

Case Study of Fluvial Modeling of River Responses to Dam Removal

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Abstract: A plan was made to remove Matilija Dam on the Ventura River. With dam removal, the delta in the reservoir and the downstream channel were expected to undergo major changes in morphology. The FLUVIAL-12 model was employed to simulate reservoir and river channel responses after dam removal. As a first step, the model was calibrated using the Ventura River data to establish its validity. In calibration, the model was used to simulate the fluvial processes starting from the time of dam completion. The simulated sediment deposition above the Matilija Dam matches closely with the deposits measured by the U.S. Bureau of Reclamation. A large amount of sediment was stored in the reservoir; some of the stored sediment was transported downstream after dam removal. An important consequence of dam removal is the major increase of sediment release to the river channel downstream. The sediment supply to the downstream reach is not only from the stored sediment in the reservoir but also from natural sediment inflow from the upstream watershed. Therefore, sediment supply to the downstream reach will exceed the natural sediment flow before the dam presence. This situation tends to overload the downstream reach with sediment, resulting in excessive deposition. The amount of sediment release from the area above the removed dam is closely related to the changes in reservoir morphology. It is necessary to model changes in the channel bed profile and channel width during erosion in order to determine the amount of sediment removal. The amount of sediment release may not be simulated using an erodible-bed model but it may be determined using an erodible boundary model.

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Introduction

A plan has been made to remove Matilija Dam as shown in Figs. 1 and 2 on the Ventura River. After the dam is removed, sediment stored in the reservoir will be flushed down the river channel. It is necessary to determine the amount and process of sediment release from the reservoir and to assess downstream river channel responses to a major increase of sediment input. The impact of sediment release from the reservoir needs to be assessed in order to develop proper mitigation measures for potential adverse impacts. A fluvial modeling study has been made to analyze and quantify potential stream channel changes after dam removal. The results will be used to develop controlling or protection measures for flood control and stream channel stabilization, and to recommend mitigation measures for environmental concerns and issues. Matilija Dam was completed in 1947. The reservoir above the dam has become smaller resulting from siltation. At this time, the area above the dam has the three following parts: the small remaining reservoir, the delta, and the upstream channel. Sediment deposit in the reservoir consists of silt and some clay. In the delta, the deposited sediment is sand with up to 50% fines. In the up-

stream channel, the bed sediment consists of sand and gravel with a minor amount of fines.

The amount of sediment flushing from a reservoir after dam removal is closely related to the changes in morphology in the reservoir. It is necessary to model changes in channel bed profile and in channel width during erosion in order to determine the amount of sediment removal. The amount of erosion can be determined using an erodible boundary model, such as FLUVIAL-12, but not an erodible bed model. Leopold et al. (1964) stated that deposition in a river tends to spread out in the channel and to flood adjoining areas but a channel undergoing erosion tends to slide back into its banks. Gully formation, typically, occurs in the process of reservoir bed erosion. The channel width affected by erosion tends to be small but sediment deposition in the downstream channel tends to spread out to a large width. Such processes occur after dam removal.

Modeling Study

The geometry of the stream channel is defined by a series of cross sections. Points of interest and their respective river stations are listed in Table 1. Cross-sectional data of the stream channel below the dam were prepared and supplied by the U.S. Bureau of Reclamation (USBR). These cross sections are viewed toward downstream.

The modeling study for stream dynamics was made for a 50-year flood series based on stream gauging records. The FLUVIAL-12 model (Chang 1988) was employed for this study. For a given flood hydrograph, the FLUVIAL-12 model simulates spatial and temporal variations in water-surface elevation, sediment transport, and channel geometry. Scour and fill of the stream

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Fig. 1. Matilija Dam viewed from downstream

ambed are coupled with width variation in the prediction of river channel changes. The FLUVIAL-12 model is an erodible boundary model since it simulates the interrelated changes in channel-bed profile and channel width. Computations are based on finite-difference approximations to energy and mass conservation that are representative of open channel flow.

