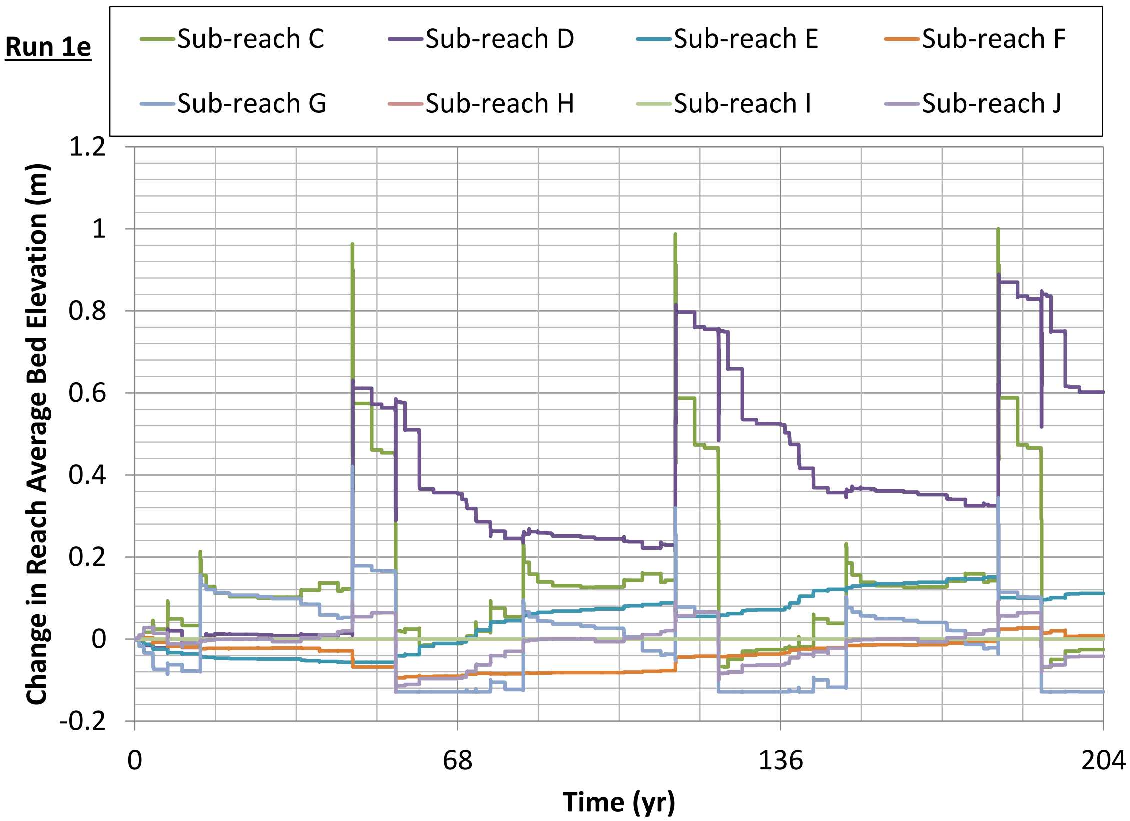

Figure D-10. Simulated change in reach averaged bed elevation for eight subreaches, Run 1e. Periodic sediment deposition/erosion are predicted to occur in subreaches upstream of Robles Diversion Dam (subreach C, 1.05–3.74 km downstream of Matilija Dam) and downstream of Robles Diversion Dam (subreach D, 3.74–7 km downstream of Matilija Dam). Part of the sediment deposition in the subreach downstream of Robles Diversion Dam seems to be permanent. Other subreaches also experience periodic sediment deposition and erosion, but the magnitude of such deposition and erosion are seen to be relatively small and believe to be within the range of natural conditions. Subreach A is not simulated; subreach B has minimal sediment deposition/erosion.

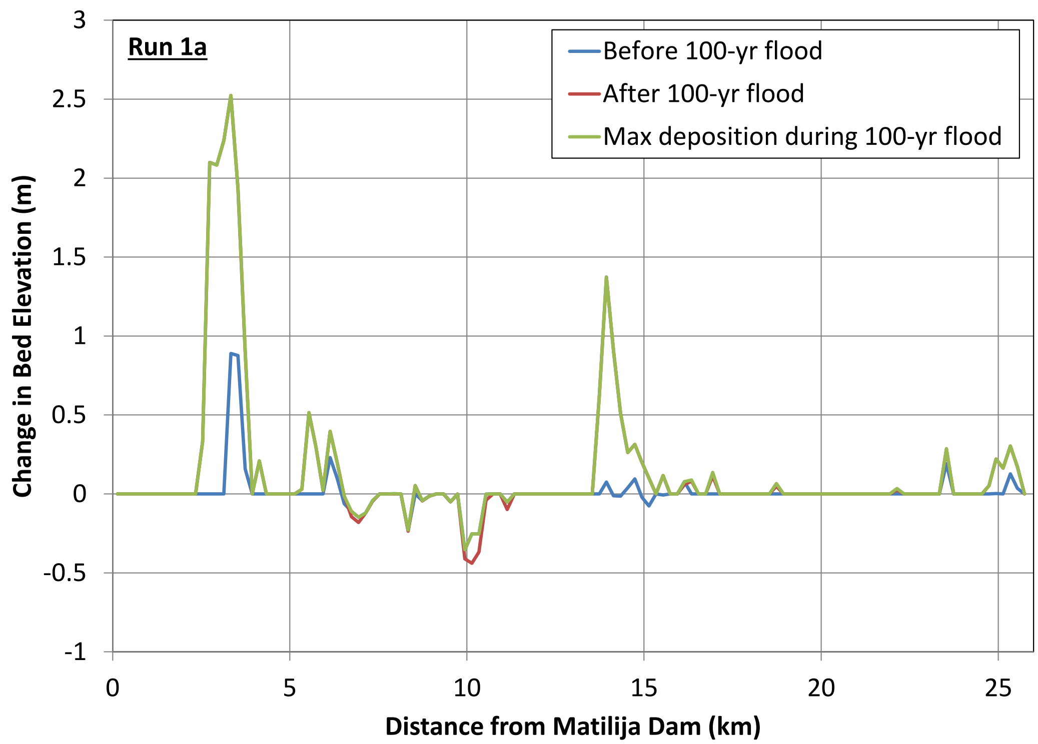

Figure D-11. Simulated change in bed elevation before, after, and during the day of January 1969 flood, which is approximately a 100-year recurrence interval event, Run 1a.

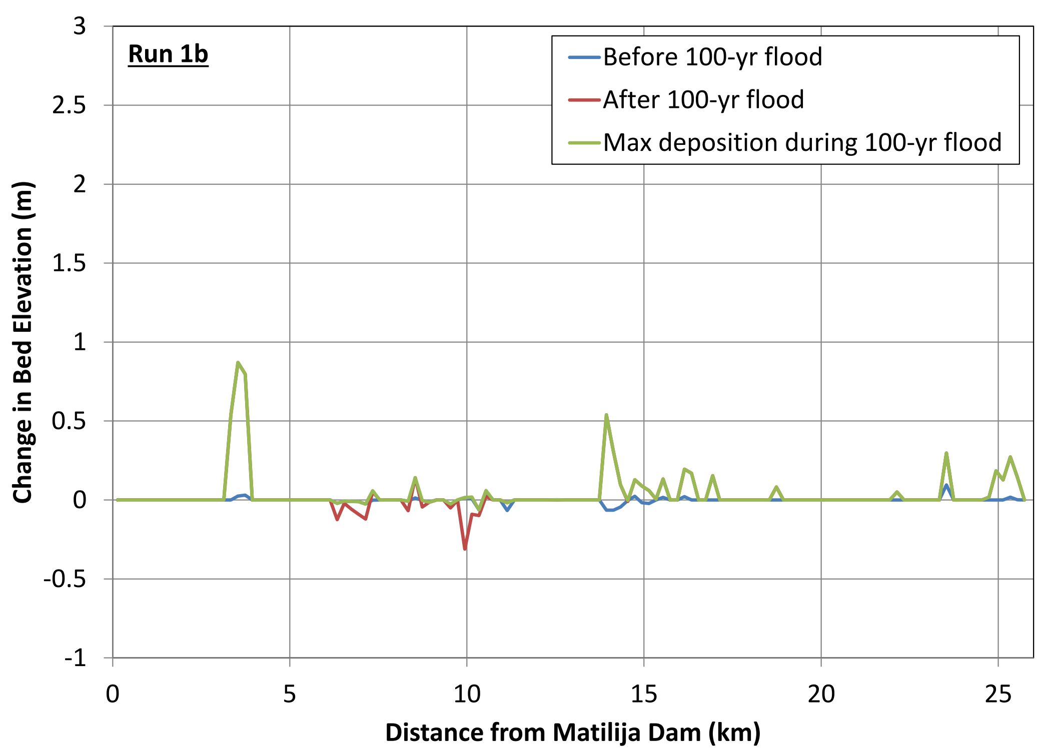

Figure D-12. Simulated change in bed elevation before, after, and during the day of January 1969 flood, which is approximately a 100-year recurrence interval event, Run 1b.

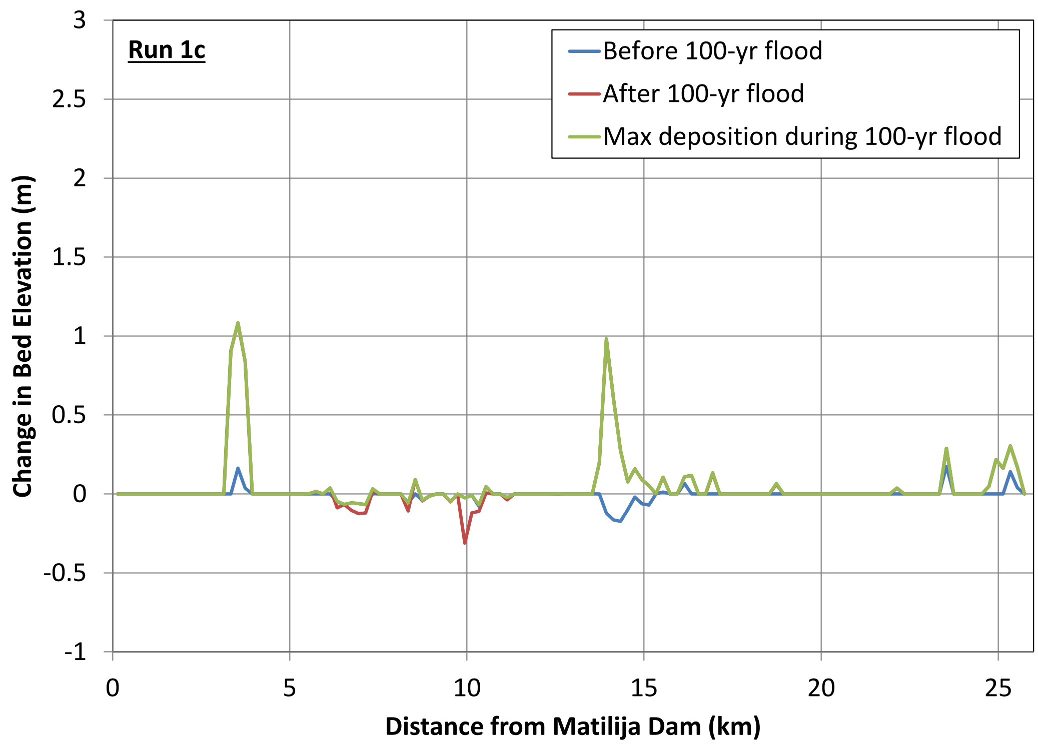

Figure D-13. Simulated change in bed elevation before, after, and during the day of January 1969 flood, which is approximately a 100-year recurrence interval event, Run 1c.

