FINAL REPORT, PHASE 2:

Restoration of the Merced River through Yosemite Valley, Yosemite National Park

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1 BACKGROUND

1.1 Purpose

The purpose of this project is to provide scientific and engineering design support to Merced River restoration efforts in east Yosemite Valley being considered or implemented by the National Park Service (NPS). This work is being conducted in an area of both great natural resources and intensive human activity, with complex and potentially conflicting goals articulated by the Merced Wild and Scenic River Final Comprehensive Management Plan and Environmental Impact Statement, issued in February 2014. The Study Area includes is the 5-km reach of the Merced River between Happy Isles Bridge and Sentinel Bridge (Figure 1-1), although the influence of watershed and riverine conditions outside of this reach must also be evaluated considerations to achieve our overall purpose.

Figure 1-1. An overview of the Study Area, the focus of this report. The subsequent phase of this project will emphasize an analysis and potential treatments to improve conditions in the Project Reach.

The objectives of this report are three-fold:

1. To document and summarize the data collection and analyses focused on the Merced River through Yosemite Valley, emphasizing the work of the last three years but incorporating the information and insights of several decades' worth of prior work by multiple investigators;
2. To summarize the past evolution and future trajectory of the river in terms of its geomorphic context and history of anthropogenic influence; and
3. To explore the implications of these findings on the ongoing management of this iconic river.

1.2 The Outstandingly Remarkable Values of the Merced River through Yosemite Valley

Although there are many lenses through with the river can be viewed, we suggest that the previously identified Outstandingly Remarkable Values (ORV's; ESA 2012) are most likely to provide the most relevant guidance for identifying the key geomorphic drivers of the river's current conditions and future trajectory. This framework notes in particular the association of the Merced River with the Biological, Recreational, and Geologic and Hydrologic ORV's within Yosemite Valley.

Within the Valley, the Biological ORV's emphasize the large meadows and riparian vegetation communities, which are "rare and unusual at a regional and national scale" (ESA 2012, p. 2). They are created and sustained by high groundwater levels, in large part determined by river level; the locations and magnitude of bank erosion and channel migration; and the activity of people, on both the uplands (particularly Native American burning) and along the riparian zone itself (particularly modern recreational users).

The Recreational ORV's are identified as both "primary" activities within the river and "secondary" activities along the banks or within the riparian zone. These activities not only have direct effects on the river but also influence management of the river by the National Park Service, particularly the removal or repositioning of large tree trunks and logs that pose a hazard to boaters but also form a key element of mid-elevation river geomorphology.

The Geological and Hydrological ORV's owe their existence to the glacial topography of the Valley, unimpeded by subsequent damming or channelization. "The Merced River, from Happy Isles to the west end of Yosemite Valley, provides an outstanding example of a rare, mid-elevation alluvial river. In Yosemite Valley, the Merced River is alluvial, characterized by a gentle gradient, a robust flood regime with associated large woody debris accumulation, and complex riparian vegetation. There are few examples in the Sierra Nevada of similar river morphology at this scale and elevation (about 4,000 feet)." (ESA 2012, p. 79) Given the present level of protection afforded the watershed of the Merced River upstream of the Valley, there is little credible "threat" to the underlying conditions that have given rise to these ORV's. Nonetheless, understanding how these geological and hydrological conditions have given rise to attributes of the river that remain valued and unique to the present day can highlight those processes that must be preserved or restored if those valued attributes are to persist into the future.

1.3 An Overview of the Merced River

Prior study of the Merced River has generated a valuable picture of the river and its watershed through time. Four studies in particular provide a robust foundation for our present work: a Master's thesis by Millstone (1978) emphasizing human impacts to the river, a technical report by the US Geological Survey

(Madej et al. 1991, and its subsequent journal summary in 1994) emphasizing the magnitude and causes of bank erosion, a comprehensive inventory of channel and riparian-zone conditions along a 16-km reach of the Merced River that fully encompasses the present study (Cardno 2012), and a US Geological Survey open-file report (Minear and Wright 2013) that made use of a hydraulic model to evaluate the potential consequences of alternative bridge-removal scenarios.

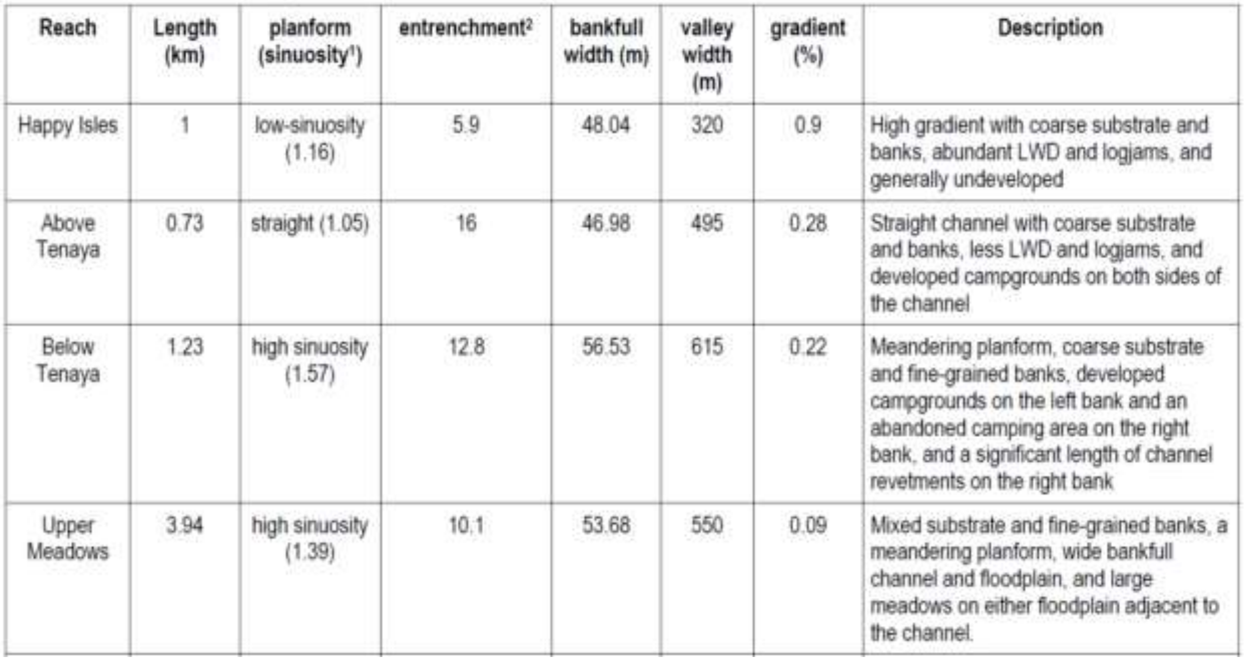
The most spatially and temporally broad of these studies is that of Milestone (1978). Through the use of historical records and photographs, he documented a variety of post-European settlement activities, beginning in the 19th century, that have left their imprint on the river up to the present day:

- The river had a predominantly braided channel pattern as of 1851; meadows within the meander belt were swampy with water in adjacent oxbows and sloughs. Stream erosion was common in photos in 1866.
- The El Capitan moraine dam was blasted in 1879 in an effort to lower the base level of the river and alleviate wet-meadow conditions. This had resulted in 4.5’ of lowering of the river bed at the moraine as of 1977, with declining influence for the next 5 km upstream.
- Instream gravel was mined extensively (20,000 cubic yards recorded, presumably much more actually removed).
- Logs and stumps were aggressively cleared, which left a fully free-flowing river as of 1899, in contrast to view of abundant log jams as late as 1877. These efforts continued for decades; for example, 126 trees and 161 stumps were removed from 1.2 miles of channel in 1934.
- By 1900, channel was largely single-thread by virtue of bank stabilization and downcutting, and by loss of sediment input from extensive bank revetments.
- Trampling of river banks by campground users was noted in 1964.
- The first systematic tabulation of “bridge” and “natural” channel widths (as of 1977) was included in this report (Milestone’s Table 15). The association of deep scour pools with bridges was also noted.

Madej et al. (1991) followed Milestone’s initial work with a more focused evaluation of the history, distribution, and causes of changing channel widths. They compared measurements made in 1986 and 1989 with USGS topographic maps from 1919, documenting extensive bank erosion and channel widening along much of the present Study Area. Through this reach, they documented both pervasive channel widening, particularly in areas with much bare ground associated with high human use, and channel constrictions associated with the bridges. By river segment, they noted severe bank erosion between Clarks Bridge and Sugar Pine Bridge, “almost exclusively associated with human trampling.” Downstream to Ahwahnee Bridge the channel was stable but fully hardened along its outside bend. Downstream to Stoneman Bridge, severe erosion was noted, with the major contributor being ill-placed riprap and insufficient flow capacity through the bridge openings. Disturbance, primarily human trampling, was identified as a continuing but declining impact downstream from Stoneman Bridge to Sentinel Bridge. Based on these observations, Madej et al. (1991) offered a suite of management recommendations: limit human access in the riparian zone, remove or replace what they termed “problem bridges” (i.e., those severely constricting the channel width or with inadequate capacity for flood flows), remove “problem revetments,” replant the riparian zone, and leave large woody debris (LWD) in the channel wherever possible.

Cardno (2012) inventoried channel and riparian conditions throughout the Valley, with the objectives of characterizing changes since Wild and Scenic River designation in 1987 and identifying metrics to support future monitoring efforts. This work produced a systematic inventory of selected channel conditions for their named "geomorphic reaches" that constitute the Study Area of the present effort (Table 1-1 and Table 1-2).