The model simulates the interrelated changes in channel-bed profile and channel width, based upon a stream's tendency to seek uniformities in sediment discharge and power expenditure. At each time step, scour and fill of the channel bed are computed based on the spatial variation in sediment discharge along the channel. Channel-bed corrections for scour and fill will reduce the nonuniformity in sediment discharge. Width changes are also made at each time step, resulting in a movement toward uniformity in power expenditure along the channel. Because the energy gradient is a measure of the power expenditure, uniformity in power expenditure also means a uniform energy gradient or linear



Fig. 2. Aerial view of Matilija Dam and its reservoir

Table 1. Important Locations along River Channel

Location	River station (km)
River mouth	0
San Antonio Creek	12.71
Robles Diversion Dam	22.75
North Fork	25.42
Matilija Dam	26.48
Upstream limit of modeling	29.76

water-surface profile. A river channel may not have a uniform power expenditure or linear water-surface profile, but it is constantly adjusting itself toward that direction. The model was calibrated using 14 sets of field data. Such calibration studies are listed in the users manual for FLUVIAL-12. Most of the calibration studies were peer reviewed.

The Engelund–Hansen formula was selected for this study because the results generated by the Engelund–Hansen formula can be correlated with the measured sediment deposition (Engelund and Hansen 1967).

The basic data requirements for a modeling study include (1) topographic maps of the river reach from the downstream end to the upstream end of study; (2) digitized data for cross sections in the HEC-2 format with cross-sectional locations shown on accompanying topographic maps; (3) flow records or flood hydrographs and their variations along the study stream reach, if any; and (4) size distributions of sediment samples along the study reach. Additional data are required for special features (such as physical constraints) of a study river reach.

Simulation of Sediment Delivery

Sediment delivery is defined as the cumulative amount of sediment that has been delivered passing a certain channel section for a specified period of time, that is

$$Y = \int_T Q_s dt \quad (1)$$

In which Y =sediment delivery (yield); Q_s =sediment discharge; t =time; and T =duration. The sediment discharge Q_s pertains only to bed-material load of sand, gravel, and cobble. The fine sediment of clay and silt that constitute the wash load may not be computed by a sediment transport formula. Sediment delivery is used herein to keep track of sediment supply and removal along the channel reach.

Spatial variations in sediment delivery are manifested as channel storage or depletion of sediment-associated stream channel changes since the sediment supply from upstream may be different from the removal. The spatial variation of sediment delivery depicts the erosion and deposition along a stream reach. A decreasing delivery in the downstream direction, i.e., negative gradient for the delivery–distance curve, signifies that sediment load is partially stored in the channel to result in net deposition. On the other hand, an increasing delivery in the downstream direction (positive gradient for the delivery–distance curve) indicates sediment removal from the channel boundary or net scour. A uniform sediment delivery along the channel (horizontal curve) indicates sediment balance, i.e., zero storage or depletion. Channel reaches with net sediment storage or depletion may be designated in each figure on the basis of the gradient.

Model Calibration

In order to assess the applicability of the FLUVIAL-12 model for the study, model calibration was made using available data as described below. Matilija Reservoir has been trapping sediment since its completion in 1947. Matilija Dam has a watershed area of 141.7 km². The U.S. Army Corps of Engineers (USACE 2002) estimated sediment deposition in the reservoir; the USBR (2002) measured the volume of sediment deposit. According to the