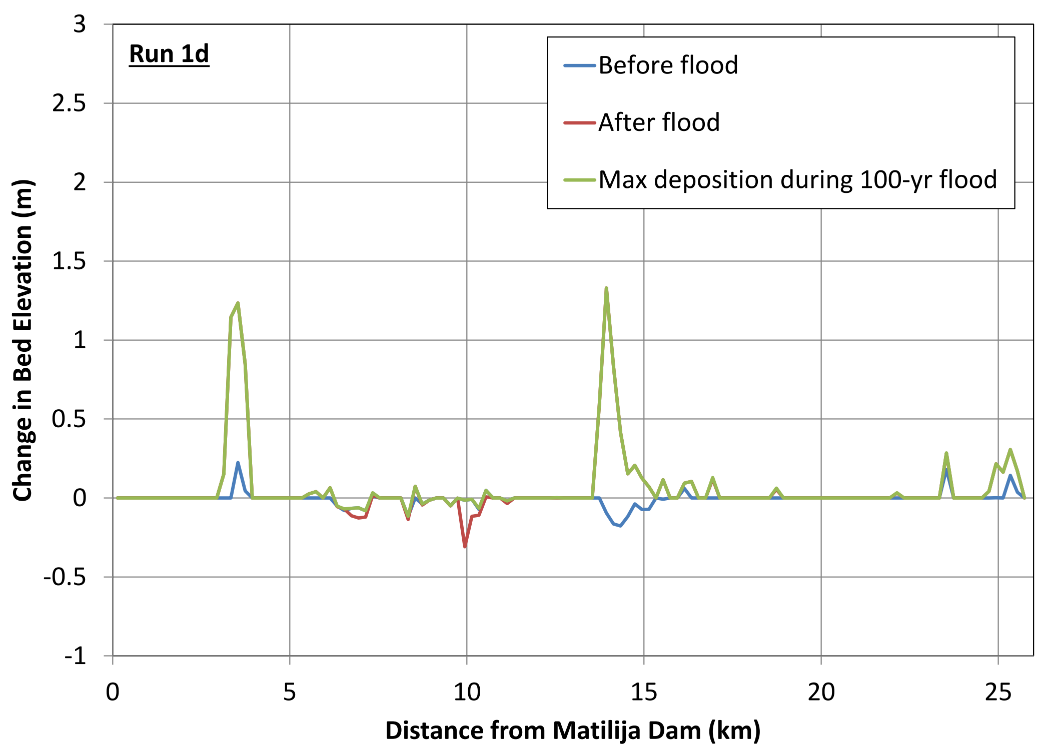

Figure D-14. Simulated change in bed elevation before, after, and during the day of January 1969 flood, which is approximately a 100-year recurrence interval event, Run 1d.

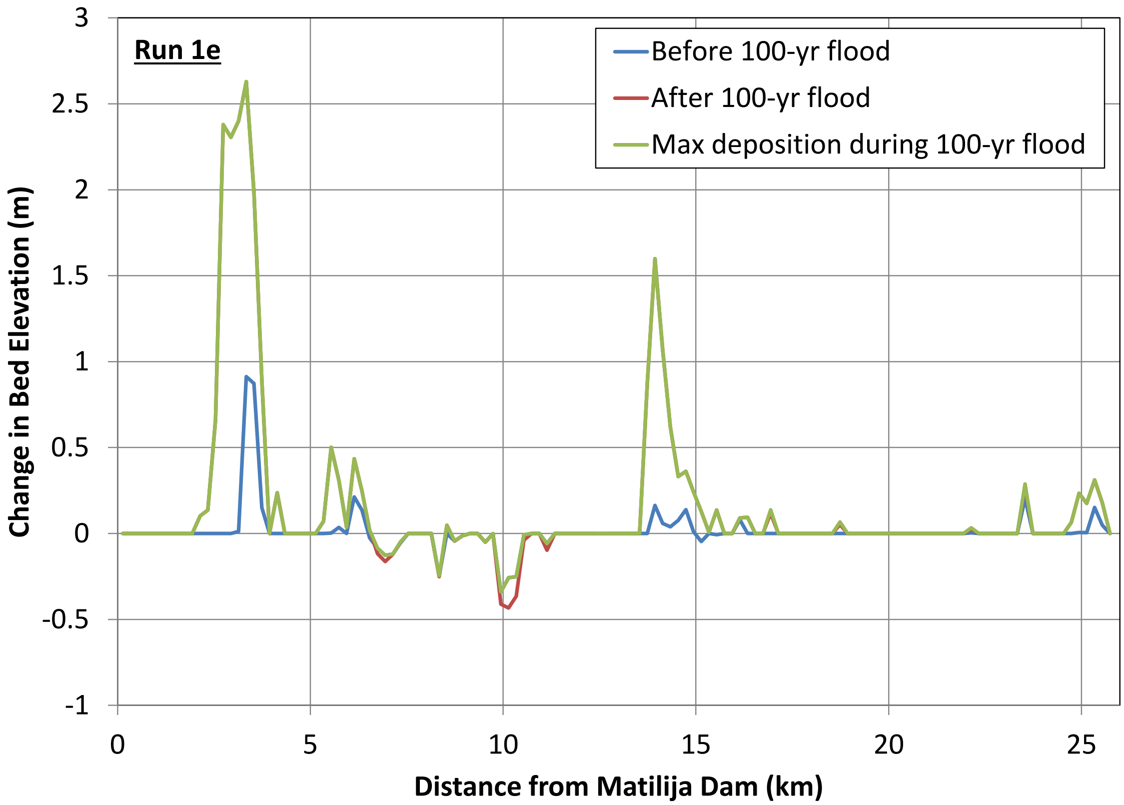

Figure D-15. Simulated change in bed elevation before, after, and during the day of January 1969 flood, which is approximately a 100-year recurrence interval event, Run 1e.

D.2 Future Condition Following Dam Removal

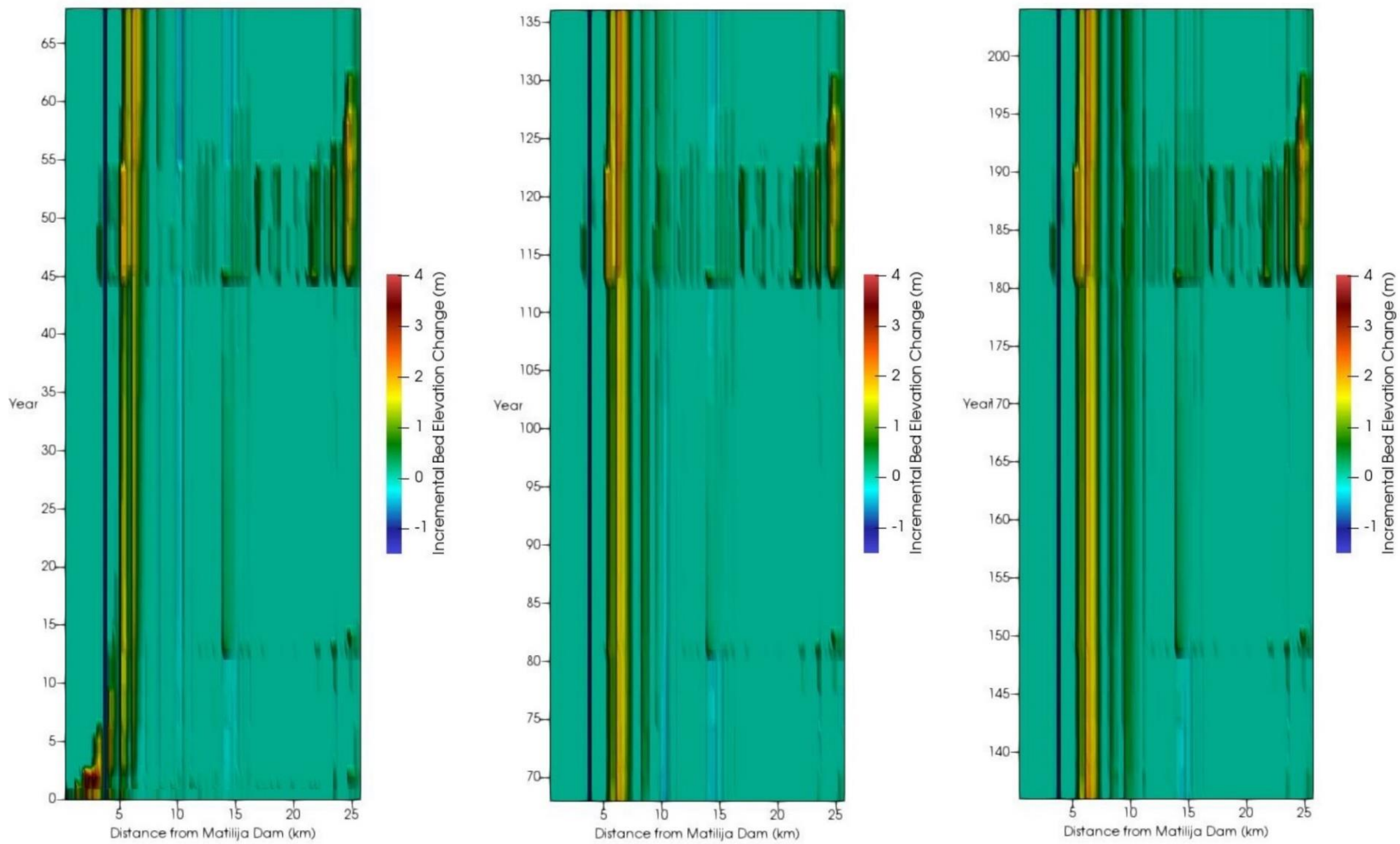

Figure D-16. Simulated change in bed elevation, Run 2a. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