Table 1-1. Cardno's (2012) Table 3-1, characterizing their individual geomorphic reaches that fall within the present Study Area.



Reach	Length (km)	planform (sinuosity[1])	entrenchment[2]	bankfull width (m)	valley width (m)	gradient (%)	Description
Happy Isles	1	low-sinuosity (1.16)	5.9	48.04	320	0.9	High gradient with coarse substrate and banks, abundant LWD and logjams, and generally undeveloped
Above Tenaya	0.73	straight (1.05)	16	46.98	495	0.28	Straight channel with coarse substrate and banks, less LWD and logjams, and developed campgrounds on both sides of the channel
Below Tenaya	1.23	high sinuosity (1.57)	12.8	56.53	615	0.22	Meandering planform, coarse substrate and fine-grained banks, developed campgrounds on the left bank and an abandoned camping area on the right bank, and a significant length of channel revetments on the right bank
Upper Meadows	3.94	high sinuosity (1.39)	10.1	53.68	550	0.09	Mixed substrate and fine-grained banks, a meandering planform, wide bankfull channel and floodplain, and large meadows on either floodplain adjacent to the channel.

[1] Sinuosity is calculated as the ratio of channel (thalweg) length to downvalley length.

[2] Entrenchment ratio was calculated by dividing the flood prone width (the width of the valley at two times the bankfull depth) by the bankfull width. Smaller numbers indicate greater entrenchment.

Table 1-2. Cardno’s (2012) Table 5-1, summarizing Merced River conditions by their geomorphic reaches.

Metric	Happy Isles	Above Tenaya	Below Tenaya	Upper Meadows
				RIPARIAN
CRAM[1]	Higher	Lower	Lower	Moderate
Buffer Condition	Moderate	Lower	Lower	Moderate
Buffer Width	Higher	Higher	Moderate	Moderate
Hydroperiod or Channel Stability	Higher	Moderate	Lower	Moderate
Biotic Condition	Moderate	Moderate	Lower	Moderate
Physical Structure	Moderate	Lower	Moderate	Moderate
				CHANNEL
CMZ Area	Moderate	Moderate	Low	High
CMZ Connection	High	High	Low	Low
LWD Loading	High	Moderate	Low	Moderate
LWD Recruitment	Fluvial / Bank Erosion	Fluvial / Tree Fall	Fluvial / Tree Fall	Fluvial / Bank Erosion
LWD Association	Jams	Jams	Single Piece	Jams
Pool Formation	High	High	Low	Moderate
Potential LWD Loading	High	High	Moderate	Moderate
				WILDLIFE
Habitat Area	Moderate	Moderate	Low	High
# of Species	High (Reptiles)	High (bats, birds)	Low (Birds only)	High (birds, bats)
				STRESSOR
Stressor	Human use	Human use	Limits on channel migration Human use	Limits on channel migration Human use Invasive species

Their key findings include a marked reduction in LWD between the segments above and below the Tenaya Creek confluence, but an overall increase in numbers relative to the Madej et al. (1991) survey two decades earlier; a steady increase in channel area (resulting from channel widening) throughout the second half of the 20th century, with some acceleration since 2005 ascribed to a reduction in revetments from washout during the 1997 flood; little change in overall channel planform; and a reiteration of earlier findings that the primary stressors to the geomorphic and ecological health of the river are human use of the riparian zone and structural confinement from infrastructure and revetments.

Minear and Wright (2013) developed a hydraulic model to support anticipated applications for alternative river management scenarios. A review of prior data and newly collected geomorphic information offered additional perspective on the river's current form and function. They documented a general downstream decline in sediment sizes that mirrors the downstream reduction in channel gradient, and they noted that the gravel-sized sediment was unlikely to have entered the Merced River from either Tenaya Creek or the watershed upstream of Nevada Fall. They also noted that simulation of flows in the 1919-era channel geometry resulted in floodplain inundation at a 2-year flood, but that now that surface requires about a ~5-year flood to overtop the channel banks (about a 60% increase in discharge).

2 AN OVERVIEW OF THE PRESENT STUDY (Figure 2-1)

Since the beginning of the project in late 2015, a variety of data-compilation, data-collection, and mapping efforts have been conducted to develop a comprehensive characterization of the Study Area and associated riparian and floodplain areas, addressing the geomorphic, hydrologic, and vegetative attributes and conditions. This report documents those efforts and summarizes their findings, with a particular emphasis on the geomorphic drivers of channel conditions and their implications for future restoration work on the Merced River throughout the eastern portion of Yosemite Valley.

The work done to accomplish these tasks has comprised data compilation, field data collection, channel-migration modeling, in-stream project design and construction monitoring, and stakeholder outreach. As a result of this work we have developed a variety of map-based characterizations of channel and riparian-zone attributes throughout the Study Area, complementing those developed by prior studies (particularly Cardno 2012). We have contributed to the development of a new geologic map of the valley, whose primary scientific leadership has been provided by National Park Service staff and which plays a key role in understanding the past history and future trajectory of the Merced River. Most importantly, we have developed an understanding of the key geomorphic processes and conditions that have given rise to the river's form and function, that should guide restoration efforts along the river and its riparian zone, and that support the riverine-dependent ORV's of Yosemite Valley.

Figure 2-1. Overview map of the Study Area, highlighting the bridges over this part of the river and the numbered segments referenced in several of the subsequent analyses.

3 GEOLOGY AND CHANNEL GEOMORPHOLOGY

3.1 The geology and fluvial landforms of Yosemite Valley

The earliest study of the geology of Yosemite National Park, and in particular the origin of Yosemite Valley, was published by the US Geological Survey (Matthes 1930). It provided comprehensive overviews of the region's bedrock geology and the then-current understanding of the history of glacial advances and retreats in this part of the Sierra Nevada range, motivated by the question "To what extent is the valley a product of glacial action, to what extent a product of stream erosion?" (p. 1). Although the study documented multiple periods of Merced River downcutting during the millions of years of Sierra Nevada uplifting, the modern form of the valley is unquestionably a result of glacial action, and which provides one of the classical case studies of this process for geologists world-wide.

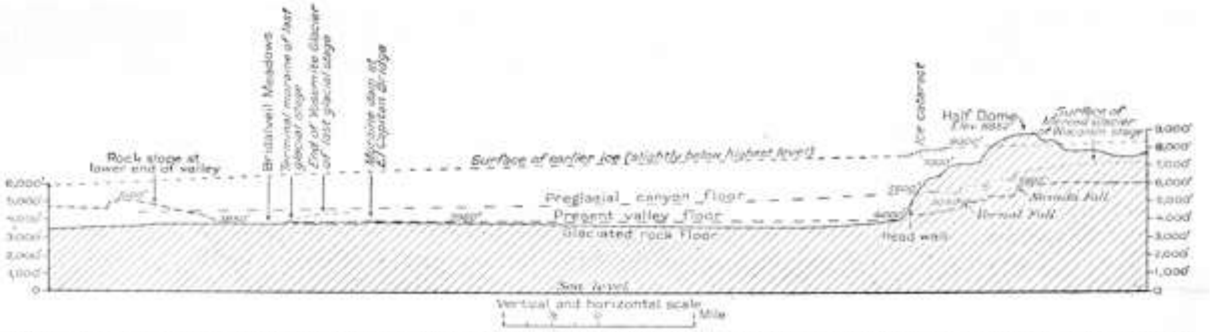


FIGURE 35.—Longitudinal section of Yosemite Valley showing the depth of glacial excavation, which increases headward to a maximum of about 1,500 feet; also the head wall and the platform above, whence the earlier ice plunged in the form of a great cataract. For comparison there is shown the relatively small cascade by which the Merced Glacier of the last ice stage descended from the giant stairway. Vertical scale same as horizontal scale

Figure 3-1. Reconstructed profiles of Yosemite Valley. Note the vertical scale—the magnitude of erosion between “preglacial” and “postglacial” time is as much as 1500 vertical feet (from Matthes 1930, his Figure 35). The feature labeled “Terminal moraine of last glacial stage” on the figure is called in modern parlance the “El Capitan moraine.”

This reconstruction emphasizes that today’s overall valley topography is not “fluvial”—it has been inherited from the last glaciation of the Sierra Nevada, modestly reworked by hillslope and riverine processes over the last 15,000 years since deglaciation. Matthes (1930) believed that the retreat of the ice from its terminal position at the foot of El Capitan (marked by the El Capitan moraine) resulted in the occupation of the valley by a widespread, continuous lake that persisted for an indeterminate period of, presumably, some centuries. The upstream end of the lake began filling by sediment transported from farther upvalley, forming a prograding delta whose front progressively advanced downvalley. Matthes believed that the moraine breached before the lake had been completely filled by sediment, resulting in an abrupt 14- to 16-foot drop in river level that extended upstream from the location of the breach. Continued lateral migration of the river created the modern valley bottom at this lower elevation, with only a few localities retaining fragments of this prior lake-filling surface (Matthes identified them as sites overlooking Tenaya Creek near the head of the valley, the level plain in front of Camp Curry, and north of the Cathedral Spires and the Cathedral Rocks).