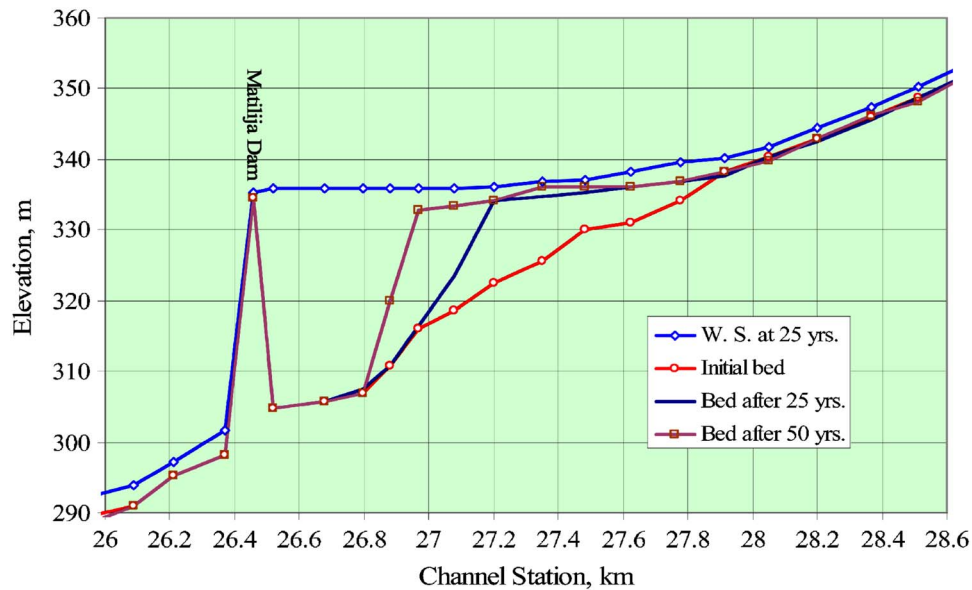


Fig. 3. Longitudinal profiles of water surface and channel bed during reservoir deposition after dam completion

USACE, material trapped behind the dam is 4.4 million cubic meters, of which 2.28 million cubic meters are considered to be coarse sediments (sand and gravel). The USBR made a more-detailed measurement of sediment deposition in Matilija Reservoir, delta, and upstream channel for a total length of about 1 mile. According to the USBR, total sediment deposition in the surveyed area was 4.5 million cubic meters, with 2.91 million cubic meters in the coarse sediment size range.

The processes of reservoir deposition during the 50 years since dam completion are simulated as shown in Figs. 3 and 4. It can be seen from Fig. 3 that deposition of coarse sediment starts from the reservoir entrance and it advances into the reservoir gradually. At a cross section in the reservoir, the deposition tends to build up the bed elevation in horizontal layers. A low-flow channel gradually forms in the reservoir deposit.

Simulated spatial variations of sediment delivery in the 50-year time span are shown in Fig. 4. Fig. 4 shows approximate sediment equilibrium above Channel Station 28 km and sediment deposition from Channel Station 28 km to the dam. The total amount of sediment delivered passing Channel Station 28 km is 4.31 million t. The USBR measured the deposited sediment from the dam to Channel Station 28 km. Since no significant amount of coarse sediment passed over the dam before 2002, the delivery passing Channel Station 28 km is also the amount of measured deposit.

The sediment deposit has more or less consolidated; therefore, it is estimated to have a unit weight of 1.6 t/m^3 . The estimated deposit of 2.28 million m by the USACE has a weight 3.65 million t. The measured volume of 2.91 million cubic meters by the Bureau weighs 4.66 million t. This simulated sediment yield is

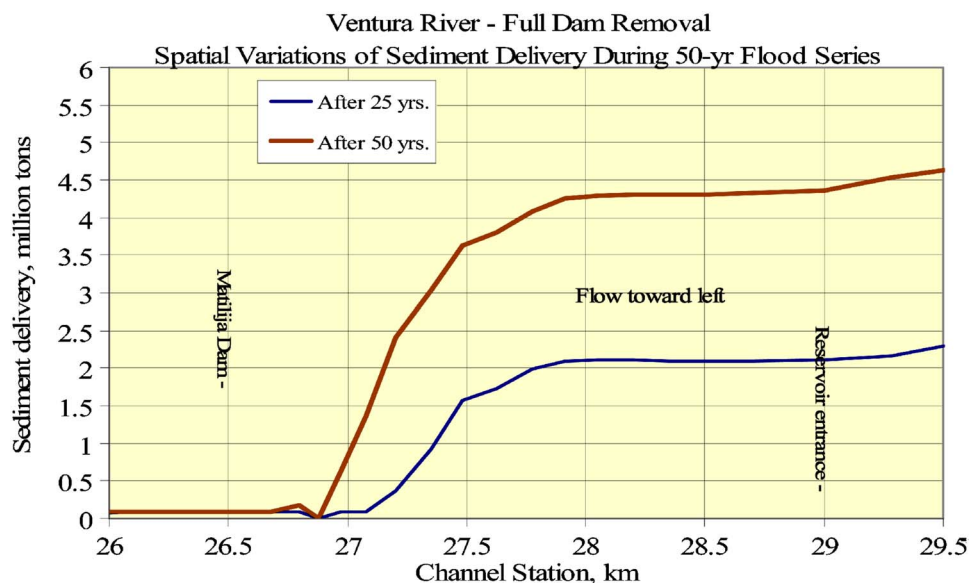


Fig. 4. Simulated spatial variations of sediment delivery during 50-year flood series since dam completion showing sediment deposition in the reservoir