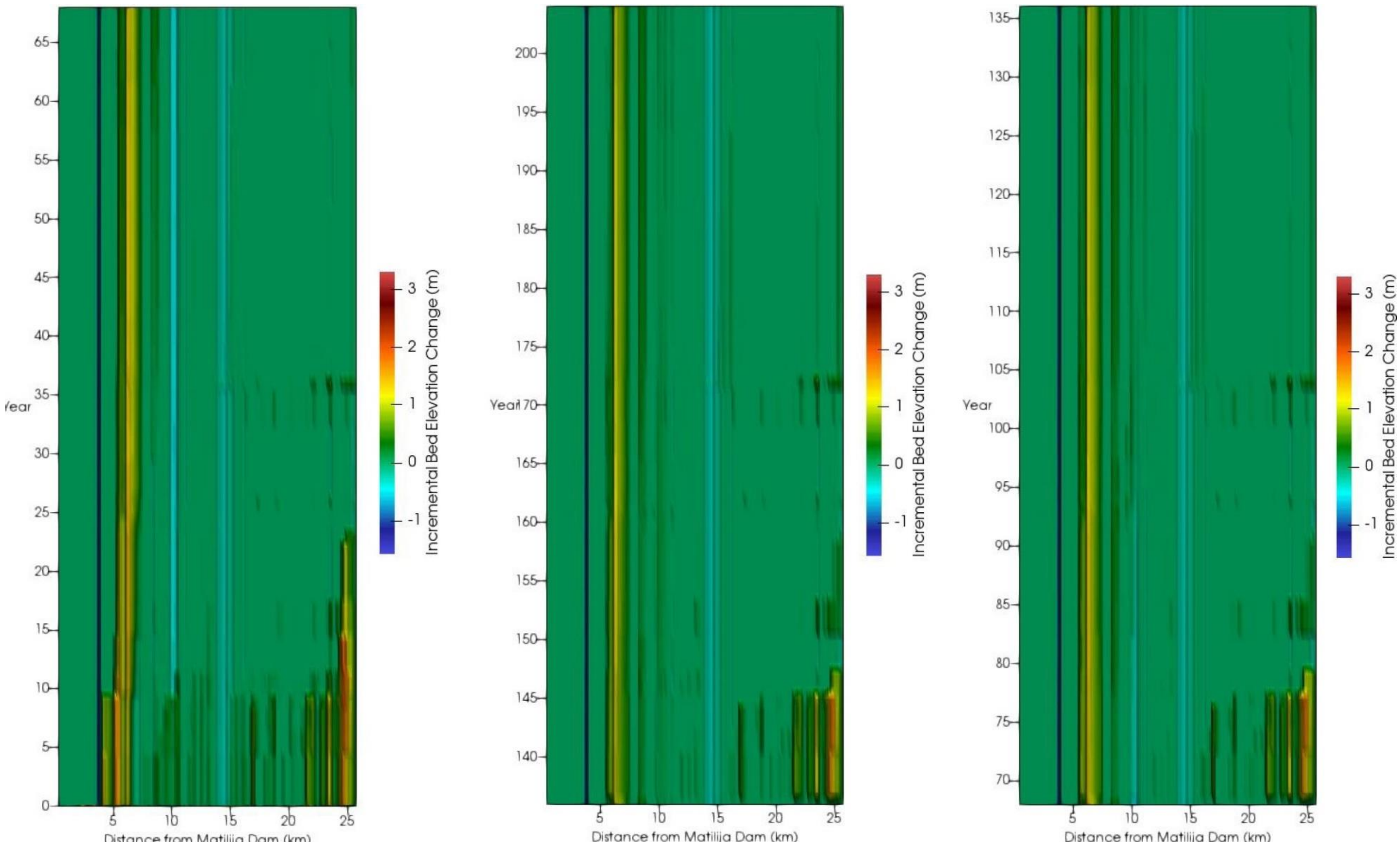

Figure D-17. Simulated change in bed elevation, Run 2b. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

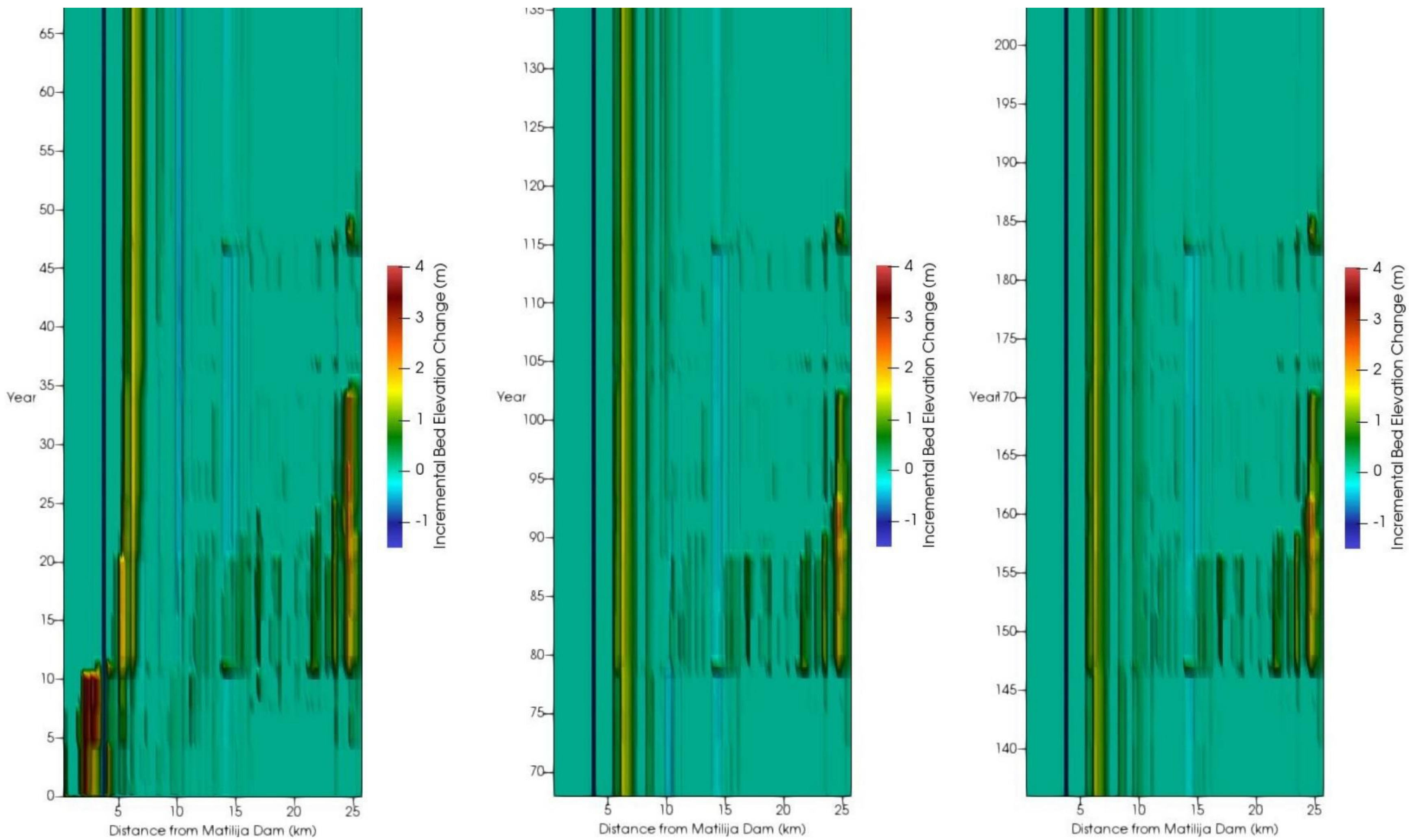

Figure D-18. Simulated change in bed elevation, Run 2c. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

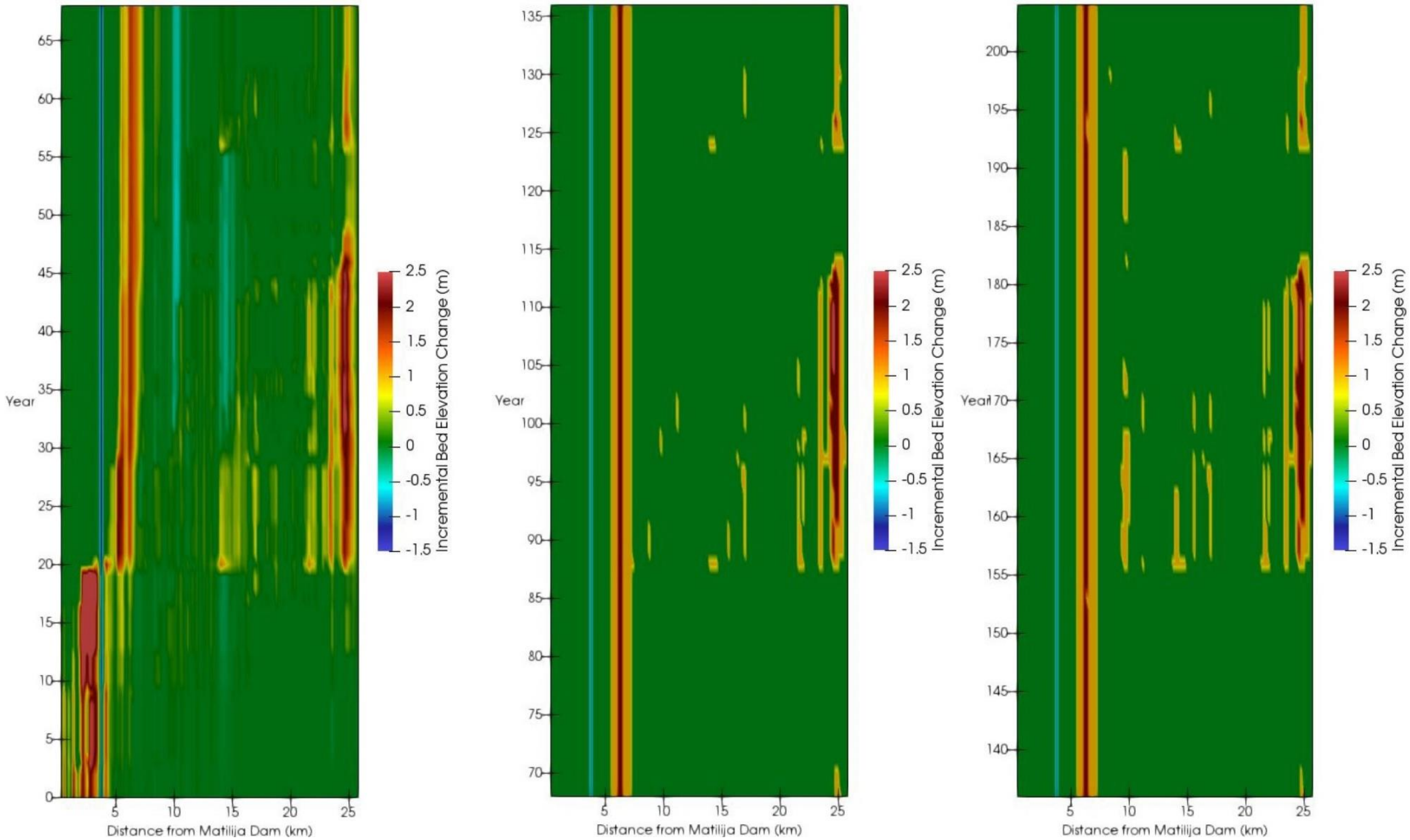

Figure D-19. Simulated change in bed elevation, Run 2d. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