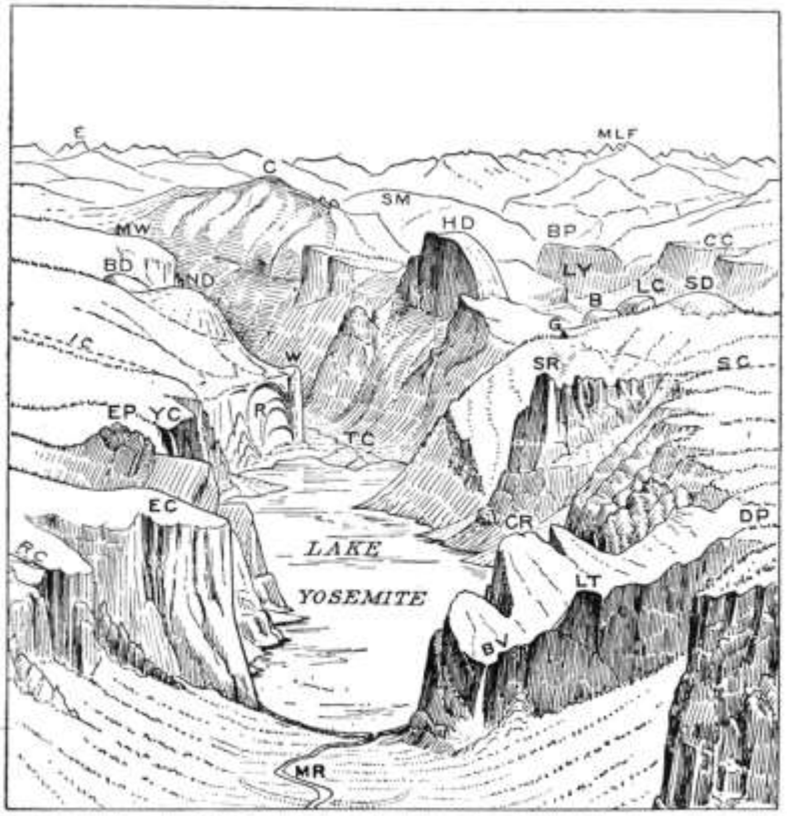


FIGURE 16.—Bird's-eye view of the Yosemite Valley as it probably was immediately after the ice age. The valley had been broadened and deepened to essentially its present proportions. The deepening accomplished by the ice ranged from 600 feet at the lower end to 1,500 feet at the upper end. A third set of hanging valleys had been added, and the Bridalveil Fall was produced. A lake 5½ miles long occupied a basin gouged into the rock floor of the valley and dammed in addition by a glacial moraine. The vegetation consisted in the main of types now prevailing. The drawing is based primarily on a systematic survey of the moraines and the other glacial features of the valley

RC, Ribbon Creek.
EC, El Capitan.
EP, Eagle Peak.
YC, Yosemite Creek.
IC, Indian Creek.
R, Royal Arches.
W, Washington Column.
TC, Tenaya Creek.
ND, North Dome.
BD, Basket Dome.
MW, Mount Watkins.
E, Echo Peak.
C, Clouds Rest.
SM, Sunrise Mountain.
HD, Half Dome.
M, Mount Maclure.
L, Mount Lyell
F, Mount Florence
BP, Bunnell Point.
CC, Cascade Cliffs.
LY, Little Yosemite Valley.
B, Mount Broderick.
LC, Liberty Cap.
SD, Sentinel Dome.
G, Glacier Point.
SR, Sentinel Rock.
SC, Sentinel Creek.
CR, Cathedral Rocks.
BV, Bridalveil Creek.
LT, Leaning Tower.
DP, Dewey Point.
MR, Merced River.

Figure 3-2. Oblique view of Yosemite Valley immediately following retreat of the glacier, with a continuous valley-filling lake impounded behind the El Capitan moraine (not labeled; at the foot of "EC"). From Matthes (1930, his Figure 16).

In the present study, mapping of deposits and landforms was combined with geochronology to reconstruct the geomorphic evolution of Yosemite Valley, particularly the valley-bottom deposits associate with the Merced River, since glacial retreat (Figure 3-3). The other set of prominent post-glacial deposits, rockfall avalanches, only locally impinge on the river and are addressed more comprehensively in other documents (e.g., Stock et al. 2014).

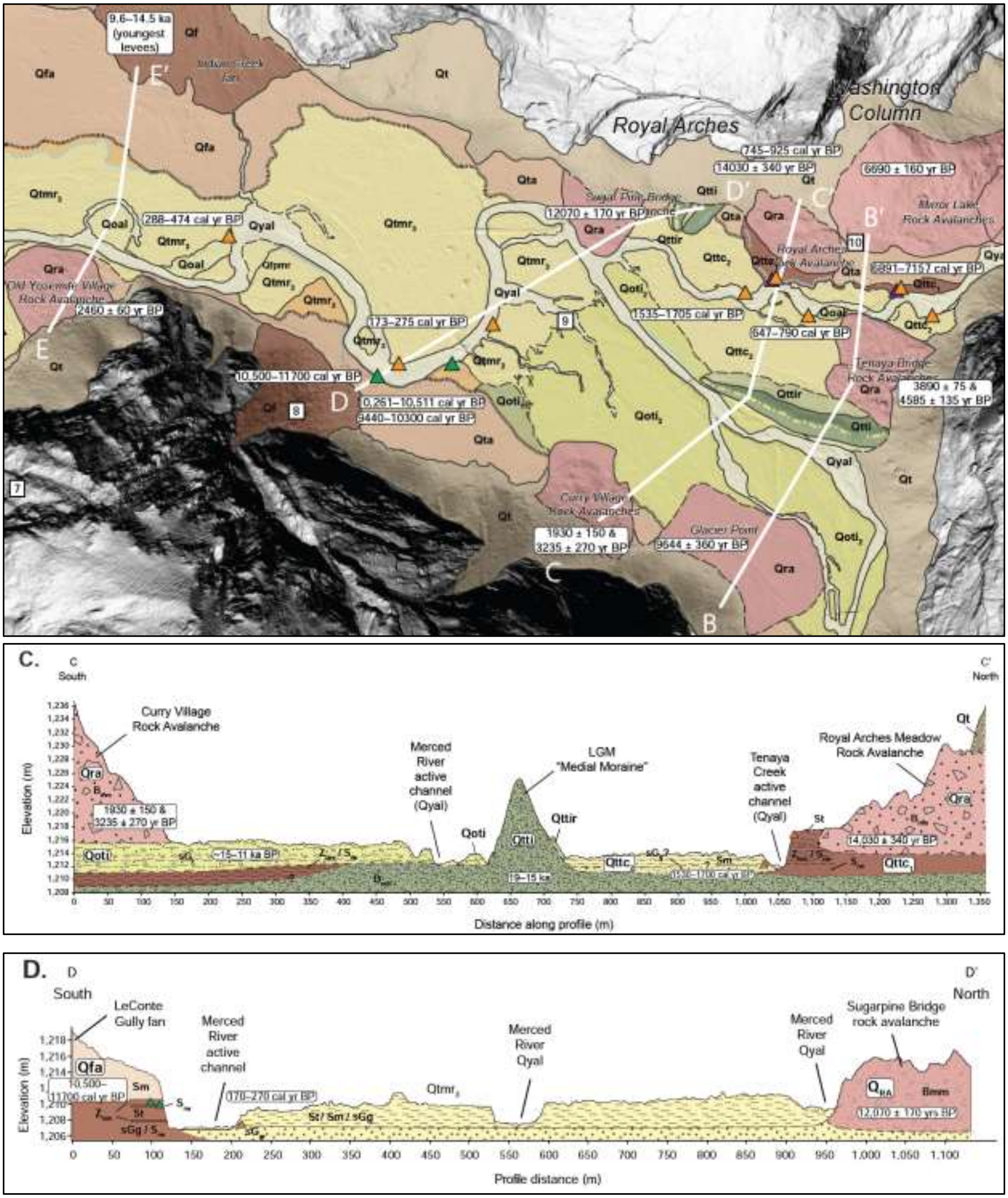


Figure 3-3. Geologic map and selected cross sections in the Study Area (from Haddon et al. 2017).

Association of dated sediments with fluvial landforms through Yosemite Valley document a sustained period of relative landscape stability during the late Pleistocene, characterized by valley-bottom aggradation of glacial till, mass wasting deposits, fluvial sediments, and lacustrine silts. Late-glacial recessional moraines and post-glacial, episodically emplaced rock avalanches and alluvial fans have impeded flow of the Merced River within Yosemite Valley and into the Merced Gorge downstream of the El Capitan moraine. Fans and terraces remain preserved at relatively high elevations (5–9 m) above the modern channel, possibly the relict surface of sediment infilling of Lake Yosemite identified by Matthes (1930). A predominantly aggradational regime then shifted to incision around the Pleistocene–Holocene transition. Subsequent cycles of fluvial incision throughout the Holocene has left a flight of terraces, inset by up to ~9 m. Cosmogenic ^{10}Be and ^{14}C dates of rock-avalanche boulders, deltaic sedimentary sequences, and inset fluvial gravels suggest variable rates of incision over the Holocene averaging ~0.5 mm/yr. Although some periods of incision likely record changes in local base level within Yosemite Valley itself, such as inferred by Matthes (1930), the presence of perched, well-developed outwash terraces below the El Capitan moraine marking the downvalley extent of glacier ice indicates a more systemic and widespread cause of incision, likely controlled by climate.