Table 2. Comparison of Sediment Deposits above Matilija Dam

Source	Total deposit (million tons)	Time span (years)	Mean annual deposit (tons/year)
USACE	3.65	55	66,400
USBR	4.66	55	84,700
This study	4.31	50	86,200

compared with previous measurement and estimate as shown in Table 2.

It can be seen from Table 2 that the simulated value based on the 50-year flood series is similar to the measured value by the USBR and the estimated value by the USACE. For this reason, the FLUVIAL-12 model was calibrated based on data from the Ventura River and its 50-year flood series. The model was, therefore, adopted as the basis for the modeling study. The mean annual deposit in the reservoir also represents the mean annual sediment supply to the reservoir from the watershed.

Simulation of Complete Dam Removal

The 50-year flood series was used to simulate reservoir and stream channel dynamics after the dam is completely removed. The results pertaining to sediment delivery and changes in reservoir and channel morphology are described below.

Spatial variations of sediment delivery during the 50-year flood series after complete dam removal are shown in Figs. 5 and 6. The spatial pattern depicts the following:

1. Erosion above the removed dam. The increase in sediment delivery from Channel Station 28 km to the dam site at Station 26.5 km is about 1.8 million t. This amount represents erosion from the area above the dam, principally from the delta deposit.

2. No major changes in delivery through the channel gorge between Stations 25.5 and 26 km.
3. Deposition below the dam. The decrease in sediment delivery from the North Fork confluence at Station 25.4 km down to Station 22.5 km is about 2.8 million t in the 50-year time span. This amount represents sediment storage along the channel reach. Most of the sediment supply for the reach is from the area above the dam but a small portion of the sediment is supplied by the North Fork.
4. Approximate sediment equilibrium from Station 22 km to the San Antonio Creek confluence.
5. The river channel is subject to erosion from Station 4 km to Station 8 km. It is subject to deposition below Station 4 km.

The spatial variations of sediment delivery along the study river reach are shown in Fig. 5; those in the vicinity of the removed dam are shown in Fig. 6. The spatial pattern depicts erosion from the delta area above the dam and deposition below the North Fork confluence. From the removed dam site to the North Fork confluence (26.5–25.5 km) is a narrow gorge, where sediment does not settle. The diversion dam at Station 25.75 km has a height of 3.2 m. The major deposition that occurs from the North Fork confluence to the diversion dam is related to the decrease in channel slope, increase in channel width and backwater from the diversion dam.

An important consequence of dam removal is the large amount of sediment released to the downstream river channel. This major increase in sediment supply tends to overload this downstream reach with sediment. The sediment supply to the downstream reach is not only from the stored sediment in the reservoir delta but also from the natural sediment inflow from the upstream watershed. In other words, the sediment supply to the downstream exceeds the natural sediment inflow before the dam presence. Amounts of sediment supply to the dam site are as follows:

1. Natural conditions before dam presence: 86,200 t per year; and
 2. After full dam removal: 109,000 t per year
- A large amount of sediment has been stored in the reservoir