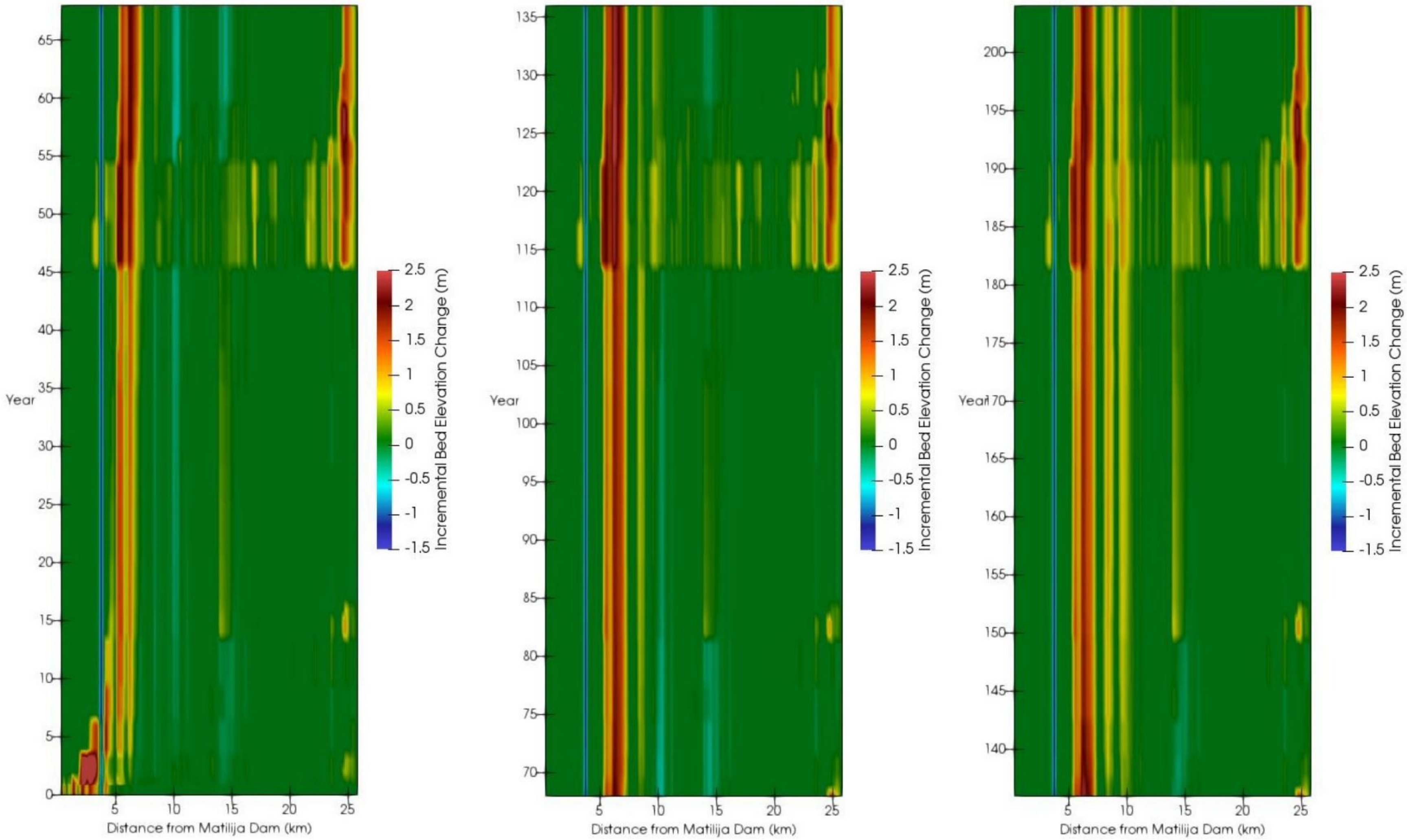

Figure D-20. Simulated change in bed elevation, Run 2e. The horizontal axis is distance from Matilija Dam, in km; vertical axis is time, in years (plates from left to right are continuous, each plate presents 68 years of results).

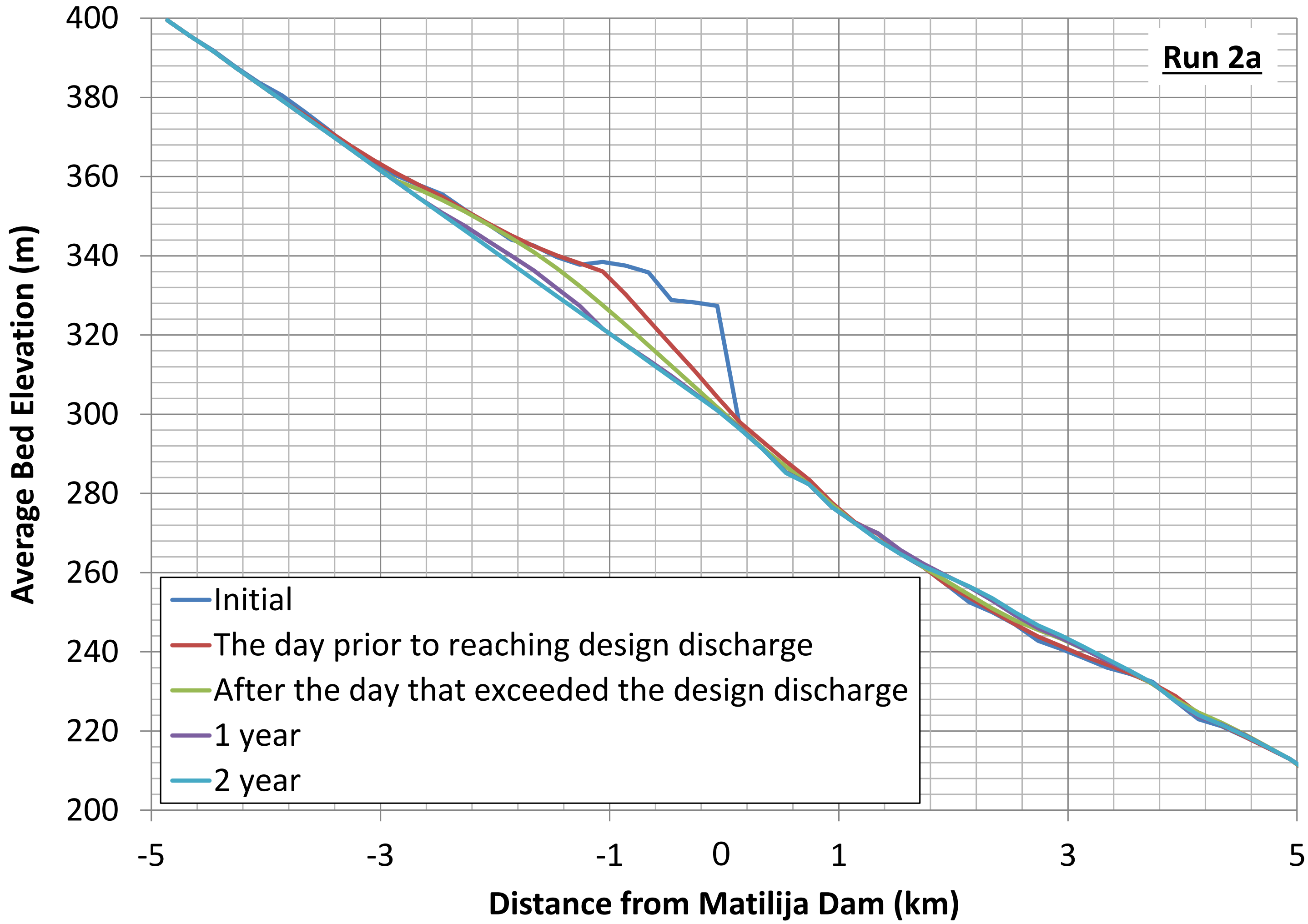

Figure D-21. Simulated bed elevation near Matilija Dam, Run 2a. The highest daily average discharge in Matilija Creek prior to reaching the design discharge was 1,459 cfs. Matilija Creek daily average discharge on the day it reached design discharge was 3,906 cfs, corresponding to a 10.2-year recurrence interval event.

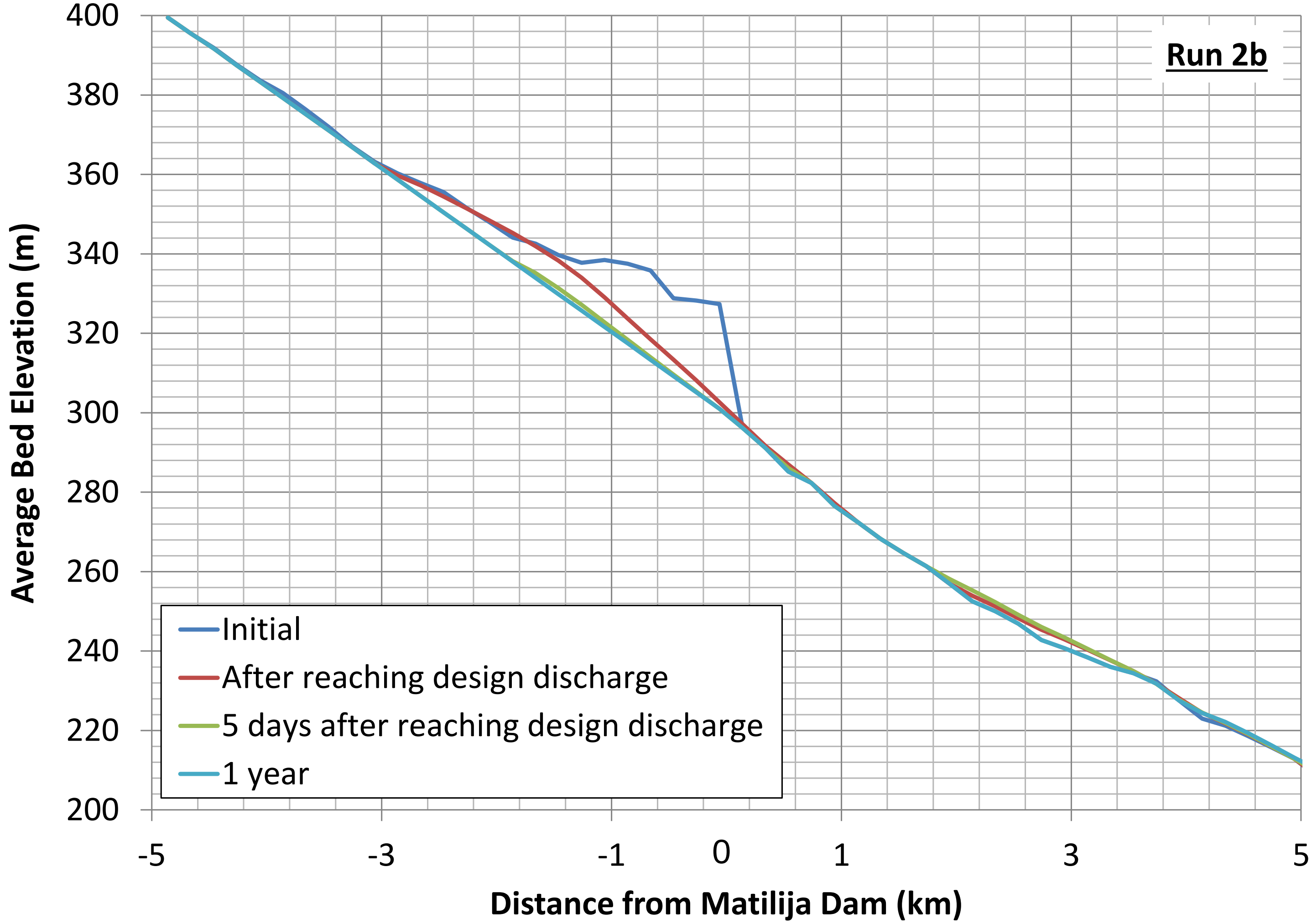

Figure D-22. Simulated bed elevation near Matilija Dam, Run 2b. Matilija Creek daily average discharge on the day it reached design discharge was 3,620 cfs, corresponding to a 10-year recurrence interval event; the largest daily average discharge was 8,340 cfs four days after, which is a close to 100-year event.

