FINAL REPORT ◦ JUNE 2024

Preliminary Feasibility Study for the Removal of Brown Mountain Dam

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Cover photos: Brown Mountain Dam.

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1 INTRODUCTION

1.1 Background

The Arroyo Seco is a major tributary of the Los Angeles River (LA River), linking the Angeles National Forest and the San Gabriel Mountains to the LA River near downtown Los Angeles. A century ago, the Arroyo Seco provided essential habitat for the now-endangered Southern California steelhead trout (*Oncorhynchus mykiss*). The general term *O. mykiss* is used to refer to the existing population of steelhead in the Arroyo Seco. While native rainbow trout still exist in the Arroyo's headwaters, a variety of human impacts have diminished the flow and have degraded the habitat and conditions necessary for successful migration and reproduction. Prominent among these impacts is Brown Canyon Debris Barrier, also known as Brown Mountain Dam (BMD), which lies across the Arroyo Seco about 3.2 river miles north of the mouth of the river (34º 14' 18"N, 118º 10'54"W) (Figure 1-1).

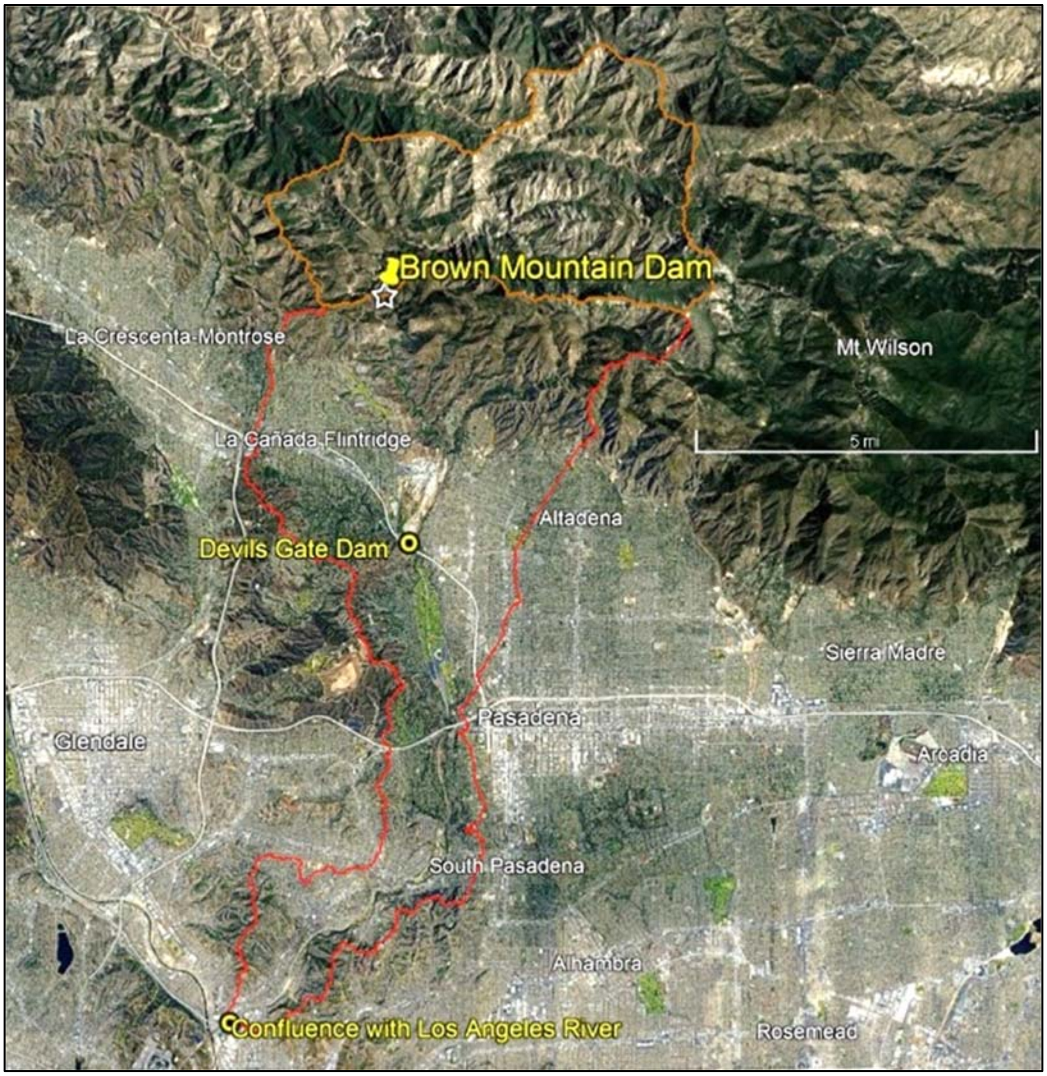


Figure 1-1a. The Arroyo Seco watershed and the location of Brown Mountain Dam. Red lines outline the watershed boundaries of the contributing area to the dam, and to the Arroyo Seco as a whole.

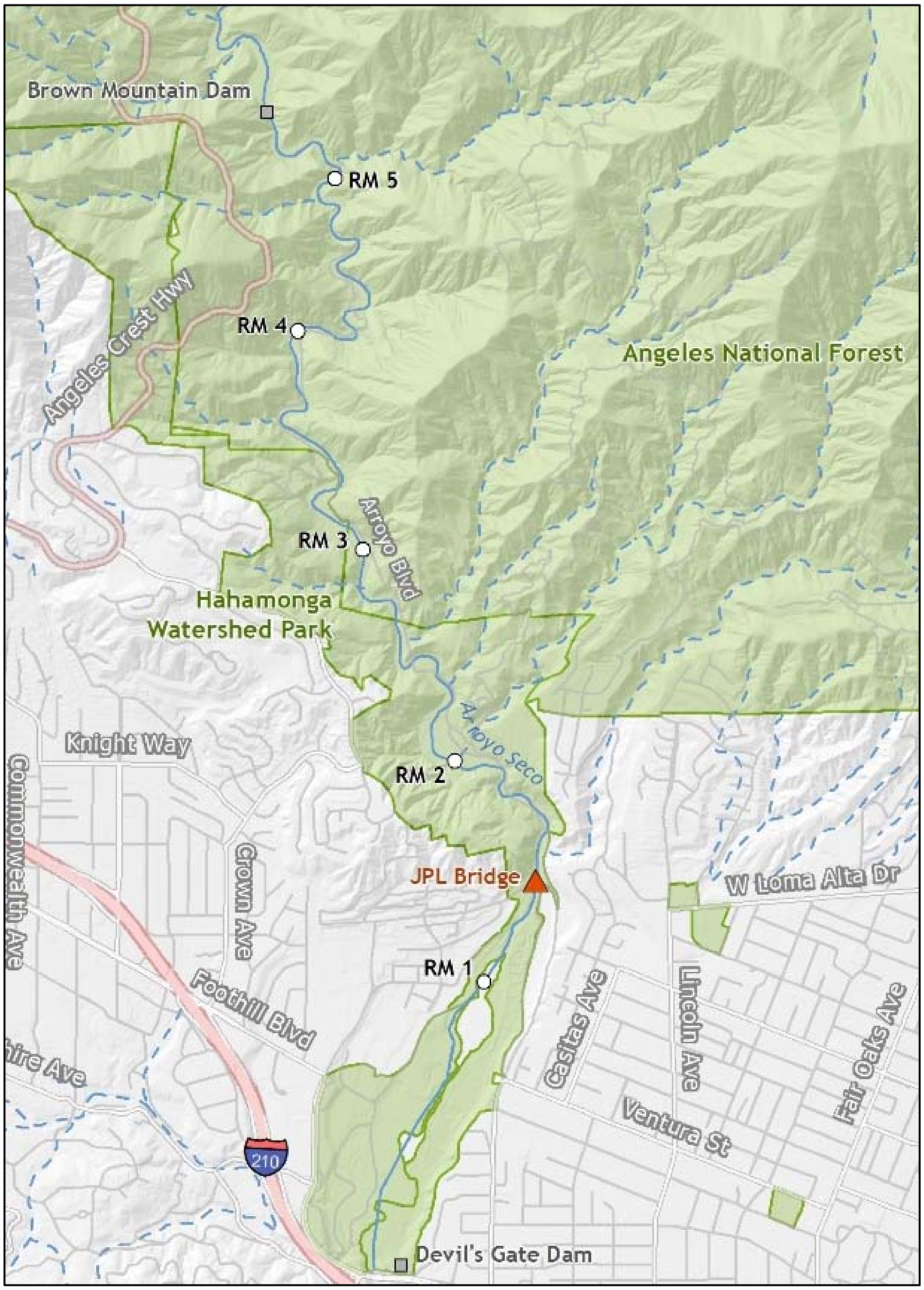


Figure 1-1 (cont.) b. The reach of primary concern for this report, from Devil's Gate Dam to Brown Mountain Dam. The reservoir deposits behind Brown Mountain Dam are present upstream to about river mile 6.7.

Built in 1942 and completed in early 1943, BMD is an arch dam with an overall height of about 86 feet, owned by the U.S. Forest Service (USFS; Figure 1-2). It was a component of the first upstream flood control project ever attempted in the United States. BMD's primary function was to capture debris and sediment, but it is also a total barrier to fish migration with no provision for facilitating passage. At present, the dam is full of sediment to the top of the spillway crest elevation and does not impound any open water beyond the stream channel itself. Therefore, the dam is currently acting as a retaining wall, and, as such, the California Division of Dam Safety has removed this dam from its jurisdiction.

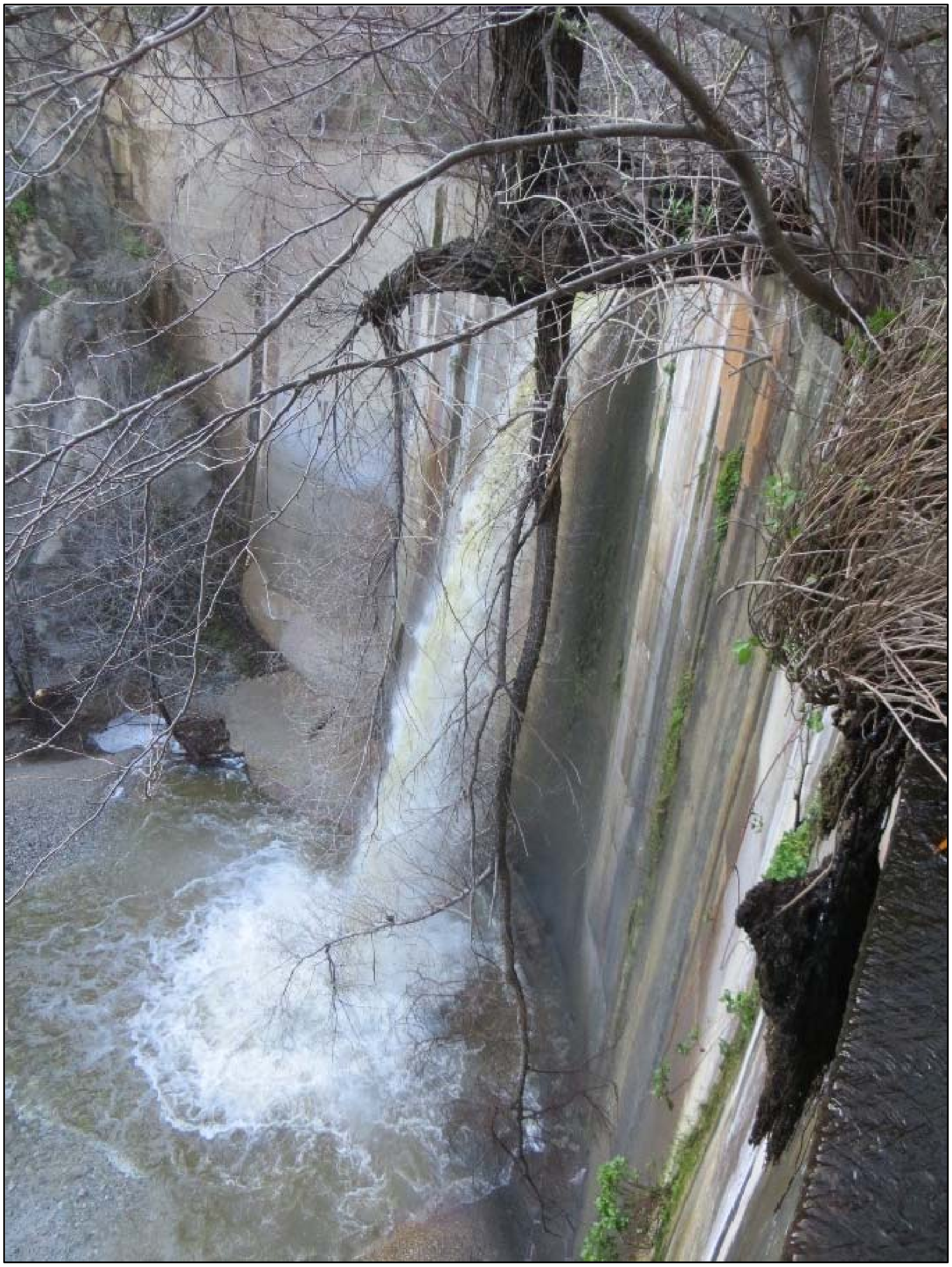


Figure 1-2. Brown Mountain Dam. At the time of this photograph (6 January 2023), the downstream gage (U.S. Geological Survey gage #11098000) registered a discharge of 11 cubic feet per second.

Currently, the State of California is moving forward with implementation of biodiversity, connectivity, and access to nature policies that reinforce the importance of regional and local measures to remove barriers to wildlife connectivity. The Arroyo Seco is a potentially key tributary for advancing steelhead recovery, through reconnection of its headwaters to the ocean and so supporting the fishes' full lifecycle. Focused actions downstream that restore LA River fish passage, restoration, and flows are linked to streamflow enhancement and barrier removals in the headwaters, such as the prospect for dam removal explored in this report. The integrated implementation of these projects will be critical to recovery of the species and to meet the statewide directives supporting healthy connected watersheds.

In 2022, the California Wildlife Conservation Board awarded a grant to the Arroyo Seco Foundation in the amount of $427,488 for the *Stream Flow Enhancement Program for the Arroyo Seco*, a scientific study to map and analyze streamflow barriers to improve stream flow and prioritize additional stream flow enhancement projects on publicly owned land in the upper Arroyo Seco watershed within the City of Pasadena and the Angeles National Forest located in Los Angeles County, California. This report has been prepared by Stillwater Sciences in accordance with Task 5 of the Grant Agreement WC-2274EA between the California Wildlife Conservation Board and Arroyo Seco Foundation.

1.2 Purpose

The purpose of this preliminary feasibility study is to advance the long-term goal of removing this barrier to fish migration, and so improve the ecological integrity of the Arroyo Seco. This report describes the existing ("baseline") conditions of the Arroyo Seco watershed, emphasizing the physical and biological conditions in the upper Arroyo Seco both upstream and downstream of BMD, and presents and evaluates alternatives for the removal of BMD and the management of the sediment it currently impounds. This study is "preliminary" insofar as it is being conducted under financial and scheduling constraints that are far more restrictive than those of a Feasibility Study normally conducted by the U.S. Army Corps of Engineers (USACE) for projects such as this. Nevertheless, even this modestly scaled investigation into the conditions and opportunities for BMD removal should provide a firm foundation for more detailed biological, geomorphological, and engineering studies that can bring the goal of dam removal closer to reality.

1.3 Dam History

The Arroyo Seco was the earliest focus of flood-control efforts in the LA River basin. Devil's Gate Dam was the first major facility built along any tributary of the LA River, with construction beginning in 1919 following the damaging floods of January and February 1914 (van Wormer 1973). Subsequent major floods in 1934 and (particularly) 1938 led to a program of major flood works throughout the LA River and San Gabriel River watersheds, which included the construction of BMD in 1942 (Raya 2014). BMD was constructed to capture debris and sediment, while providing some attenuation of high flows. Construction was apparently still ongoing in 1943 (Figure 1-3), although the dam was sufficiently completed by the winter storms of 1943 that the reservoir area already began to fill with sediment (see below). Since that time, water has continued to spill over the top of the dam as sediment has collected in the reservoir area. Today, the channel of the Arroyo Seco is fully graded to the spillway elevation (Figure 1-4); no open-water reservoir area remains.

January 20, 1943 -- In the middle of World War II, a dam rises in the Arroyo Seco, the first project in the US Forest Services Los Angeles River watershed program. Note the construction elevator for people and equipment, the Reo truck and the compressors in the foreground.

Figure 1-3. View of the nearly completed Brown Mountain Dam in early 1943 (photo from https://www.arroyoseco.org/BMDam.htm).

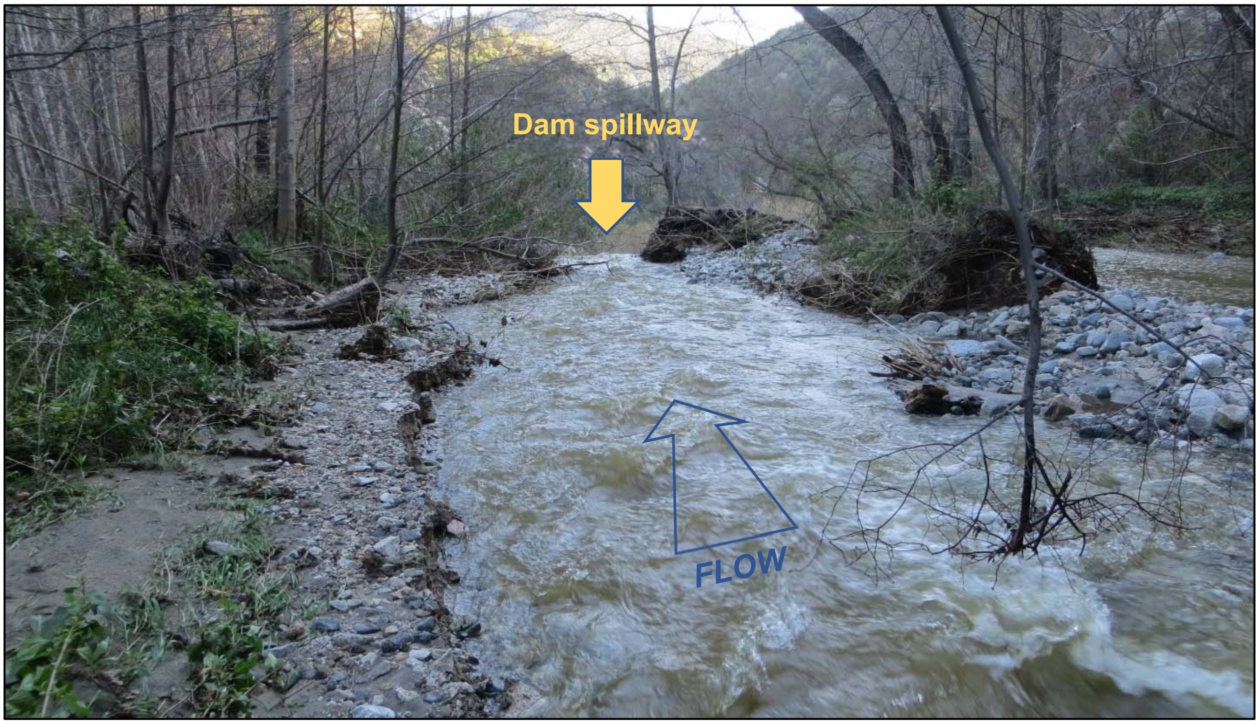


Figure 1-4. View looking downstream to the dam spillway. Immediately past the lip visible in this photograph, the water falls vertically for more than 80 feet over the downstream face of the dam to the channel below (see Figure 1-2).

At one time, BMD was included in the National Inventory of Dams (https://nid.usace.army.mil/), which has the following guidance (from https://hub.arcgis.com/datasets/fedmaps::national-inventory-of-dams-1/about):

The National Inventory of Dams (NID) consists of dams meeting at least one of the following criteria:

- High hazard potential classification: loss of human life is likely if the dam fails
- Significant hazard potential classification: no probable loss of human life but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns
- Minimum height and reservoir size requirements:
  - Equal or exceed 25 feet in height and exceed 15 acre-feet in storage
  - Equal or exceed 50 acre-feet storage and exceed 6 feet in height.

The goal of the NID is to include all dams in the United States that meet these criteria.

BMD was removed from the inventory in 2013, reportedly at the request of USFS (see https://www.arroyoseco.org/History/ArroyoSecoFloodTimeline.pdf). According to the manager of the NID program, "This structure is no longer included in the National Inventory of Dams because it has no water storage and no longer functions as a dam or meets the definition. It is full to the top with soil and was built as a large grade-control structure. It is essentially a large retaining wall with water running over it, whereas "A dam is an artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control of water (FEMA 148, Federal Guidelines for Dam Safety, Glossary of Terms)" (R. Ragon, USACE, pers. comm., 2022).

2 APPROACH

Although this preliminary study provides an insufficient basis to proceed directly to full dam removal, the material presented here has been organized to follow a well-established framework for such investigations. The U.S. Bureau of Reclamation (USBR) provided such a framework in its 2017 *Dam Removal Analysis Guidelines for Sediment* (2017 Guidelines; USBR 2017), following the guidance of two technical workshops in 2008 and 2009 (with participation by Yantao Cui and Peter Downs, both of Stillwater Sciences) and a publication by the United States Society on Dams (*Guidelines for Dam Decommissioning Projects*; USSD Committee on Dam Decommissioning 2015).

The 2017 Guidelines recommended a 10-step analysis focused on the management of sediment in the reservoir, typically the most problematic element of a dam-removal project (as is almost certainly true for BMD as well):

1. Identify sediment concerns
2. Collect reservoir and river data
3. Evaluate potential for contaminated sediment
4. Determine relative reservoir sediment volume and probability of impact
5. Refine potential sediment consequences and estimate risk
6. Develop dam removal and sediment management alternative

7. Conduct sediment analysis based on risk
8. Assess uncertainty
9. Determine if sediment impacts are tolerable and, if needed, modify sediment management plan
10. Develop monitoring and adaptive management plan

These steps are illustrated by a flow chart (Figure 2-1), which highlights the particular focus on Step 4 (sediment volumes and impacts). While outlining the analytical process required to develop plans, this framework presupposes that the purpose of the dam-removal effort is already established. In the case of BMD, this purpose is widely acknowledged but bears explicit statement: the overall goal is to recover volitional fish passage, both up- and downstream, along the length of the naturally fish-passable extent of the Arroyo Seco. Although BMD is not the only such impediment to passage here, it is by far the largest barrier upstream of Devil's Gate Dam (at the mouth of the Arroyo Seco) and merits the most careful investigation.

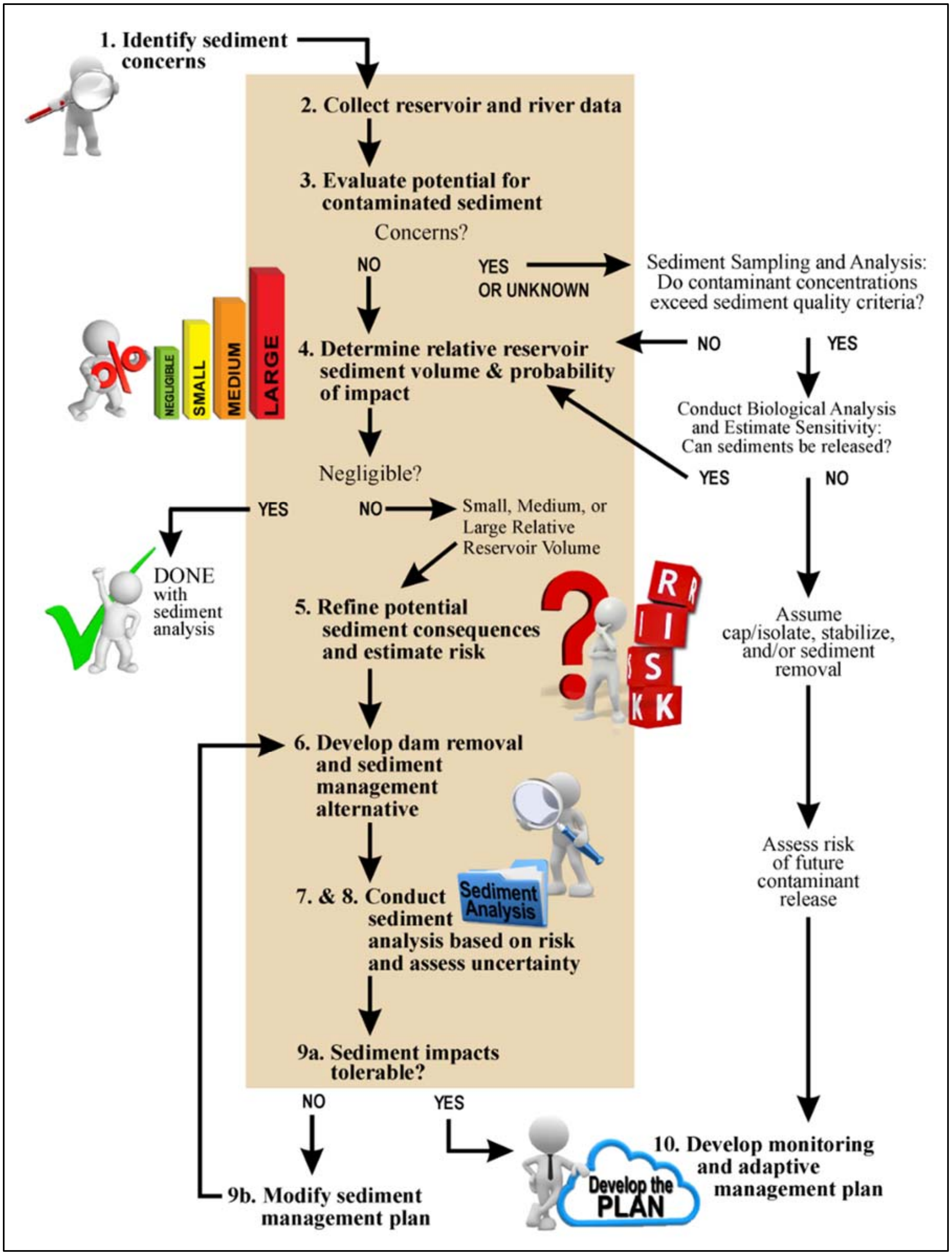


Figure 2-1. The recommended steps for addressing sediment-related impacts from a prospective dam removal (Figure 7 of USBR 2017).