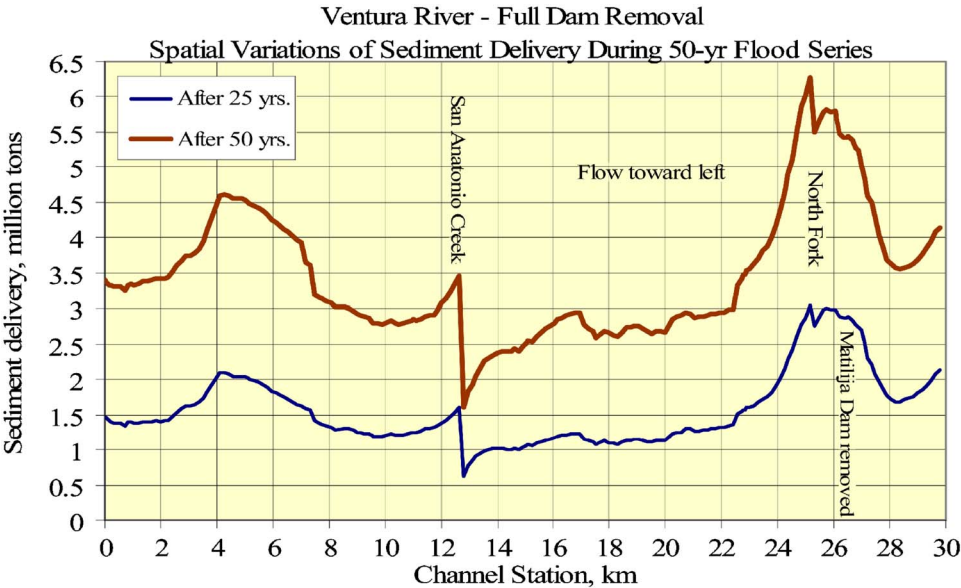


Fig. 5. Spatial variations of sediment delivery during the 50-year flood series after dam removal

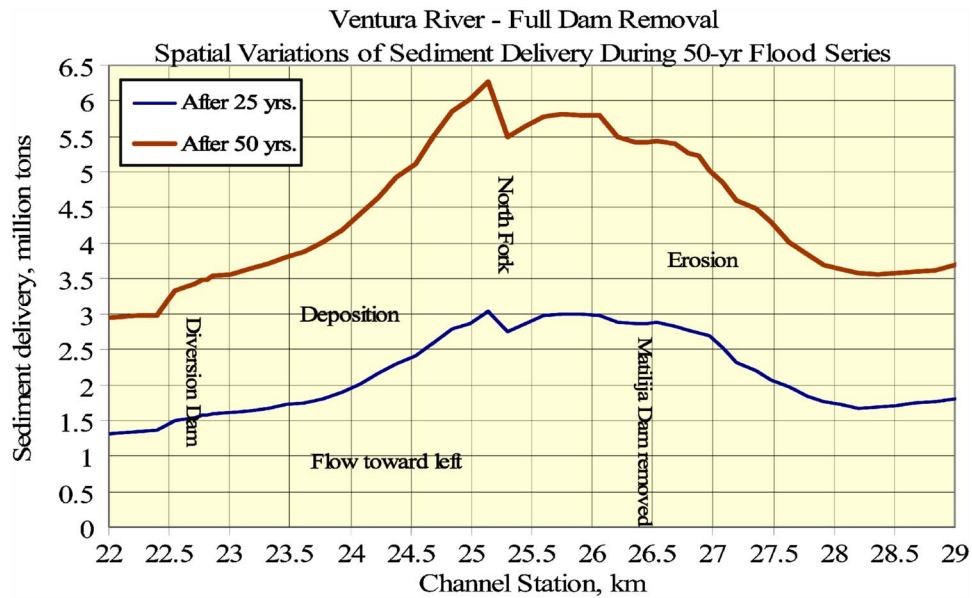


Fig. 6. Spatial variations of sediment delivery during the 50-year flood series after dam removal in the vicinity of the removed dam

since the dam completion and some of the stored sediment will be transported downstream after the dam removal. The amount of sediment release from the area above the removed dam is closely related to the changes in reservoir morphology; therefore, simulation of the morphological changes are of great importance for dam removal projects.

Morphological Changes after Dam Removal

It was assumed in the study that the dam is totally removed and the fines in the reservoir are also removed. Simulated water-surface and channel-bed profile changes are shown in Fig. 7. The following features characterize channel-bed profile changes near the dam site:

1. Aggradation in the downstream channel. Dam removal increases sediment supply to overload the downstream channel. Aggradation occurs as released sediment settles in the downstream channel. The simulated results show major channel-bed aggradation in the downstream reach from Station 25.5 km down to the diversion dam.
2. Degradation in the delta and upstream channel. The delta is located above Station 26.85 km about 400 m upstream from the removed dam. After the dam removal, simulated channel-bed profile changes depict rapid degradation that also extends gradually upstream.
3. The aggradation and degradation have high initial rates as most of the changes occur in the first half of the flood series. The rate slows down considerably later on. After dam removal, stored sediment is released to cause down-