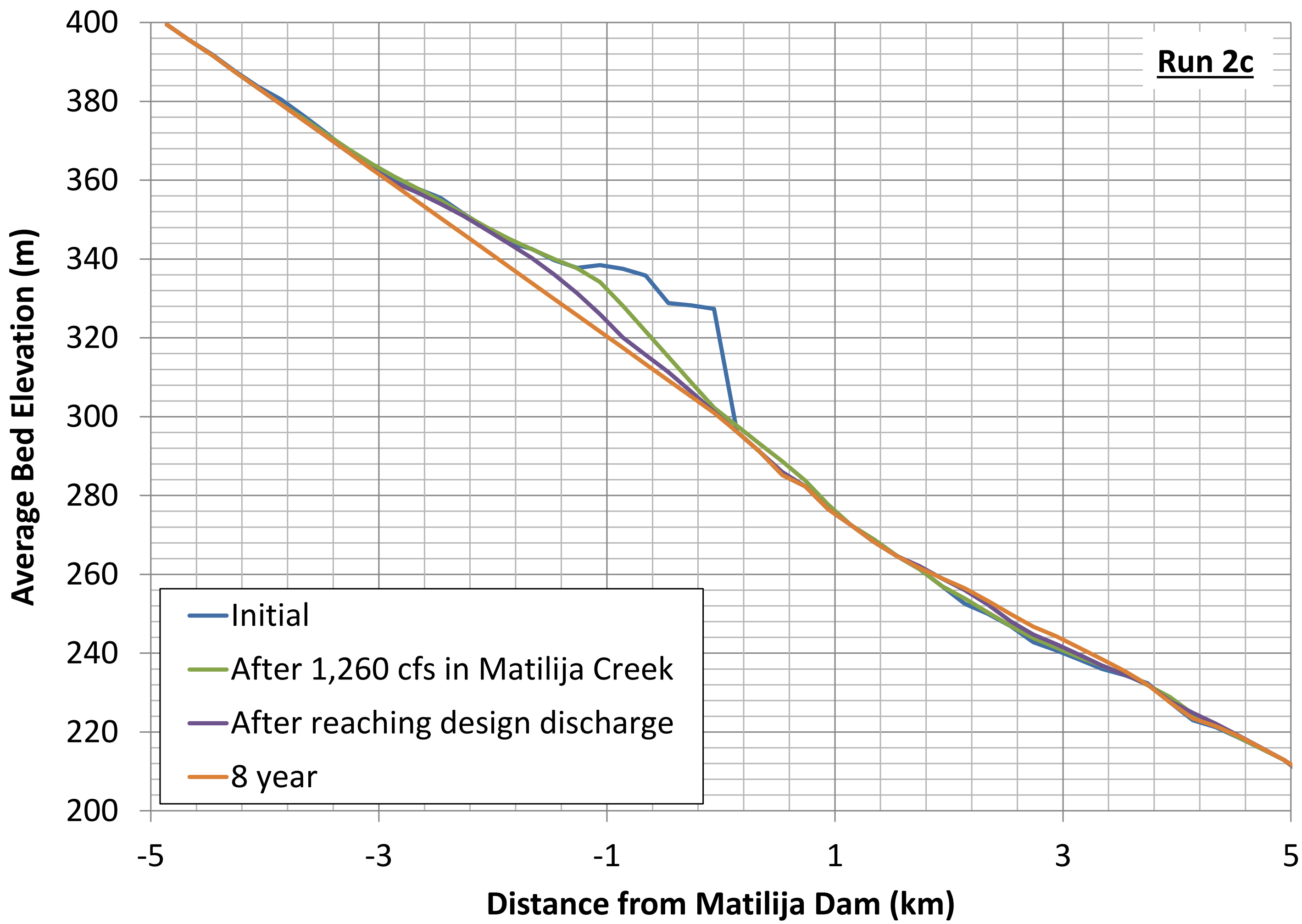

Figure D-23. Simulated bed elevation near Matilija Dam, Run 2c. The first significant event after dam removal is 1,260 cfs in Matilija Creek, which is smaller than the design discharge of 1,700 cfs. The daily average discharge on the day that flows first reach design discharge was 2,390 cfs, corresponding to a 4.4-year recurrence interval event.

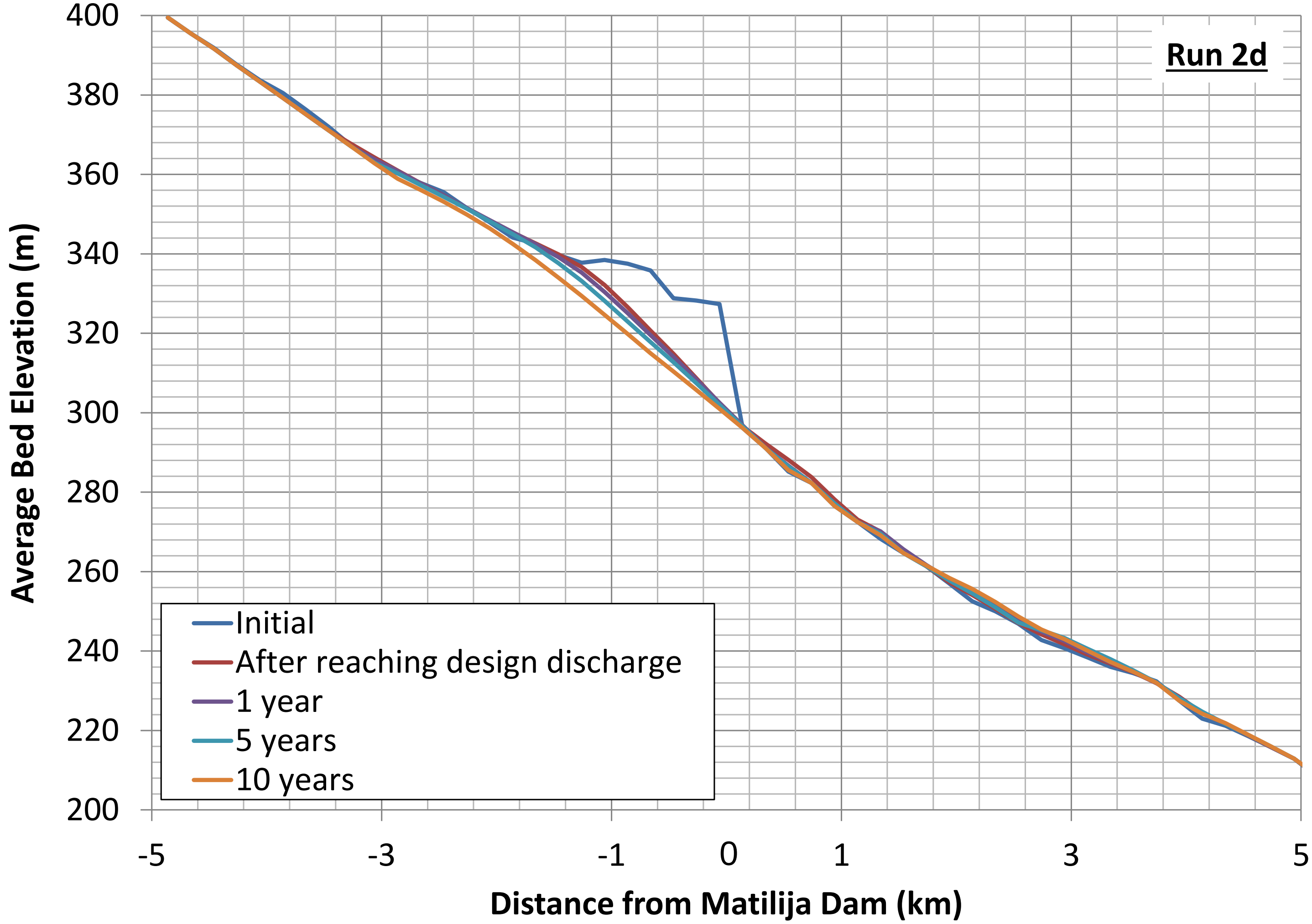

Figure D-24. Simulated bed elevation near Matilija Dam, Run 2d. Matilija Creek daily average discharge on the day it reached design discharge was 2,120 cfs, corresponding to a 4.2-year recurrence interval event.

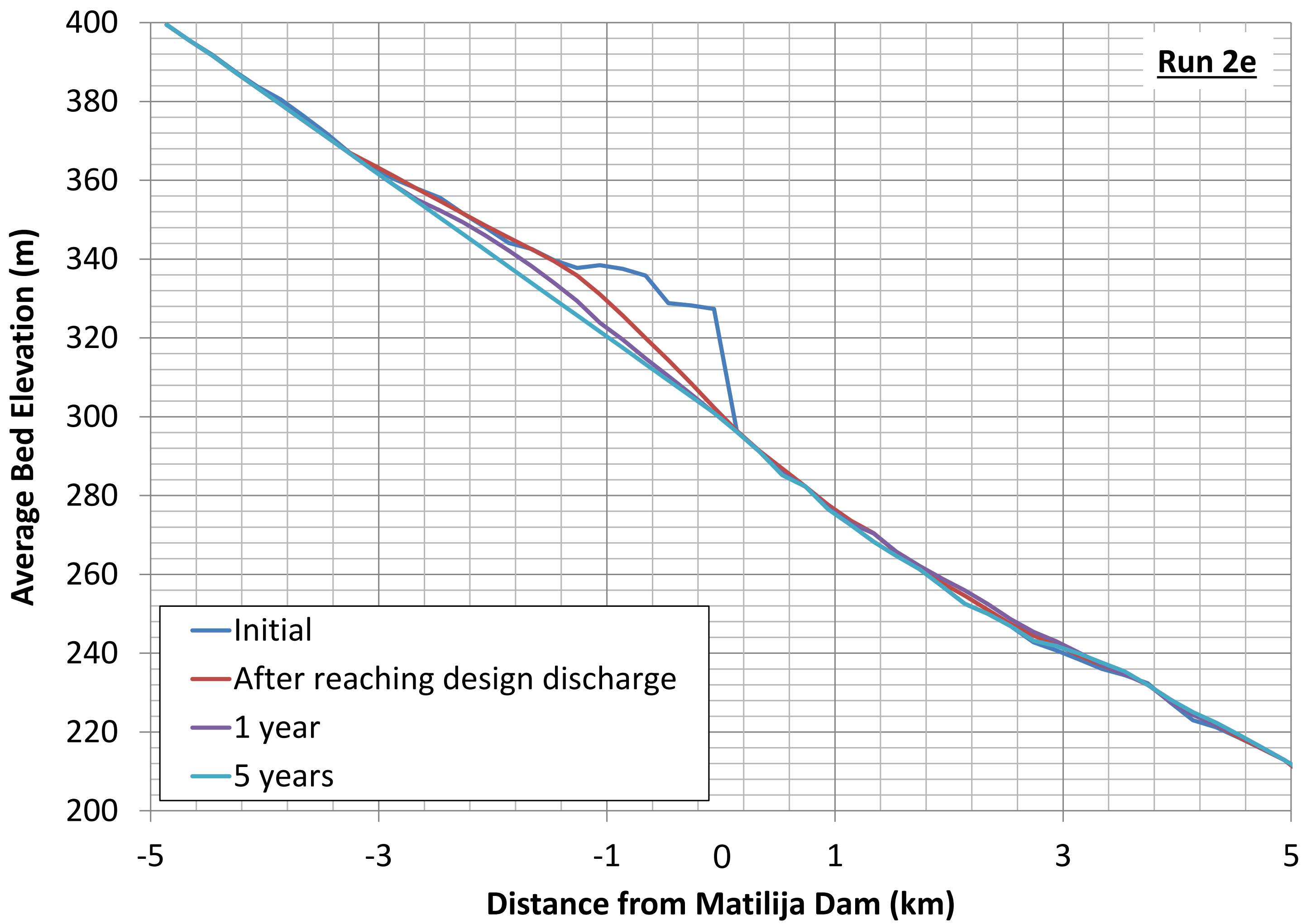

Figure D-25. Simulated bed elevation near Matilija Dam, Run 2e. Matilija Creek daily average discharge on the day it reached design discharge was 1,720 cfs, corresponding to a 3.7-year recurrence interval event.