3 BASELINE CONDITIONS (STEPS 1-5 OF THE 2017 GUIDELINES FRAMEWORK)

3.1 Step 1: Sediment Concerns

3.1.1 Background

The Transverse Ranges of southern California have been long-recognized as generating some of the largest watershed-scale sediment loads in the world (e.g., Scott and Williams 1978, Ludwig and Probst 1998). As with a number of dams constructed throughout this region in the early to mid-20th century, BMD lost virtually all of its water-retention capacity to reservoir sedimentation within a few decades (see below). In addition, over 1 million cubic yards (yd^3) of sediment was delivered into Devil's Gate Reservoir, near the mouth of the Arroyo Seco, following the 2009 Station Fire (LACFCD 2014), posing a sediment-management challenge that has required more than a decade to resolve. The magnitude of sediment, both retained behind BMD and delivered annually from the watershed, indicates that the downstream management of sediment is likely to be the primary environmental management concern for this dam-removal effort.

3.1.2 Sediment concerns

USBR (2017, pp. 30–32) offers an exhaustive list of the concerns associated with dam-removal sediment loads. With minor modifications, this list has been used to judge concerns related to the removal of BMD (Table 3-1). Not all of these concerns are relevant ("N/A" in Table 3-1); most of the others are "low" or "none," largely a consequence of the dam's location in a relatively isolated, natural canyon. However, significant water-supply, flood-control, and sediment-management infrastructure lie only a few miles downstream and protect a population of many millions. Thus, here as elsewhere, sediment issues following dam release are of primary concern.

Table 3-1. Conceptual assessment of sediment concerns related to the removal of Brown Mountain Dam (modified from USBR 2017, pp. 30–32).

Categories of sediment concern	Sediment concerns at Brown Mountain Dam
Sediment impact concerns within the reservoir and upstream river reach	
Aesthetics of future landscape after dam removal	Low: wilderness area improved by removal of structure
Speed at which future reservoir landscape will revegetate and become more stable	Low: revegetation likely to be rapid
Invasive vegetation establishing on newly exposed landscape after dam removal	Low: site is far from local disturbance; no upstream rhizome rooters reported or observed
Chronic reservoir sediment erosion for several years post-dam removal	Moderate: rapid initial erosion likely, some downstream delivery for years not dissimilar from watershed sediment loads
Potential for hillslope failure and bank erosion during or following reservoir drawdown that could endanger infrastructure, roads, recreation access points, impact land use functions, or human safety	Low: Only localized failures expected; no adjacent infrastructure on landslide-susceptible materials
Impacts to cultural or historical resources from the possible erosion, exposure, or burial of cultural properties	No assessment made for this study
Reduced water level and yield for wells and water intakes associated with the reservoir (related to extent of reservoir drawdown)	N/A

Categories of sediment concern	Sediment concerns at Brown Mountain Dam
Reduced capacity of wells impacted by reservoir drawdown	N/A
Temporary or permanent loss of recreation activities in the reservoir and downstream river channel	Low: recreational opportunities likely to increase following sediment and dam removal
Knickpoint migration endangering upstream infrastructure such as bridge piers, culverts, utility crossings, or property that may be at risk from undermining or bank erosion	None: no upstream infrastructure
Stranding of fish during reservoir drawdown	Low: limited population of resident fish upstream of dam
Erosion of spawning areas upstream of the reservoir during or after drawdown	Low: limited population of resident fish upstream of dam
New access upstream or downstream past dam site by aquatic invasive species	Moderate: uncertain downstream presence of mobile invasive species
Odor of exposed organics in exposed sediment	Low: low concentration of organics anticipated; no adjacent odor-sensitive land uses
Increased mosquito or insect populations once reservoir is drawn down	None: no water in reservoir.
Sediment impact concerns in the downstream river	
Possible release of contaminants during reservoir sediment erosion	Low: no upstream commercial activity or industry
Deteriorated water quality due to increased suspended sediment levels or contaminants that could impact drinking water, cost of water treatment, or aquatic species (mussels, fish, etc.)	Moderate: short-term high suspended sediment concentrations likely; long-term concentrations likely similar to natural flood concentrations
Increased sediment concentration in diverted water that can lead to sedimentation in pipelines and canals	High: concern for City of Pasadena downstream water diversion
Reduced permeability and capacity in wells due to fine sediment deposition along the river channel and floodplain	Moderate: potential for effects to downstream spreading grounds
Sediment deposition or burial at downstream water diversion structures, effluent or drainage outfalls	High: concern for City of Pasadena downstream water diversion
Significant sediment deposition leading to increased flood stage and ground water levels in downstream river that would put land or infrastructure at risk such as levees, bridges, or culverts	Moderate: JPL bridge on Explorer Road, other bridges along Gabrieleno Trail may require assessment and potential modification
Increased streambank erosion and channel widening that would result in loss of land or infrastructure (e.g., levees, bridges)	Moderate: channel is largely constrained by bedrock and coarse alluvium and debris-flow deposits; Gabrieleno Trail could be locally compromised by channel widening
Burial of downstream aquatic spawning, rearing, and holding areas for threatened or endangered species or species of concern	Low: minimal occurrence; prior studies suggest only short-term impact
Burial of downstream aquatic species that cannot find refuge or quickly mobilize out of sediment impact areas (mussels, invertebrates, etc.)	Low to moderate: uncertain, presumed limited occurrences
Increased deposition in floodplains that could result in change in riparian vegetation when existing species are not tolerant of burial	Low: floodplain species are burial-tolerant or regenerate quickly
Change in aesthetics of river landscape or water color	Low: wilderness riverscape will be restored

Categories of sediment concern	Sediment concerns at Brown Mountain Dam
Increased wood loads that could block culverts or impact conveyance through bridge openings	Low: no change to any wood loading from upstream of dam (no existing impoundment)
Burial or erosion of recreational use areas including boat ramps, swimming areas, beaches, campgrounds, fishing areas, docks, and moorings	None present
Increased sediment loads from legacy sediments that may have been deposited during periods of excessive landscape erosion due to land use impacts	None: upstream watershed almost entirely undeveloped
Sediment impact concerns in the downstream receiving waters	
Sediment deposition blocking aquatic species migration routes	Low: prior studies suggest minimal long-term concerns
Sedimentation in downstream reservoirs	High: magnitude of sediment delivery into Devil's Gate Reservoir likely would require management
Deposition at coast exacerbating tidal inundation of coastal roads or infrastructure	N/A

3.1.3 Benefits of sediment release

The 2017 Guidelines (pp. 32–33) also list potential sediment-related benefits that arise from dam removal, and these benefits are likewise assessed for potential applicability to the removal of BMD (Table 3-2). However, the USBR list does not include either the primary objective of dam removal here (volitional fish passage) or recognize the value of alleviating concern that an 80+ year old dam constructed in a seismically active region may pose a significant safety hazard. These considerations are added below. A complete inventory of all such benefits of dam removal provides a worthwhile reminder of the overall value of such efforts.

Table 3-2. Conceptual assessment of sediment benefits related to the removal of Brown Mountain Dam (modified from USBR 2017, pp. 32-33).

USBR categories of sediment benefit	Sediment benefits at Brown Mountain Dam
Restoration of riverine habitat in reservoir area	Low: existing habitat through 7,000-foot reservoir area is currently good
Restoration of fish passage into upstream watershed	High: removal of Brown Mountain Dam will open up ~6 miles of ancestral habitat
Restoration of heterogeneous grain sizes and sediment bars that support development of more diverse channel processes such as channel migration	Moderate: gorge location provides little room for expression downstream, but coarsest sediment size fraction will move below dam
Increase in physical habitat features that provide ecosystem benefits, such as channel spawning gravels, bars, islands, large wood features, and side channel activation	Moderate: nearly all sediment is already moving past the dam
Reduction of potential safety hazard to downstream communities from elderly dam in seismically active area	Potentially High: removal of Brown Mountain Dam will reduce potential impact related to dam failure during earthquake
Facilitate growth of invertebrate communities	Low: conditions for invertebrates unlikely to materially change
Natural disturbance and sedimentation required for riparian vegetation	Low: downstream length of potential benefits not great before other disturbances occur

USBR categories of sediment benefit	Sediment benefits at Brown Mountain Dam
Replenishment of sediment sources to coastal beaches at the mouths of rivers potentially reversing erosion	Low: sediment management at Devil's Gate Reservoir unlikely to allow downstream passage
Positive benefits to estuary ecosystem	N/A
Turbidity may benefit certain species by providing protection from predators (e.g., humpback chub and razorback sucker on Colorado River native)	N/A
Sedimentation may help reconnect floodplains where lack of sediment supply has caused incision	Low: sediment continuity largely recovered already
Connectivity of nutrients and organic matter (vegetation and all sizes of woody material) from upper watershed can be restored	Moderate: more uniform-gradient channel will facilitate downstream transport
Restoration of the floodplain and of sediment bars for wildlife use	Low: floodplain and bars already sufficiently developed in constrained valley
Enhanced river recreation opportunities	Moderate: dam is presently an impediment to hiking through this reach of the Arroyo Seco
Less chance of uncontrolled flow releases	N/A

3.2 Step 2: Environmental Assessment—Watershed, River, Reservoir, and Dam

USBR (2017, pp. 35-36) offered a list of the features typically relevant in conducting a dam-removal assessment. Those of particular relevance to BMD that have been evaluated in the course of this preliminary assessment are as follows, and they are addressed in subsequent sections of this report:

- Geomorphic setting (topography, geology, hydrology, channel geomorphology, sediment)
- Geologic controls (e.g., constrictions, bedrock, terraces)
- Spatial extent of reservoir sedimentation both laterally and upstream
- Reaches downstream of the dam
- Depositional zones with relatively lower transport capacity such as inlets to natural or dammed lakes (from preliminary sediment transport modeling)
- Confluences with a downstream river (i.e., Devil's Gate Reservoir)

Other data recommended for collection by USBR (2017) are relevant here, but owing to time and resource limitations of the present effort they are deferred for subsequent investigation. These future efforts should include data obtained through intensive field work (i.e., reservoir sediment composition and river channel surveys), detailed two-dimensional (2D) hydraulic and associate sediment-transport modeling, and engineering design analyses:

- Probes of reservoir sediment to estimate potential grain sizes present
- Geophysical techniques to evaluate deep sediment properties
- Surveyed river channel cross sections to support for more detailed modeling
- Evaluation of infrastructure and land use potentially at risk from dam removal
- Infrastructure built on low-level floodplains
- Areas containing bridges, levees, recreation use
- Reaches with water intakes or effluent outfalls

3.2.1 Topography

The Arroyo Seco originates in steep tributaries draining the southern flanks of the San Gabriel Mountains. The watershed of BMD is fully mountainous and constitutes more than half of the watershed area draining to the major debris basin behind Devil's Gate Dam (see Figure 1-1; Table 3-3). In total, the Arroyo Seco constitutes about 8% of the watershed area of the LA River at their confluence.

Table 3-3. Contributing areas for key locations in the Arroyo Seco watershed (all values from StreamStats; https://streamstats.usgs.gov/ss/).

Location	Contributing area (mi^2)
Brown Mountain Dam	14.4
U.S. Geological Survey gage #11098000 (~2 river miles downstream of Brown Mountain Dam)	16.1
Devil's Gate Dam	23.6
Confluence with Los Angeles River	44.3
Combined Los Angeles River + Arroyo Seco	560.8

The Arroyo Seco expresses two topographic zones that, in turn, largely determine its fluvial geomorphology. In the mountains, the mainstem Arroyo Seco and its tributaries are confined within steep canyons (Figure 3-1). Depending on their drainage area and water source, the tributaries in the mountains are often perennial. The mountain front here abuts the zone of alluvial and debris-flow fans at the upstream end of the debris basin behind Devil's Gate Dam. BMD lies in the mountain zone, but if the dam were to be removed, the ultimate disposition of its impounded sediment would be critically influenced by the flatter topography about 4 river miles downstream.

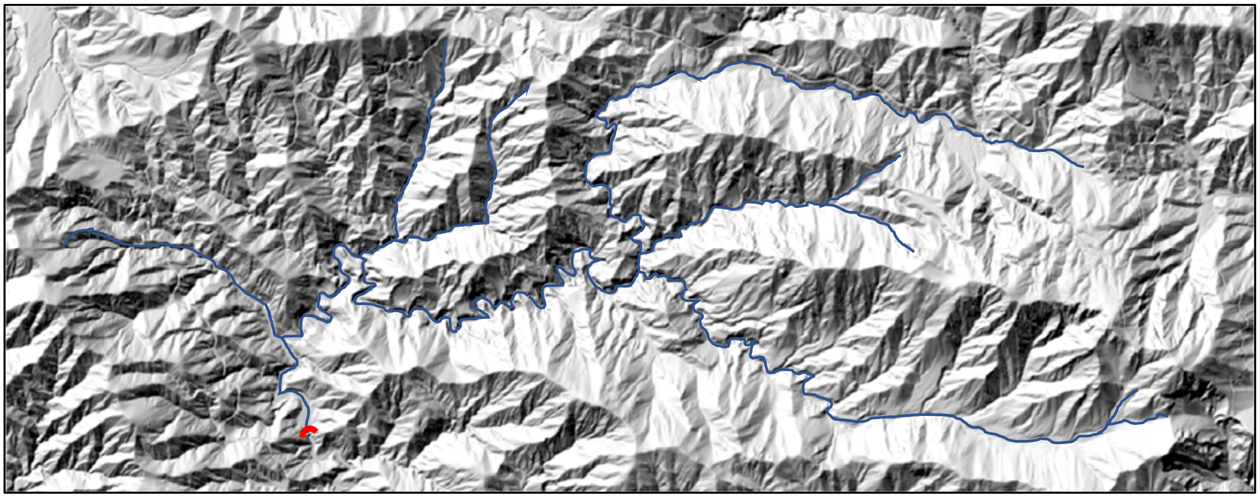


Figure 3-1. Main channel network and topography of the Arroyo Seco watershed upstream of Brown Mountain Dam (red arc). To the north lies the watershed of Big Tujunga Creek, and to the west that of the San Gabriel River.

Within the watershed draining to BMD, the land use is almost entirely undeveloped National Forest System land and part of the San Gabriel National Monument, covered by a mix of chaparral and evergreen forest (the latter particularly on the high-elevation north-facing slopes of the upper watershed). Nearly 10 miles of the Angeles Crest Highway (CA Route 2) traverses the western and northern slopes of the watershed, but other developed areas are scattered and quite limited in extent.

3.2.2 Geology

The present-day LA River watershed was formed by the uplift of the San Gabriel and Santa Monica Mountains over the last 7–10 million years (Lavé and Burbank 2004). The Arroyo Seco flows off the northern flank of that watershed, draining almost exclusively granitic rocks that were originally crystallized over 100 million years ago. Thus, uplift of these rocks is a geologically "recent" affair, ultimately driven by movement along the transform boundary between the Pacific and North American tectonic plates.

This boundary is best known by its surface expression as the San Andreas Fault, which extends more than 800 miles from the Salton Sea to Cape Mendocino. Its trace in southern California passes just north of the San Gabriel Mountains. The fault is not perfectly straight, however, and so additional deformation in the rocks on either side of the fault has occurred wherever that boundary bends and so the plates cannot simply slip past each other. The most prominent of these bends (the "Big Bend"; Kellogg 2004) lies northwest of the San Gabriel Mountains (Figure 3-2). Continued plate motion through this zone has resulted in uplifting of the Transverse Ranges of coastal southern California, of which the San Gabriel Mountains contain the highest peaks. The Arroyo Seco cuts across one of the major faults along which this uplift is occurring (the Sierra Madre Fault, which runs along the base of the San Gabriel Mountains).

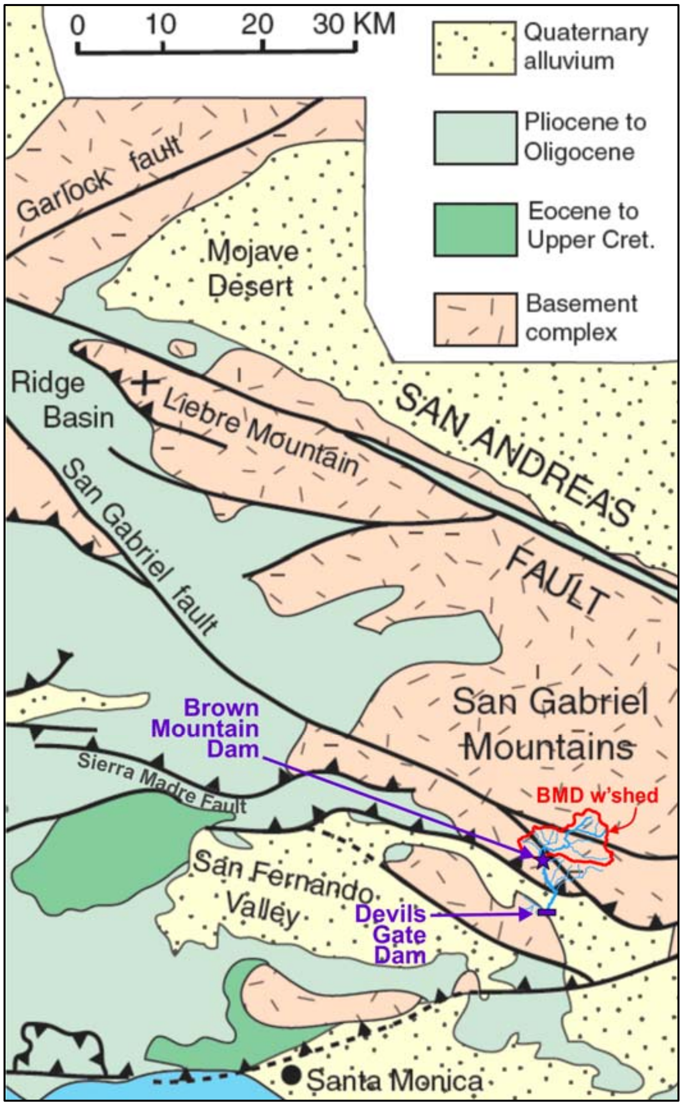


Figure 3-2. Regional geologic map, showing the relationship of the Brown Mountain Dam watershed (red outline) to major geologic structures and rock types. The Sierra Madre Fault is the "frontal fault" of the San Gabriel Mountains, along which much of the recent (7–10 million year) uplift has taken place. Base map modified from Figure 1 in Kellogg 2004.

The mechanical properties of the rocks underlying the watershed, almost exclusively grantic intrusions (variously granodiorite, tonalite, quartz monzonite, and quartz diorite; Yerkes and Campbell 2005) provide the raw materials for sediment ultimately delivered to and carried by the Arroyo Seco. The unweathered rock is hard and competent, capable of supporting steep slopes. However, the rock is cut with numerous joints and fractures associated with the faults and tectonic activity of the region, and so both mechanical and chemical weathering is locally intense, particularly on the oldest rock units in the watershed (e.g., Figure 3-3). Clast sizes range from large blocks down to the individual sand-sized mineral grains derived from the weathered granitics, which suffer further attrition during hillslope and fluvial transport.

Figure 3-3. Outcrop of weathered gneiss (cut by a dark dike running horizontally through the exposure) along the Angeles Crest Highway, yielding an abundance of fine- to medium-grained sediment to the drainage network (34.26345°N, 118.1777°W).

The recent uplift of the San Gabriel Mountains has been extensively studied, with rates that are among the most rapid world-wide. Estimated long-term uplift rates for the San Gabriel Mountains vary spatially from approximately 0.1 to more than 1 millimeter per year (mm/yr). Lavé and Burbank (2004) argued that uplift rates across the region should be fairly well-represented by sediment production rates, calculating a value of 1.3 mm/yr from a 76-year record of sediment removal at Devil's Gate Dam (1919 through 1995, the last survey prior to their published data). DiBiase et al. (2010) used measured concentrations in alluvial sands of ^{10}Be, a cosmogenic nuclide that decays at a known rate, to infer significantly lower uplift rates in the vicinity of the upper Arroyo Seco watershed (0.1–0.6 mm/yr; Figure 3-4). Although these two estimates cannot be directly reconciled, the general magnitude of uplift, and thus the sediment-production rates that are ultimately driven by this process, is apparent from the geologic data.

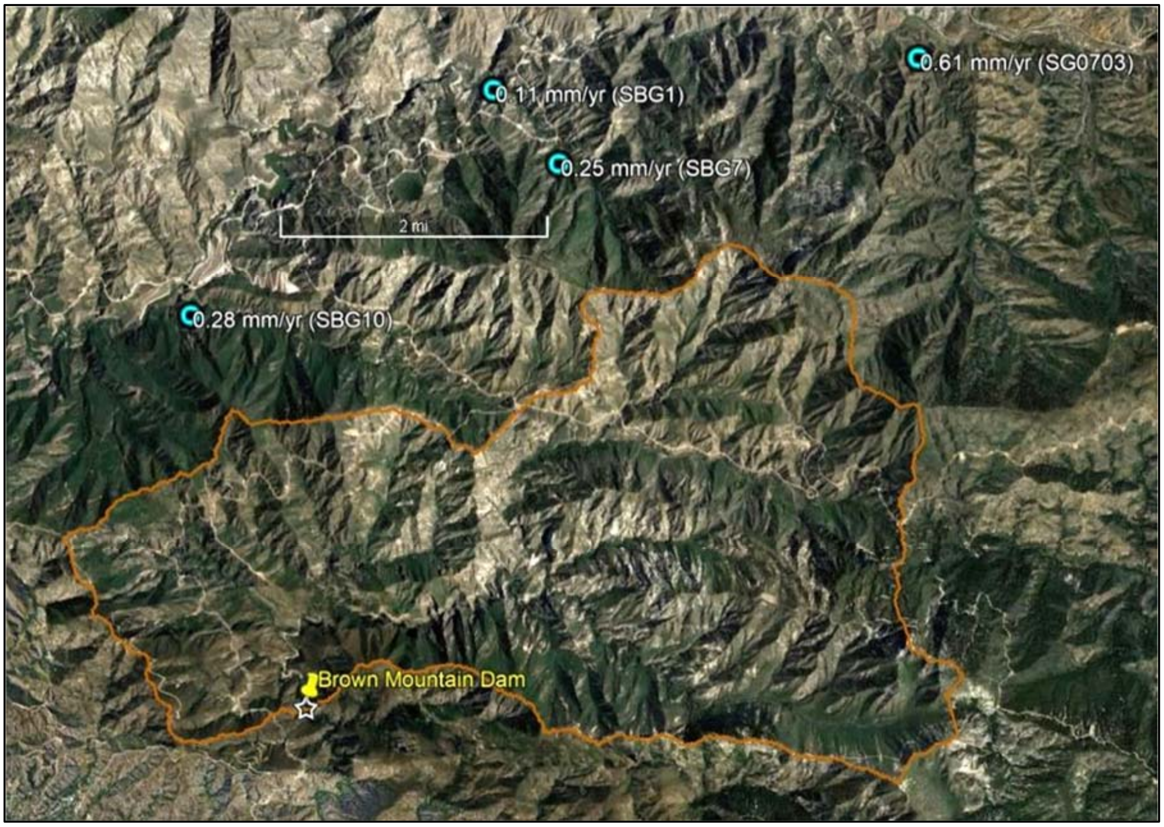


Figure 3-4. Uplift rates in the vicinity of the Brown Mountain Dam watersheds, from the closest samples reported by DiBiase et al. (2010). Their sample numbers (from Table 1) in parentheses.

3.2.3 Hydrology

The Arroyo Seco is typical of southern California rivers and streams, with long periods of low (and, locally, no) flow, punctuated by episodic large discharges from winter-season rainfall events. The history of flows at Brown Mountain Dam is well-represented by the long-term gage record at U.S. Geological Survey (USGS) gage #11098000 ("Arroyo Seco nr Pasadena, CA"; latitude 34°13'20", longitude 118°10'36", elevation 1,398 feet), which has recorded flows somewhat sporadically beginning in 1910 and continuously since mid-1916. The gage, located about 2 river miles downstream of BMD, provides a reliable surrogate for flows at the dam, given their near-equivalent drainage areas (14.4 square mile [mi^2] at the dam versus 16.1 mi^2 at the gage). An example of the daily flow record from the gage is shown in Figure 3-5, and the record of annual peak flows is shown in Figure 3-6.

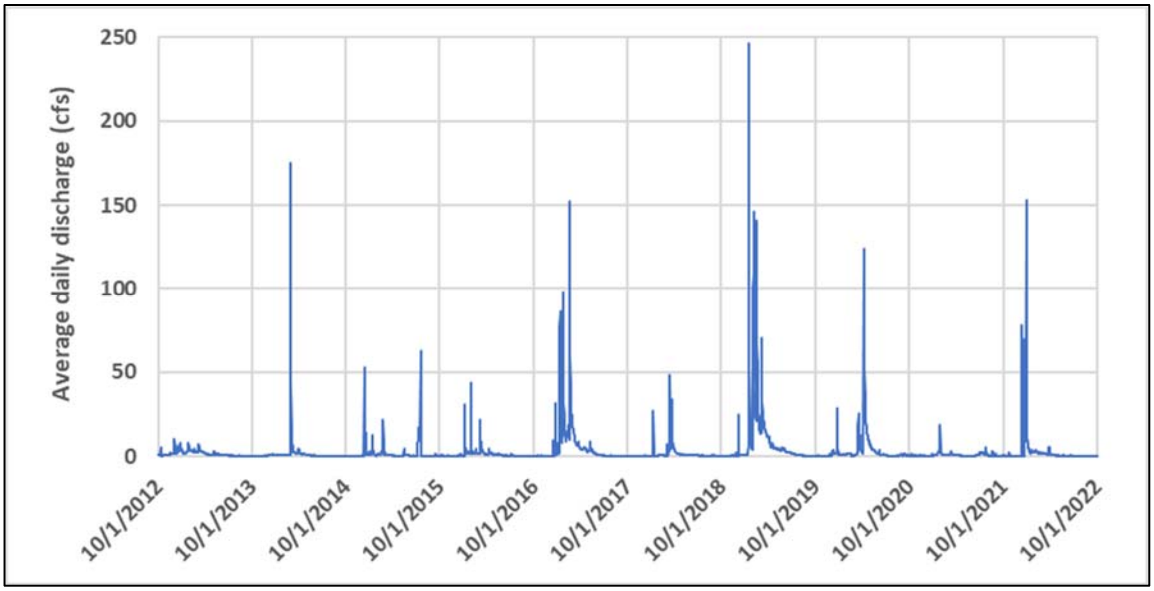


Figure 3-5. Average daily flows at U.S. Geological Survey gage #11098000 for the last decade, emphasizing both the sporadic nature of high flows and the interannual variability between wet (e.g., 2019) and dry (e.g., 2013) years. Vertical grid lines mark the start of each water year (October 1).