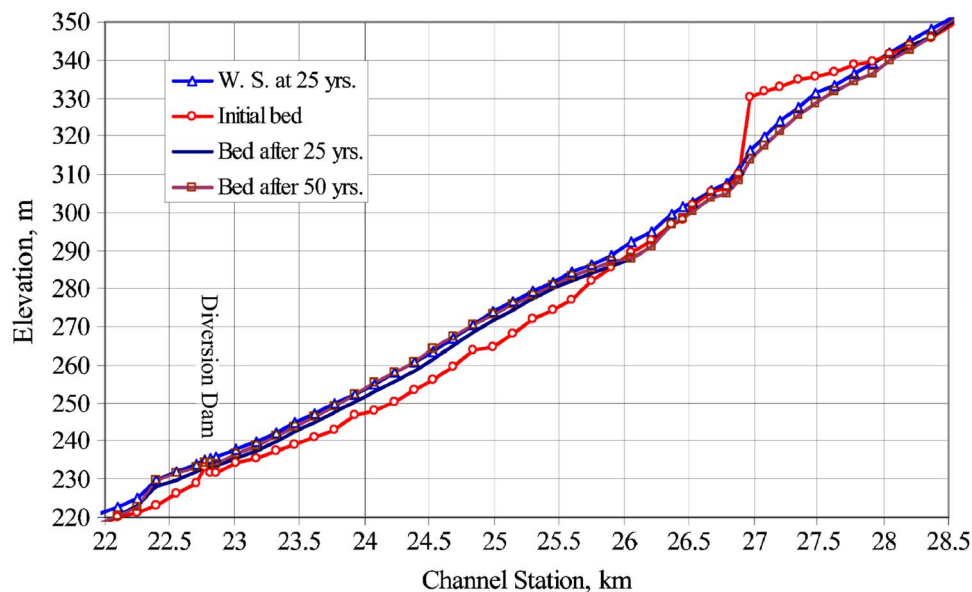


Fig. 7. Simulated water-surface and channel-bed profile changes after dam removal

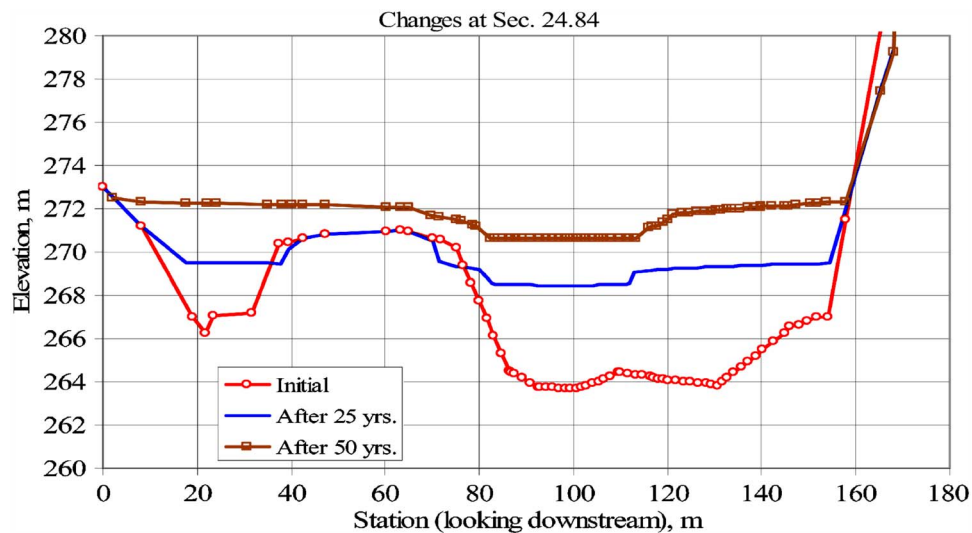


Fig. 8. Morphological changes in downstream river channel at Channel Station 24.84 after dam removal

stream channel-bed aggradation. In the time period of 50 years, the amount of deposition from Channel Station 25.5 km down to 22.5 km is computed to be 2.8 million t. Those shown in Fig. 8 for Channel Station 24.84 and in Fig. 9 for Channel Station 25.45 km exemplify morphological changes in the river channel along the reach. Figs. 8 and 9 illustrate the characteristic changes in channel morphology below the dam. In the process of deposition, sediment tends to build up the bed profile in horizontal layers. The bed profile during deposition is rather flat but not totally flat. A small low-flow channel also forms in the flat channel bed. Simulated morphological changes above the removed dam are depicted in Figs. 10 and 11 by the changes in cross-sectional profile at Channel Stations 26.97 and 27.48 km, respectively. Section 26.97 is near the tip of the delta and section 27.48 is about 0.5 km below the upstream end of the delta. The simulated morphological changes have the following features.