The overall high volume of valley-margin deposits (alluvial fans and rockfalls) in comparison with valley-bottom material demonstrates the importance of these sediment sources to overall postglacial sediment supply. Alluvial fan deposits and talus flanking the valley walls interfinger with valley-bottom stratigraphy comprised of glacial till, lacustrine silts, and fluvial sediments. Widespread cut and fill sequences demonstrate episodes of incision and channel reoccupation recorded as early as ~1600, 800, and possibly 500 cal yr BP.

The most prominent, widespread valley-bottom feature is the 2-2.5 m surface (unit Qtmr$_3$; Figure 3-3), on which most of the Valley's iconic meadows are located. This surface is still active, at least episodically—the oldest age is 1520 cal yr BP from a sample at a depth of 2.17 m from the south bank near Swinging Bridge; the youngest dates to the late 19th century from a depth of 0.72 m along the south bank of the river in the Yellow Pines area. Today that surface is broadly inundated by about a 10-yr recurrence flood, but 100 years ago it was activated at least twice as frequently (Figure 3-4). Earlier, prior to any significant human disturbance, it likely was an even more active geomorphic floodplain, with annual to biannual inundation frequencies typical of temperate-latitude alluvial rivers.

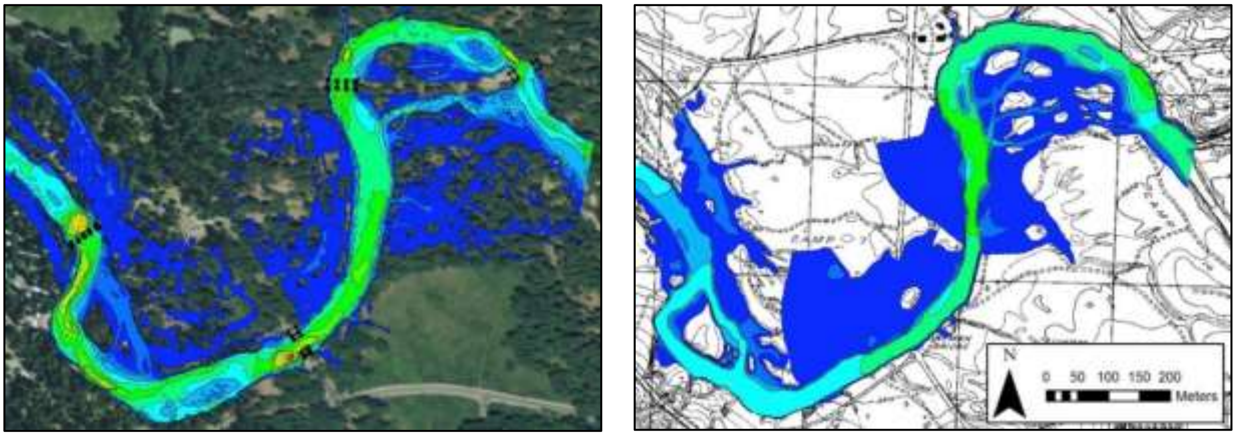


Figure 3-4. Hydraulic model projections (from Minear and Wright 2013) of floodplain/terrace inundation. Left panel, 10-year flood under existing channel topography. Right panel, near-equivalent inundation at a 5-year flood

using the 1919 channel geometry. The 10-year discharge is about 25% larger than the 5-year discharge. Dark blue, 0–1 m depth; light blue, 1–2 m; green, 2–4 m.

The apparent recent, partial abandonment of this floodplain surface is not consistent across all flood recurrences (Figure 3-5), and it cannot be readily explained by the lowering of the El Capitan moraine. Milestone (1978) reported this event (in 1879) as constituting a 4.5-ft (1.4-m) lowering of the river at the moraine itself, with effects attenuating over the next 5 miles (8 km) upstream. Although there is some suggestion of an upstream reduction in terrace height above the modern river (Figure 3-6), Milestone's limit-of-effects lie well downstream of the present study area. We tentatively infer the underlying cause to be primarily are result of de-snagging the river of its large woody debris, reducing roughness and so enhancing the efficiency of flows to transport sediment. A secondary element may be related to long-term changes in climate patterns, particularly the relative sediment-transport competence of high-magnitude winter rain-on-snow floods and the more moderate snowmelt-dominated floods. Minear and Wright (2013, p. 30) note that substantial bedload movement and deposition in the vicinity of the Tenaya–Merced confluence was associated with the 1997 flood, the last major rain-on-snow flood. Subsequent years have resulted in a progressive (re)expansion of the channel, suggesting that flows associated with all flood types are competent to move sediment, but that only the large rain-on-snow events can move significant quantities of coarse, channel-forming sediment down through the channel network. A long-term change in the distribution of these flood types could thus impose systematic, long-term changes in channel response.

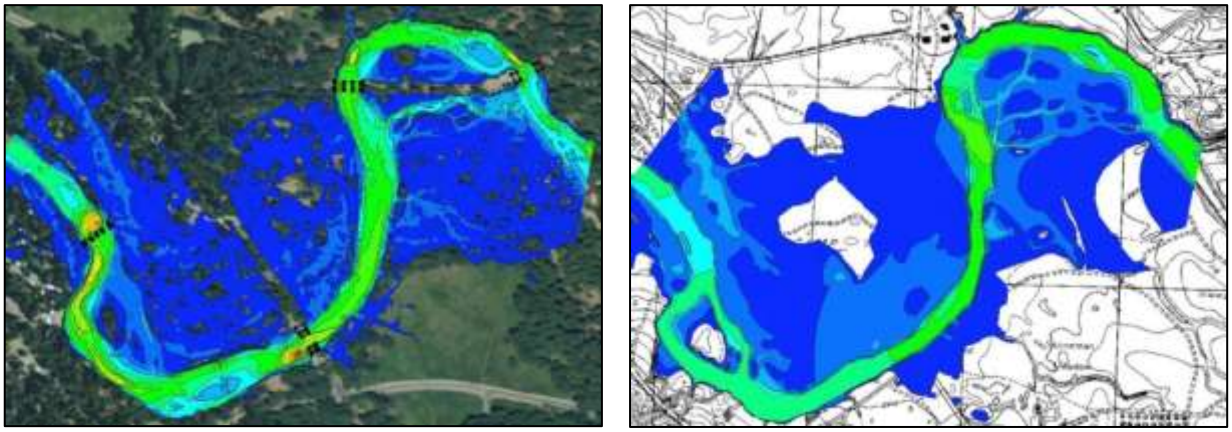


Figure 3-4. Hydraulic model projections (from Minear and Wright 2013) of floodplain/terrace inundation during the 20-year flood (about 25% greater discharge than the 10-year flood). Left panel, existing topography; right panel, 1919 topography. Except for the recent road fills, the extent of floodplain/terrace inundation is nearly identical, indicating that sufficiently large flows overwhelm any differnces in channel capacity between the two scenarios. Dark blue, 0–1 m depth; light blue, 1–2 m; green, 2–4 m.