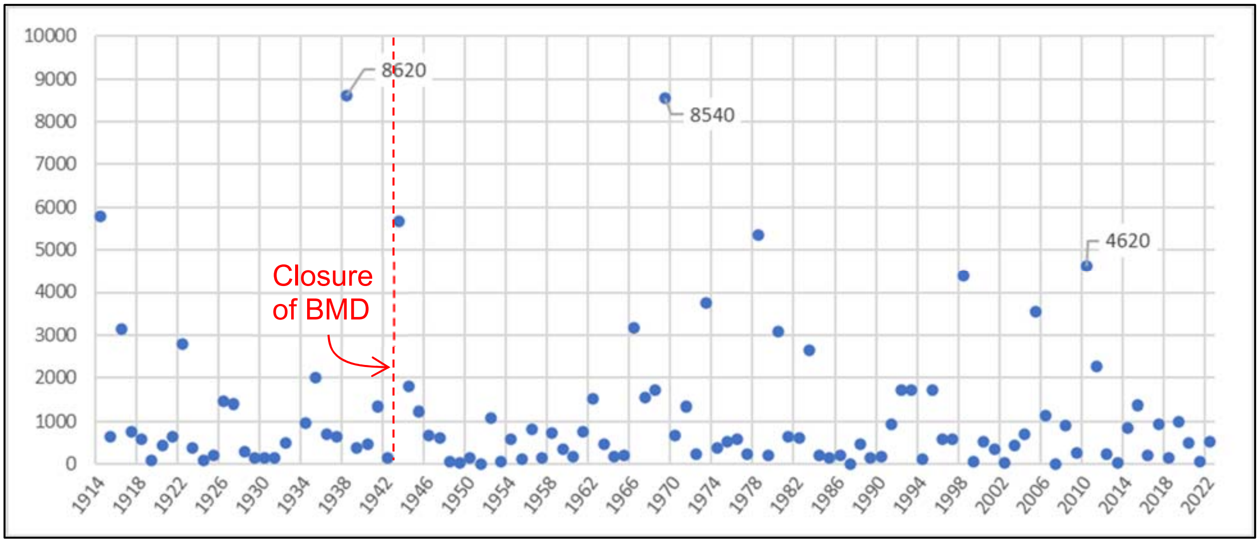


Figure 3-6. Annual peak discharges at U.S. Geological Survey gage #11098000, by water year (October 1-September 30). Values (in cfs) labeled for the two largest peaks in the record, plus largest peak of the last 40 years. The relatively modest peak discharges of the last decade relative to the full record are apparent.

With a long gage record, the magnitude of various flood recurrences can be reliably estimated using US-standard methodology (Table 3-4). The ratio of the 100-year to the 2-year flood (over 16:1) puts the Arroyo Seco amongst the most hydrologically variable river systems world-wide (Lewin 1989). Similarly, a flow-duration analysis (Figure 3-7) emphasizes the dramatic differences between “wet” and “dry” years here. In general, the channel is recorded as fully dry (i.e., Q = 0) less than 3% of the time, and only in about one-quarter of the years of record, but it registers less than 1 cfs for more than one-third of the time (i.e., over 100 days/year, on average). The Arroyo Seco can thus be characterized as "nearly dry" for much of the year.

Table 3-4. Flood recurrence discharges from the gage record at U.S. Geological Survey gage #11098000 (using Bulletin 17B methodology, as implemented at www.eRAMS.com).

Return period (year)	Instantaneous peak discharge (cfs)	Range (95% confidence intervals) (cfs)	Representative years
200	11,347	7,753–17,996	< none recorded >
100	8,824	6,155–13,619	1938, 1969
50	6,635	4,734–9,936	
40	5,999	4,315–8,891	1914, 1943
25	4,769	3,490–6,907	2011
20	4,236	3,126–6,064	1998
10	2,784	2,113–3,832	1973, 2005
5	1,628	1,273–2,147	2015
2	535	428–670	2020
1.5	293	231–367	1928, 2009
1.25	157	119–200	1988, 2018

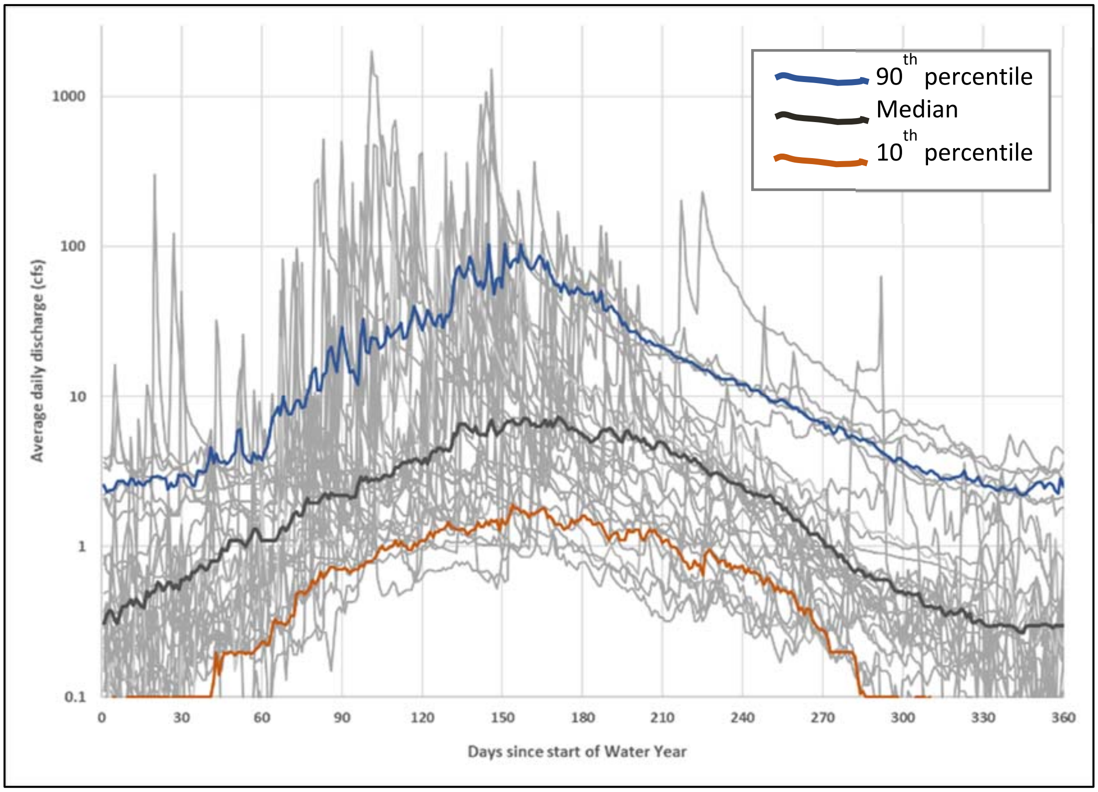


Figure 3-7. Flow-duration curves for U.S. Geological Survey gage #11098000 based on average daily flows. The 90th, median (50th), and 10th percentile flows are based on the continuous flow record (water years 1917–2022); the gray lines show the daily flows for each of the last 30 individual years. Day 1 = October 1st of each year. Note the nearly two orders of magnitude difference between the 10th and 90th percentile flows, reflecting the dramatic differences between dry and wet years.

Climate-change projections (e.g., Swain et al. 2018) suggest that the values in Table 3-4, all based on a presumed continuation of the current climatic regime, may be modest underestimates of the likely flood-recurrences magnitudes over the remainder of the 21st century. Nonetheless, they provide a good indication of the overall magnitude of anticipated peak flows. Because they are generated from a gage with about 10% greater watershed area than at BMD, they also modestly overestimate the current flow regime at the dam (although probably just for the immediate present and near-term future). Climate-change scenarios have generally been based on projections out to the mid- or late 21st century, but the last 100 years suggest that divergence from the historical record are, as yet, difficult to discern from natural variability—except, perhaps, for an earlier end of peak winter storms by about a month, and a correspondingly earlier end of the spring recession (Figure 3-8).

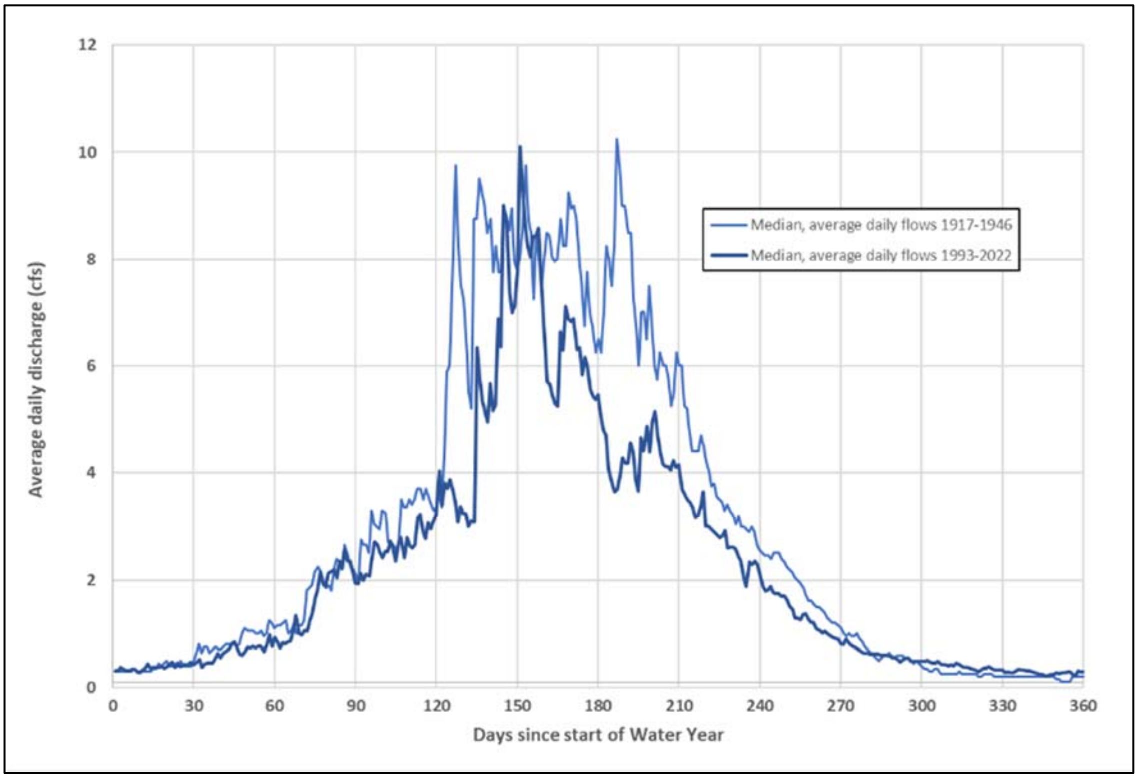


Figure 3-8. Median flows for two 30-year intervals at the beginning and the end of the gage record at U.S. Geological Survey gage #11098000. Overall magnitudes and dry-season flows are quite similar for both periods, but the end of winter storms appear to have shifted earlier in the water year to around Day 180 (end of February), thus reducing the overall wet-period duration. Day 1 = October 1.

3.2.4 Channel conditions and instream infrastructure

3.2.4.1 Upstream of BMD

Based on limited field observations, the Arroyo Seco upstream of BMD is predominately a boulder-cascade to plane-bed channel. Abundant coarse boulders, with median grain diameters of about 60 mm but maximum sizes up to half a meter, dominate the channel morphology and limit the formation of more regular pool–riffle sequences that would otherwise be expected at channel gradients between 1% and 2%. The channel is marginally in the “braided” field by the analytical frameworks of both Eaton et al. (2010) and Kleinhans and van den Berg (2011), and some braiding is present in wider portions of the valley (Figure 3-9). Along most of the channel, however, the active channel is confined to a relatively narrow valley by bedrock walls or in wider sections of the valley, by older flood sediments (Figure 3-10), presumably deposited during periods of high sediment delivery (e.g., recent post-fire high flows). Thus, lateral space is generally limited for developing a consistently multi-thread planform.

Figure 3-9. Braided reach of the Arroyo Seco at a broad zone of the valley, about 3,000 feet upstream of Brown Mountain Dam (view looking upstream on 6 January 2023). Inset image from Google Earth marks the location of the photograph (yellow pin).

Figure 3-10. Multiple levels of flood deposits confining the active channel of the Arroyo Seco, about 5,500 feet upstream of Brown Mountain Dam.

3.2.4.2 Downstream of BMD

The Arroyo Seco downstream of BMD is similar to the upstream channel—predominately a boulder-cascade to plane-bed channel, albeit with a lower density of coarse boulders. The channel is somewhat flatter with an average gradient of about 0.8%, in the field of "moderate braiding and meandering" of Kleinhans and van den Berg (2011).

For the 3 miles immediately downstream of BMD, multiple crossings associated with degraded infrastructure pose moderate-to-severe barriers to fish passage and limited impediments to downstream sediment transport. A more complete inventory and assessment of these features has been prepared (Stillwater Sciences 2024) under a separate phase of this project.

The first significant feature in the channel geomorphology downstream of BMD is a constructed sediment trap at river mile (RM) 2.19, about 3.2 miles below the dam and 4,200 feet upstream of Explorer Road bridge. Three large concrete barriers and a right-bank weir provide sufficient flow resistance to induce upstream sedimentation in the form of a large, low-relief gravel bar (Figure 3-11).

Figure 3-11. Top, the two right-most barriers and the attached weir at the downstream end of the sediment trap. Bottom, view upstream of the sediment deposit.

During the January 2023 storms, the flow resistance imposed by the sediment trap was too great to allow full passage of the discharge. The channel broke through an upstream deflection berm along the left bank, avoiding this area altogether and taking out a section of the access road (with repairs completed in early February 2024).

Between the sedimentation facility and the next major barrier, the Pasadena Water and Power diversion weir at RM 1.81, the channel is a fairly uniform boulder cascade channel. The diversion weir imposes a drop in the channel profile of about 2 feet, followed by an even larger step at the bridge crossing by the Gabrieleno Trial at RM 1.71. Downstream of this bridge, the channel retains a cascade morphology and passes through another trail-crossing bridge at RM 1.53 without apparent significant impediment (albeit a somewhat undersized opening for passing high flows). For the final 1.2 miles before Devil's Gate Dam, the flow emerges into a broadly unconstrained basin where deposition of all but the finest sediment occurs before passing through the dam, under I-210, and flowing through a concrete flood-control channel to the confluence with the LA River.

3.2.5 Reservoir sediment grain-size distribution

In the absence of direct measurements, data from various other debris basins draining granitic-dominated watersheds, similar to the bedrock geology of the Arroyo Seco, provide a reasonable initial estimate of the sediment characteristics of the deposit behind BMD. Taylor (1981, his Tables B4-3 and B4-4) suggested that a ratio of 20:50:30 (fines:sand:gravel, with the boundaries set at 0.06 mm and 2 mm) provided a reasonable generalization of the sediment derived from such terrains. Some corroboration can be gained from later measurements based on hand-augered test pits behind Devil's Gate Dam (LACDPW 2013; Figure 3-12), which yielded ratios that ranged from 0:60:40 to 35:15:50. Additional borings reported in Appendix F of LACFCD (2013) yielded sediment-size ratios that varied over a range similar to that shown in Figure 3-26—near the head of the reservoir deposit, the fines:sand:gravel ratio averaged about 10:75:15; closer to the dam itself, at a depth of 10 feet, the distribution was about two-thirds fines with no gravel.

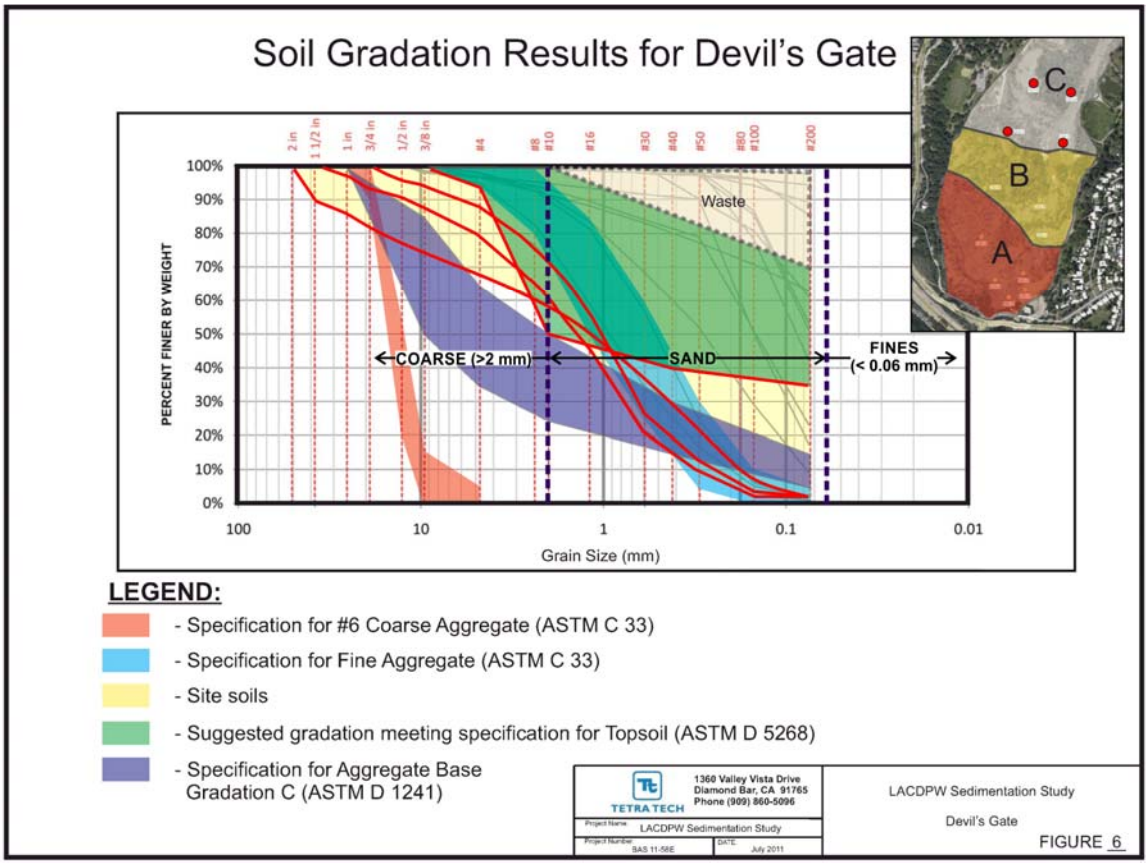


Figure 3-12. Sediment size gradations for 12 samples taken behind Devil Gate Dam. The four sites closest to the upstream end of the reservoir (red circles on inset map, red curves on graph) are assumed to most closely represent the grain sizes farther upchannel (e.g., behind Brown Mountain Dam). Modified from Figure 6 in Appendix E of Los Angeles County Department of Public Works 2013.

3.2.6 Sediment volume behind Brown Mountain Dam

Multiple methods are available to determine the current sediment volume impounded behind BMD. The difference between the original and modern valley topography yields the volume of impounded sediment, but that original surface is challenging to reconstruct. The modern sediment surface is well-represented by a USGS light detection and ranging (LiDAR) survey performed in 2015–2016 (see https://www.usgs.gov/3d-elevation-program) that covered much of the greater LA River basin (including all of the Arroyo Seco watershed) (Figure 3-13). To generate a representation of the original topography, four methods have been used that, in combination, provide a robust order-of-magnitude estimate of the average long-term sediment delivery to BMD.

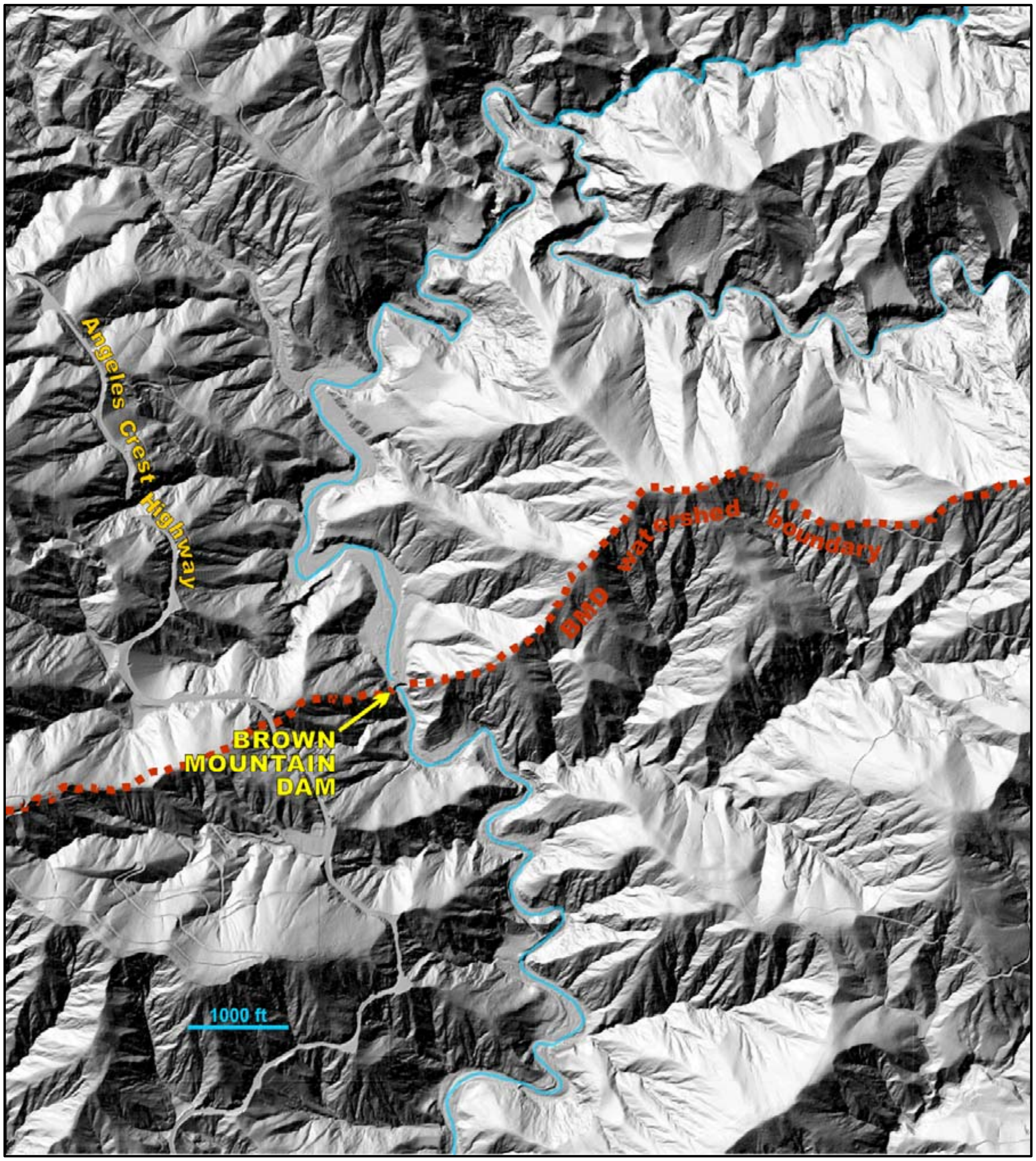


Figure 3-13. Shaded relief image centered over the channel of Arroyo Seco in the vicinity of Brown Mountain Dam. LiDAR base from U.S. Geological Survey.

3.2.6.1 Triangular valley cross section

The Arroyo Seco Foundation (Frame 2012) assumed a simplified original triangular valley cross section and, based on visual inspection of Google Earth imagery, a uniform modern valley width of 140 feet and a uniformly thinning valley fill from 81 feet at the dam itself to zero thickness 7,000 feet upstream (Figure 3-14). The volume of this tapering triangular prism was reported as "just over one million cubic yards."

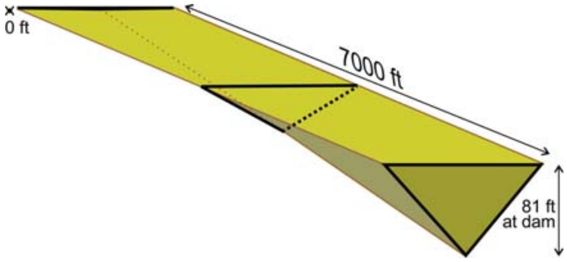


Figure 3-14. The simplified geometry from Arroyo Seco Foundation's (2012) estimate of reservoir sediment volume.

3.2.6.2 Historical documentation

A second method presented in the 2012 analysis made use of a mid-1943 survey conducted by the USFS following a major storm in early 1943. At the time of that survey the reservoir had already accumulated a significant sediment load, reported by Raya (2014) to have been estimated at 320,000 yd^3. By approximating the width and surface elevation of the modern reservoir sediment deposit at each of the 32 USFS cross sections (Figure 3-15) using the then-current (2011) Google Earth imagery, Frame (2012) calculated 650,000 yd^3 of post-1943 accumulation, yielding 970,000 yd^3 of total sediment accumulation behind BMD since its construction.

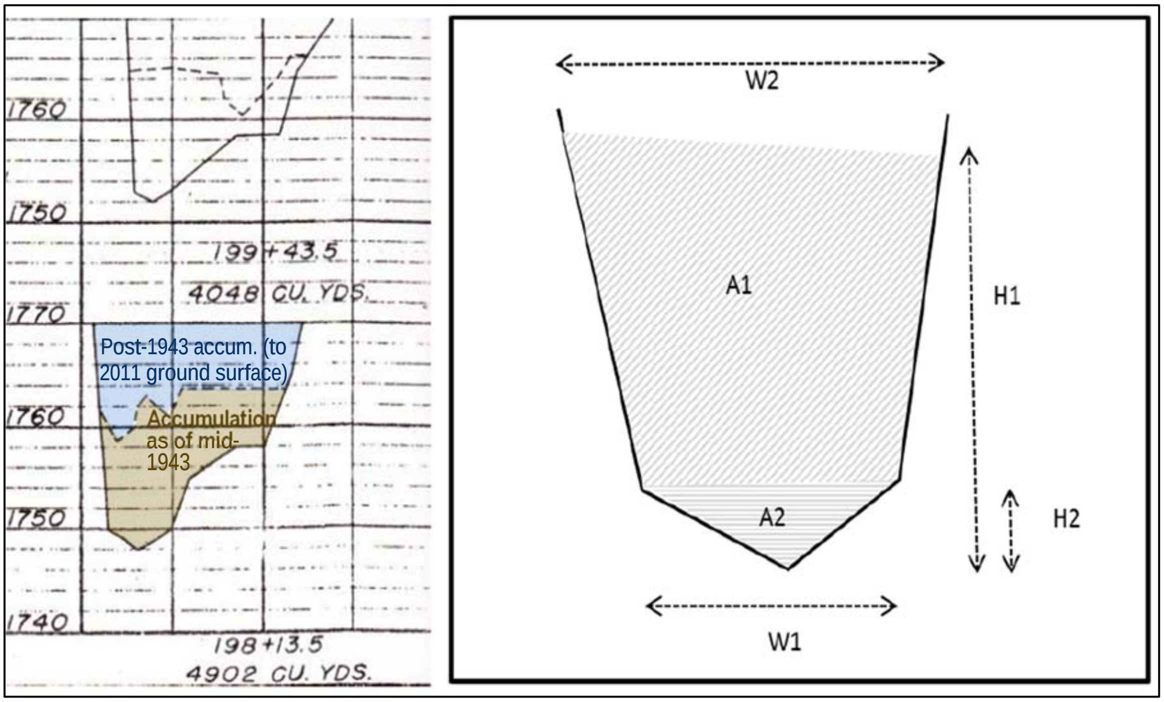


Figure 3-15. Geometry for calculating sediment volumes from the post-1943 survey. Left panel, examples from the 1943 survey—dashed line shows the top of the deposit as of mid-1943, brown area is accumulation as of mid-1943, and blue area is the post-1943 accumulation. Right panel, the simplified geometry used to estimate post-1943 volume, where "W2" is the width of the modern deposit (from Google Earth) and "H1" is the maximum difference in elevation between the 1943 and modern surfaces.