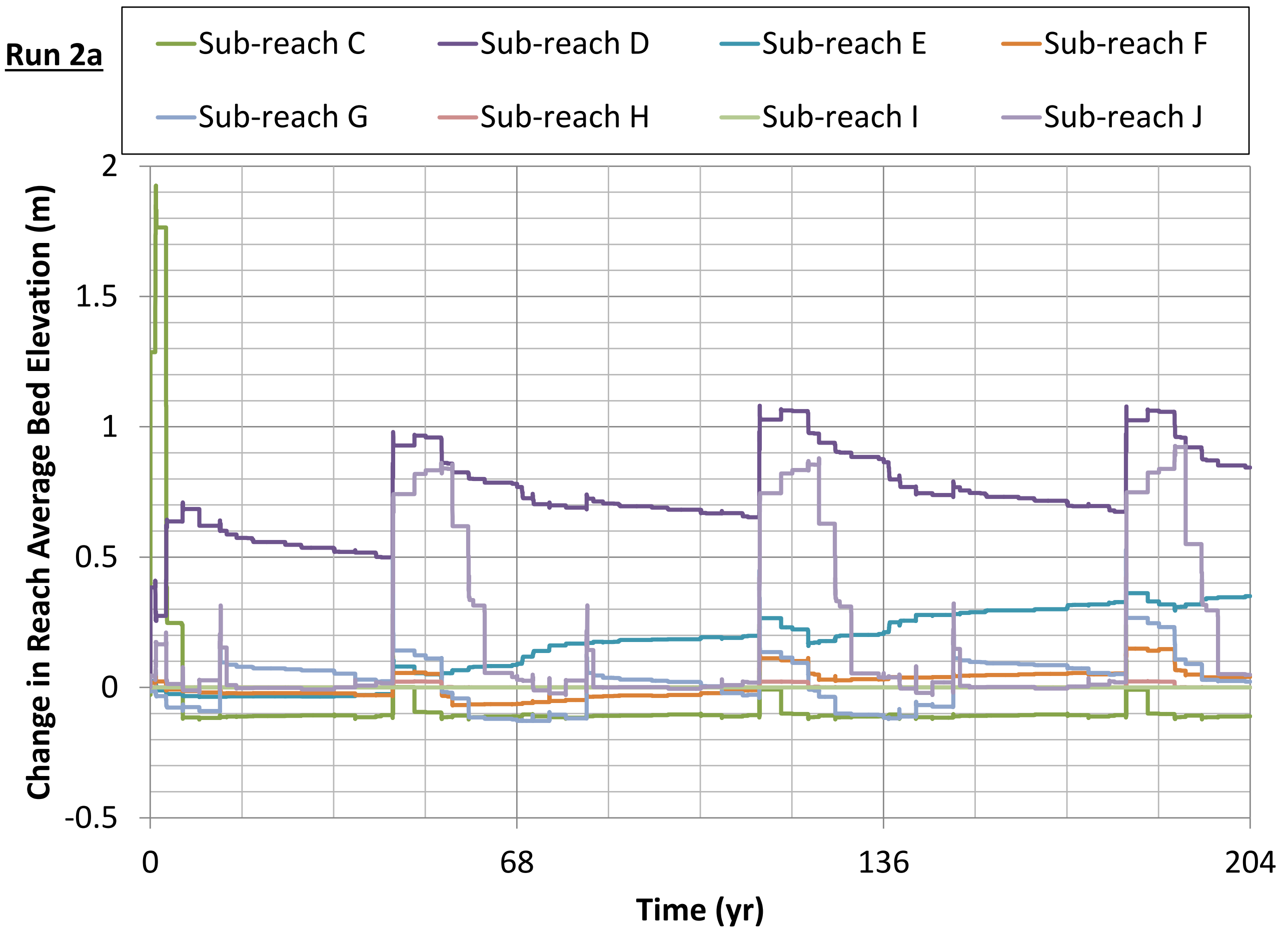

Figure D-26 Simulated change in reach averaged bed elevation, Run 2a. Comparing with the corresponding case without dam removal (i.e., Run 1a), less sediment deposition is predicted upstream of Robles Diversion Dam (subreach C) except during the first few years following dam removal, but more is predicted downstream of Robles Diversion Dam (subreach D) and near the river mouth (subreach J). There is also increased sediment deposition in subreach E over time, although the increase is likely within the discernable resolution of the model for the next 50 years. Subreaches A and B are not presented because they do not show up well in the scale presented and are presented in other formats.

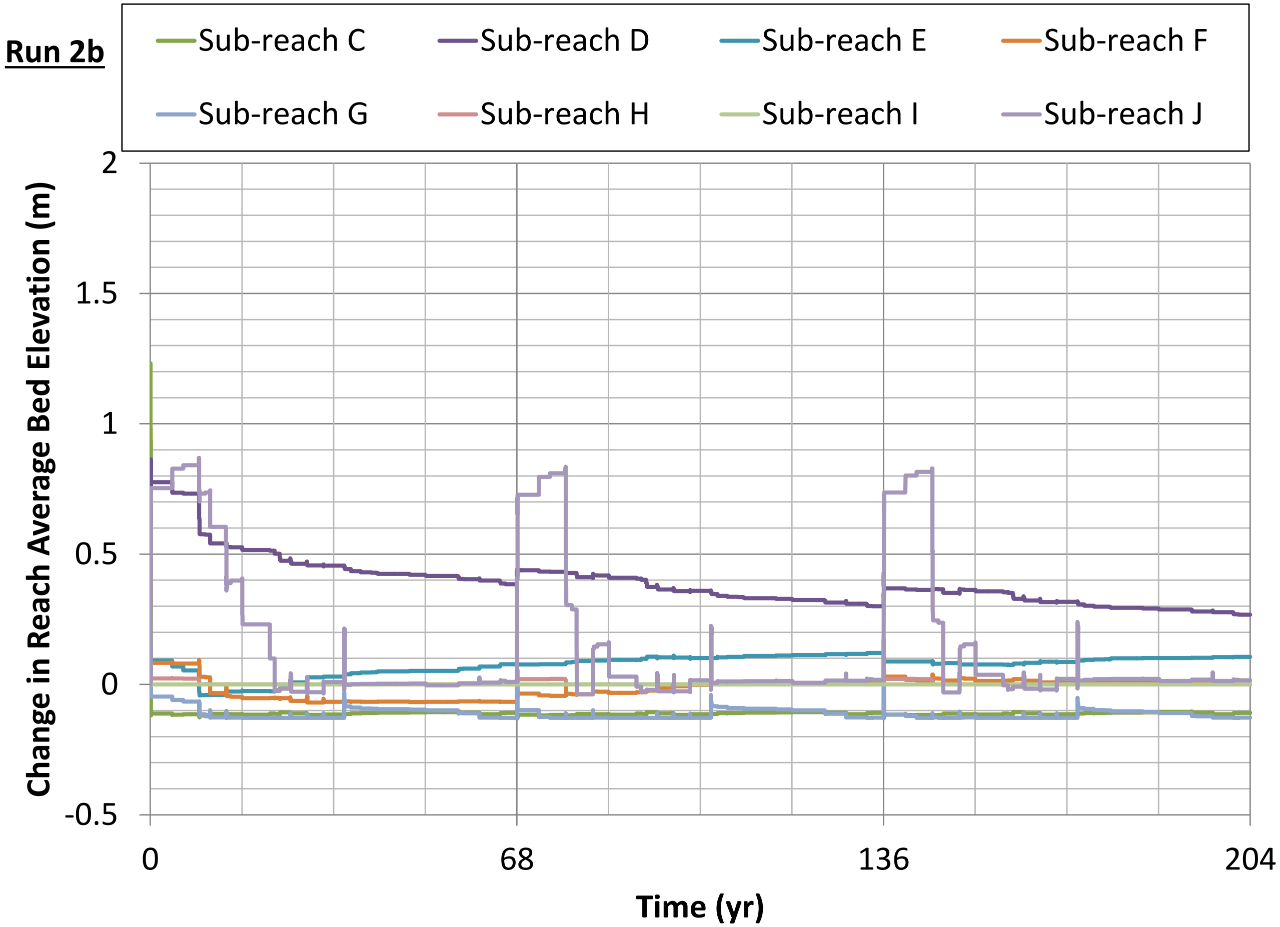

Figure D-27. Simulated change in reach averaged bed elevation, Run 2b. Comparing with the corresponding case without dam removal (i.e., Run 1b), less sediment deposition is predicted upstream of Robles Diversion Dam (subreach C) except during the first few years following dam removal, but more is predicted downstream of Robles Diversion Dam (subreach D) and near the river mouth (subreach J). There is also increased sediment deposition in subreach E over time, although the increase is likely within the discernable resolution of the model for the next 50 years. Subreaches A and B are not presented because they do not show up well in the scale presented and are presented in other formats.