1. Dam removal will cause higher flow velocities on the delta and upstream channel to induce head cutting. An incised

- channel will first develop on the delta starting from the tip and it will extend gradually upstream. The incision is the most pronounced on the delta.
2. The incised channel has a small width at the initial stage. After the incision reaches the original bed elevation before the dam, the incised channel begins to expand in width. The width change is a slow process. Simulated results show that channel width at the end of the 50-year time period is much smaller than the natural channel width before the dam.
3. After dam removal, sediment stored in the delta and upstream channel will be removed gradually with time. Sediment removal is a slow process. Complete removal of all stored sediment will take a time span much longer than 50 years.

The amount of sediment release resulting from erosion in the delta is closely related to the changes in the channel morphology on the delta. Such changes include the changes in channel-bed profile as well as changes in channel width. The changes in

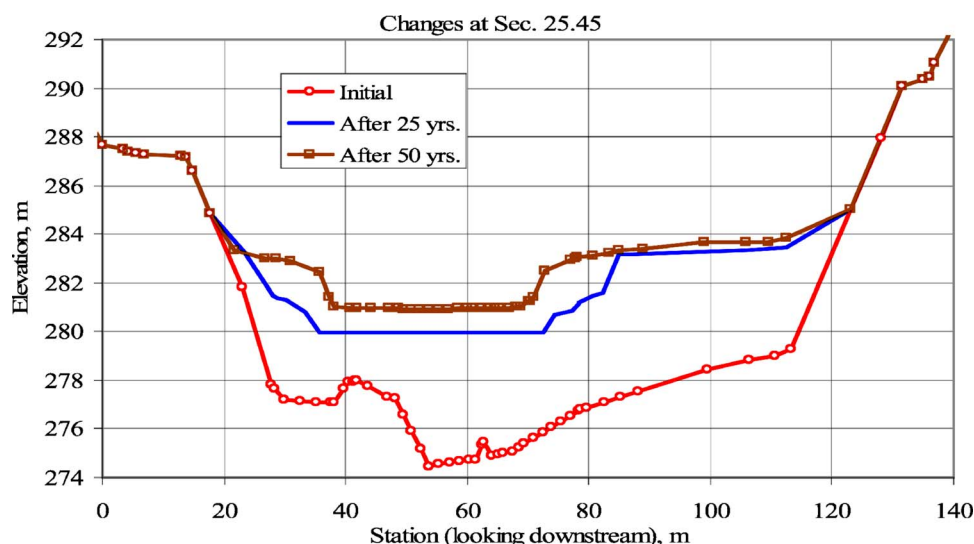


Fig. 9. Morphological changes in downstream river channel at Channel Station 25.45 km after dam removal