3.2.6.3 LiDAR-based estimates

The recent availability of LiDAR topography (see Figure 3-13) has allowed further refinement of the above volume estimates. An accurate profile of the channel thalweg (low point along every valley cross section) shows a virtually uniform gradient of 1.73% that diverges, between stations -7575 and -6000, from a gradient of 2.45% projected from farther upstream (Figure 3-16). Eleven valley cross sections were cut from the LiDAR digital elevation model (DEM) to capture the dominant variability in topography through the ~7,000 feet of channel upstream of the dam that appears to be measurably affected by sediment accumulation (Figure 3-17). Using a modern valley width measured at each station, an assumed original valley width, and the depth from the modern ground surface to the projected original ground surface, trapezoidal cross sections through the reservoir deposit can be generated. Averaging these trapezoidal cross-sectional areas of adjacent stations and multiplying by the distance between them yields a volume, which can then be summed for all segments. The least well-constrained parameter, the original width of the (now-buried) valley, is also the least sensitive parameter: an original valley width of 50 feet yields a total accumulation of 1.3 million yd^3; using a width nearly twice as wide (90 feet), the value is still about 1 million yd^3.

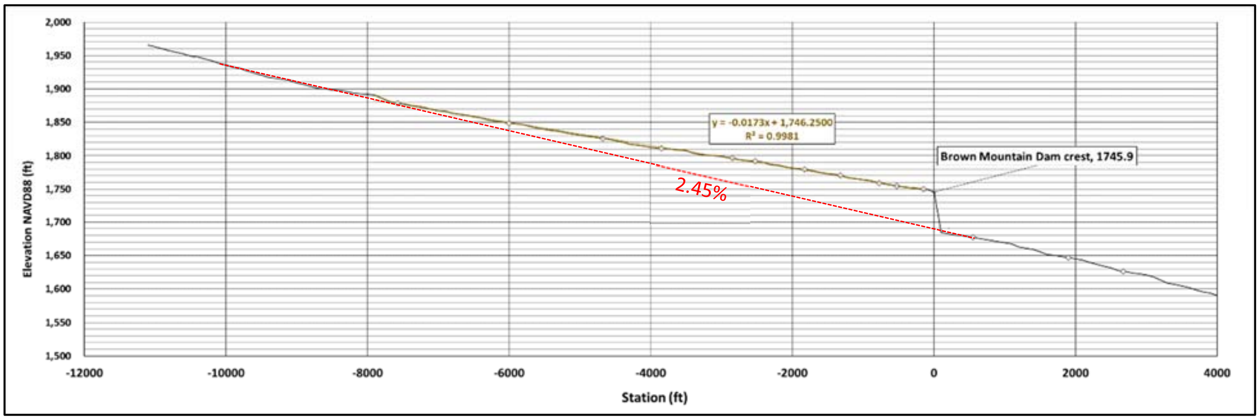


Figure 3-16. Channel profile derived from the 2015-2016 LiDAR survey, following the lowest point in the valley at each station. The resulting profile is virtually linear with a gradient of 1.73%; a steeper (pre-dam) slope results from projecting the gradient from farther upstream and connecting it with the channel downstream of the dam (red dashed line). Individual cross sections used in the volume analysis are marked by open diamonds.

Figure 3-17. Shaded topography from the 2015–2016 LiDAR. Station numbering marks distance in feet upstream (negative) and downstream (positive) of the dam. Dashed black lines mark cross-sectional locations for volume calculations.

3.2.6.4 Cross sections using LiDAR

The final method for calculating the volume of the reservoir deposit makes use of the geometry of each individual valley cross section, also derived from the LiDAR topography. At each cross section, the valley walls were projected down at a constant gradient to the level of the pre-dam profile shown in Figure 3-16. A flat pre-dam valley bottom was assumed, as with the previous approach, but the presumed width at each cross section varied between 50 and 160 feet depending on the valley-wall gradients and the separation of the valley walls at the elevation of the projected original channel grade. The result is a set of crudely trapezoidal cross sections (Figure 3-18), with adjacent sections’ areas measured graphically and averaged, multiplied by their separation, and summed as above (Table 3-5).

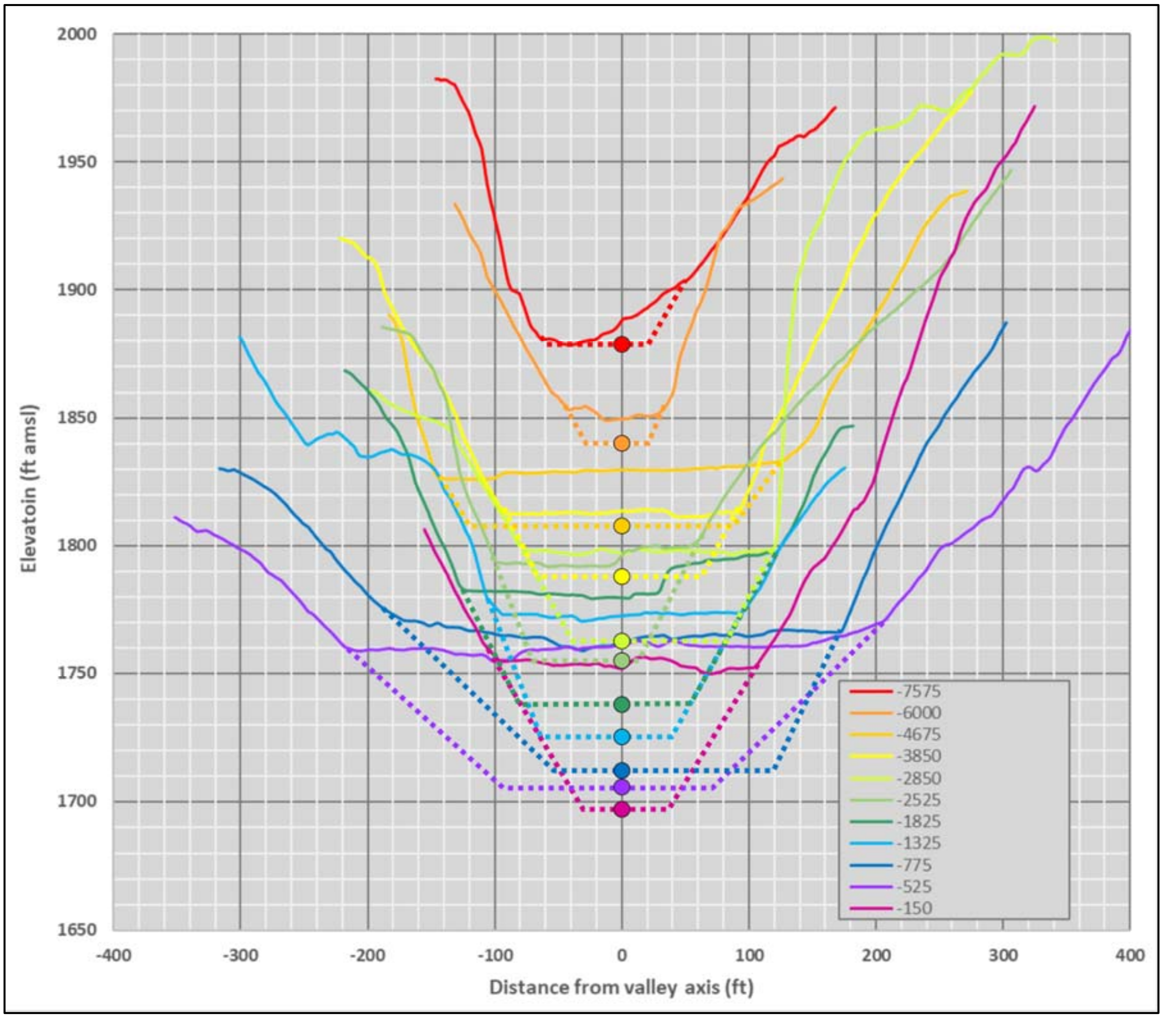


Figure 3-18. Valley cross sections from LiDAR (solid lines), with their projection (dotted lines) to the level of the projected pre-dam profile (colored circles). Station numbers indicated in the graph legend. The area of accumulated sediment at each section was determined by summing the number of 10-foot × 20-foot squares between the dotted and solid lines (vertical exaggeration 2×).

Table 3-5. Volume calculations using the graphical layout of Figure 3-18. The final value, nearly 1.3 million yd^3, is assumed to provide the most accurate estimate of the sediment volume accumulated behind Brown Mountain Dam.

Station	X-sect area (ft^2)	Distance to next station (ft)	Averaged x-sect area (ft^2)	Segment volume (ft^3)	Segment volume (yd^3)
-150	6,800	150	6,800	1,020,000	37,800
-525	13,200	375	10,000	3,750,000	138,900
-775	12,000	250	12,600	3,150,000	116,700
-1325	6,800	550	9,400	5,170,000	191,500
-1825	7,200	500	7,000	3,500,000	129,600
-2525	4,000	700	5,600	3,920,000	145,200
-2850	5,600	325	4,800	1,560,000	57,800
-3850	3,600	1,000	4,600	4,600,000	170,400
-4675	4,600	825	4,100	3,382,500	125,300
-6000	640	1,325	2,620	3,471,500	128,600
-7575	500	1,575	570	897,750	33,300
				34,422,000	1,274,000

In summary, four semi-independent methods for estimating the sediment volume accumulated behind BMD yield broadly equivalent results. They range between 970,000 and 1.3 million yd^3, with three of the four converging at somewhat greater than 1 million yd^3. Because the fourth approach (Figure 3-18) is likely the most accurate and also among the most conservative (i.e., largest) estimate for evaluating potential future implication of sediment release, its value of **1.27 million yd^3** is presumed to be most appropriate for the present application. Somewhat coincidentally, this is essentially the *same* volume of sediment delivered to Devil's Gate Reservoir in the two wet seasons following the 2009 Station Fire (1.3 million yd^3; LACFCD 2014, p. ES-4).

3.2.6.5 Sediment-release dynamics

However, the volume of reservoir sediment is not necessarily equivalent to the volume of sediment that would be released in the period immediately following dam removal. Downcutting of the flow to regain the original, pre-dam grade of the Arroyo Seco through the reservoir area (see Figure 3-19) will leave a crudely trapezoidal valley whose volume will include some, but not necessarily all, of the sediment infill (see Cui et al. [2017] for an equivalent analysis). Existing upstream channel analogs for the initial post-dam geometry suggest a 45-foot-wide valley bottom with 2:1 sideslopes, which result in a calculated initial eroded volume of 870,000 yd^3, about two-thirds of the total fill (compare to Figure 3-18).

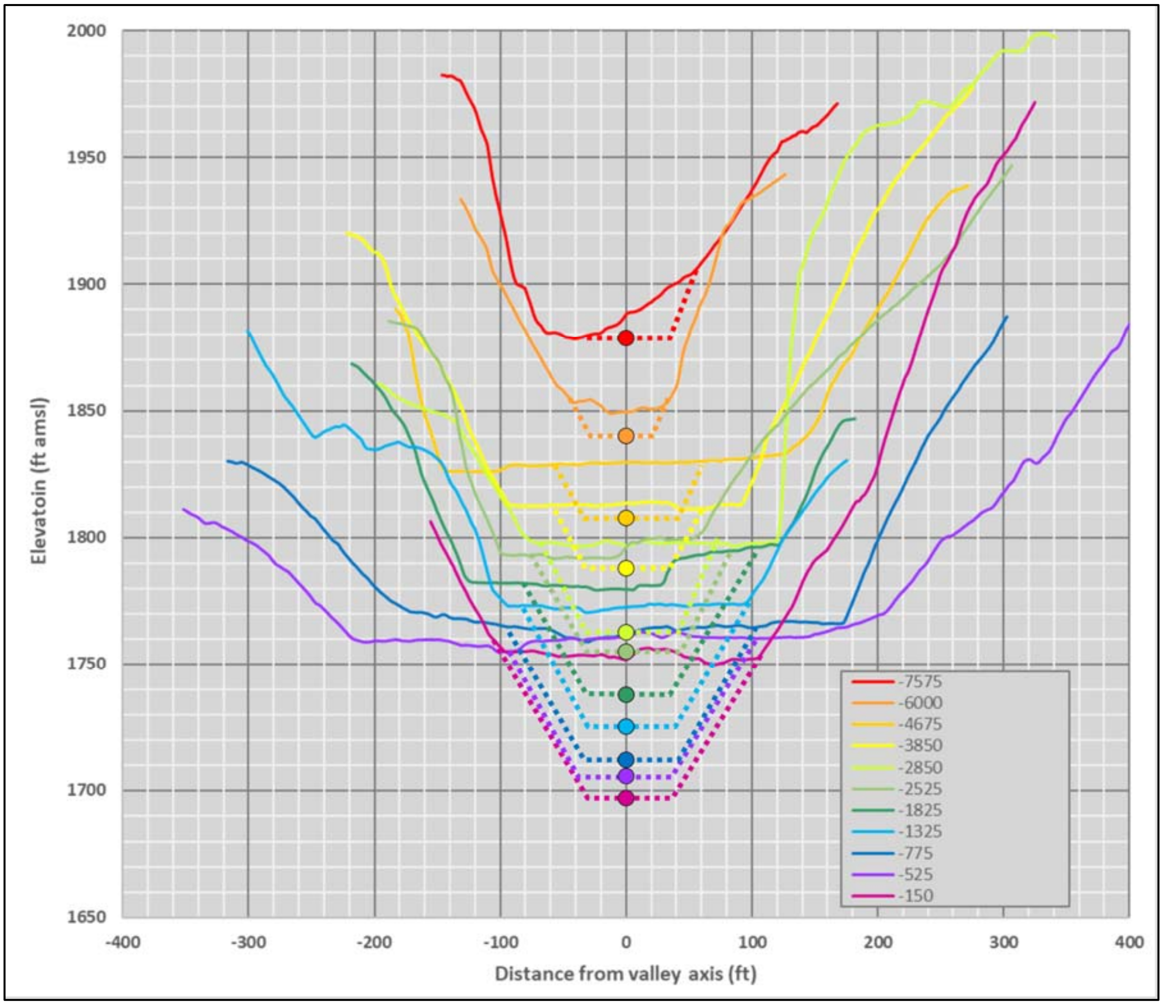


Figure 3-19. Valley cross sections as in Figure 3-18, but the dashed profiles here show a uniform post-dam-removal geometry with 45-foot bottom widths and 2:1 sideslopes, similar to the upstream-most valley cross sections. The areas enclosed by the dotted and solid lines represent the generalized volume of sediment that would have to be initially eroded for the channel to regain its original grade following dam removal (vertical exaggeration 2×).

3.2.7 Ecology

The presence of large barriers, such as BMD, limit natural movement patterns of aquatic and semi-aquatic species and disrupt ecological processes within stream and riparian habitats. This section describes the exiting ecology within the upper Arroyo Seco watershed and the impacts of BMD on that ecology.

BMD is located in a region with a Mediterranean climate, characterized by long, hot, dry summers and cooler, wet winters. Ninety-five percent of the precipitation occurs from November to April with seventy-five percent occurring from December to March. Precipitation increases with altitude. The average annual precipitation is 20 inches in the lower elevations and up to 30 inches in the higher elevations. Most years, however, deviate substantially from these averages during frequent years of drought and flood. Climatic records show dramatic cyclic variations with little predictability (NET and ASF 2002). Wildfires are also a natural feature of the region but have increased in frequency and severity due to climate change and other anthropogenic factors, particularly land use. Overall, the biota that now exist in the region have been shaped by and adapted to these dynamic conditions, but anthropogenic changes, such as dams, have further altered these relationships.

Despite heavy anthropogenic influences within the watershed, vegetation in the upper Arroyo Seco watershed is relatively undisturbed and retains much of its historical ecological character (Jigour et al. 2002). Due to the climate and geology, vegetation within the upper Arroyo Seco is dominated by Valley Foothill Riparian, Montane Hardwood, Montane Hardwood-Conifer, Mixed Chaparral, and Coast Oak Woodland habitat types (according to the California Wildlife Habitat Relationship classification; CDFW 2024).

Of the major habitats in the watershed, the Valley Foothill Riparian has the closest interdependence with the stream channel itself. It is dominated by cottonwoods (*Populus* sp.) and California sycamore (*Platanus racemose*). These riparian habitats can also contain white alder and bigleaf maple. Riparian vegetation shelters and provides the food web for riverine ecosystems supporting *O. mykiss* and other aquatic species. Riparian habitats are strongly influenced by the structure and health of their associated riparian vegetation, as well as by natural fluvial (flooding) disturbance and renewal. For example, the semi-open canopies favored by species such as Yellow Warbler (*Setophaga petechia*) are typically shaped by the combination of flood disturbance and ensuing natural succession by disturbance adapted riparian plant species.

The Montane Hardwood habitat is dominated by canyon live oak (*Quercus chrysolepis*) and California black oak (*Quercus kelloggii*). This habitat type is very stable because of the large number of hardwood and conifer species present. It can persist in a wide range of environments, including a variety of soil types, slopes, and disturbance regimes. The oaks provide acorns and foliage as food for a variety of birds and mammals, and many amphibians and reptiles are found on the forest floor in this habitat type.

Montane Hardwood–Conifer habitat is dominated by ponderosa pine (*Pinus ponderosa*), incense cedar (*Calocedrus decurrens*), and California black oak (*Quercus kelloggii*), typically found in the higher elevations of the watershed. The canopy cover and understory vegetation are variable, which provides suitable habitat for many wildlife species. Mature trees provide habitat for cavity nesting birds. Amphibians can sometimes be found in the detrital layer.

The Mixed Chaparral habitat is dominated by scrub oak (*Quercus berberidifolia*), ceanothus (*Ceanothus* sp.), and manzanita (*Arctostaphylos* sp.). This habitat can also contain California buckwheat (*Eriogonum* sp.), laurel sumac (*Malosma laurina*), black sage (*Salvia mellifera*), California sagebrush (*Artemisia californica*), birchleaf mountain mahogany (*Cercocarpus betuloides*), and chamise (*Adenostoma fasciculatum*). Chaparral associations are characterized by the typically small, thick, stiff, evergreen leaves of its dominant species. This leaf feature is referred to as schlerophyllous, meaning "hard-leaved"—a moisture-conserving adaptation to the summer droughts. As the quintessential fire-adapted vegetation type in California, chaparral typically experiences fire-return intervals of 10 to 40 years (Hanes 1977). Along with an abundance of fire-following annuals and perennials, coastal sage scrub species may serve as early colonizers of chaparral sites for some years after a burn.

The Coastal Oak Woodland habitat is dominated by coast live oak (*Quercus agrifolia*) as well as Engelmann oak (*Quercus engelmannii*), which is mainly found in Hahamongna (a Tongva village archeological site) just above Devil's Gate Dam. Fire is also important here in maintaining some open stands of coastal oak woodland, as the dominant oak species are able to survive most fires. The oaks provide food and habitat for a variety of wildlife species, especially birds and mammals.

Streams in the foothill and mountain regions are dominated by riffle and step-pool bed morphology and relatively coarse substrates including gravel, cobble, and boulder that provide spawning and rearing habitat for steelhead and some other native fishes. Cool groundwater, combined with dense vegetation and steep canyon walls can shade these streams and support water temperatures that are favorable for native fish (Mongolo et al. 2017). These conditions may have historically supported native fish species, including arroyo chub (*Gila orcuttii*), rainbow trout (resident *O. mykiss*), Santa Ana speckled dace (*Rhinichthys osculus*), and Santa Ana sucker (*Catostomus santaanae*). Many non-native fish occur across the LA River watershed, but non-native species have not been observed in the Arroyo Seco above Devil's Gate Dam (J. Stanovich, CDFW, pers. comm. March 14, 2024). The removal of this barrier downstream of BMD, although motivated to provide fish passage for anadromous steelhead, will potentially create the opportunity for dispersal of non-native fish, if any exist.

Although rainbow trout historically occurred upstream of BMD, no fish (including rainbow trout) were observed in the upper Arroyo Seco following the 2009 Station Fire, indicating they were potentially extirpated or present at extremely low densities. In 2020, following the Bobcat Fire, rainbow trout from the West Fork of the San Gabriel River and Bear Creek were translocated into the Arroyo Seco between BMD and Devil's Gate Dam (Paretti 2020).

Favorable habitat for *O. mykiss* (i.e., deep pools, riffles, cool, clean, oxygen-saturated water, instream cover, clean permeable gravel, woody debris, and boulders) still occurs in the Arroyo Seco above Devil's Gate Dam, as evidenced by the presence of a persistent resident population and successful spawning in recent years (CDFW 2023; The Arroyo Seco Foundation, unpubl. data; K. Uhl, pers. comm., February 3, 2024). The reaches upstream of BMD contain more than 6 miles of high-quality habitat, but fish are not able to access this habitat. Eleven potential anthropogenic barriers, including the Pasadena Water and Power diversion and several road crossings, exist between Devil's Gate Dam and BMD and further limit movements of fish (Stillwater Sciences 2024).

BMD also likely blocks the movement of some terrestrial species. Many terrestrial species use washes and culverts as movement corridors, including California quail (*Callipepla californica*) and mule deer (*Odocoileus hemionus*) (Jigour et al. 2002). Artificial structures can block the movement of mountain lions (*Puma concolor*), and in their absence, gray fox (*Urocyon cinereoargenteus*) populations can increase and lead to depletion of native bird populations. Natural movement of larger predators like bobcats (*Lynx rufus*) and coyotes (*Canis latrans*) can keep gray fox populations in check to protect native bird populations in the absence of mountain lions (Jigour et al. 2002).

3.2.8 Preliminary seismic assessment

3.2.8.1 Foundation conditions

As-built construction drawings of BMD prepared by USFS show the dam being founded on bedrock (USFS 1943). The foundation elevation varies along the axis of the dam. The drawings indicate the deepest section of the foundation is at an approximate elevation of 1,677 feet above mean sea level. The foundation is benched into the bedrock in steps and becomes shallower toward the abutments (Figure 3-20).

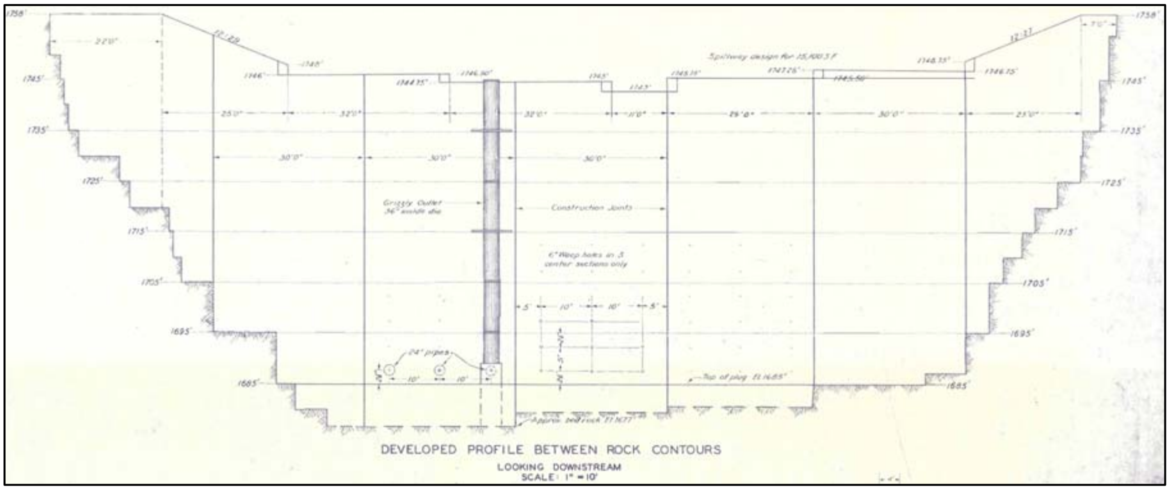


Figure 3-20. As-built construction drawing for the profile of Brown Mountain Dam looking downstream (USFS 1943).

Regional geologic mapping classifies the bedrock at the project site as Mesozoic biotite monzogranite (Mzmg). The rock is mantled by young alluvial wash deposits from the Holocene era (Figure 3-21, Campbell et al. 2014).

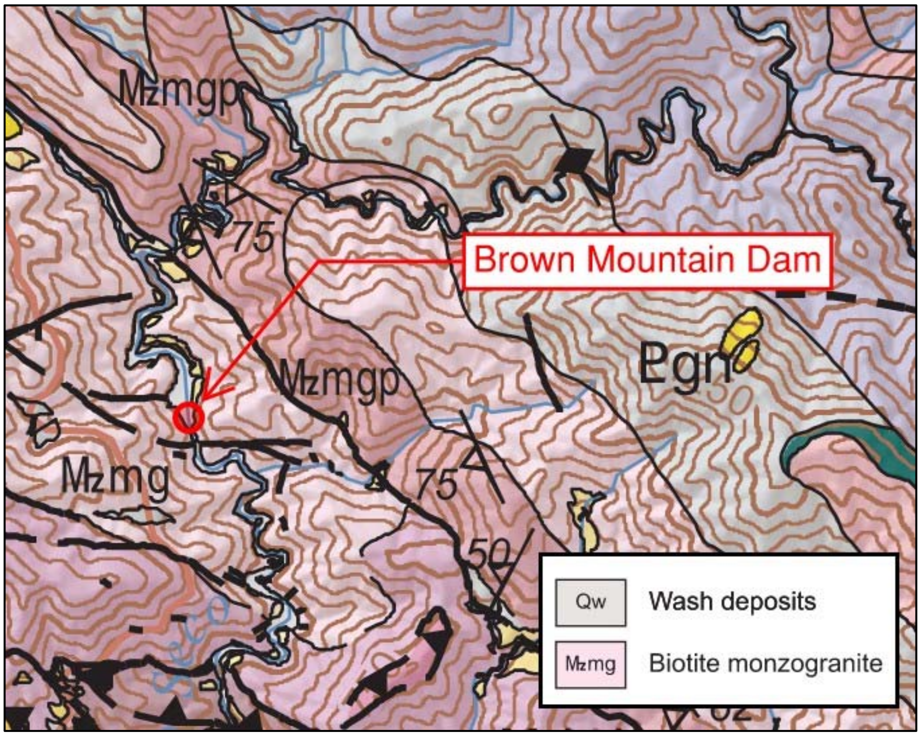


Figure 3-21. Geologic map with the approximate location of Brown Mountain Dam in red. Base map modified from the preliminary geologic map of the Los Angeles 30’ x 60’ quadrangle (Campbell et al. 2014).