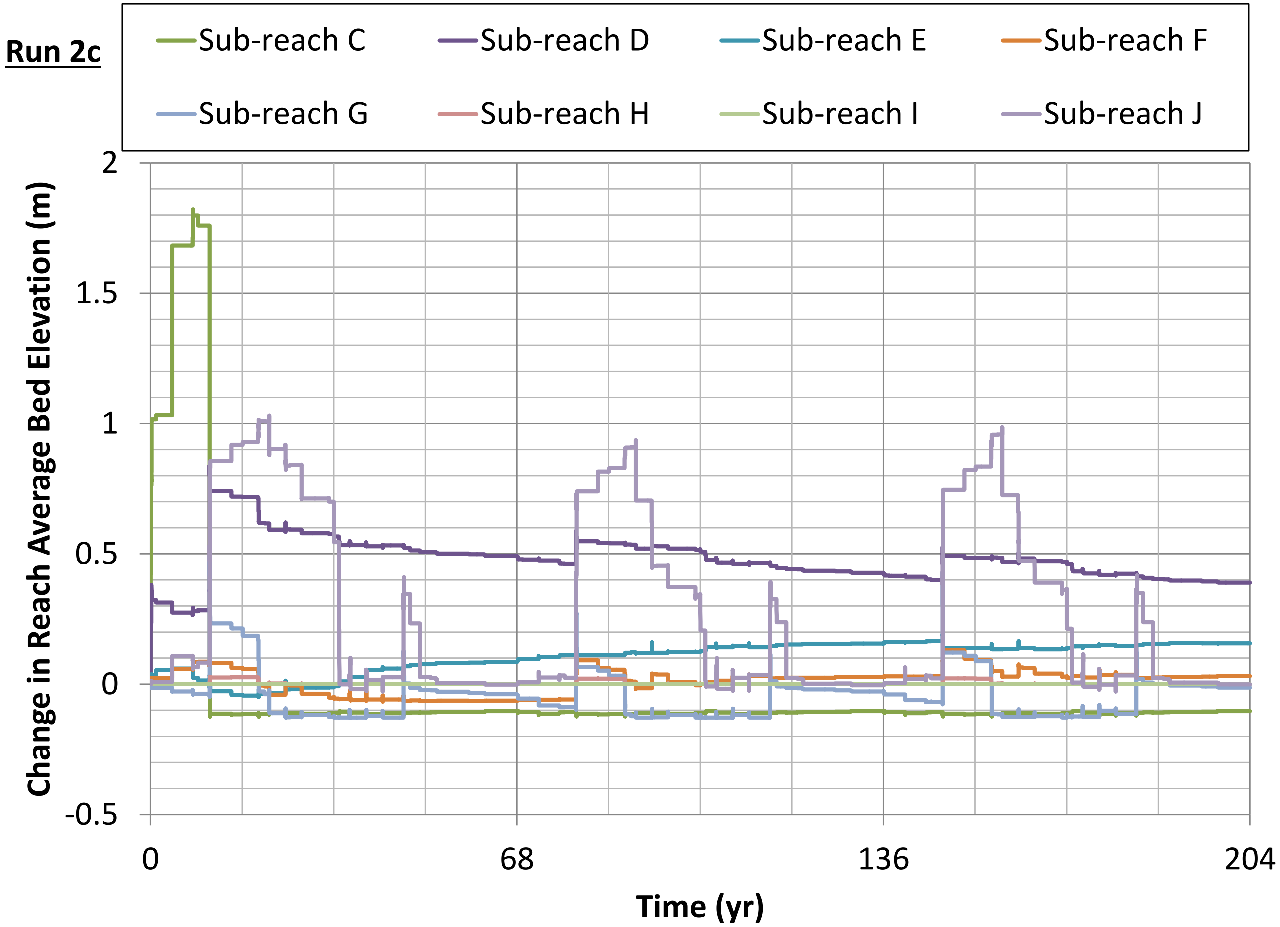

Figure D-28. Simulated change in reach averaged bed elevation, Run 2c. Comparing with the corresponding case without dam removal (i.e., Run 1c), less sediment deposition is predicted upstream of Robles Diversion Dam (subreach C) except during the first few years following dam removal, but more is predicted downstream of Robles Diversion Dam (subreach D) and near the river mouth (subreach). There is also increased sediment deposition in subreach E over time, although the increase is likely within the discernable resolution of the model for the next 50 years. Subreaches A and B are not presented because they do not show up well in the scale presented and are presented in other formats.

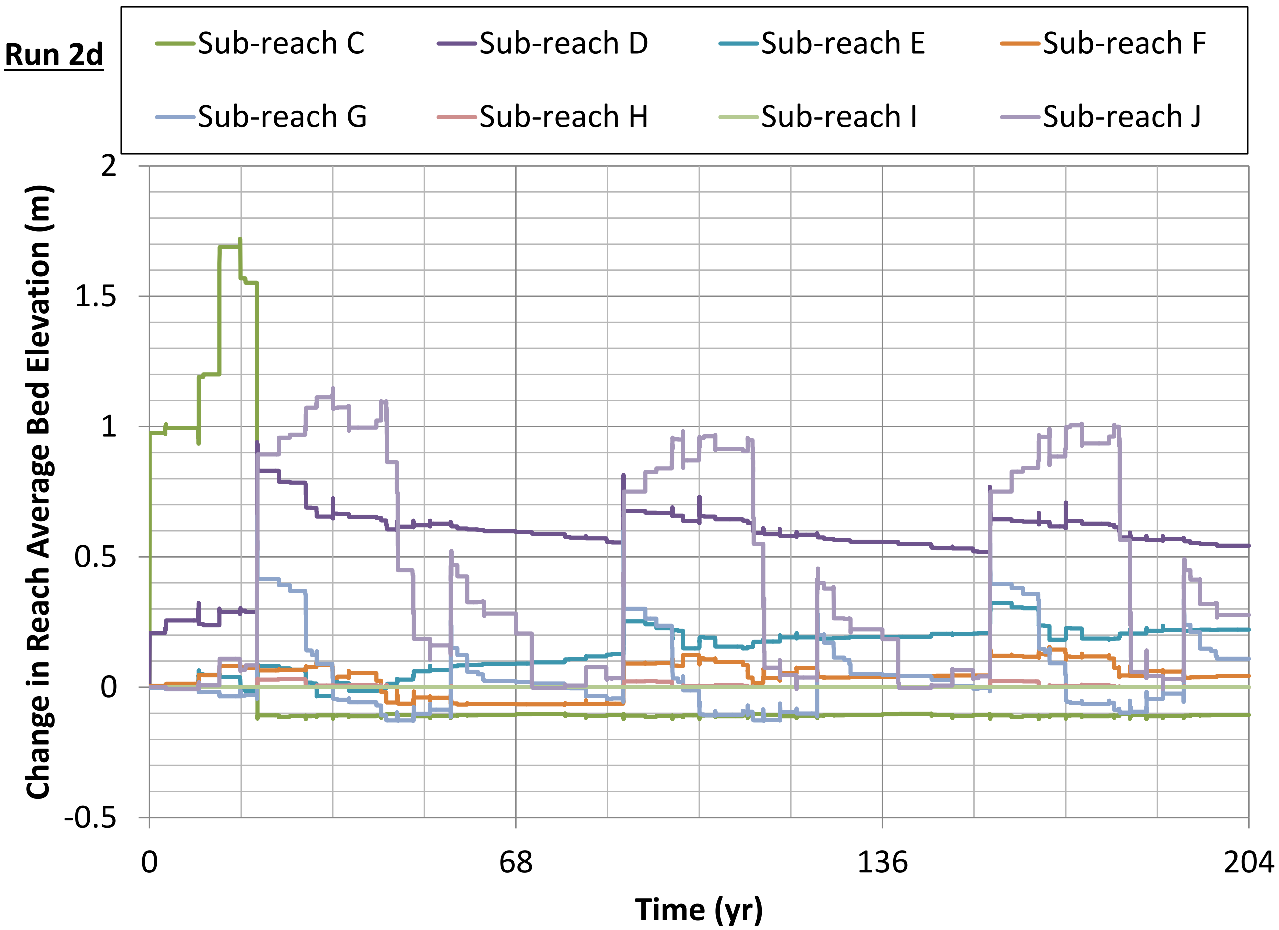

Figure D-29. Simulated change in reach averaged bed elevation, Run 2d. Comparing with the corresponding case without dam removal (i.e., Run 1d), less sediment deposition is predicted upstream of Robles Diversion Dam (subreach C) except during the first few years following dam removal, but more is predicted downstream of Robles Diversion Dam (subreach D) and near the river mouth (subreach J). There is also increased sediment deposition in subreach E over time, although the increase is likely within the discernable resolution of the model for the next 50 years. Subreaches A and B are not presented because they do not show up well in the scale presented and are presented in other formats.

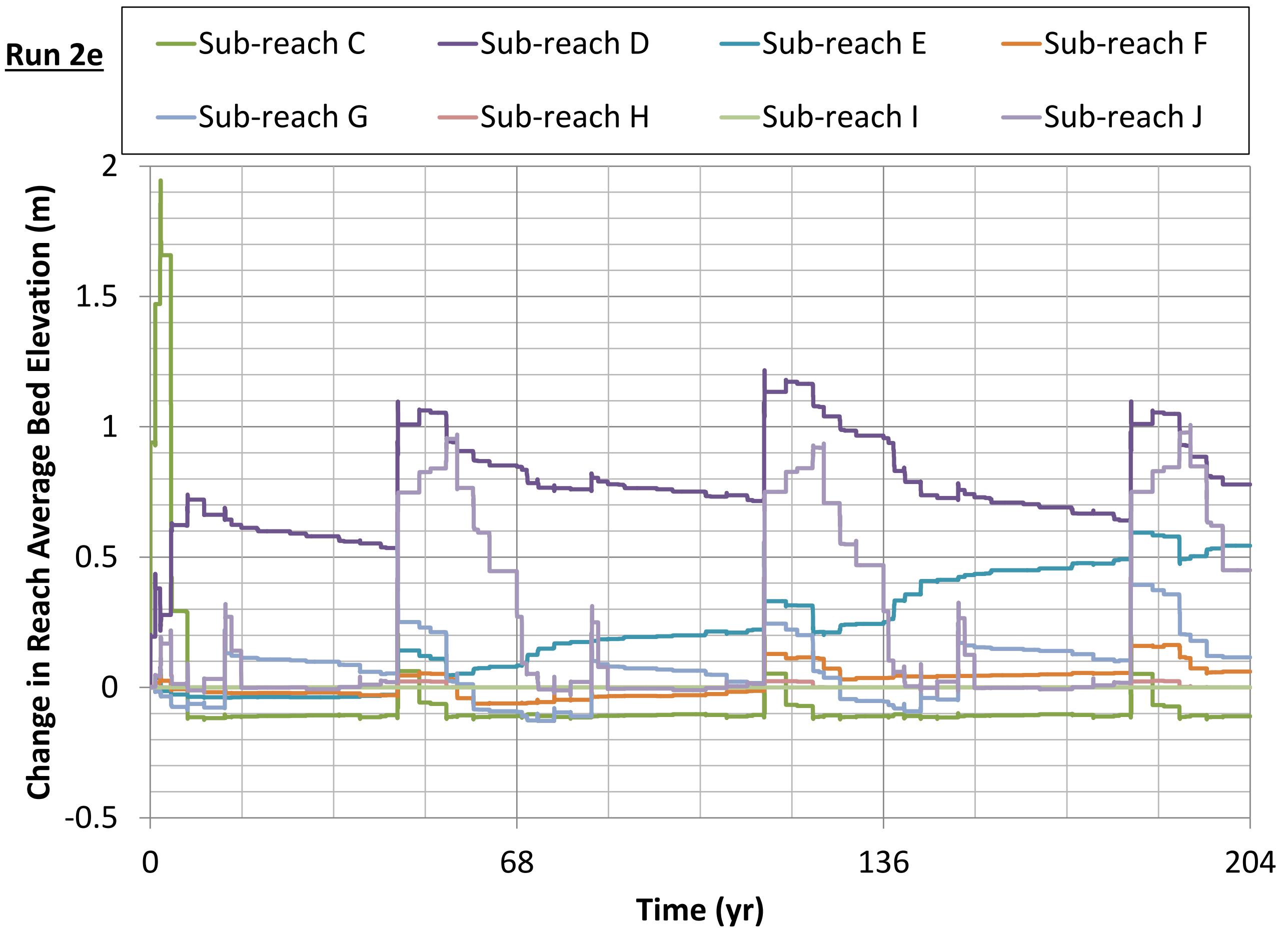

Figure D-30. Simulated change in reach averaged bed elevation, Run 2e. Comparing with the corresponding case without dam removal (i.e., Run 1e), less sediment deposition is predicted upstream of Robles Diversion Dam (subreach C) except during the first few years following dam removal, but more is predicted downstream of Robles Diversion Dam (subreach D) and near the river mouth (subreach J). There is also increased sediment deposition in subreach E over time, although the increase is likely within the discernable resolution of the model for the next 50 years. subreaches A and B are presented because they do not show up well in the scale presented and are presented in other formats.