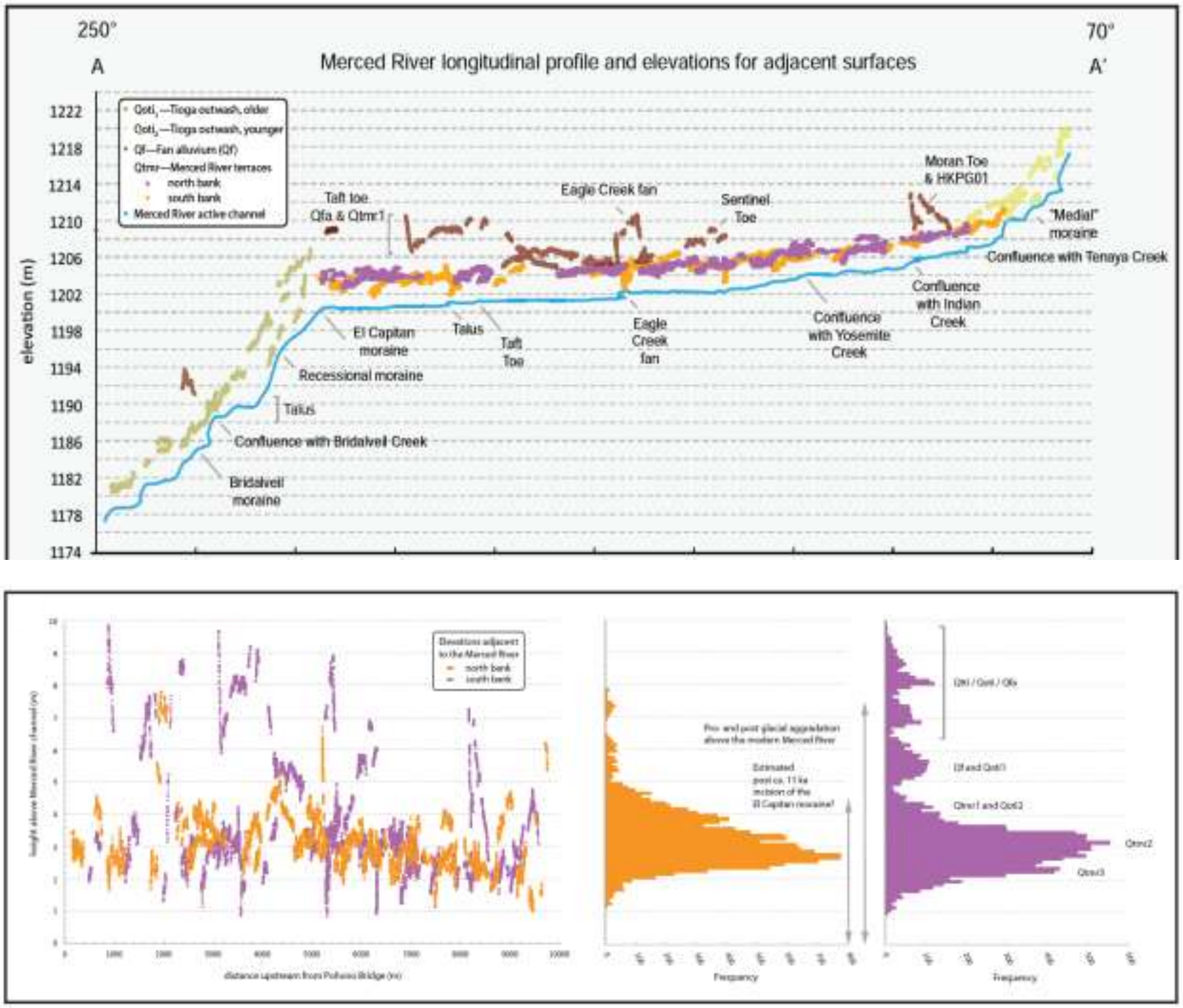


Figure 3-5. Terrace levels above the Merced River from Pohono Bridge (left side of both graphs) upstream to Clarks Bridge (from Haddon et al. 2017). The Study Area covers about km 8–10 on the x-axis (which is measured along the valley axis, not along the river channel itself). On the top panel, note the modest convergence of the terrace with the river from about km 2.5 (at the El Capitan moraine) to km 7.5. This pattern apparently continues up to at least km 9.5, above Milestone's (1978) zone of moraine-lowering influence, suggesting that it cannot provide a complete explanation for the presence of the terrace. Note also the systematically higher south (i.e., left) bank terrace, likely a reflection of the river's preferential position on the south side of the valley, closer to valley-wall sediment sources.

In summary, the landforms of the Yosemite Valley floor are dominated by two processes—the lateral delivery of sediment from the steep bedrock walls, contributed primarily by episodic rockfalls and less dramatic (but probably more voluminous) alluvial fans built by the tributary channels; and the downvalley delivery and transport of sediment by the Merced River. The river emerges from the primary influence of glacial-age sedimentary deposits in the reach between Clarks Bridge and Sugar Pine Bridge, and it continues downvalley largely encased by its own floodplain deposits except where locally impinged upon by rockfalls, alluvial fans, and talus deposits.

The river has incised by up to a few meters into these floodplain deposits over the last one to several centuries, converting them into surfaces more akin to upland terraces than active floodplains. During the largest multi-decadal floods these surfaces continue to be inundated, however, and to approximately the same extent as in earlier time, indicating that recent changes to this system are largely limited to increased channel capacity. Reduced channel roughness (resulting in channel incision), physical disturbance to the riparian zone (resulting in channel widening), and possible augmentation of these processes by long-term shifts in the predominance of snowmelt to rain-on-snow flood events are the likely causes of this systemic change in river–floodplain morphology. Understanding the underlying drivers can provide invaluable guidance, both fur understanding the genesis of the modern landscape of the Valley and for identifying opportunities to restore the underlying natural form and functions of the Merced River.

3.2 Sediment sources and in-channel sediment distribution

The sediment load of the Merced River is somewhat unusual of most rivers, insofar as much of the load originating from upstream watershed is disconnected from Yosemite Valley by the stairstep topography above the Study Area. Along the mainstem river, Vernal Fall and Nevada Fall present a near-insurmountable barrier to the downstream transport of coarse sediment; Mirror Lake presents a similar blockage along Tenaya Creek. Only the headwaters of Illilouette Creek have relatively unobstructed access from ridgeline to river confluence, with the result that the Merced River flows through Yosemite Valley with a “whole watershed’s” worth of accumulated water but only a fractional load of the watershed’s overall sediment production. Coupled with this is the intrinsic resistance of the granitic rocks that dominate this part of the Sierra Nevada, which further depresses sediment yields and the relative ratio of water to sediment in the mainstem river.

The prior effort to quantify the sediment load of the river (Madej et al. 1991) relied primarily on the suspended sediment measurements made by the USGS at the Happy Isles gage station in 1975–1989, validated by a variety of other empirical sources. The estimate based solely on the gage was about 1330 tons per year, or 7.4 tons per square mile per year—a very small value relative to most other temperate-region rivers, likely a consequence of the resistance of the granitic bedrock (the upstream waterfalls probably have only limited effect on trapping suspended sediment). Based on analogy to other basins, bedload is probably on the order of 10% of the suspended yield, or no more than a few hundred tons per year. A potential analog, that of a small granitic basin in northeastern France (Viville et al. 2012), has a measured bedload yield several times larger; measurements reported by Madej et al. (1991) at other downstream sites along the Merced River suggest the potential that the sediment load of bedload-sized material may be as high as 400 tons (between 250 and 300 cubic yards) per year through the Study Area. By way of comparison, this is only a scant fraction of the volume of sediment removed by bank erosion during the period 1919–1989 (about 900 tons/year; Madej et al. 1991) or Milestone’s minimum estimate of early-20th century gravel mining (20,000 tons) that occurred throughout the Valley.

Thus, the sediment budget of the Merced River through the 20th century was almost evenly split between upland and in-channel sources, with most of the bedload derived from the latter. Mining at rates many times the rate of replenishment occurred at least locally, and for an indeterminate period into the early/mid 20th century. The slow rate of coarse sediment input relative to the magnitude of documented recent erosion, therefore, means that recovery of a pre-20th century channel form cannot rely solely on natural bedload sediment sources to rebuild the adjacent streambanks if rapid recovery is envisioned or attempted.

MInear et al. (2013, p. 28) also recognized the limitations of bedload supply to the Study Area resulting from watershed topography. “In the Tenaya Creek watershed, the low-gradient reach of Tenaya Creek upstream of Mirror Lake (slope of about 0.0015) and the low-gradient reach immediately upstream of the confluence with the Merced River (slope of about 0.003) likely limit the supply of sediment larger than sand from being transported to the Merced River…Upstream of Nevada Fall, however, the Merced River decreases in gradient (slope of about 0.0015) as it flows through Little Yosemite Valley, making it unlikely that sediment larger than sand exits Little Yosemite Valley.” They noted the confluence of Illilouette Creek with the Merced River downstream of Nevada Fall and speculated that it could be a significant source of coarse sediment.

Field investigations conducted as part of the present project confirm these inferences. The confluence of Illilouette Creek with the mainstem Merced River marks an abrupt and dramatic change in river morphology. Upstream, the river channel is nearly devoid of bedload, with the sediment load overwhelmingly composed of 1-4 m angular blocks delivered to the valley bottom by rockfalls; immediately downstream, abundant gravel-sized clasts delivered from Illilouette Creek line the bed of the river channel and form extensive bars (Figure 3-6).

Figure 3-6. Views upstream (left) and downstream (right) along the Merced River from the same location, on the alluvial fan of Illilouette Creek (gravel deposit on the left side of the right panel). The character of the Merced River changes abruptly at this location, from a sediment-starved, boulder-choked cascade to a gravelly plane-bed and pool-riffle channel.

Upstream along Illilouette Creek, the source of the sediment is obvious (Figure 3-7). This tributary stream is a steep but rapidly flattening gravel step-pool channel that has built a massive alluvial fan at its confluence with the Merced River, several hundred meters on a side.

Figure 3-7. Views of Illilouette Creek upstream of its confluence with the Merced River. Left, looking upstream (south) about 70 m from the Merced River confluence. Median grain diameter 12 cm, largest clasts visible in this view about 60 cm. Right, view east from the downstream-most distributary on the Illilouette Creek fan (right side of photo). Junction with the Merced River (visible in the upper left corner) is just off the left side of the photo.

In addition to the massive influx of sediment and the abrupt change in the alluvial character of the Merced River, other geomorphic indicators demonstrate the fundamental importance of this source to the sediment load of the river through the Study Area. The channel gradient changes substantially across the Illilouette Creek fan--upstream, the river descends at a gradient of about 2%; downstream, it steeps abruptly to about 8%. The bed sediment sizes also decline monotonically from the confluence downstream, reflecting not only the declining competence of the river with a progressive flattening of its gradient, but also the lack of any significant lateral sediment inputs (Figure 3-8).