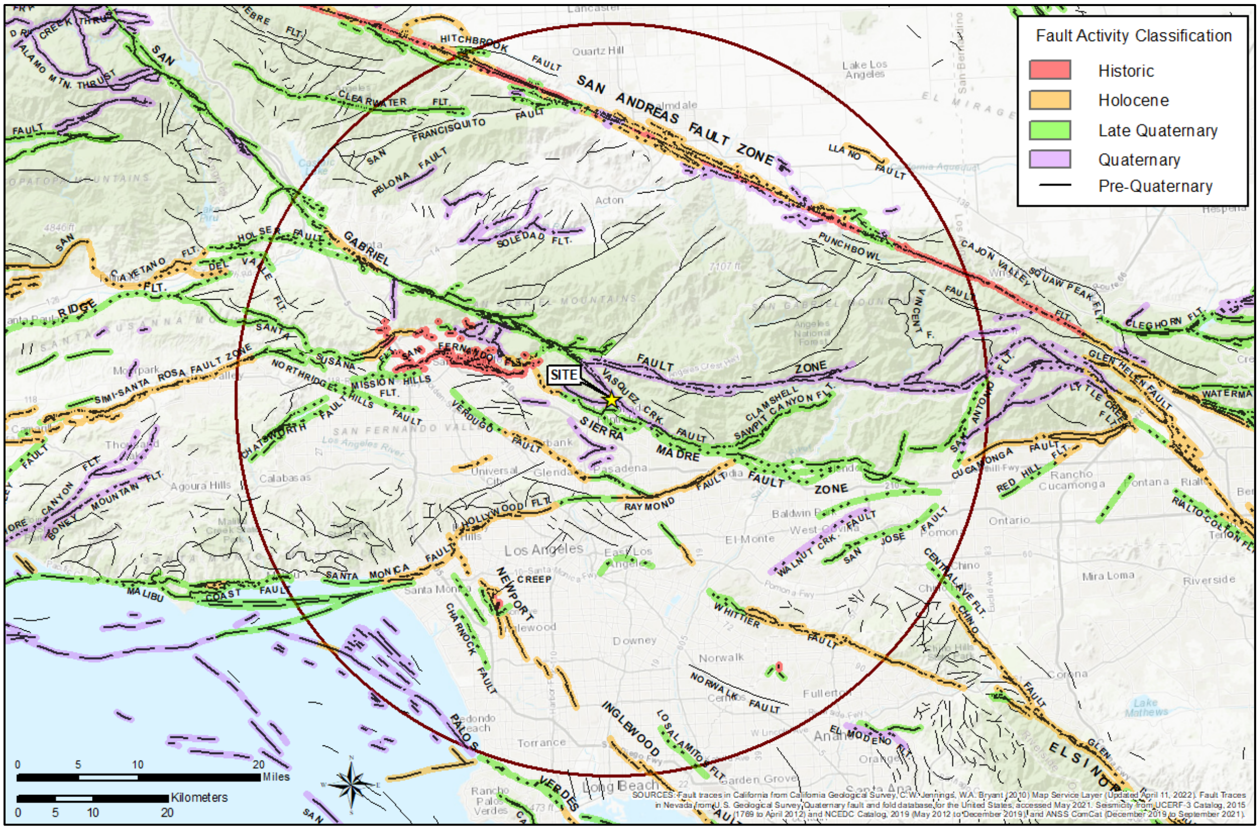
3.2.8.2 Regional faulting

BMD is located within the highly seismic Central Transverse Ranges Province. Many active and potentially active faults are present within and around the region and are potential seismic sources, including the San Andreas, San Gabriel, and Sierra Madre Fault zones (USGS 2008). Table 3-6 lists significant Quaternary faults and their respective properties (orientation, slip rate, site distance, probable moment magnitudes) within 25 miles of BMD. Figure 3-22 shows a regional map of the fault traces listed in Table 3-6.

Table 3-6. Significant Quaternary faults with highest potential for ground shaking within 50 kilometers of Brown Mountain Dam. Fault data obtained from the National Seismic Hazard Maps – Source Parameters (USGS 2008). Distances measured using Google Earth and GIS data from the Southern California Earthquake Center (SCEC 2023).

Fault name	Fault sections within 25 miles of BMD	Dip angle, dip direction	Slip rate (mm/yr)	Slip sense	Nearest fault trace distance to site (mi)	Probable moment magnitude (Mw)
Hollywood	N/A	70°, N	1	Strike-slip	10.0	6.5–6.7
Raymond	N/A	79°, N	1.5	Strike-slip	8.0	6.5–6.8
San Andreas fault zone	Mojave	Vertical	>5*	Strike-slip	21.0	6.5–8.0
San Gabriel fault zone	Honor Rancho Newhall Big Tujunga San Gabriel River	61°, N	1	Strike-slip	0.3	6.5–7.3
Sierra Madre fault zone	Santa Susana San Fernando Clamshell-Sawpit Section B, C, D E	53°, N	2	Reverse	1.5	6.5–7.3
Verdugo	N/A	55°, NE	0.5	Reverse	6.5	6.5–6.9

* The Mojave section of the San Andreas Fault zone has had local slip rates of 27.7 millimeter/year over the past 23,000 years (Moulin et al. 2023).



SOURCES: Fault traces in California from California Geological Survey, C.W. Jennings, W.A. Bryant (2010) Map Service Layer (Updated April 11, 2022). Fault Traces in Nevada from U.S. Geological Survey Quaternary fault and fold database for the United States, accessed May 2021. Seismicity from UCERF-3 Catalog, 2015 (1769 to April 2012) and NCEDC Catalog, 2019 (May 2012 to December 2019), and ANSS ComCat (December 2019 to September 2021).

Figure 3-22. Regional map of fault traces located within 50 kilometers of Brown Mountain Dam. Fault trace data obtained from the California Geological Survey, C.W. Jennings and W.A. Bryant (2010) map service layer (updated April 11, 2022).

3.2.8.3 Historic seismicity

Figure 3-23 shows the locations of historical earthquakes with moment magnitude (Mw) of 5 or greater within a 50-kilometer radius of BMD for the period between 1769 and 2021. Significant recent events include the 1971 San Fernando earthquake (Mw 6.6) and the 1994 Northridge earthquake (Mw 6.7), which resulted in significant loss of life and property damage, and initiated landslides and areas of soil liquefaction (Table 3-7).

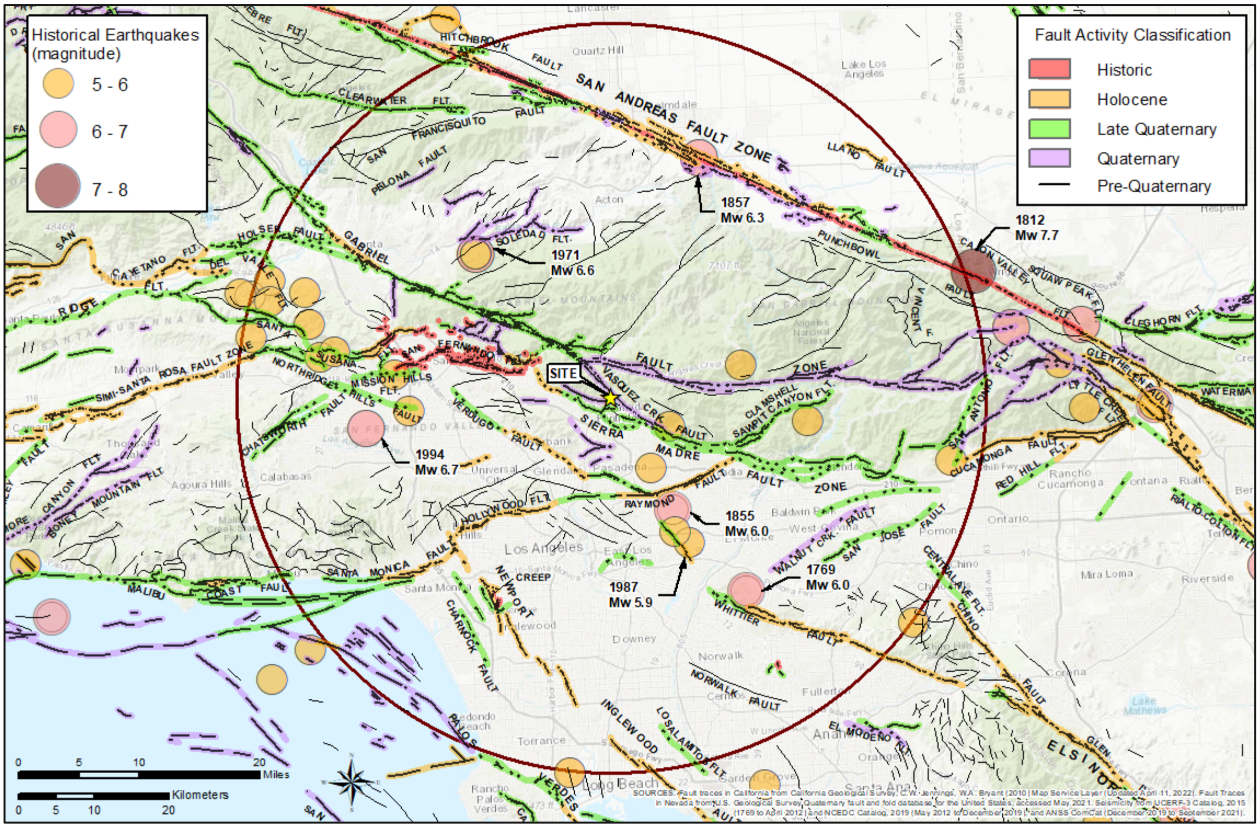


Figure 3-23. Earthquake epicenters moment magnitude greater than 5 and locations within 40 miles of Brown Mountain Dam for the period between 1933 and 2023. Earthquake event data obtained from the U.S. Geological Survey earthquake catalog located at https://earthquake.usgs.gov/earthquakes/search/.

Table 3-7. Significant earthquake events within 40 miles of Brown Mountain Dam for the period between 1933 and 2023. Earthquake event data obtained from the U.S. Geological Survey earthquake catalog located at https://earthquake.usgs.gov/earthquakes/search/.

Earthquake event	Year	Moment magnitude (Mw)	Rupture depth (mi)	Source-to-site distance (mi)	Geologic hazards
San Fernando	1971	6.6	5.6	13	Significant landslides, limited liquefaction
Whittier Narrows	1987	5.9	9.1	13.5	Little or no landslides or liquefaction
Sierra Madre	1991	5.8	5.0	6.5	Some rockslides
Northridge	1994	6.7	11.3	20.5	Significant landslides, limited liquefaction

3.2.8.4 Landslides and debris flows

BMD is surrounded by zones of potential earthquake-induced landsliding, as shown within the Pasadena quadrangle (Figure 3-24, CGS 1999). The Department of Conservation Division of Mines and Geology (DMG) defines these zones as areas where "previous occurrence of landslide movement, or local topographic, geological, geotechnical and subsurface water conditions indicate a potential for permanent ground displacements" (CGS 1999). Landslide hazards in the region are largely a result of the steepness of the San Gabriel mountains and the lower shear strength of the younger alluvial and colluvial deposits overlying the site bedrock (DMG 1998).

Rock slopes may also be susceptible to kinematic failure from toppling, wedge sliding and/or planar sliding, especially during a seismic event. This was demonstrated during the Mw 5.8 Sierra Madre earthquake of 1991, where rockfalls were observed in numerous places along the Angeles Crest highway. The nearest landslide mapped following this event is approximately 0.5 miles west of BMD in the west roadcut for the highway (DMG 1998). It is possible that unmapped landslides could be located closer to the dam.

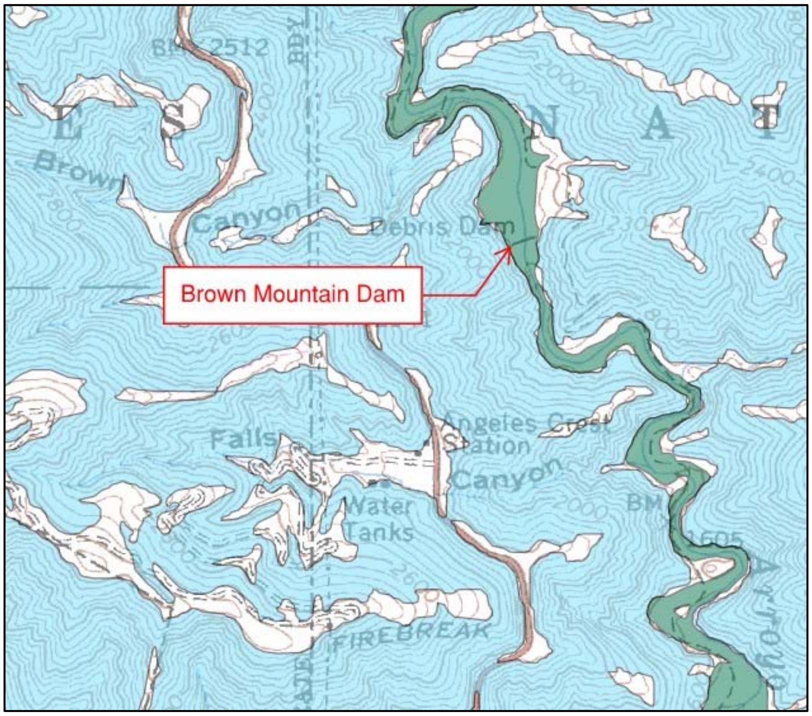


Figure 3-24. Earthquake zones of required investigation in the Pasadena quadrangle (CGS 1999) near Brown Mountain Dam. Blue highlighted areas indicate potential for earthquake-induced landslide and green highlighted areas indicate potential for liquefaction.

3.2.8.5 Liquefaction

BMD is located within an area of potential liquefaction, as shown on Figure 3-24 (CGS 1999). DMG defines these zones as areas where "historical occurrence of liquefaction, or local geological, geotechnical and ground water conditions indicate a potential for permanent ground displacements" (CGS 1999). The liquefaction hazard zone at BMD is a result of the highly susceptible stream channel (Qw) deposits in the area (DMG 1998). Given that the BMD was prepared on bedrock, liquefaction susceptibility during a seismic event is negligible. However, surrounding younger alluvial deposits, particularly in the area upstream of the dam structure, may be susceptible to liquefaction during a significant seismic event.

3.2.8.6 Ground rupture

The nearest "active" fault trace to BMD is the Big Tujunga section of the San Gabriel Fault zone. The Big Tujunga section, also referred to as the Vasquez Creek Fault (Bryant 2017), has a fault trace within 0.3 mile northeast from BMD (see the southeast-trending fault splay near BMD in Figure 3-22). The southeast-tending Mount Lukens Fault is also approximately 0.3 mile south of BMD. Neither of these fault traces are projected through BMD. Given that no known active fault traces have been mapped through the BMD footprint, the potential for surface fault rupture at the dam is considered low.

3.2.8.7 Ground shaking

To estimate the potential for ground shaking at BMD from seismic sources in the region, a probabilistic seismic hazard analysis was performed using gridded seismicity from the 2018 USGS national seismic hazard model. The 2018 national seismic hazard model contains the latest seismic maps published by USGS (see https://earthquake.usgs.gov/nshmp/).

In performing the analysis, a National Earthquake Hazards Reduction Program Site Class BC was assumed. The Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE 7-22) recommends selecting Site Class BC where shear wave velocity data are not available and the site geology consists of "competent rock with moderate fracturing and weathering" (ASCE 2022).

The results from the probabilistic seismic hazard analysis are presented in Table 3-8, which lists the estimated horizontal peak ground acceleration associated with potential earthquakes with multiple seismic return periods.

Table 3-8. Seismic ground shaking hazard at varying return periods for Brown Mountain Dam.

Return Period (years)	Peak Ground Acceleration (g)
475	0.41
975	0.56
2,475	0.80
4,950	1.00
10,000	1.27

3.3 Step 3: Potential for Contaminated Sediment

No sampling of sediment, either for grain-size analysis or for contaminants, has been conducted behind BMD. In preparation for sediment removal at Devil's Gate Reservoir, however, rigorous testing of that downstream location was conducted (LACDPW 2014, p. 166). That work found "detectable concentrations of VOCs [volatile organic compounds], petroleum, hydrocarbons, organochlorine pesticides, SVOCs [semivolatile organic compounds], and heavy metals"; all except arsenic were below regulatory thresholds. Arsenic concentrations were determined to be consistent with background (i.e., natural) levels, so no mitigation was found necessary. Although these results are not directly applicable to the sediment behind BMD, they provide strong indication that future testing of those sediments will find similarly low concentrations that do not preclude their natural release downstream.

3.4 Step 4: Relative Reservoir Sediment Volume and Probability of Impact

3.4.1 Watershed sediment yields

Sediment yields from a watershed can be calculated either directly, from debris-basin or reservoir records of sediment accumulation; or indirectly, from geological uplift rates under the critical assumption that these long-term geology-derived rates are a reasonably surrogate for much shorter-term sediment-accumulation rates. In the Arroyo Seco watershed, both approaches have been used, with the “direct” measurements of sediment infilling being most immediately relevant for determining two parameters of interest: the time required to initially fill BMD and the likely magnitude of ongoing present-day (and future, post-dam) delivery of sediment.

Three sets of calculations have been published for infill rates behind Devil’s Gate Dam. Lavé and Burbank (2004, their Table 1) reported infilling rates equivalent to 1.3 mm/yr lowering derived from the mountainous portions of the contributing watershed (i.e., assuming a negligibly small contribution from the flatter areas immediately adjacent to the dam). This calculation corresponded to about 90,000 yd^3/yr of sediment accumulation at this downstream location. Taylor (1981, his Table B4-1) calculated a somewhat higher uplift rate (1.6 mm/yr) using data compiled over a shorter time frame (1920–1974), which corresponds to about 110,000 yd^3/yr of sediment accumulation. LACDPW (2013, their Table 8-12) presented the raw data for sediment accumulation behind Devil’s Gate Dam from 1919 through 2011, which extended the Lavé and Burbank period of data. They concluded that 12.03 million yd^3 of sediment had been delivered over this 92-year period, equivalent to an average delivery rate of 130,000 yd^3/yr. The discrepancy between these results can be partly explained by different periods of record (the last survey available to Lavé and Burbank would have been in 1995, that of Taylor in 1974). As the underlying (and most extensive) data source of all such calculations, the result published in LACDPW (2013) (i.e., 130,000 yd^3/yr) is assumed to be the best long-term estimate at this location by this method.

Of course, long-term average rates express the combined influence of minimal delivery during dry, low-yield years and greater transport during wetter years. When those wetter years follow wildfire, delivery can substantially exceed the “average” rate (e.g., Andrews and Antweiler 2012). In the case of the 2 years following the 2009 Station Fire (which burned the entire mountainous area of the Arroyo Seco watershed), LACDPW (2014) reported “The storms that occurred in the two wet seasons after the fire increased sediment accumulation in the reservoir by approximately 1,300,000 cy” (p. ES-4). This value will have particular utility in evaluating the potential downstream effects of releasing the sediment currently impounded behind BMD.

Scaling the Devil’s Gate infill rate to that of BMD could be a simple matter of drainage-area ratios, except that the two watersheds are not entirely equivalent in their sediment-generating character. There is obvious overlap in the 60% of the Devil’s Gate watershed that *is* the BMD watershed, but the remaining 40% is split between similarly mountainous terrain and the much flatter areas lying beyond the mountain front. Lavé and Burbank classified 5.2 mi^2 of the lower Devil’s Gate watershed as “flat, inhabited zones,” which suggests that the average annual sediment delivery to BMD should be calculated as:

[Contributing area to BMD] ÷ [(Total – Flat) contributing area to Devil's Gate] × 130,000 yd^3/yr

$$\approx \mathbf{100{,}000\ yd^3/yr}$$

This is assumed to be the best estimate for the long-term sediment-delivery rate to BMD, and thus corresponding to the accumulation rate in the BMD reservoir for as long as the dam trapped all sediment. This latter assumption (i.e., 100% trap efficiency) would have become progressively less accurate as the sedimentary fill approached the dam spillway, but it nevertheless provides a useful first-order estimate for comparison with the measured impoundment volume to determine the period over which reservoir infilling occurred.

3.4.2 Age of reservoir infilling

The arithmetic combination of sediment volume (1.27 million yd^3, from the previous section) and the previously derived long-term average rate of sediment production from the BMD watershed (about 100,000 yd^3/yr**)** suggests that slightly more than one decade (and surely less than two decades) of "average" sediment transport would have been sufficient to completely fill the reservoir. Greater insight, however, can be gained by considering post-dam peak flows in the Arroyo Seco as recorded at USGS gage #11098000 for the decades immediately following dam closure (i.e., by the beginning of 1943; Figure 3-25), given the extreme interannual variability in southern California rainfall amounts.

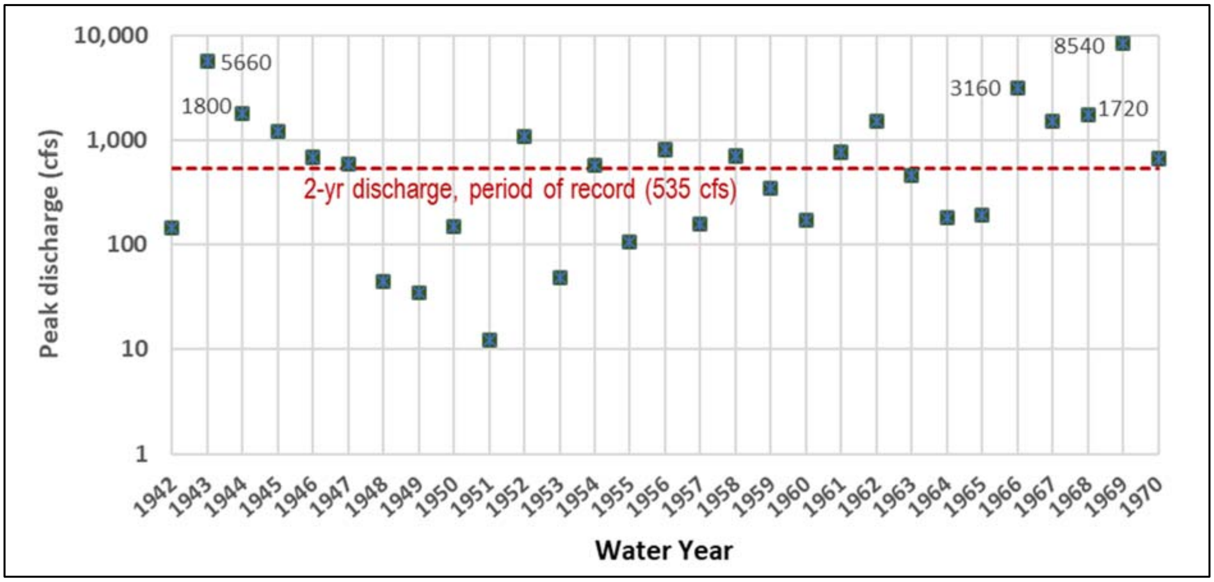


Figure 3-25. Annual peak flows for the 27 years following dam closure at U.S. Geological Survey gage #11098000 (with values in cfs specified for the five largest peaks). The indicated 2-year discharge was calculated from the entire period of record (1914–2021) using the Bulletin 17-B methodology (as implemented at www.eRAMS.com).

Inspection of the flow record indicates seven peak flows at or modestly above the 2-year peak discharge, four at or slightly above 1,000 cfs (about $Q_{3\text{-yr}}$), and five (labeled) discharges corresponding to 5-year, 6-year, 20-year, 40-year, and ~100-year recurrences. Given the previously noted report that the 1943 flood (the 40-year event) was responsible for one-third of the sediment deposit behind the dam, the subsequent nine floods that exceeded a 2-year peak discharge from 1944 through 1962 were likely sufficient to entirely fill the reservoir area. If any capacity remained, sediment transported into the reservoir by the 20-year 1966 flood surely filled it.

Thus, BMD has provided essentially no reduction in the watershed sediment load being delivered to the channel of the lower Arroyo Seco for at least the last half-century. This also implies that the "trap efficiency" of the dam is presently close to zero—in other words, virtually no sediment from upstream is continuing to further aggrade the reservoir, except potentially for the coarsest (and least voluminous) size fractions that cannot be readily transported down the reduced surface slope of the reservoir deposit.

3.4.3 Rate of sediment evacuation following dam removal

The rate at which BMD's sedimentary fill would be eroded following dam removal is highly dependent on the grain-size distribution of the bulk deposit. Although at present there are no direct measurements of grain-size distribution here, field observations behind BMD and reported grain sizes 5.5 miles downstream at Devil's Gate Dam (LACFCD 2014, see Figure 3-12) show that the deposit is almost certainly coarser than that used in the analysis of Cui et al. (2017) for Matilija Dam. Thus, their projection that near-complete evacuation of the ravine-filling sediment would occur in just a few days following dam removal is probably not applicable here. Instead, channel evolution and incision down to its original grade, and thus the delivery of sediment downstream, will likely be spread out over many storm events (and thus multiple storm seasons). Full evacuation of the 1.27 million yd^3 of impounded sediment will probably never occur, with some portion of the deposit left stranded high along the valley walls, so the magnitude of increased sediment delivery to the reservoir would likely be substantial but somewhat less than that experienced following the 2009 Station Fire. Even the lesser amount of sediment that would be eroded to reestablish an at-grade channel through the reservoir would not reach Devil's Gate Reservoir over the course of a single year, based on the post-Station Fire experience of 2+ years of post-fire accumulation.

The sediment that first accumulated against BMD immediately following dam closure probably reflected the character of regional sediment yields, which likely includes even more fines than the 20% proportion estimated by Taylor (1981) from debris-basin data. However, continued infilling of the reservoir area would have reduced trapping efficiency for suspendible sediment sizes, resulting in a deposit that now grades upwards into progressively coarser sediment more similar to the upstream Devil's Gate samples (i.e., ~10% fines with a substantial gravel component). The spatial variation in impounded sediment sizes will influence the rate of both initial and long-term sediment delivery into the downstream system following dam removal, but to a degree that cannot be further resolved with the data presently available.

3.4.4 Probability of sediment impact

USBR (2017) suggested that the potential post-removal sediment impacts to the downstream channel can be coarsely quantified by comparing the volume of sediment to the average annual sediment yield, thus representing the equivalent number of years of natural sediment production that the reservoir holds. USBR's graphic representation of this ratio (Figure 3-26) suggests that this ratio (1,270,000 $yd^3 \div 100,000\ yd^3/yr$) falls in the lower end of "large" impacts. If instead the evaluation is made for the likely magnitude of sediment released following dam removal (870,000 yd^3; see previous section), the ratio falls in the upper end of "medium" impacts.