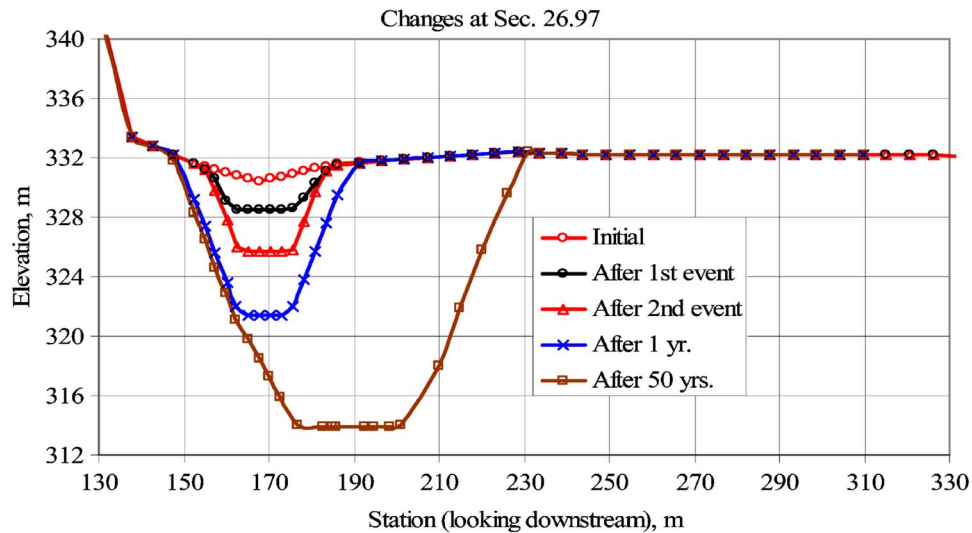


Fig. 10. Simulated morphological changes after dam removal at Channel Station 26.97 km near the tip of the delta

channel-bed profile and channel width are also closely interrelated. Any effort to quantify sediment release after dam removal hinges on adequate simulation of morphological changes associated with erosion and deposition. It may, therefore, be concluded that the fluvial process after dam removal can only be simulated using an erodible boundary model that allows for bank erosion and not an erodible bed model.

Summary and Conclusions

In planning for dam removal, it is essential to determine the processes of sediment release from the area above the dam. It is also important to quantify erosion and deposition after dam removal and the pattern of sediment redistribution along the channel reach. FLUVIAL-12 was employed to simulate the fluvial processes related to the proposed removal of Matilija Dam on the Ventura

River. As a first step, the model was calibrated using data of reservoir deposition above Matilija Dam since its completion. The simulated deposition was confirmed by measurements.

The simulated results for full dam removal are presented in this paper. The results show that dam removal will result in a major increase of sediment supply to the channel reach below the dam over the natural sediment supply before the dam presence. The quantity of sediment release from dam removal is closely associated with the changes in channel morphology. Since the channel adjusts in bed profile as well as in channel width, any effort to quantify sediment release after dam removal hinges on adequate simulation of morphological changes associated with erosion and deposition. The changes in channel-bed profile and channel width are also closely interrelated. It may, therefore, be concluded that the fluvial processes after dam removal can only be simulated using an erodible boundary model but not an erodible bed model.

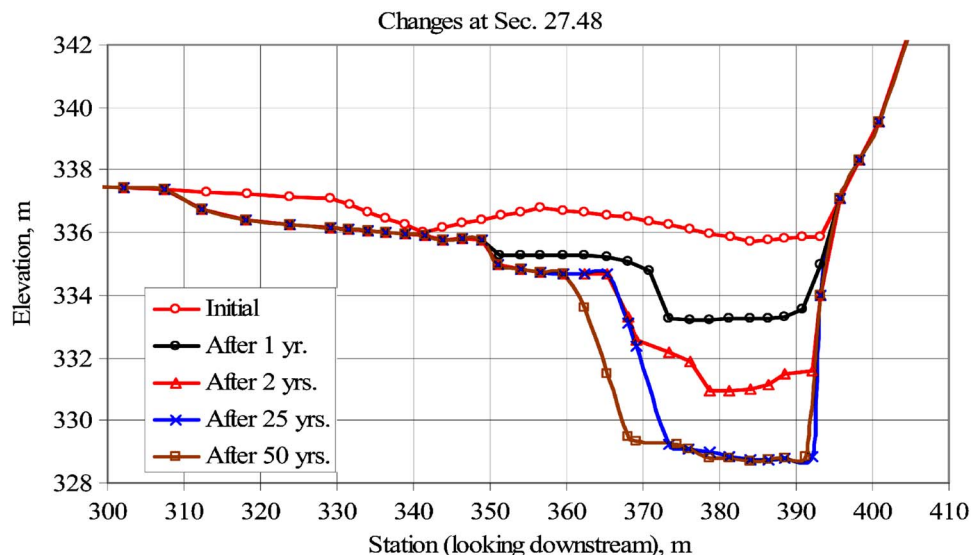


Fig. 11. Simulated morphological changes after dam removal at Channel Station 27.48 km located at one half kilometer above the tip of the delta

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