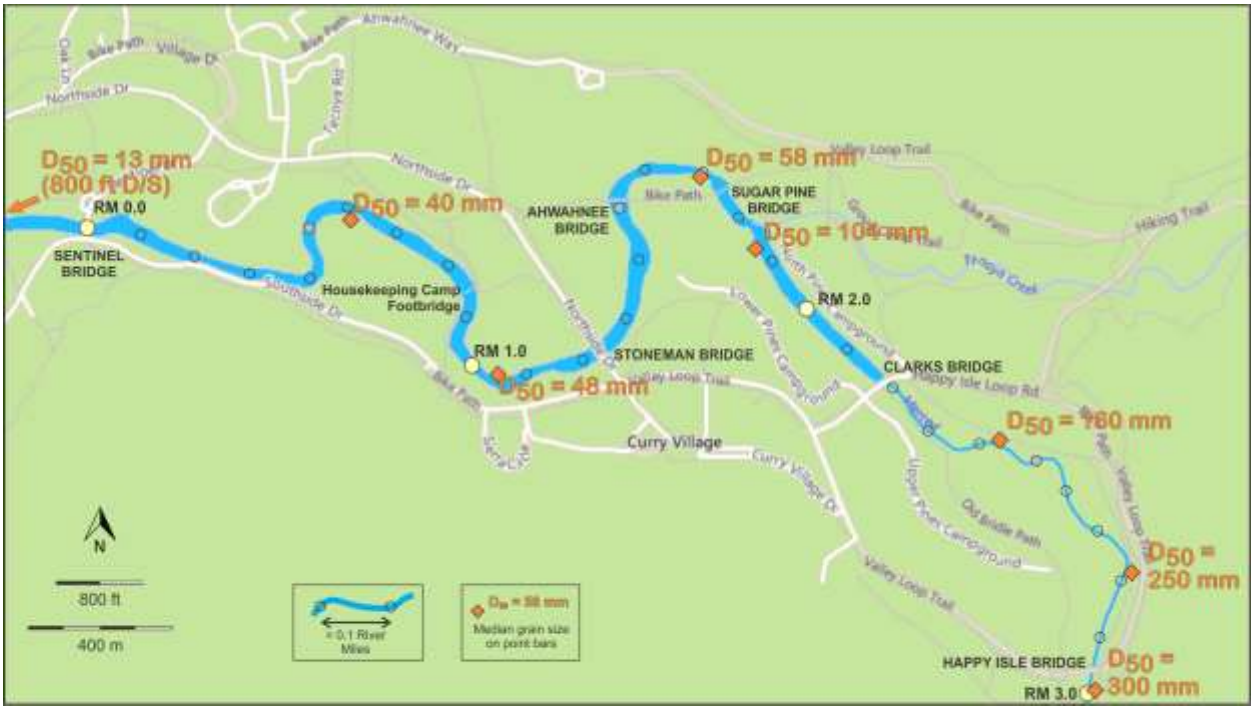


Figure 3-8. Median grain diameters (D_{50}), measured on the upstream low-water margin of point bars or mid-channel bars, sites where the clasts are most likely to reflect the active bedload during transport events (Kondolf et al. 2003). Note the progressive, monotonic decline in median size, with particularly rapid changes where the river emerges from confining bedrock and talus fields downstream of Happy Isles Bridge, and as it passes through the short reach that includes Sugar Pine Bridge.

In summary, the Merced River carries a "whole watershed's" quantity of discharge, but only about one-third of that area contributes to its coarse sediment load (Table 3-1). As a consequence, the bedload of the river is further depleted from what might otherwise be provided from this already low-sediment-producing granitic landscape. Over the 15,000 years since deglaciation the river has apparently adjusted to these conditions, resulting in rapidly declining channel gradient and sediment size in the upper portion of the Study Area, followed by more gradual declines farther downstream. This transition between rapid-to-gradual changes occurs in the vicinity of the Tenaya Creek confluence and Sugar Pine Bridge, suggesting that the influence of one or the other (or both) of these features merits closer evaluation, particularly if it is the bridge that has imposed this change on what previously had been a natural, more gradual transition.

Table 3-1. Drainage areas of selected localities within and upstream of the Study Area.

	Drainage area (sq mi)	Drainage area (sq km)
Merced River U/S of Illilouette Ck.	119.5	310
Illilouette Ck.	61.3	159
Tenaya Ck	47.3	123
Merced River at Sugar Pine Bridge	229.7	595
Merced River at Sentinel Bridge	236.7	613

Regardless of this local influence, the sediment load of the Merced River is low relative to many other temperate-region rivers, and abundant sediment is largely unavailable to rapidly rebuild a more natural, pre-disturbance channel form. This condition will persist regardless of any future treatments designed to improve the passage of sediment through the reach that includes Sugar Pine Bridge. It also means that future restoration efforts will need to proceed with a clear understanding of the multi-decadal time frame over which system-wide recovery of a pre-disturbance (or, at least, a less disturbed) channel form might be recovered. Small-scale restoration projects are likely to see sufficient flux and deposition of sediment to support their desired outcomes (Figure 3-9); but more extensive, widespread efforts will risk a shortfall of the alluvial material needed to produce a truly sustainable outcome.

Figure 3-9. Channel-narrowing and riparian-recovery project on the right bank of the Merced River just downstream of Ahwahnee Bridge, one year after project construction. In the intervening year (Oct. 2016–Oct. 2017), bedload sediment had filled in behind the projecting logs (left panel) and had developed bedforms immediately riverward of the structures (right panel).

4 RIPARIAN CORRIDOR CONDITIONS

4.1 Introduction

A healthy riparian corridor is critical for maintaining a healthy river. The ecological functions and structural and compositional complexity of riparian systems are created and maintained by a hierarchy of watershed characteristics and processes that vary in time and space. Watershed characteristics, such as geology, slope, channel pattern, and long-term inter-annual variability in flows control the distribution of vegetation along a river corridor. Across the riparian corridor, riparian areas with lateral connectivity to the channel are largely controlled by the fluvial conditions, whereas ecological functions and vegetation characteristics at higher elevations are influenced more by terrestrial processes. For example, different species assemblages are associated with different geomorphic landforms and topographic variability with differences in substrate, inundation, and moisture conditions. Vegetation composition and structure along the channel are also influenced by the recent flow pattern. Infrequent high flows scour existing vegetation and banks creating potentially suitable seed bed conditions for riparian recruitment. Water availability after seed germination is an important control for seedling survival. At a local scale, riparian characteristics are influenced by interactions between species physiologies such as the timing of seed release and rooting depth, and channel geometry that controls stage recession rates, depth to water during the summer months, and potential areas for establishment (e.g., wetted widths and depths).

In Yosemite Valley, human activities on the stream banks and within the floodplain have contributed to the degradation of the riparian corridor through reduced floodplain connectivity and topographic variability of geomorphic surfaces; narrower riparian corridor widths that reduce lateral connectively between the channel and terrestrial ecosystems; extensive bank erosion; and soil compaction and trampling of riparian vegetation from high recreation use within the riparian corridor. Various uses of bank protection measures to protect infrastructure, property, and public safety have also reduced lateral connectivity between the channel and riparian corridor in a number of locations throughout the reach.

The NPS has also implemented several restoration projects on the Merced River in Yosemite Valley since 1991 to improve the aquatic and riparian ecosystems (Figure 4-1). These projects ranged from removal of bank revetment to riparian revegetation with focus on restoration of specific sites rather than a programmatic approach to alter the river channel or riparian corridor. Recently, the NPS has constructed two recent restoration projects in the reach upstream of Stoneman Bridge in 2016 and 2017. These projects included a combination of bioengineered treatments to build floodplains, stabilize banks, increase instream habitat complexity, and enhance the riparian community (Figure 3-9, above, shows the 2016 project one year after construction).

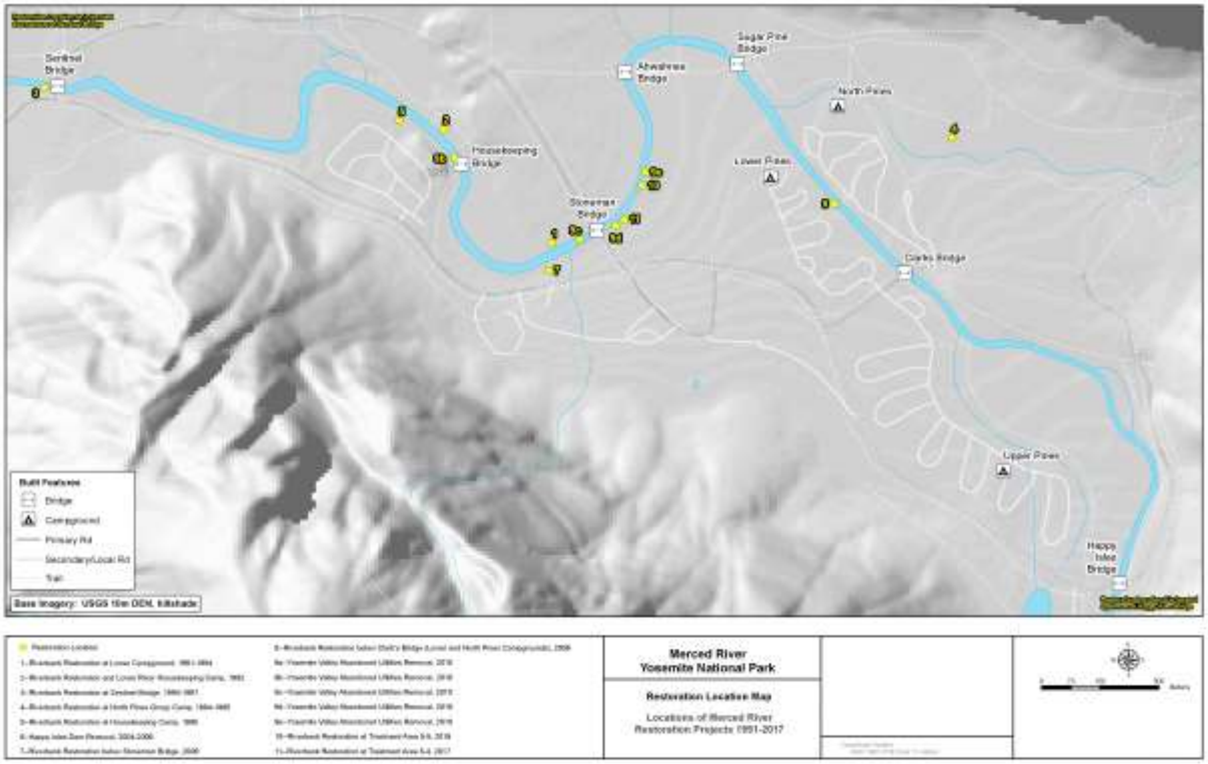


Figure 4-1. Locations of Merced River restoration projects 1991-2017 between Happy Isles Bridge and Sentinel Bridge.