This framework carries an implicit assumption that the "average" year is a reasonable representation of the long-term behavior of the river. This reflects the common geomorphic finding that over a long period, "intermediate" events (e.g., the 2 year or the bankfull flow, commonly termed the "dominant discharge") do the greatest geomorphic work (Wolman and Miller 1960). However, southern California rivers and streams do not follow this pattern because peak annual discharges can vary by more than an order of magnitude from year-to-year, and their associated sediment yield can vary by an even greater degree. As found for the nearby Santa Clara River watershed (Stillwater Sciences 2011), the dominant discharge for these settings is simply the largest storm in the record. In other words, the probability of sediment impacts from the removal of BMD, as estimated by this framework, will be seen as "medium" (or even "low")—until a very large flow/sedimentation event (such as seen in the years immediately following the 2009 Station Fire) imposes far greater sediment impacts on the downstream receiving waters.

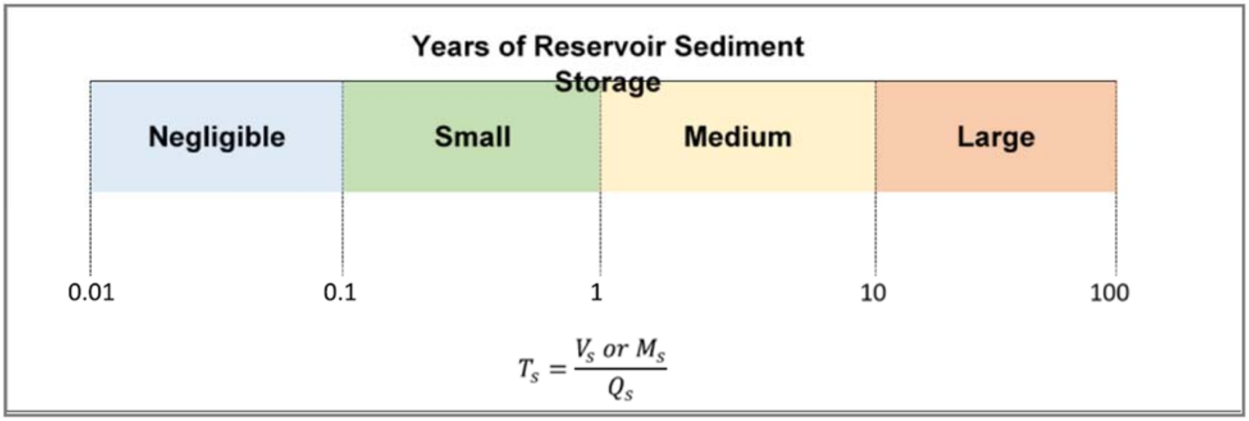


Figure 3-26. Stratification of downstream sediment impacts following dam removal, based on the number of years (T_s) of average annual sediment yield (Q_s) represented by the volume of sediment retained in the reservoir (V_s). Figure 16 of USBR (2017).

3.5 Step 5: Estimate of Sediment-related Risk Factors

It is logical that an assessment of sediment-related factors following dam removal is presented in terms of the risks intrinsic to dam removal. The probability component of risk is defined above (Figure 3-26). In Section 3.5.1, the consequence of the primary risks outlined in Table 3-1 are assessed in the context of sediment impact concerns. We use a "sediment wave" numerical model of sediment transport to refine our preliminary understanding of the dynamics of sediment following dam removal in Section 3.5.2 and bring these actors together as a risk assessment in Section 3.5.3.

3.5.1 Consequences of sediment release

Because of BMD's landscape setting in relative "'wilderness", its removal presents few sediment impact concerns within or upstream of the dam site (Table 3-1). We identify "moderate" levels of concern for the rapid erosion that will follow dam removal, intrinsic to the process itself, and the possible spread of aquatic invasive species if any exist downstream that are capable of upstream propagation. Levels of impact are potentially far higher downstream of the removed structure, however, particularly at the Pasadena Water and Power diversion weir (RM 1.81) where short-term spikes in turbidity and suspended sediment concentrations will occur, as well as the potential for intake-blocking coarse-sediment aggradation. Moderate concerns also exist for the impact of short-term high turbidity on aquatic species and the potential for sediment deposition raising bed levels (or the subsequent eroding of streambanks) in the vicinity of bridges and creekside roads and trails. The most significant impact for downstream receiving waters will likely be the requirement for elevated sediment-management activities at Devil's Gate Dam for the one-time delivery of additional sediment if natural transport is the selected approach for the reservoir deposit. Because coarse sediment slugs disperse in a fan-like tail of deposition that thins downstream, deposition into Devil's Gate Dam may be skewed toward the finer fractions of the sediment currently impounded behind BMD, and the delivery of sediment will likely be dispersed over several wet seasons.

The ecological benefits of removing BMD are associated primarily with the opening of approximately 6 miles of upstream aquatic habitat for native salmonids and the economic and safety benefits associated with the removal of an obsolete structure that may present a structural liability in the event of strong seismic activity. More broadly, there are landscape and recreational benefits associated with removing a major barrier in the Arroyo Seco valley. The potential impacts and benefits (see Tables 3-1 and 3-2) are summarized below in Table 3-9.

Table 3-9. Anticipated key impacts and benefits following removal of BMD.

Consequence of BMD removal	Where relative to dam?	When are impacts expected	Short- or long-term consequences	Impact rank
Potential impacts				
Sediment management at Devil's Gate Dam	Downstream	Several years after removal, or first significant flood event	Long-term but not indefinite	1
Water quality at water diversion	Downstream	First flood after dam removal	Over first several winters, waning over time	2
Viability of bridges and Creekside trails	Downstream	First significant flood after dam removal	Short-term if depositional only; persistent if structure/bank erosion occurs	3
Erosion of impounded sediment	At the site and immediately upstream	Immediately following dam removal	Short-term; decreasing over time	4
Spread of aquatic invasive species	Downstream to upstream	Immediately following dam removal	Long-term (if at all)	5
Potential benefits				
Opening of habitat	Upstream	Within the first wet season after dam removal	Long-term	
Improved safety from removal of obsolete structure	Dam site and downstream	Immediately after dam removal	Long-term	
Reconnection of valley	Downstream to upstream	Immediately after dam removal	Long-term	

3.5.2 Modeling of post-removal sediment transport

To refine levels of concerns related to removing BMD, and to provide later guidance for evaluating alternative dam-removal approaches, a preliminary analysis of sediment transport along the Arroyo Seco following dam removal was conducted using the sediment-wave-based Dam Removal Express Assessment Model (DREAM; Cui et al. 2006a, b). DREAM was developed explicitly to characterize sediment transport following dam removal. It calculates sediment transport driven by a daily hydrograph, using standard equations well-represented in the technical literature and in more typical model applications (see Cui et al. 2006a, b). DREAM assumes a simple and generally uniform channel geometry, although it accommodates the erosion of the reservoir deposits immediately following dam removal, and it accounts for the interactions between upstream erosion and downstream deposition in the vicinity of the (removed) dam itself. The one-dimensional (1D) framework of the DREAM is well suited to the relatively uniform channel geometry and confined valley topography of the Arroyo Seco, and its ability to represent the transport of sediment through the dam site itself (although not accomplished during this analysis) makes it an appropriate modeling environment here.

As a preliminary modeling exercise, the required model input parameters were drawn from available sources:

- Topography/stream geometry: 2016 USGS LiDAR, with the average bankfull channel width and depth estimated from LiDAR and Google Earth imagery.
- Reservoir grain-size distribution: uniform distributions for coarse and fine sediment was assumed, with proportions of silt, sand, and gravel based on an existing example from southern California (York Creek) and an approximation of the reported distribution from one boring at the head of Devil's Gate Reservoir (see above).
- Sediment supply: see prior section of this report.

Two simplified modeling scenarios were explored, namely continuous discharges of 500 cfs (nearly equivalent to a 2-year peak discharge, continued for 24 hours) and 2,800 cfs (the magnitude of a 10-year peak discharge). Although these preliminary simulations were run for multiple days, the "Day 1" results are most informative because they are most representative of the broad patterns of erosion and deposition under relatively commonplace and more extreme high-flow events (Figure 3-27).

Gravel is mobilized under both flow scenarios—at modest rates at 500 cfs, and (obviously) at far greater rates at 2,800 cfs. Sand is actively transported under both flows, and at 2,800 cfs, sand is fully mobilized through the full extent of the channel. More than about 0.5 mile downstream of the dam, the 500-cfs flow results in very low (<1 foot) of predicted deposition. In contrast, the 2,800-cfs flow yields deposition from 1 to more than 3 feet in two main zones: 4.5–3.5 miles upstream of Devil's Gate and downstream of the JPL bridge on Explorer Road in the Devil's Gate Reservoir.

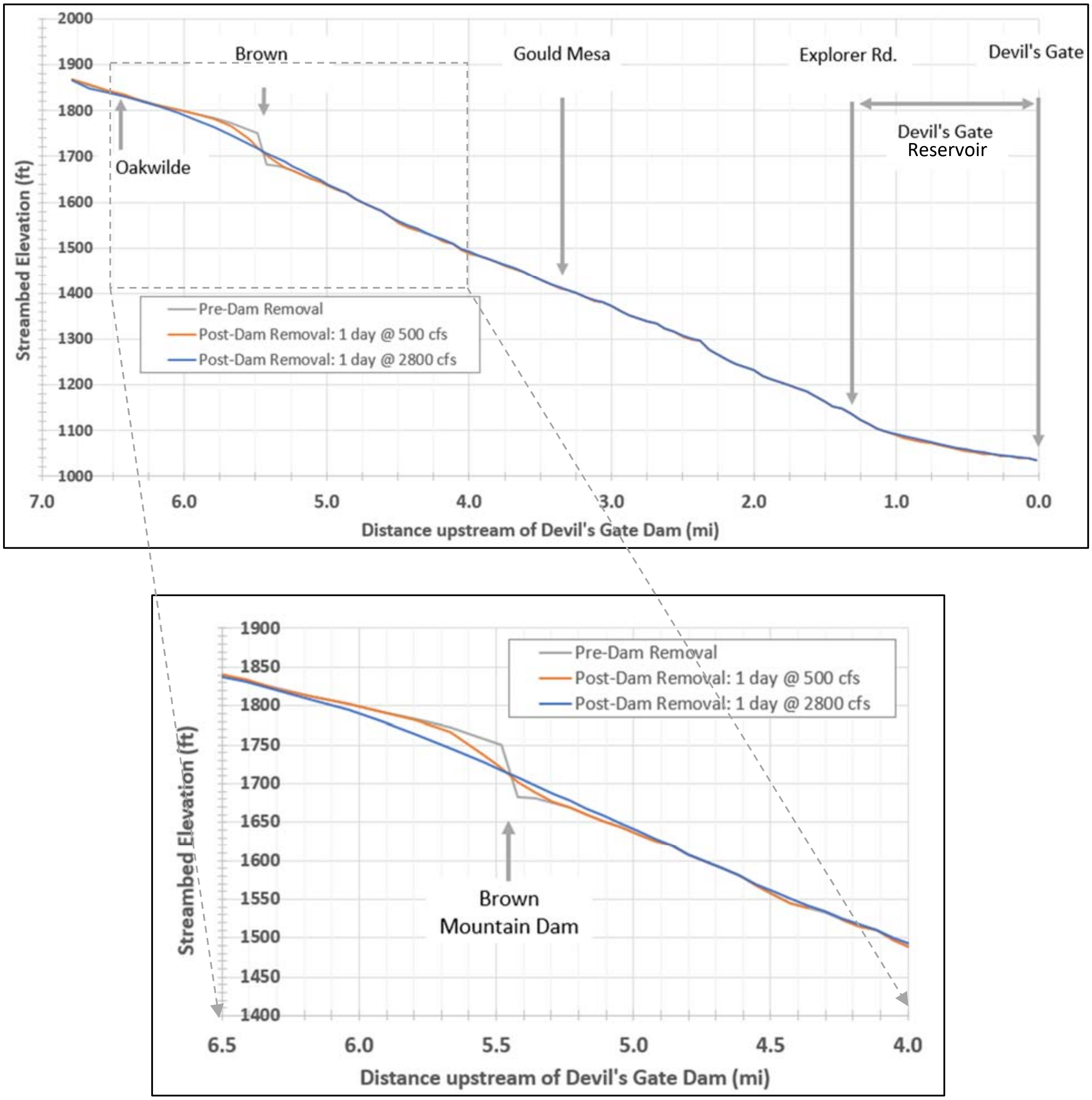


Figure 3-27. DREAM model results for at 500 cfs (~2-year peak discharge) and 2,800 cfs (10-year peak discharge) for 1 day immediately following dam removal). Top, full extent of modeling domain; bottom, focus on the 2.5 miles centered on Brown Mountain Dam.

Given the steady discharge and presumed instantaneous dam removal, these results are not “realistic”—but they do highlight the magnitude and general locations of likely deposition following such events, and the evolution of the sediment wedge of downvalley reservoir sediment. The model’s least well-constrained input, the grain-size distribution of the reservoir sediments, is noted as the most critical piece of field information for accurate model results (Cui et al. 2006b) and is thus a necessary focus for further study. The accuracy of future investigations would also benefit from reducing the timestep of each hydraulic calculation because the average daily flow of flashy southern California streams, such as the Arroyo Seco, can mask much larger (but shorter duration) peak discharges that have a disproportionate influence on the net quantity of transported sediment. Future modeling efforts should also consider developing a more detailed stand-alone 1D hydraulic model (such as HEC-RAS) for the project reach and, potentially, a 2D hydraulic model for Devil's Gate Reservoir area to refine and cross-check hydraulic parameters of the DREAM and provide a basis to perform alternative sediment transport analyses.

3.5.3 Risk of sediment impact

Risk associated with an activity is defined as the product of the probability of the risk occurring and the consequences (i.e., loss) if it does. Gauging the level of risk to a dam-removal project at the feasibility stage is most useful in identifying the focus for further, more detailed studies. In regard to sediment impacts following dam removal, the probability of impact was gauged as the number of years of average annual sediment load stored behind BMD (Figure 3-26). Depending on the average annual load used, the result spans the high end of *medium probability* to the low end of *high probability*. The consequences of sediment impact were identified from an exhaustive list provided by USBR (2017) and were ranked in Table 3-9 using expert judgment. Impacts related to the three highest ranked impacts are financial. Following USBR (2017), risk is judged as a matrix of *low*, *medium*, and *high* categories; we have added a *medium-high* category to improve our discrimination of impacts (Figure 3-28).

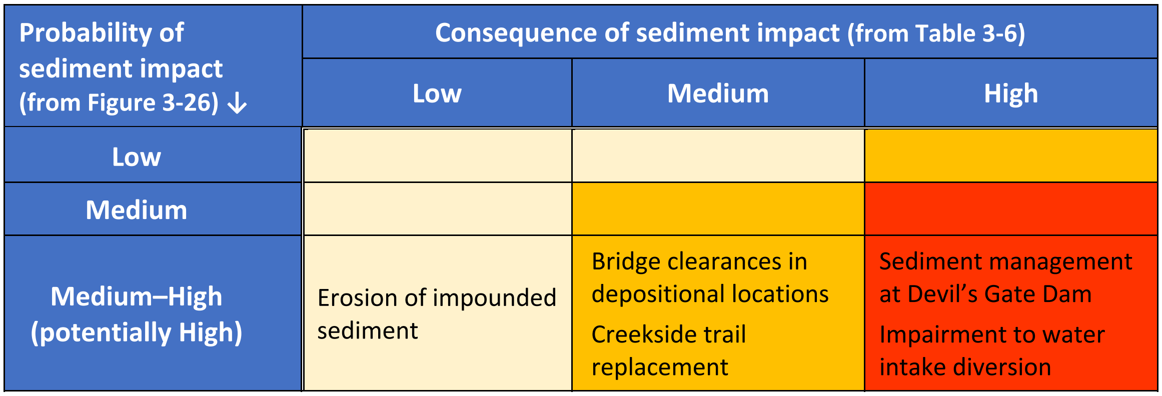
High risk factors include the prospect of extra sediment being impounded at Devil's Gate Dam for an extended period as the pulse of sediment released from BMD reaches the site. Because BMD has almost no trap efficiency at present, the volume of extra sediment will return to "average annual" conditions once the pulse has passed. The sediment reaching Devil's Gate reservoir will likely consist primarily of finer sediments (i.e., fine gravel, sand, and silt). Coarse sediment will be preferentially deposited in the fan of sediment accretion downstream from the current dam site, in "hollows" in the long profile of Arroyo Seco upstream of Devil's Gate Dam (e.g., around RM 4.5 in Figure 3-27), and at the break of slope at the mountain valley (about 1.3 miles upstream of Devil's Gate Dam near the Explorer Road bridge). Residual coarse sediment will reach the Devil's Gate Reservoir, but the majority of the released washload (fine sands and finer) will pass through. The coarse load will ultimately require excavation following the first 10-year or greater flood event because preliminary modeling indicates that this event will scour the majority of sediments behind BMD.

High risk is also associated with the prospect of losing bridge clearance for flood events where deposition occurs. This risk is composed of two parts: (1) a temporary risk as fine-sediment pulses passes under a structure and (2) a more permanent risk if any of the bridge structures are located at depositional zones in the valley downstream of BMD, or if flood capacity is significantly reduced within Devil's Gate Reservoir.

Medium level risk is associated with two factors. First, an unusually high turbidity spike will occur immediately following dam removal and potentially during the first subsequent rainfall event. These possibilities will require additional investigation into the potential impacts to and precautionary protective measures for the Pasadena Water and Power diversion. Also at risk are a utility access road and creekside access trails in locations where bed levels will be raised permanently and trails may need to be rebuilt.

The current plans for modifications to the existing Pasadena water-diversion headworks at RM 1.81 are sensitive to any significant, persistent sediment aggradation in the vicinity of the diversion structure and intake grate immediately upstream. The proposed fishway would also prove ineffective under such conditions. The current sediment-transport modeling (Section 3.5.2) provides insufficient resolution to determine whether or not the structure lies in a zone of potential deposition, but the preliminary results suggest that this may not be the case (see also Section 4.2.1, below). The potential significance of such impacts, however, emphasize the importance of more detailed modeling in any subsequent phase of this project.

The erosion of the impounded sediment mass itself is judged to present only a *low* level of risk, a consequence of the lack of valley side infrastructure alongside and upstream of the sediment deposit.



Probability of sediment impact (from Figure 3-26) ↓	**Consequence of sediment impact (from Table 3-6)**		
	Low	**Medium**	**High**
Low	🟨	🟨	🟧
Medium	🟨	🟧	🟥
Medium–High (potentially High)	🟨 Erosion of impounded sediment	🟧 Bridge clearances in depositional locations Creekside trail replacement	🟥 Sediment management at Devil's Gate Dam Impairment to water intake diversion

Figure 3-28. Summary of risk associated with releasing sediment stored behind BMD upon its removal (risk assessment modified from USBR 2017, Table 6). Cell shading relates to risk: red = high, orange = moderate, and pale yellow = low.

4 ALTERNATIVES ANALYSIS (STEPS 6–10 OF THE 2017 GUIDELINES)

The latter steps of the 2017 Guidelines methodology (Figure 4-1) evaluate alternative methods of dam removal, assuming a fully implemented (and funded) project. Prospective alternatives are analyzed with respect to structural limitations and sediment-related impacts, and subsequently evaluating whether the risks are tolerable with appropriate mitigation.

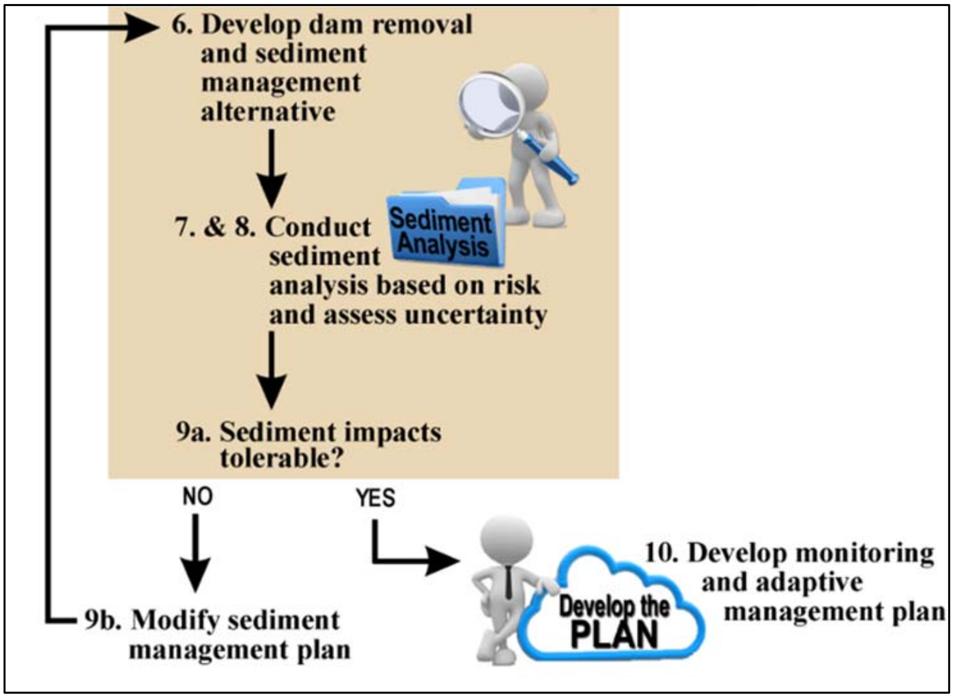


Figure 4-1. Steps 6 through 10 of the 2017 Guidelines, advocating an iterative approach (Step 9b returning to Step 6) to identifying a preferred dam-removal alternative.

Because the data and resources are not presently available to execute the full range of analyses necessary to render a definitive judgment for the optimal dam-removal alternative (Step 9), the following sections segregate the range of prospective dam-removal approaches, as previously implemented at other sites throughout the world, into those that are (1) almost certainly infeasible (unless future analysis shows otherwise) and (2) potentially viable at this site, pending future work. Discussion in the sections that follow thus highlights the relevant information presently available and the data and modeling that are still required to adequately follow the guidance. While we cannot definitively arrive at a "recommended" dam-removal alternative, through the following discussion we seek to narrow the universe of potential approaches to those most likely to be successful and to highlight the steps required to move this effort forward.

4.1 Step 6: Dam Removal Plans and Sediment Management Alternatives

4.1.1 Preliminary structural assessment of Brown Mountain Dam

4.1.1.1 Dam geometry and layout

Brown Mountain Dam is a constant-angle arch dam with a spillway height of approximately 66 feet above bedrock and 211 feet wide at the crest. The dam was designed to be a debris barrier with 134 feet of the dam crest designed as a stepped overflow crest spillway.

The elevation of the dam foundation varies with a stepped foundation on bedrock. A majority of the spillway portion of the dam is supported on a concrete plug at elevation 1,685 feet above mean sea level (Figures 4-2 to 4-4).

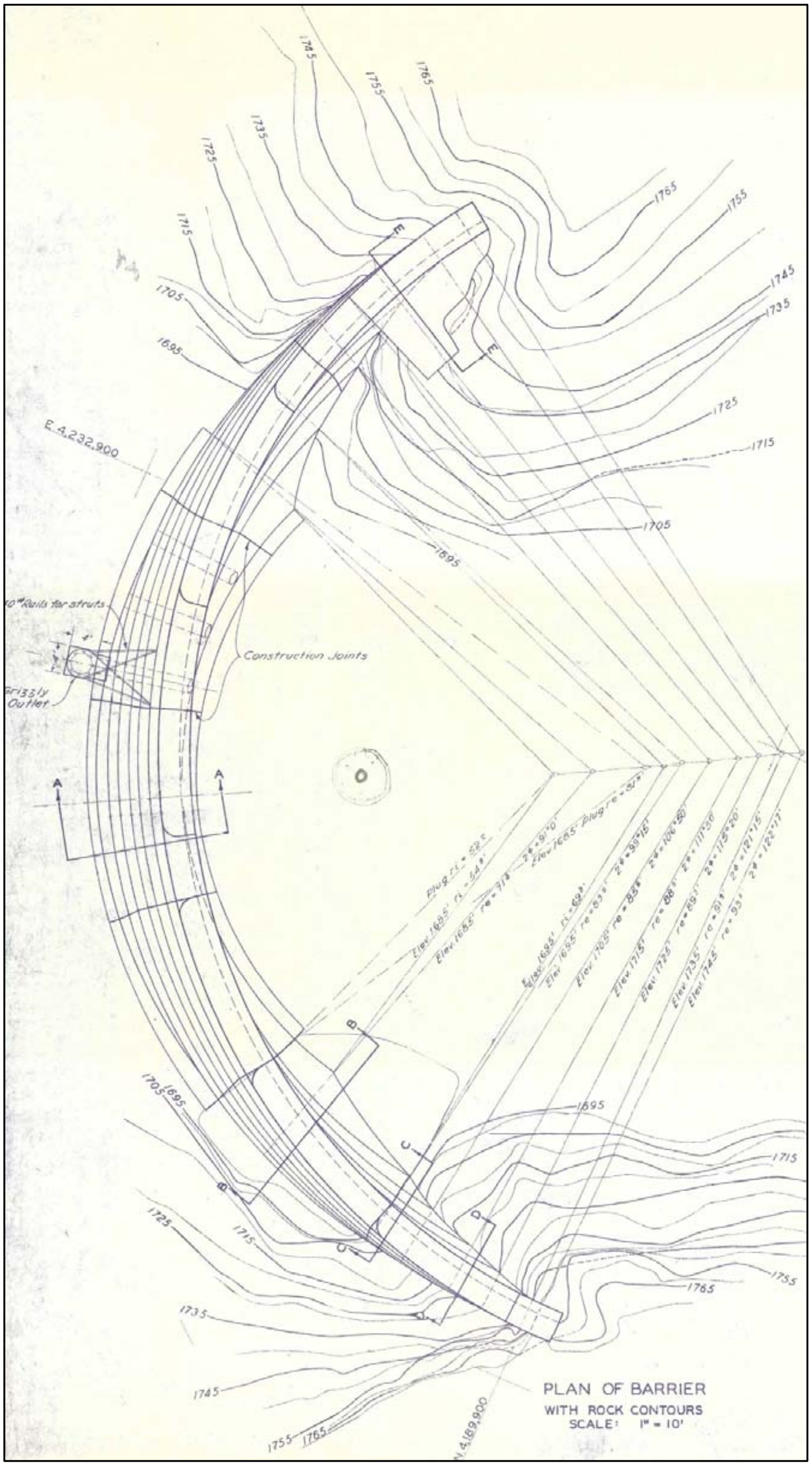


Figure 4-2. Plan view of Brown Mountain Dam.