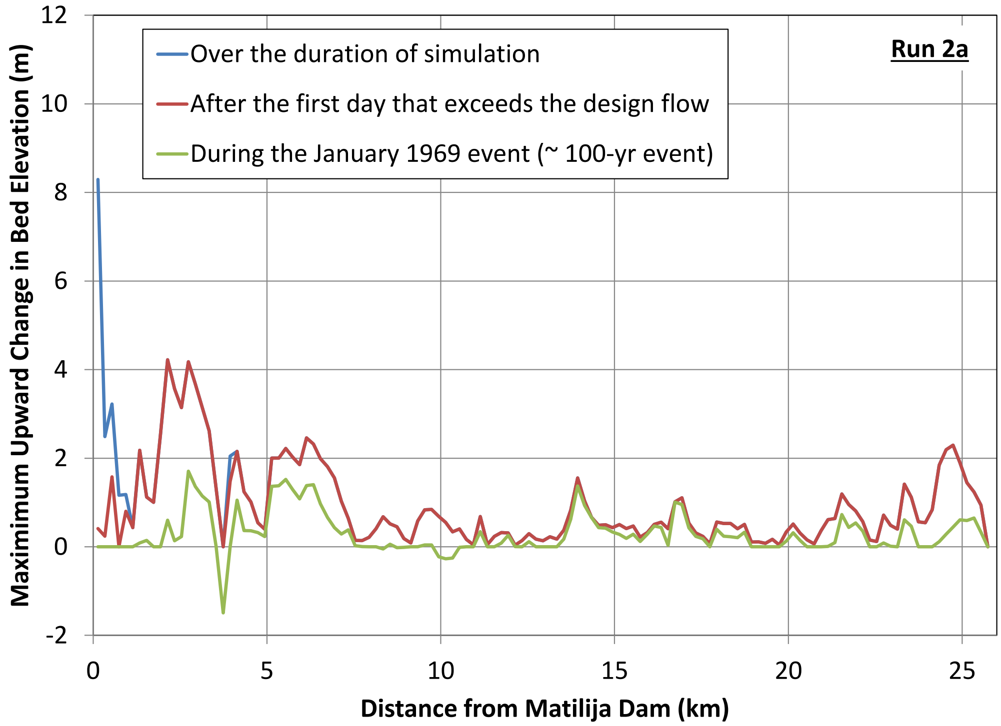

Figure D-31. Simulated maximum change in bed elevation during different periods of time, Run 2a.

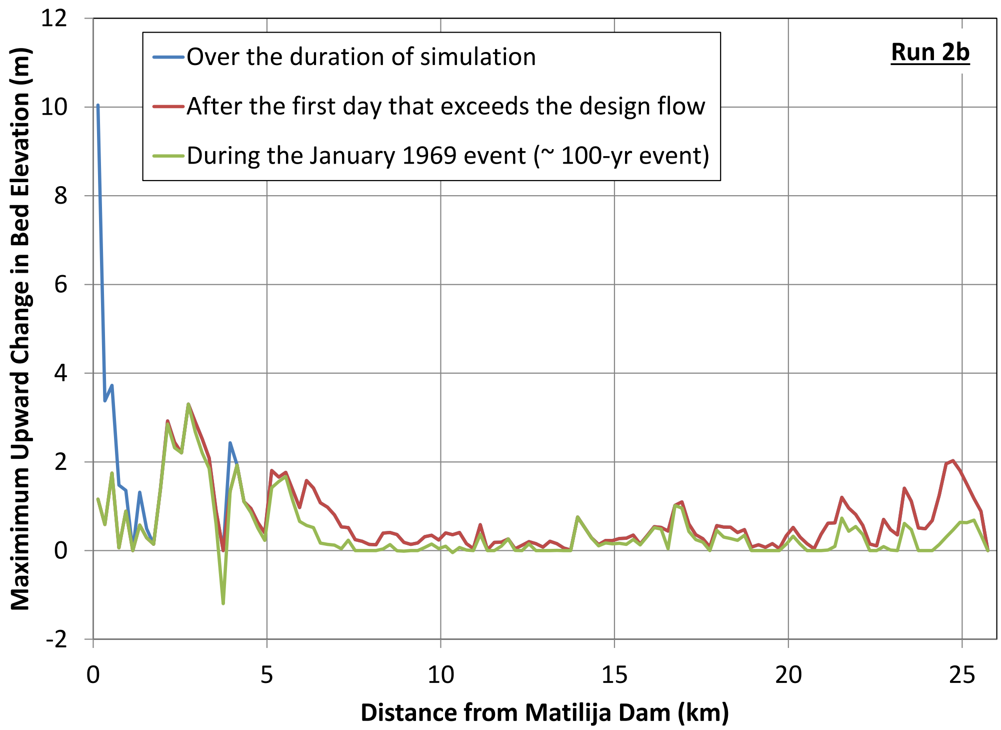

Figure D-32. Simulated maximum change in bed elevation during different periods of time, Run 2b.

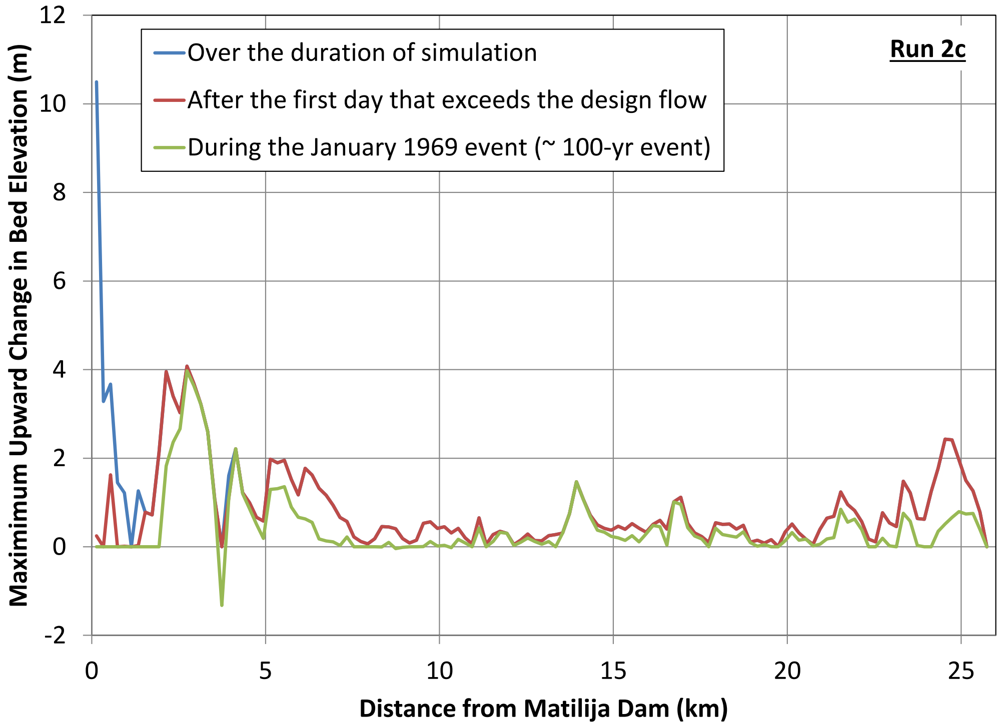

Figure D-33. Simulated maximum change in bed elevation during different periods of time, Run 2c.

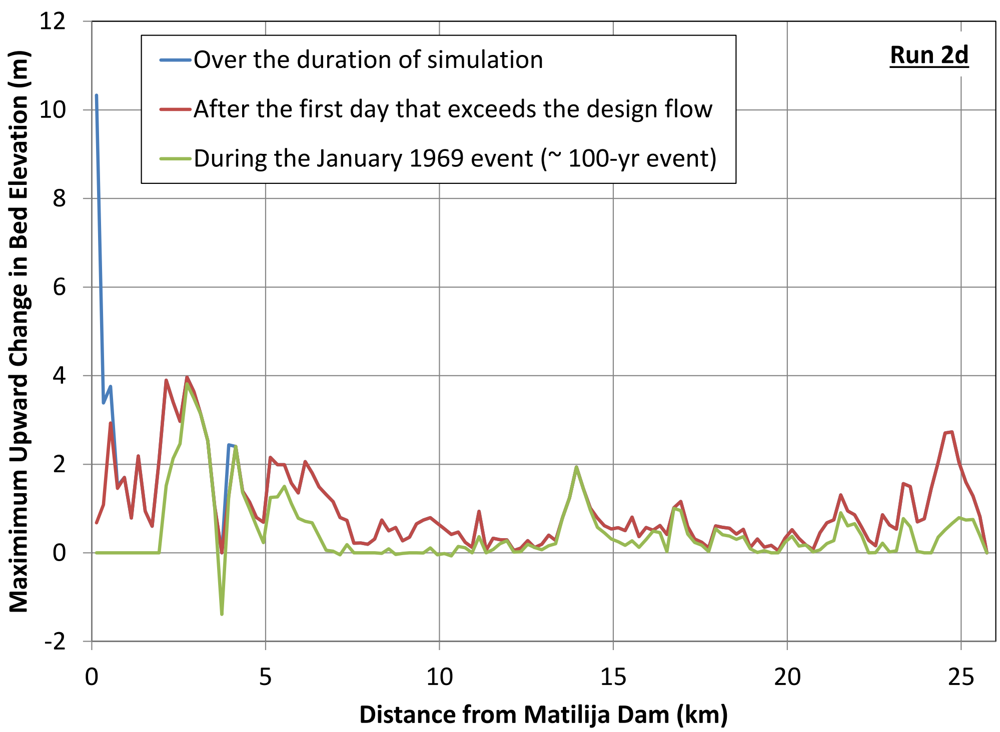

Figure D-34. Simulated maximum change in bed elevation during different periods of time, Run 2d.

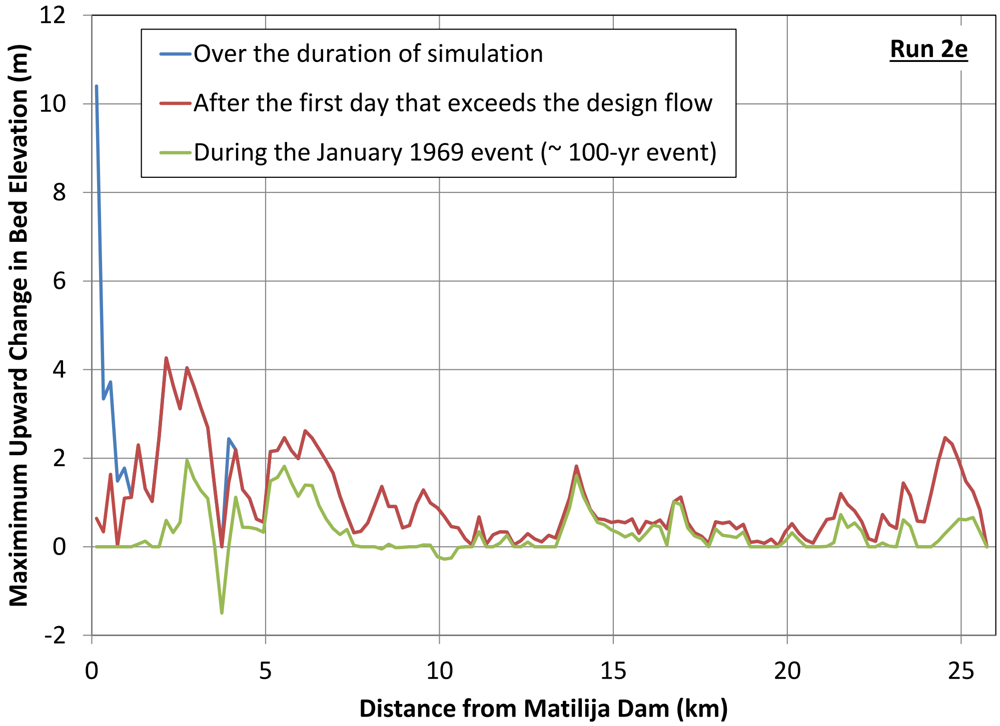

Figure D-35. Simulated maximum change in bed elevation during different periods of time, Run 2e.