This section summarizes the existing conditions of the riparian corridor and examines factors that may constrain the potential for enhancement and expansion of the riparian corridor between Happy Isles Bridge to Sentinel Bridge. This information is used to categorize reaches with potential for enhancement and to identify metrics for measuring success of enhancing geomorphic conditions of the Merced River and the ecological functionality of the riparian corridor.

4.2 Approach

The identification of reaches with potential for enhancement and expansion of the riparian corridor and metrics for measuring success of restoration management actions was informed by field inspections to assess the condition of the stream banks and vegetation within the riparian corridor conducted in summer and fall of 2015 to 2017, supplemented by information from previous reports and unpublished materials and personal communications with NPS. Additionally, numerous relevant reports were reviewed, including Cardno (2012, 2016), Haddon et al. (2017), NPS (2014), Minear and Wright (2013), NRCS (2007), and Madej et al. (1994).

The 2015-2017 field inspections included an assessment of the existing bank conditions and streambank vegetation composition and age structure. The bank condition assessment involved walking along the river from Happy Isles Bridge to Sentinel Bridge and documenting the bank shape, bank material and condition of the toe, face, and top of the bank at a minimum of 0.01-mile intervals. The definitions and inventory of the data collected are included in Appendix A. Photograph examples of the bank condition inventory status are also provided in Appendix A.

The vegetation assessment involved walking along the stream and mapping the dominant woody species within the riparian corridor[1] and the age classes[2] present. F or this assessment, the riparian corridor was mapped within 30 meters (m) along the river channel[3]. This information supplemented and refined the Cardno (2012) riparian assessment and riparian community mapping. For this report, the vegetation was categorized to differentiate riparian and upland species with different life history strategies, water availability requirements, and canopy cover (e.g., tree or shrub) as follows:

Category	**Description**
Bare (including bare bars)	
Oaks and conifers	Areas dominated by these species; assemblage may include (*Calocedrus decurrens*) incense cedar and various upland understory species.
Cottonwood	Stands primarily comprised of cottonwood (*Populus balsamifera ssp. trichocarpa)*
Cottonwood/Alder, Cottonwood/Willow, Cottonwood/Alder/Willow, Alder/Willow mixed stands	Stands with co-dominant riparian species.
Alder	Stands primarily comprised of alder (*Alnus rhombifolia)*.
Willow Riparian	Stands primarily comprised of willow species (*Salix* spp*)*.
Wet Herbaceous	Areas vegetated by various herbaceous species.

Photograph examples of these vegetation assemblages are provided in Appendix B. The vegetation inventory data are also summarized in Appendix B.

The bank condition inventory, vegetation, and geology data (Haddon et al. 2016) were mapped on GIS maps and plotted graphically to examine the relationship between the underlying geology, bank condition, and characteristics of the riparian corridor vegetation to provide insights into their controls on the existing vegetation and to identify reaches with the highest potential for enhancement and expansion.

4.3 Findings

The general riparian corridor vegetation community distribution patterns and age structure diversity within the study reach between Happy Isles Bridge and Sentinel Bridge reflects the interaction between watershed geology, lateral connectivity and geomorphic processes, and plant species' life history

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[1] In 2012, the vegetation was categorized according to the Yosemite National Park National Vegetation Classification System (NatureServe 2007). The scheme is based on the United States National Vegetation Classification System, developed as part of a larger effort to standardize vegetation data for each national park (NatureServe 2007). Areas dominated by these species; assemblage may include various upland understory species. Conifer and oaks were similarly mapped in a single category in Cardno (2012).

[2] Areas mapped as Mature contained primarily trees with diameter at breast height greater than 5 inches and greater than 3 inches for woody riparian shrubs. Areas containing primarily trees and shrubs with smaller diameters, including seedlings and saplings, were classified as Young vegetation. Areas mapped as mixed contained both mature and young individuals.

[3] The width of the riparian corridor assessment is consistent with that evaluated by Cardno (2012).

adaptations. Different combinations of late seral species, including, oaks, conifers, and incense cedar dominated the riparian corridor, with shorter interspersed segments dominated by pioneer riparian species (*Alnus rhombifolia* [white alder], *Populus balsamifera* ssp. *trichocarpa* [black cottonwood], and *Salix* spp.) (Figures 4-2 and 4-3). The majority of the corridor was composed of mature vegetation, with shorter segments of stands with recent successful recruitment (stands with young vegetation).

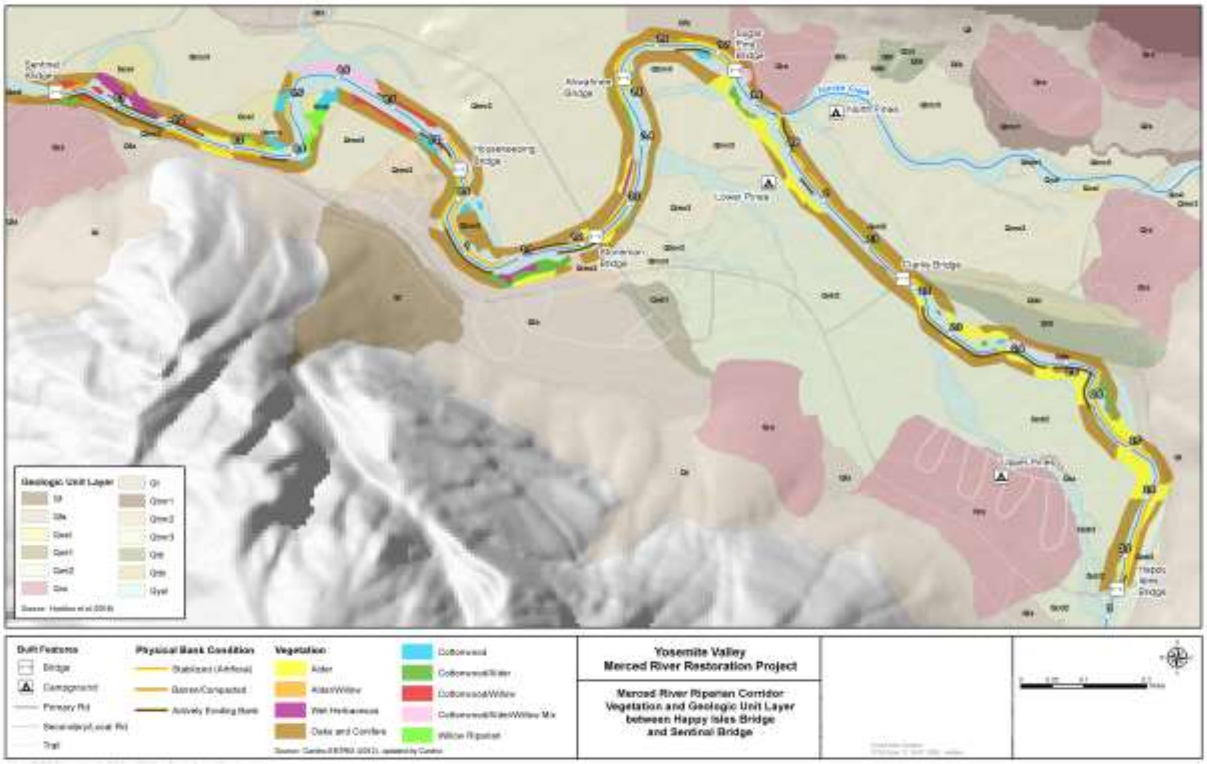


Figure 4-2. Merced River riparian corridor vegetation and geologic unit layer between Happy Isles Bridge and Sentinel Bridge.