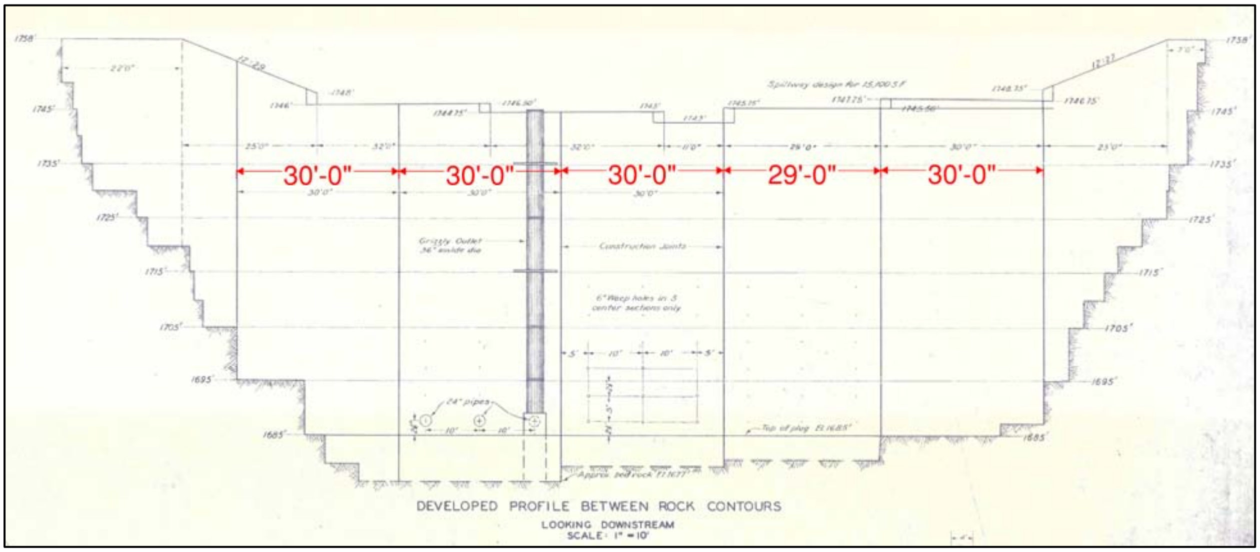


Figure 4-3. Profile of Brown Mountain Dam (figure same as Figure 3-20; repeated here for convenience). The distances between the vertical joints are enlarged and shown for clarity.

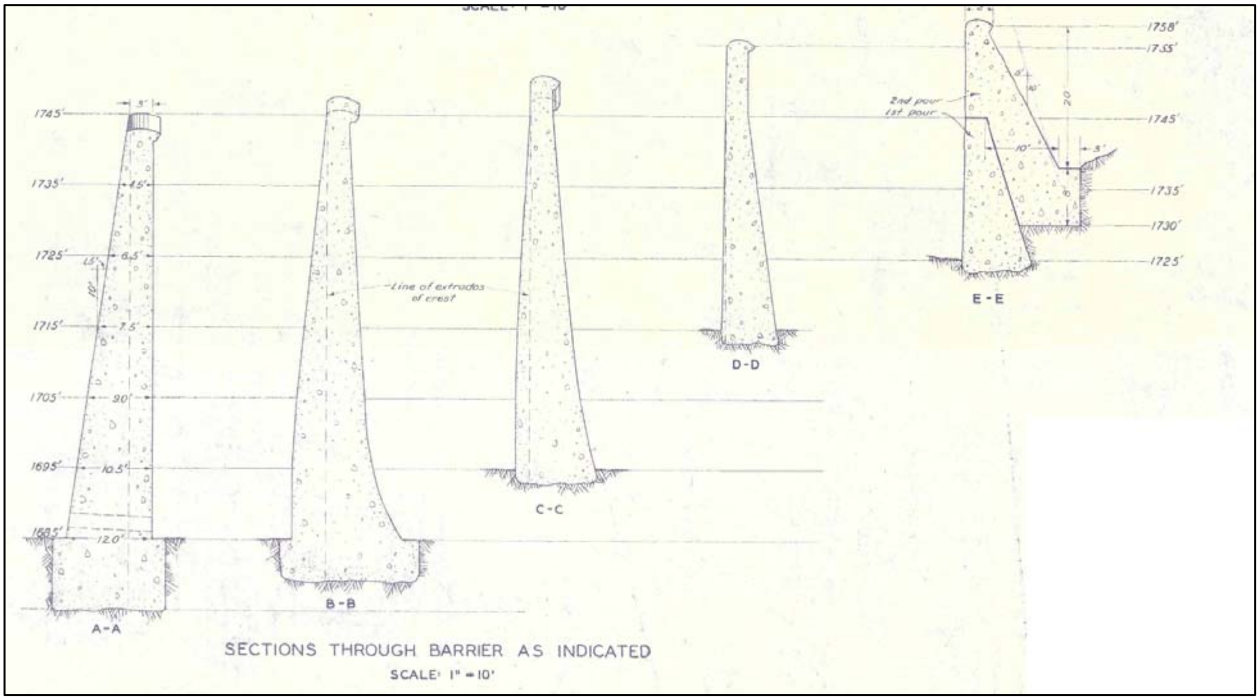


Figure 4-4. Sections through Brown Mountain Dam. Section cuts identified in Figure 4-3.

The dam was constructed with vertical construction joints spaced approximately 30 feet apart in the central portion of the dam (see Figure 4-4). Figure 4-5 shows a rendering of a typical vertical construction joint. No information is available about the spacing and placement pattern of the various lift joints.

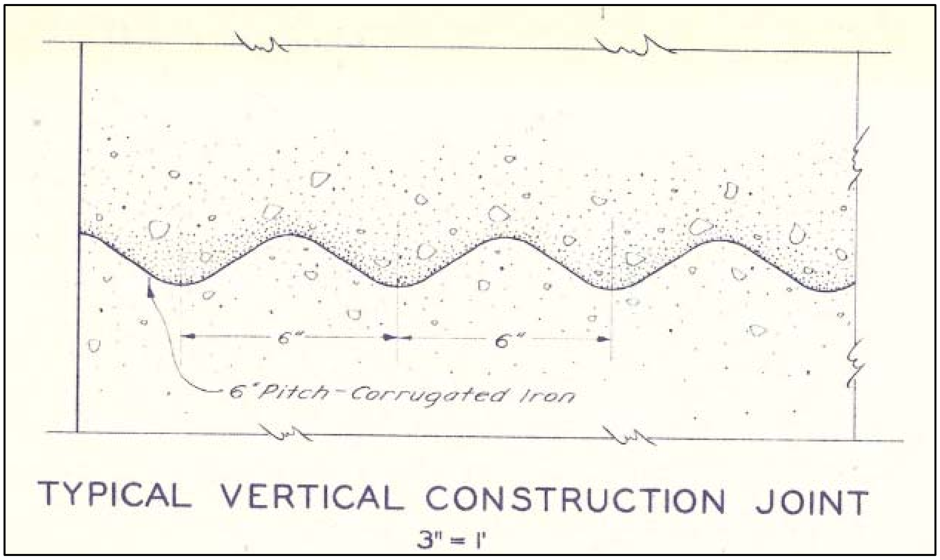


Figure 4-5. Typical vertical construction joint.

The dam was also constructed with a downstream apron of varying thickness and an approximately 10-foot-deep cut-off wall, as shown below in Figures 4-6 and 4-7.

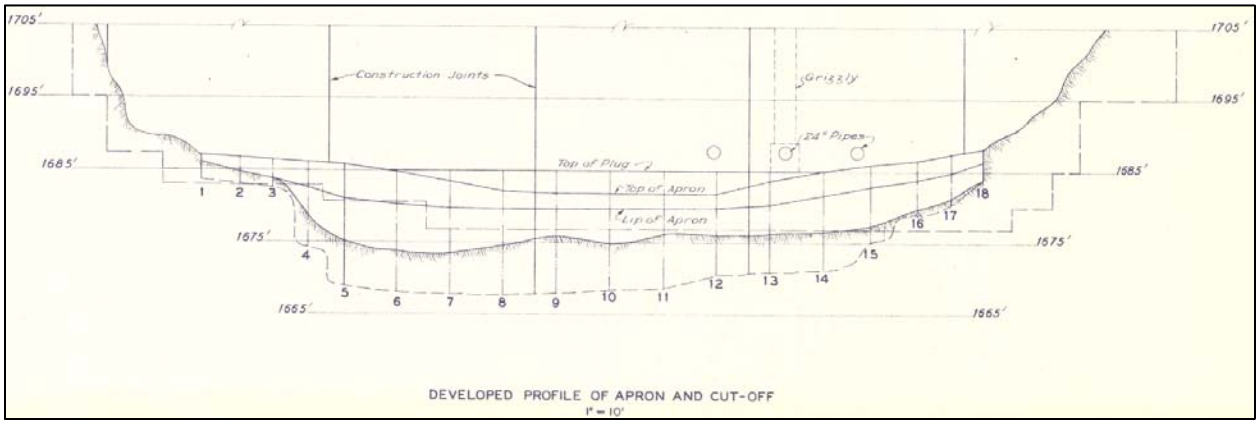


Figure 4-6. Profile of apron and cut-off wall at Brown Mountain Dam.

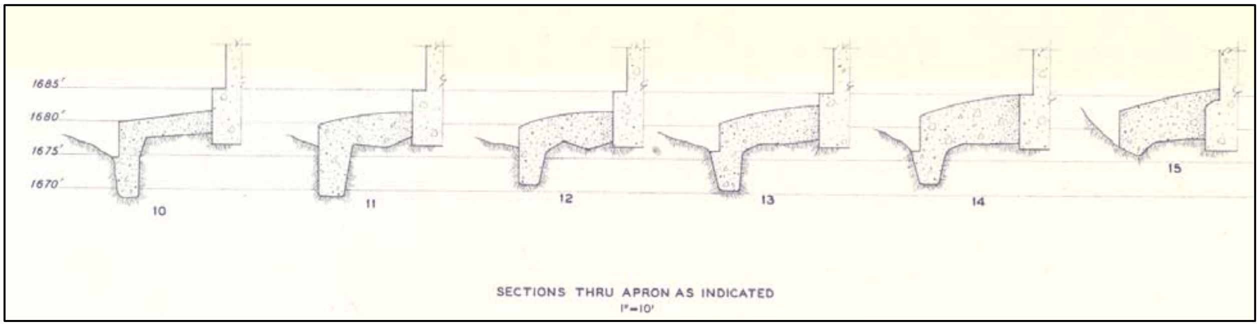


Figure 4-7. Profile of apron and cut-off wall at Brown Mountain Dam.

Based on information provided in the construction drawings, available literature, and site reconnaissance, BMD has not undergone any significant structural modifications during the life of the dam.

4.1.1.2 Stability assessment of the dam

Based on field observations, the dam is filled with sediment to the spillway elevation, elevation 1,743 feet above mean sea level (Figure 4-8).

a. View of water flowing over spillway

b. View of sediment upstream of Brown Mountain Dam

Figure 4-8. Sedimentation upstream of Brown Mountain Dam spillway.

Arch dams rely on resisting the load behind the dam by primarily transferring the load by arch action to the abutments, in addition to transferring the force to the foundation. The arches are designed such that when a load is applied on the curved upstream face of the dam, the load presses against the arch, causing the arch to straighten slightly and strengthening the structure as it pushes into the foundation and the abutments.

The stability and strength evaluation of an arch dam would require a sophisticated three-dimensional (3D) finite element analysis of the structure and consideration of the behavior of abutment blocks. For this study, the dam is simplistically assumed to behave as a simple cantilever retaining wall. This simplistic study shows that under the existing static loading, the central portion of the dam has a factor of safety (FOS) of approximately 0.9 to prevent sliding, assuming it behaves as a simple cantilever wall. USACE requires an FOS of 1.5 against sliding and the Federal Energy Regulatory Commission requires an FOS of 2.0 against sliding for dams with low hazard potential. Based on the calculated FOS of 0.9, BMD would be considered unstable in terms of sliding. However, the analysis ignores the arch behavior that provides a significant resistance to sliding. In addition, based on site reconnaissance, there is an absence of significant deterioration of the structure. Given these additional factors, the dam should continue to hold the sediment and perform satisfactorily as a retaining wall under existing static loading conditions.

The FOS to prevent sliding was evaluated for the global behavior of the dam without consideration of the dam at the various lift joints. A detailed analysis is warranted to evaluate the behavior of the dam under seismic loading conditions at the lift joints.

4.1.2 Dam removal alternatives

From the universe of potential dam-removal alternatives (USSD 2015), the following approaches for the demolition of the dam appear to merit further consideration. Each approach carries some associated risks, and additional studies will be required to fully assess them from a structural perspective. One demolition approach that can be ruled out immediately, however, is the sequential lateral removal of the dam from one end to the other. While commonly performed for smaller, straight dams that carry forces through their foundation, lateral removal will negate the arch action of the dam making the dam unstable and susceptible to catastrophic failure.

4.1.2.1 Single-season removal using explosives

Dam removal can be achieved by detonating explosives to demolish the dam. This method of removal does not require specific dam-stability evaluations. The most significant consideration for this approach is the sudden release of the retained sediment, which might result in slope instability and impacts to critical upstream or downstream infrastructure.

4.1.2.2 Staged (single or multi-year) removal involving gradual lowering of dam crest

The dam could be removed by incrementally lowering the full width of the dam by jack-hammering, diamond-wire sawcutting, or other methods. For these methods, the sediment immediately behind the portion of the dam being removed should either be removed or stabilized by sloping the sediment away from the dam. This removal method could be completed within one construction season but would warrant studies on methods of stabilizing the sediment, sequentially removing the height of the dam, and assessing the stability of the dam during the various demolition stages. If this method of dam removal remains an alternative for subsequent analysis, a detailed sequential analysis of the dam will need to be performed to evaluate the stability of the dam under normal and seismic loading conditions at various demolition and stages of dam height during demolition.

4.1.2.3 Tunnel at bottom of dam

Another method commonly used in demolition of the dams is to create a tunnel at the bottom of the dam to lower the water behind the dam and then demolish the dam either by using explosives or controlled lowering of the crest. BMD retains sediment to the top of the spillway crest and does not retain water. Depending on the particle-size distribution of the sediments, the tunnel approach could potentially be used to remove the sediment via hydrosuction. However, this method of sediment removal is better suited where the sediment primarily consists of fine particles, which is unlikely to be the case at BMD.

4.1.3 Sediment-management alternatives at Brown Mountain Dam

The method used for dam removal generally reflects a preferred alternative for sediment management (Downs et al. 2009), mediated by any structural considerations that may render certain approaches infeasible. The chosen alternative is especially critical where, as at BMD, a significant proportion of the impoundment is filled with sediment, and the identified impacts are primarily associated with the potential downstream release of that sediment.

Basic options include the full, unimpeded release of sediment following a single season's complete dam removal (aka "blow-and-go") or the metered release of sediment following a staged dam removal. The former is likely to be far more cost-effective, whereas the latter may reduce sediment-related impacts. In semi-arid environments like southern California, single-season dam removal followed by a winter with a large rainfall event (leading to a large flow event) may significantly or completely remove the impounded sediment in that first year. Whether such removal is a benefit or a risk will depend on the characteristics of the downstream receiving areas and needs specific assessment for each case. Approaches that involving drawing down water levels in the reservoir to flush some proportion of the behind-dam sediments downstream ahead of dam removal are precluded here, primarily because the reservoir has no remaining capacity to store water.

Supplementary measures for sediment management include mechanical (or hydraulic) sediment removal, stabilizing the deposit *in-situ* or constructing erosion-control structures that limit the volume of sediment that can be mobilized out of the impoundment area (Downs et al. 2009). For BMD, the mechanical removal of 1 million yd^3 of sediment is likely to be cost-prohibitive, although it cannot be dismissed as simply infeasible. Stabilizing the deposit is better suited to wider, low-gradient valleys where lateral flow pathways exist or can be developed separate from the primary sediment deposit. This approach is less well suited to (or simply infeasible in) narrow, steep valleys such as BMD where high flows extend across much of the valley floor. This valley structure would also make erosion-control structures a significant engineering challenge and would likely offset much of the landscape benefit of removing the dam. The likelihood of significant impediments to erosion of the BMD sediment deposit resulting from bedrock outcrops, large wood accumulations or earlier dam structures, while a potential opportunity in lowland dam removals, is sufficiently remote to need no further consideration here.

4.1.4 Summary of feasible alternatives

Several dam-removal alternatives can be discarded as infeasible without further detailed study. First, using a tunnel at the base of the dam is unlikely to encounter a substantial thickness of fine sediments that would facilitate hydrosuction and would thus fail to remove sediments ahead of deconstructing the dam structure. Second, as an arch dam reliant for its integrity on driving load stresses into the valley side walls, a staged dam removal consisting of sequential lateral removal is precluded because the partially removed dam would rapidly become a significant structural hazard. This leaves the primary options as either a single-season removal or a phased lowering of the dam crest over multiple years, with potentially significant differences between these two alternatives in the management and the downstream impacts of the reservoir sediment.

Sediment-management alternatives during dam removal include approaches reliant on natural (river) erosion, mechanical removal, sediment stabilization, or a combination. The steep, narrow gorge upstream of BMD means that stabilizing sediment *in situ* following dam removal is impractical in this valley setting. Assessing the cost of mechanical removal is an exercise deferred to a subsequent phase of this effort, but whether this cost is truly prohibitive must be evaluated in the context of downstream sediment management in the event that natural erosion is otherwise preferred.

Most likely, natural erosion of the reservoir sediment during single-season or multi-year dam removal will prove to be the most plausible avenues for future detailed evaluation in Steps 7 through 9 of the 2017 Guidelines. As discussed in Section 3.2.6, the full reservoir sediment volume is unlikely to be mobilized as a direct result of dam removal, but even the lesser amount (>800,000 yd^3) has the potential to significantly impact the downstream Pasadena water diversion facility and require some degree of ultimate removal behind Devil's Gate Dam. Managing this volume of released sediment, however, needs to be considered in the context of the watershed sediment yield, with the reminder that it is no more voluminous than what can be (and has been) delivered to the downstream impoundment during just one or two storm seasons.

4.2 Step 7: Conduct Sediment Analysis Based on Risk

In moving toward a preferred sediment management alternative, the 2017 Guidelines propose that the extent of further study is proportional to the assessment of the magnitude of sediment risk, with greater study detail required for higher levels of sediment risk. Essentially, responses to two questions are sought:

- What will happen to the reservoir sediment and how will this reservoir sediment affect the aquatic environment, human use, infrastructure, and property?
- What will the new reservoir landscape look like after dam removal?

Figure 3-26 suggests that a coarse estimate of "sediment risk," based on the volume of sediment relative to the background watershed supply, would place BMD near the *moderate/high* boundary. Given the high variability of annual sediment loads from southern California watersheds, a conservative assessment of the appropriate analyses (i.e., including selected modeling measures from the *high* category; see Figure 4-9) is probably warranted here. Progress on these various elements of study is provided below.

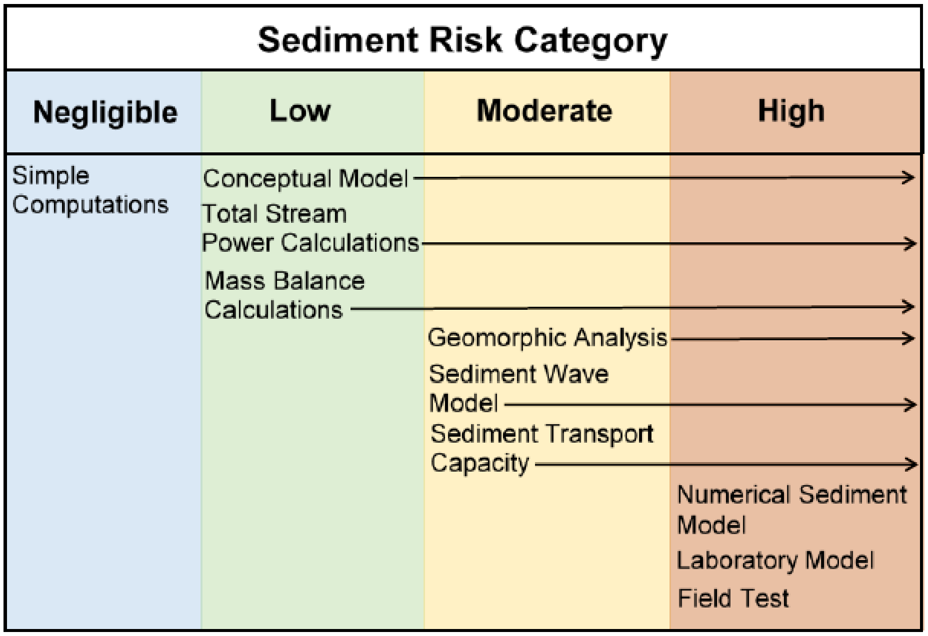


Figure 4-9. Analyses and modeling recommendations based on the category of sediment risk determined from the relative volume of reservoir sediment potentially released following dam removal (see Figure 3-26). Reproduced from USBR (2017, their Figure 24).

4.2.1 *Low* risk analyses: conceptual model, total stream power, mass balance

A ***conceptual model*** here refers to a simplified, graphical characterization of how the stream channel is expected to evolve following dam removal. Such models are informed by multiple observations of prior dam-removal projects and the geomorphic understanding expressed in "channel evolution models" developed over more than 30 years of study (e.g., Simon and Hupp 1986, Watson et al. 1986).

Following dam removal, the channel upstream of the damsite will experience the greatest changes as the channel erodes through the reservoir deposits (Figure 4-10). It is anticipated to follow a sequence of downcutting, widening, and one or more sequences of aggradation and further downcutting as the mass delivery of sediment from the eroding sideslopes of the channel coincides only imperfectly with the rate at which bed erosion occurs. Over a period of multiple storms (see Cui et al. 2017), the channel form and gradient will be established that is likely to reflect quasi-equilibrium conditions, although further long-term adjustment may continue to occur from vegetation regrowth, large storms, and wildfire.

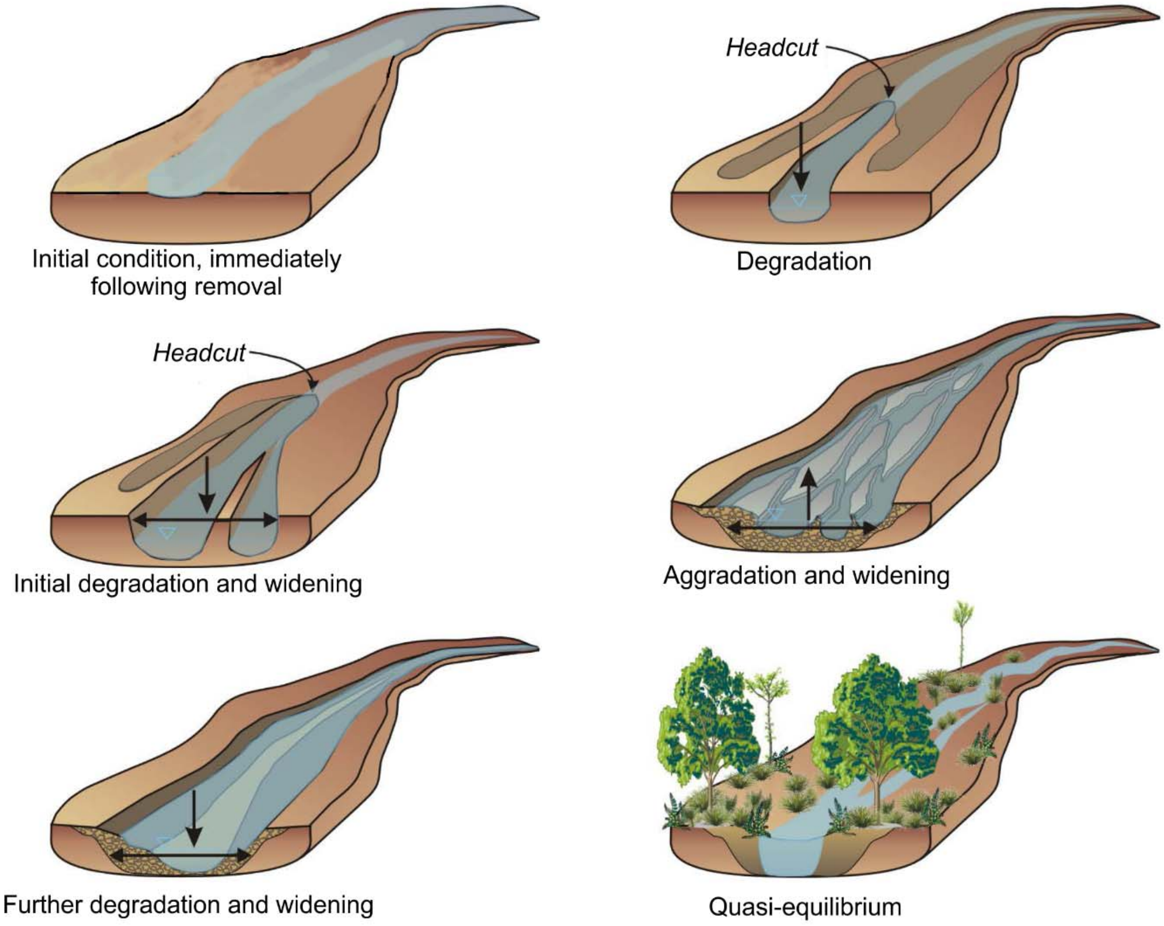


Figure 4-10. Conceptual model of the expected evolution of Arroyo Seco through the reservoir of Brown Mountain Dam following dam removal. Dark arrows indicate the direction of change in the channel at each step. Modified from USBR (2017, their Figure 25) and Cannetelli and Curran (2012).

Downstream of the damsite, the released pulse of sediment will move down the channel and evolve in ways predicted both by modeling and observation (Morgan and Nelson 2019, Cui et al. 2019). The pulse will translate, diffuse, and attenuate in broadly predictable but somewhat stochastic ways, depending on the size-distribution of the sediment, the sequence of storms, the implemented dam-removal alternative (i.e., single-removal or staged), and variability of the downstream valley geometry and gradient.

Total stream power is proportional to the slope–discharge product, and it provides a coarse measure of the amount of work that the streamflow can potentially accomplish per unit time. This fundamental characteristic of flow in a channel was first developed by Lane (1955) and Bagnold (1966). And although it obviously neglects various factors in natural channels that constrain the amount of work that can be achieved and the nature of its expression, it has proven to be a useful indicator of a channel's ability to transport sediment and adjust morphologically.

Most relevant to discerning large-scale patterns of sediment transport and deposition is the downstream *change* in the slope–discharge product: an increasing trend implies transport of the sediment load and additional energy available to erode the channel (if it is erodible), while a decreasing trend implies a zone of sediment deposition. For the Arroyo Seco, channel slopes are known from LiDAR, and because downstream trends are of interest the absolute magnitude of discharge is not critical—only how that discharge changes over the reach of interest. Thus, an "index of stream power" can be calculated as the product of local slope and the relative discharge, simply scaled as the drainage area of the watershed at BMD (14.4 mi^2) relative to the (larger) drainage area at each point progressing down to Devil's Gate Dam (23.6 mi^2). This result, plotted in Figure 4-11, suggests that sediment deposition should be pronounced in a 0.5- to 1-mile zone downstream of RM 4.3, and most markedly in the lowermost 1.3 miles beginning at about the Explorer Road crossing as the valley opens out and channel gradient decrease approaching Devil's Gate Dam. These predicted locations are fully consistent with similar findings predicted by DREAM (see Section 3.5.2).

Upstream of RM 4.5 and between these two depositional zones, stream power is predicted to be uniform or increasing, suggesting that the incoming sediment load can be transported through these areas without chronic deposition. Locally, a marked increase in gradient around RM 2.5 may be indicative of potential erosional activity. A near-equivalent rate of increase in stream power is also present between RM 1.89 and RM 1.4, extending through the reach that includes the Pasadena diversion weir. This pattern suggests that channel aggradation from the chronic deposition of coarse sediment may not severely impact this facility. However, the local hydraulics around the adjacent diversion weir and the nearby bridge opening, less than 100 yards downstream, may alter the conclusions of this coarse-scale assessment. This uncertainty emphasizes the importance of conducting more detailed, future sediment-transport evaluations.

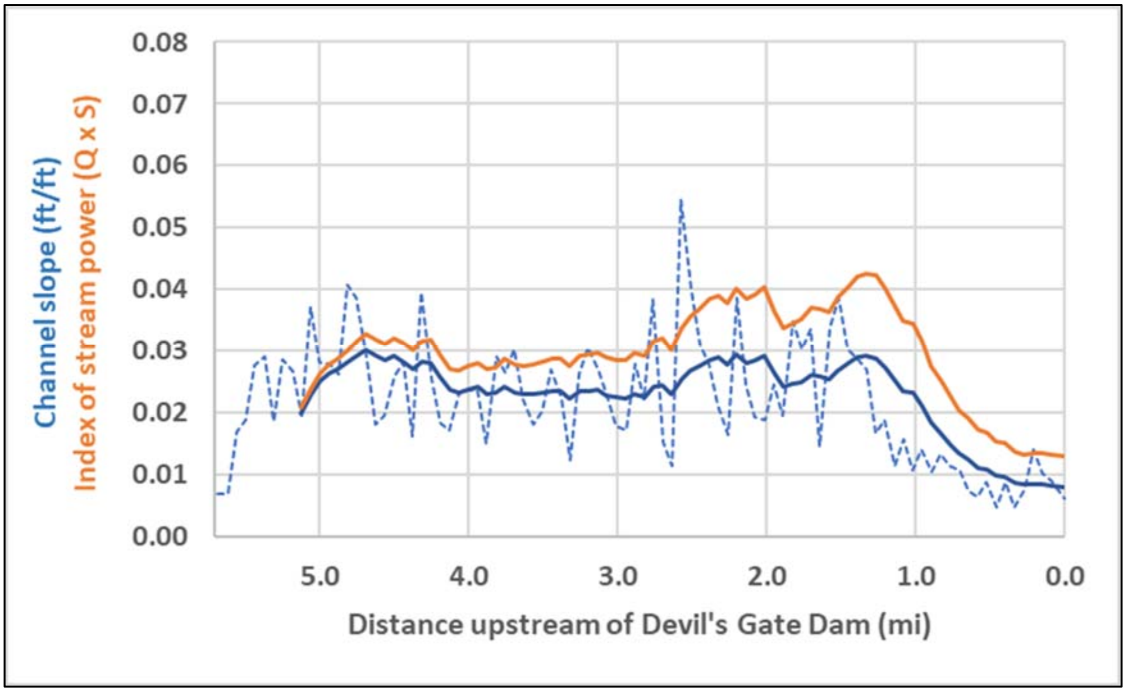


Figure 4-11. Channel slope derived from LiDAR (dashed line) at 32.8-foot (i.e., 10-meter) intervals, with smoothing over 10 individual measurements (solid blue line) to highlight broad patterns. The orange line applies a simplified, progressive multiplier to the blue smoothed slope values to approximate the effect of increasing downstream drainage area on the slope-discharge product (i.e., displaying of the pattern in total stream power along the channel).

Finally, USBR (2017, pp. 119–120) recommends a preliminary calculation of ***mass balance*** as a way to quickly evaluate whether the volume of sediment in the reservoir is likely to have significant downstream impacts. This approach is typically superseded by sediment-transport modeling in all but the simplest of cases, but the exercise is still worth investigating, if only to confirm the likely importance of downstream sediment management.

The most straightforward approach to a mass-balance evaluation is to assume that the entire thickness of evacuated reservoir sediment is spread in a uniform layer over the downstream bankfull channel. This is an obvious simplification, but if the resulting calculated thickness is only a scant fraction of the bankfull channel depth, then minimal impacts of the released sediment might be anticipated. Here, however, this is clearly not the case. The estimated volume of released sediment (870,000 yd^3), spread over the length of the channel down to Devil's Gate Dam (5.68 miles) over a bankfull channel width of approximately 30 feet, yields a uniform sediment depth of about 26 feet. Even allowing for variations in width, throughput of sediment along much of the channel, and including the fine-sediment fraction that would move as suspended load and not be part of any long-term deposition (hypothetical or otherwise), this result clearly emphasizes the significance that full sediment release following dam removal would have on the downstream channel.

This issue has already been explored in more detail above (see Section 3.5.2) and will likely require further investigation in a later stage of analysis beyond this preliminary report.

4.2.2 *Moderate* risk analyses: geomorphic analysis, sediment wave model, sediment transport capacity

Under the *moderate* risk scenario, several analyses are recommended by USBR (2017) that build upon those undertaken for the low risk condition. First, complementing and developing from the initial conceptual model (see Figure 4-10), a more comprehensive **geomorphic analysis** is recommended based on the popular "Fluvial Audit" approach of Sear et al. (1995). The Fluvial Audit combines the understanding of the physical setting of the watershed and its environmental history to derive an interpretative account of the watershed's sediment budget over recent decades as the basis for developing sustainable river management options. This account forms the basis for developing a causal understanding of the historical factors most likely to have been driving geomorphological responses in the recent past, as context for interpreting contemporary activity (Californian examples in Downs et al. 2013, 2018, 2022). A Fluvial Audit combines a historical timeline, watershed understanding of likely sediment sources, and reach-level mapping of channel morphology characteristics to understand recent changes in the fluvial system in the context of the factors likely to have caused them. The audit thus considers the channel's pre-modification condition and how this has been modified by human activities. Typically, the channel network is sub-divided into reaches that are homogenous in terms of their current conditions. In the context of dam removal, the audit will provide greater qualitative details to determine the channel's likely sensitivity to the proposed removal, adding detail to the conceptual model shown in Figure 4-10.

Undertaking a Fluvial Audit requires the integration of a wide range of data sources concerned with the geomorphology of the watershed, many of which were compiled in Sections 3.2 and 3.4 of this report. A review of historical maps and imagery and a reconnaissance walkover of the channel network recording sedimentary conditions and channel morphology is also required, but that level of detail has not been undertaken as part of this preliminary assessment. The understanding already derived from sediment wave modeling (see Section 3.5.2 and below), however, does provide a valuable extension to a typical Fluvial Audit.

Building from the stream power and mass balance estimations typically undertaken for dam removals with low sediment risk, *moderate* risk scenarios also benefit from **sediment wave modeling,** wherein a 1D sediment transport model is applied to simulate the general downstream redistribution of sediment likely following dam removal. This analysis has already been undertaken here using DREAM (Cui et al. 2006a, b), and the results provided in Section 3.5.2. Sediment wave models use simplified terrain and channel cross-sectional geometries to facilitate rapid calculations. Here the model terrain was obtained from LiDAR and Google Earth imagery with sediment grain-size distributions based on sampling undertaken in neighboring areas. LiDAR allows the sediment wave model to accommodate downstream changes in gradient, an improvement over the recommendation of USBR (2017, pp. 120).

Two preliminary scenarios were undertaken with a focus on the first day's mobilization of sediment following approximate 2-year and 10-year return period flow events. Unsurprisingly, in this steep confined terrain, gravel is mobilized under both scenarios with the 10-year event predicting to result in significant deposition (i.e., 1 foot to more than 3 feet) in a zone from 4.5–3.5 miles upstream of Devil's Gate Dam, and downstream of the JPL bridge in the Devil's Gate Reservoir (Figure 3-26). While the assumption of an instantaneous dam removal is realistic in the sense that a single-season removal in the summer may precede any such a high flow in following winter, the assumption of a day-long steady discharge is unrealistic in this area of episodic, intense and short-lived flood events. As such, the *peak magnitude* of the discharge is underpredicted but the *duration* overpredicted, so an actual event would be capable of mobilizing coarser particle sizes than predicted but the volume of sediment mobilization may be overestimated. Furthermore, all results are conditioned by the fact that there has been no grain-size sampling of the reservoir sediments, leaving this element as the least constrained part of the simulation (see also Section 4.3).

Because the sediment wave model uses a variable downstream gradient, the model results are equivalent to undertaking cross-section–based **sediment transport capacity equations**, as suggested in USBR (2017), and so there is little need to perform this separate analysis. In addition, because risk of sediment impact is *moderate-to-high*, there is clear justification for performing 2D sediment transport modeling (see next section).

4.2.3 *High* risk analyses: numerical sediment model, laboratory model, field test

In situations where sediment management poses a potentially *high* risk to downstream areas, USBR (2017) recommends one or more of numerical sediment modeling, laboratory (physical) modeling, or field testing of the potential impacts. If sediment scaling issues can be suitably accommodated (e.g., boulders are difficult to accommodate in a lab-scale model), **laboratory modeling** can be useful especially where the reservoir shape is complex or where the impounded area and/or downstream reaches are wide such that responsive locations are a significant unknown. For BMD, such modeling is unnecessary: the narrow valley of the (sediment filled) impoundment and the immediate downstream reaches is a sufficient constraint that post-removal morphological evolution can be readily estimated conceptually (see Section 4.2.1). **Field testing** requires the ability to lower the reservoir pool or open a sluice gate to test conceptual or modeled predictions and is prevented here by the fact that the entire pool is sediment-filled.

The narrow valley setting might also imply that detailed **numerical sediment modeling** is unnecessary, at least for predicting the relative morphological evolution of the downstream channel following dam removal. However, the volume of sediment involved, the potential downstream infrastructure impacts, and the complications introduced by broadening of the floodplain as the valley slope flattens above Devil's Gate Dam provide incentives for obtaining a better understanding of the absolute volumes, depth, locations, and progression of sediment following removal. For these reasons, a 2D numerical sediment model is likely to result in a more realistic and useful understanding of the naturally complex geomorphic processes involved. Previous exercises in numerical model simulations for dam removal have predicted both greater or lesser sediment deposition in comparison to 1D models along the same channel, depending on the topography involved and the complexity of the marginal environments (e.g., whether the margins and overbank areas encourage sediment deposition, which cannot be simulated with a 1D model). In general, complex channel-margin environments tend to result in a slower predicted downstream progression of the pulse of released sediment.

Overall, while differences between 1D and 2D models can be small in highly confined settings such as the Arroyo Seco, the large volume of sediment set for release suggests that undertaking a 2D model simulation would be a logical precaution in planning post-removal sediment management. Undertaking 2D numerical sediment modeling would also necessitate accurate characterization of the sediment grain-size distribution in the impounded area and upstream reach (see below).

4.3 Step 8: Assess Uncertainty

The 2017 Guidelines emphasize the importance of evaluating the uncertainty that is unavoidable in both observations and modeling. Not all uncertainty is problematic; but where the impacts of a condition or a model result could be significant, then all feasible efforts should be made to reduce that uncertainty. The current project scope does not allow for the resolution of these uncertainties, but this step of the 2017 Guidelines supports a systematic inventory of the work that the next phase of a broader dam-removal study will need to undertake (USBR 2017).

4.3.1 Observational uncertainties

Reservoir sediment volume: The quantity of stored sediment behind BMD is known to a reasonably high degree of accuracy, given the convergence of multiple lines of evidence (see Section 3.2.6). Although that estimate may be incorrect by 5–10%, that uncertainty is insufficient to alter the nature or magnitude of downstream risk or impacts. Further effort to reduce uncertainty in this parameter is probably not warranted.

Sediment grain-size distribution: This uncertainty is well-recognized in the studies to date, insofar as no measure of the bulk sediment deposit in the reservoir or channel has been made. This property of the reservoir deposit critically influences the likely duration and magnitude over which downstream impacts will be experienced. Similarly, the sediment-transport modeling needed to make these predictions is highly dependent on this parameter. At present, the only characterization of sediment sizes has been drawn from other, presumed analogous, southern California reservoir deposits. Direct measurements will be a necessary element of any subsequent assessments.

Contaminants: Although the sediments behind BMD have not been sampled for contaminants, the geology and land use upstream from BMD in the Arroyo Seco watershed strongly suggest that this uncertainty is not critical to the further development of dam-removal alternatives. Step 3 of the 2017 Guidelines (see Section 3.3) suggest that even as far down as Devil’s Gate, sediments do not require contaminant-motivated management.

Stream flow hydrograph: The existence of a near-continuous gage record close to the dam, with less than a 12% disparity in watershed areas between the gage and the dam itself, suggests that the quality of the hydrologic record is already high. In southern California, the greatest source of hydrologic uncertainty is the erratic nature of high flows, with the variability in annual peak discharges spanning more than an order of magnitude. The additional uncertainty in the frequency and magnitude of sediment-transporting flows imposed by climate change will almost certainly remain unresolved through further analysis; instead, it will require management through sufficient safety factors to accommodate the intrinsic (and largely unpredictable) variability of southern California rainfall.

4.3.2 Parameter uncertainty

The 2017 Guidelines define this uncertainty strictly in terms of sediment transport model inputs, specifically channel roughness values, the threshold-of-motion for sediment particles, and the depth of the actively transported bedload sediment. All three are normally addressed through presumed initial values, adjusted during calibration as needed to match observations (at least for channel roughness). Nominally the sediment-transport parameters could be calibrated to measured accumulation rates of sediment in Devil’s Gate Reservoir (see Section 3.4.2), but any such calculation assumes a “transport-limited system,” wherein there is always sufficient sediment to fill the transport capacity of the flow. For very high discharges, this may not always be true, as demonstrated by the variability in sediment accumulation immediately post-fire (i.e., ample sediment) and non-post-fire (i.e., low-sediment-supply) conditions of high flow. Sediment transport modeling is notoriously imprecise under the best of circumstances (Wilcock et al. 2009); this uncertainty can never be fully resolved.

4.3.3 Model structure uncertainty

The 2017 Guidelines acknowledge this uncertainty as the most difficult to quantify and almost impossible to fully resolve. However, Wilcock et al. (2009) suggest that this uncertainty is commonly overshadowed by other potential sources of error, and they caution against one of the most commonly applied strategies, calculation using different formulas with the same input data:

> Given a drop-down menu providing a choice of different transport formulas, it is tempting to select all the formulas in order to get some idea of the uncertainty in the calculated transport rate. This will, indeed, give a range of estimated transport rates, although it is hard to know what to make of it. The main source of uncertainty in calculated transport rates arises from uncertainty in the input values of grain size, boundary stress, and hydraulic roughness. Considerable effort has been spent over the years in comparing the accuracy of different transport formulas. Such comparisons…divert attention from the primary source of error in calculated transport rates: uncertainty in the boundary conditions. Too often, the transport formula is blamed for poor results when the real culprit is poor input (Wilcock et al. 2009, p. 51).

Instead, they suggest focusing first on choosing the most appropriate model for the application, wherein the range of grain sizes, channel dimensions, and gradient most closely matches the subject site; and then to conduct Monte Carlo simulations under a credible range of input parameters, with a greater focus on “parameter uncertainty” than “model structure uncertainty.” A range of plausible results will always ensue under such an approach rather than a single answer, but having a well-supported range of likely outcomes will invariably provide a stronger foundation for making engineering judgements.

4.4 Step 9: Determine if Sediment Impacts are Tolerable and, if Needed, Modify Sediment Management Plan

Our guide for this preliminary analysis, namely the 10-step sequence described in 2017 Guidelines (USBR 2017), envisions that an initial dam-removal alternative is fully analyzed through Steps 6–8 and then assessed in this step for whether its sediment impacts are “tolerable.” This approach is not entirely suitable for the present application because the resources for making a definitive evaluation of impacts are not yet available. Thus, the iterative cycle of Figure 4-1 is not yet possible, and a recommended sediment-management plan (and, by extension, a recommended dam-removal strategy) cannot yet be identified.

Nevertheless, our interpretation of Step 6 of the 2017 Guidelines (“Dam removal plans and sediment management alternatives”, Section 4.1) leads to the conclusion that natural erosion of the reservoir sediment during single-season or multi-year dam removal may be the most plausible avenues for future, detailed evaluations. The choice of single-season or multi-year removal will likely depend on the overall level of sediment management risk involved, which we currently characterize as *moderate-to-high* (Figure 4-9). While we have a reasonable qualitative understanding of the likely dynamics of the sediment pulse and subsequent morphological response of the channel (see Sections 4.2.1 and 4.2.2), a precautionary approach argues for improved understanding of the *absolute* volumes of sediment involved that can be obtained by undertaking 2D numerical sediment modeling (Section 4.2.3). An outline of the adaptive management framework that will likely be required to implement either of these approaches is presented in the following section.

4.5 Step 10: Develop Monitoring and Adaptive Management Plan

Figure 2-1 provides the flow chart for planning dam removal that has guided the approach taken in this study. However, “removal” by itself does not mark the completion of the dam-removal process. There remains sufficient uncertainty regarding every removal process and the fate of the stored sediment that dam removal is, in part, a process of “learning by doing” and so must include a program of monitoring and evaluation under an adaptive management framework. An earlier proposal for adaptive management for dam removals is provided in Figure 4-12 (derived from river restoration adaptive management plans, see SRAC 2000; Downs et al. 2011).

Critically, adding an adaptive management framework to the dam-removal process creates a feedback loop in the dam removal process (compare Figure 2-1 to Figure 4-12). Post-removal monitoring and evaluation is compared to pre-removal baseline data to refine the conceptual model of system understanding (herein, Figure 4-10) as a benefit to the global knowledge guiding dam removals. Generally, such approaches use a Before-After-Control-Impact (BACI) style of monitoring. For BMD, due to the channelized section of Arroyo Seco downstream of Devil’s Gate Dam, the “control” component of such an approach would require identification of a suitable upstream reach (i.e., beyond the influence of the impoundment).

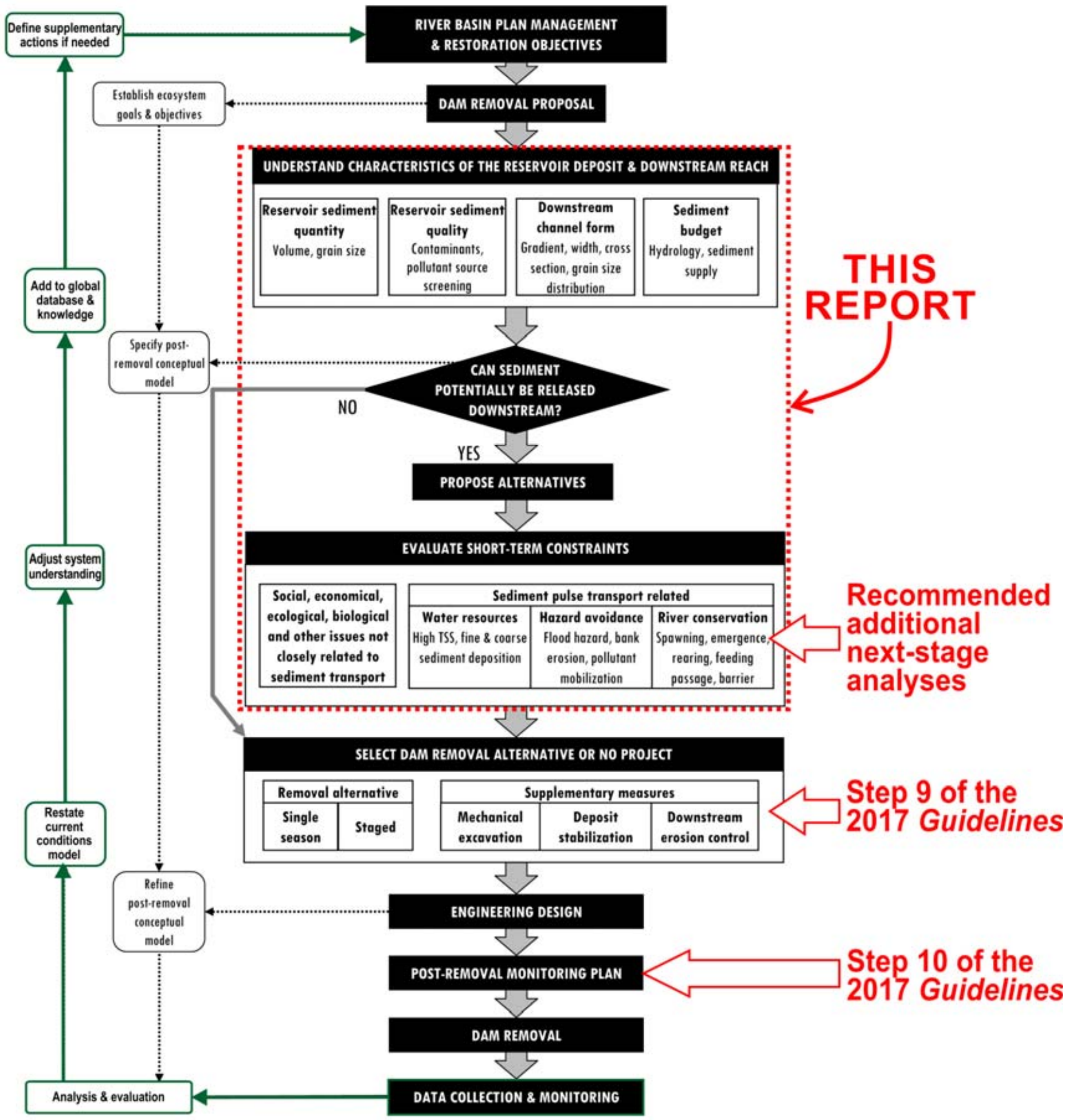


Figure 4-12. Conceptual diagram for planning and implementing dam removal (Downs et al. 2009, their Figure 9) with annotations highlighting its relationship to this report and the final two steps of the 2017 Guidelines. The adaptive management stage and feedback look are highlighted in green.

For the BMD removal process, a series of specific testable hypotheses should be derived once the removal engineering process has been confirmed, any further baseline data collected ahead of removal, and a program of periodic monitoring devised to test the hypothesized geomorphic response of the river. In general, three types of monitoring provide useful post-project information, covering implementation, effectiveness, and validation. Implementation monitoring is a short-term program (e.g., 1 to 6 months) that, as the name suggests, determines whether the project was undertaken as conceived. Where a project diverges from the intended design (or, in this case, the removal), project evaluation objectives need to be re-conceived to be logical in the context of what actually happened, rather than what was planned. Thereafter, effectiveness monitoring, over a period of up to a decade, determines whether the project met its environmental performance objectives. Validation monitoring seeks to determine whether the basic assumptions behind the project are valid, and it can extend for a period of 5 to 10 years or decades if required.

A suite of monitoring elements is suggested by USBR (2017, pp. 144-5) to determine the spatial extent and duration of changes to channel morphology and sediment processes resulting from dam removal. When, as here, the targets for dam removal include biological objectives, monitoring of biological and ecological elements will also be required. Integrating these various monitoring elements often requires a "weight of evidence" approach that links physical to biological elements across the process-form-habitat-biota spectrum to rigorously determine whether objectives have been met. However, some elements of monitoring, not least the validation hypothesis related to the upstream use of Arroyo Seco by *O. mykiss* following dam removal, should be relatively simple to detect.

5 RECOMMENDATIONS

This preliminary assessment of the opportunity for, and conditions associated with, removal of BMD has integrated much of the baseline information required to undertake the next stage(s) of analysis. The complete loss of water and sediment storage behind the dam, the absence of nearby infrastructure, and the almost entirely undeveloped upstream watershed means that the potential impacts of dam removal are almost entirely limited to the release of the reservoir sediments, which are expected to contain very low levels of contaminants. However, the significant volume of that sediment, relative to both average annual watershed sediment loads, and the potential impact of deposition on downstream infrastructure, suggests that more detailed analyses will be a necessary component of any future alternatives evaluation.

Given the primacy of potential sediment impacts here, the framework provided by 2017 Guidelines (USBR 2017) is particularly appropriate. Its initial application to BMD in this report has highlighted several critical information needs, which should be the focus of any subsequent analyses. They include:

- Detailed assessment of the structural make-up and current condition of the dam beyond that provided here in Section 4.1 to determine whether certain prospective removal alternatives (e.g., tunnelling, notching, single-stage demolition) are in fact feasible.
- Direct sampling of the reservoir sediment in sufficient density and detail to extend the preliminary estimates used here (Section 3.2.5) as the basis for accurately characterizing the grain-size distribution for input into an advanced sediment-transport model.
- Undertaking the additional field and historical assessments sufficient to develop a Fluvial Audit–style assessment of the environmental history to determine the likely sensitivity of reaches of the river in response to dam removal (see Section 4.2.2).
- Constructing a full 2D hydraulic and sediment-transport model of the Arroyo Seco between BMD and the JPL bridge to make realistic predictions of the volume and rate of sediment delivery and deposition, particularly in the vicinity of the Pasadena water-diversion intake (RM 1.81) and downstream of Explorer Road (where the sediment would become the management responsibility of the Los Angeles County Public Works).

Concurrent with (or in advance of) these additional studies, removal of additional fish-passage barriers between Devil's Gate Dam and BMD (Stillwater Sciences 2024) should occur. There is limited value in removing the dam if downstream barriers still prevent any fish from taking advantage of its absence. Lastly, the potential magnitude of downstream sediment impacts from dam removal suggest that coordination with downstream agencies (particularly the City of Pasadena and LA County Public Works) will be essential. The delivery of more than 1 million yd^3 into Devil's Gate reservoir in the 2 years following the Station Fire (LACDPW 2014), even with BMD still in place, suggests that the sediment load potentially released following dam removal would not be unprecedented in recent history. However, the management challenges (and cost) associated with any future deposition of similar magnitude would undoubtedly be substantial and require careful planning and collaboration.

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