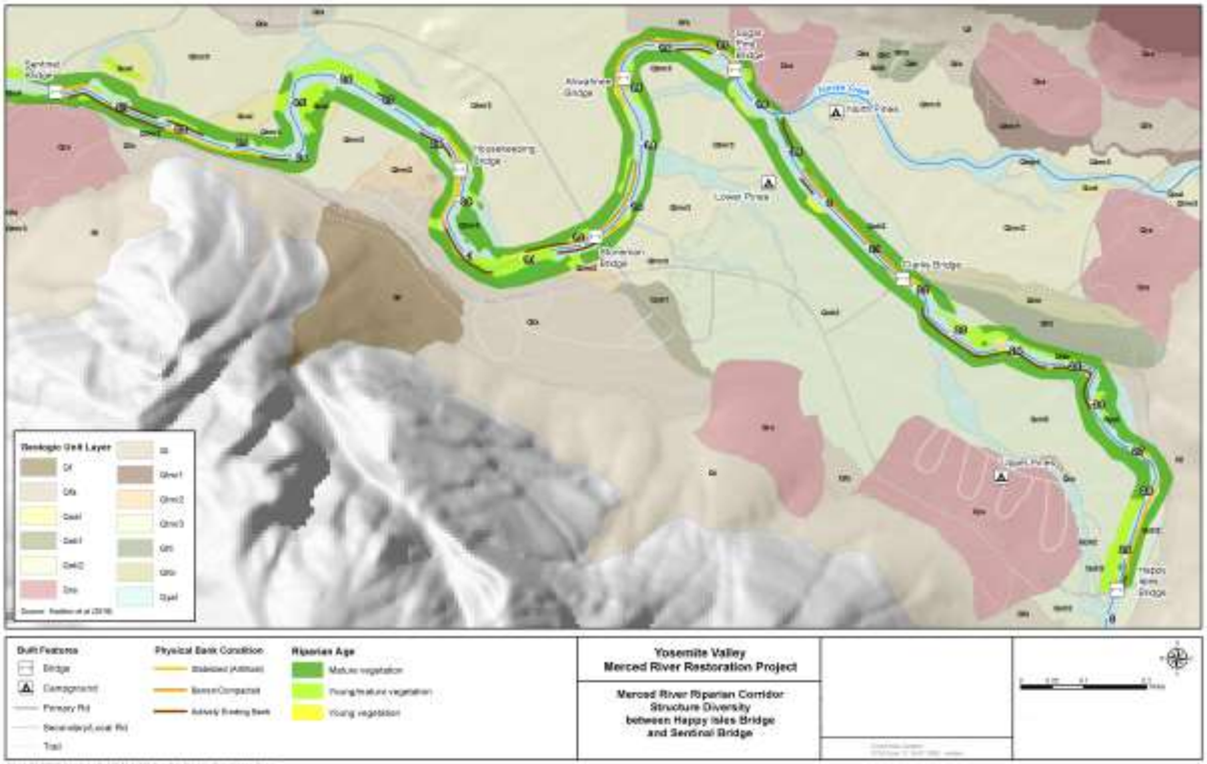


Figure 4-3. Merced River riparian corridor structure diversity between Happy Isles Bridge and Sentinel Bridge.

The distribution of species and age structure with the riparian corridor reflects the life history strategies of the different species. Common woody riparian species (alders, cottonwoods, and willows) have many life history adaptations that promote success under dynamic and episodic, yet seasonally predictable, hydrologic conditions. These species generally require, open, continuously moist, alluvial deposits for successful germination. They disperse many small seeds that are dispersed by wind and water. Once established, these species have fast initial growth rates, and out-compete slower growing species such as oaks and conifers. Alders, willows, and cottonwoods also readily reproduce vegetatively (i.e., from down limbs and trunks, and root sprouts), which enables these species to rapidly re-establish following scouring floods. New individuals sprout from abraded trucks, fallen or downed branches, or twigs or root pieces deposited during a high flow event. Differences in seed release timing and viability period result in successful germination and survival of different species under varying flow conditions, which promotes vegetation composition and structural diversity characteristic of riparian zones.

Certain adaptations may favor successful recruitment and survival of some species along streams with altered fluvial geomorphic processes. For example, alders release seeds in the fall. The seeds are viable for a long time and can germinate once suitable moisture conditions are present. In comparison, cottonwoods and willows release seeds in the spring, timed with the recession of spring flows. The seeds are only viable for a short time (weeks), requiring suitable moisture and soil conditions to be present at the time of seed release. However, for all the species to survive the first summer, recession rates from spring flows cannot exceed the root growth rates of the seedlings, and water needs to be available to the seedlings after the spring flow recession is completed (e.g., through the dry summer months). Seedling mortality is often naturally high and seedlings that establish too close to the channel where late summer and fall water is available are more susceptible to scouring and uprooting by subsequent high winter or spring flows that those that establish higher on the floodplain. Seedlings that establish too high are susceptible to dessication during the summer and early fall. As a result, riparian vegetation often establishes in elevation zones where water is available during the drier months, but not too close to the base flow (summer and fall) channel where they are susceptible to damage by higher flows. Flow duration is important because the seedbed substrate needs to be fully saturated to allow floating seeds to raft up on the floodplain and germinate. In comparison, later successional species, such as oaks and conifers, produce fewer larger seeds that optimize the ability to reserve and accumulate resources for the future slower-growing seedling. These species are competitively superior in resource-limited (nutrient, light, water) environments and usually replace riparian species such as willow, alder, and cottonwood in mature forests with stable physical environments. The seeds are large, which provide a nourishment reserve and structure possibly needed to survive stresses associated with resource competition with other individuals and emergence from below the leaf litter. These species have slower growth rates as the available resources for each individual are lower.

Along the Merced River, riparian species primarily occurred on channel bars and floodplains, less than two meters above the active channel (Figure 4-4). In comparison, oaks and conifers were primarily mapped on higher elevation terrace and glacial outwash surfaces. At a local scale, both oak/conifer stands and riparian species were mapped along impacted banks, with a slightly greater proportion of oak/conifer stands on impacted banks (Figures 4-4 and 4-5). Within stands comprised of riparian species, alder-dominant stands were most common. Alders occurred along natural alluvial reaches but were also established along banks impacted by various human activities, including actively eroding banks, barren areas with compacted soil due to human impacts, and artificially stabilized banks (Table 1-1). In comparison, stands dominated by willows or cottonwoods were infrequent, primarily established on young alluvial surfaces, and were not established in areas with compacted soils.

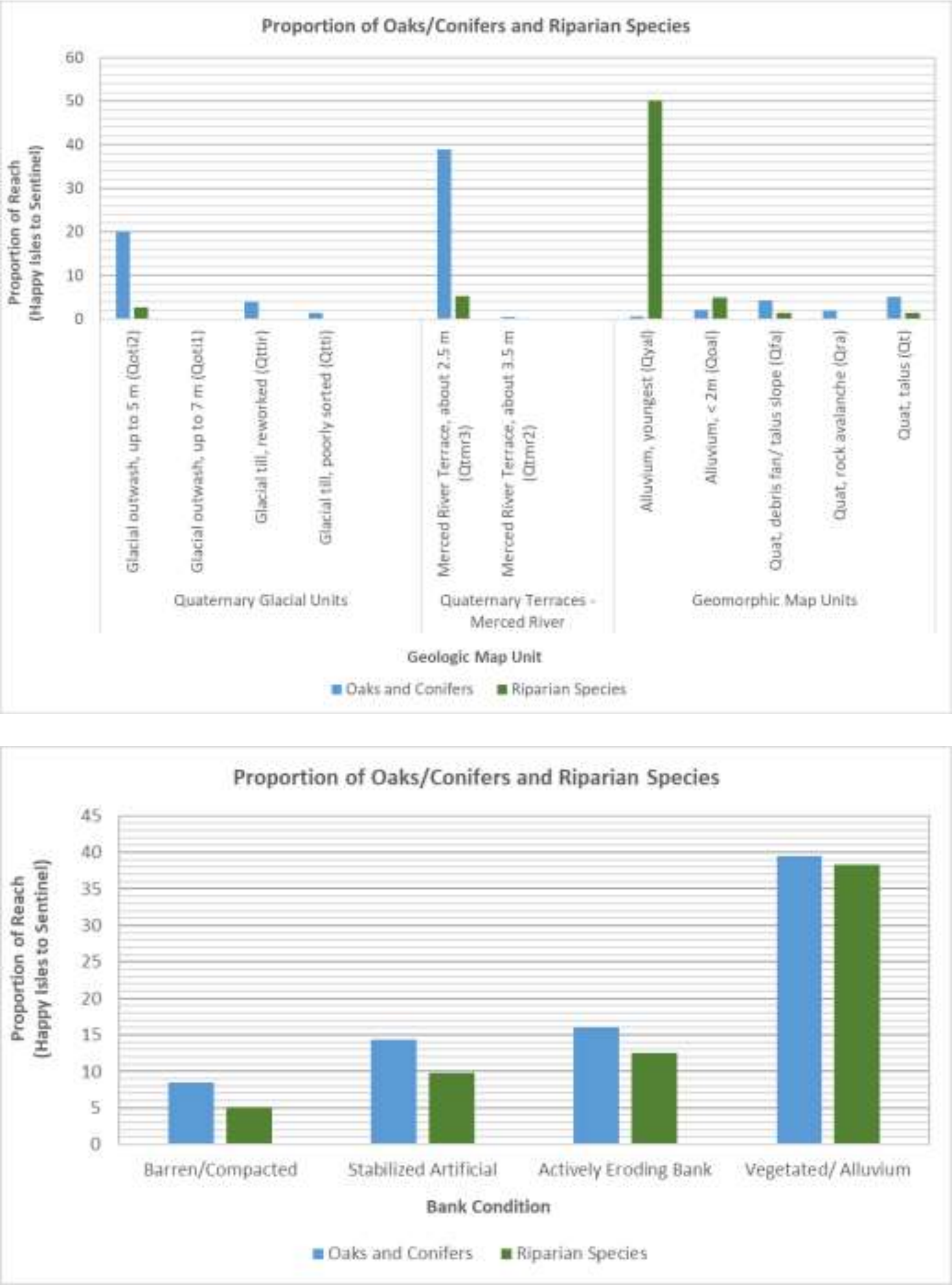


Figure 4-4. Comparison of the distribution riparian species and oaks/conifers in relation to geologic map unit (top) and bank condition (bottom). Barren/compacted – banks with barren compacted soil due to human impact; Vegetated/Alluvium included both vegetated, deformable bank and alluvium and naturally barren banks due to geomorphic processes.

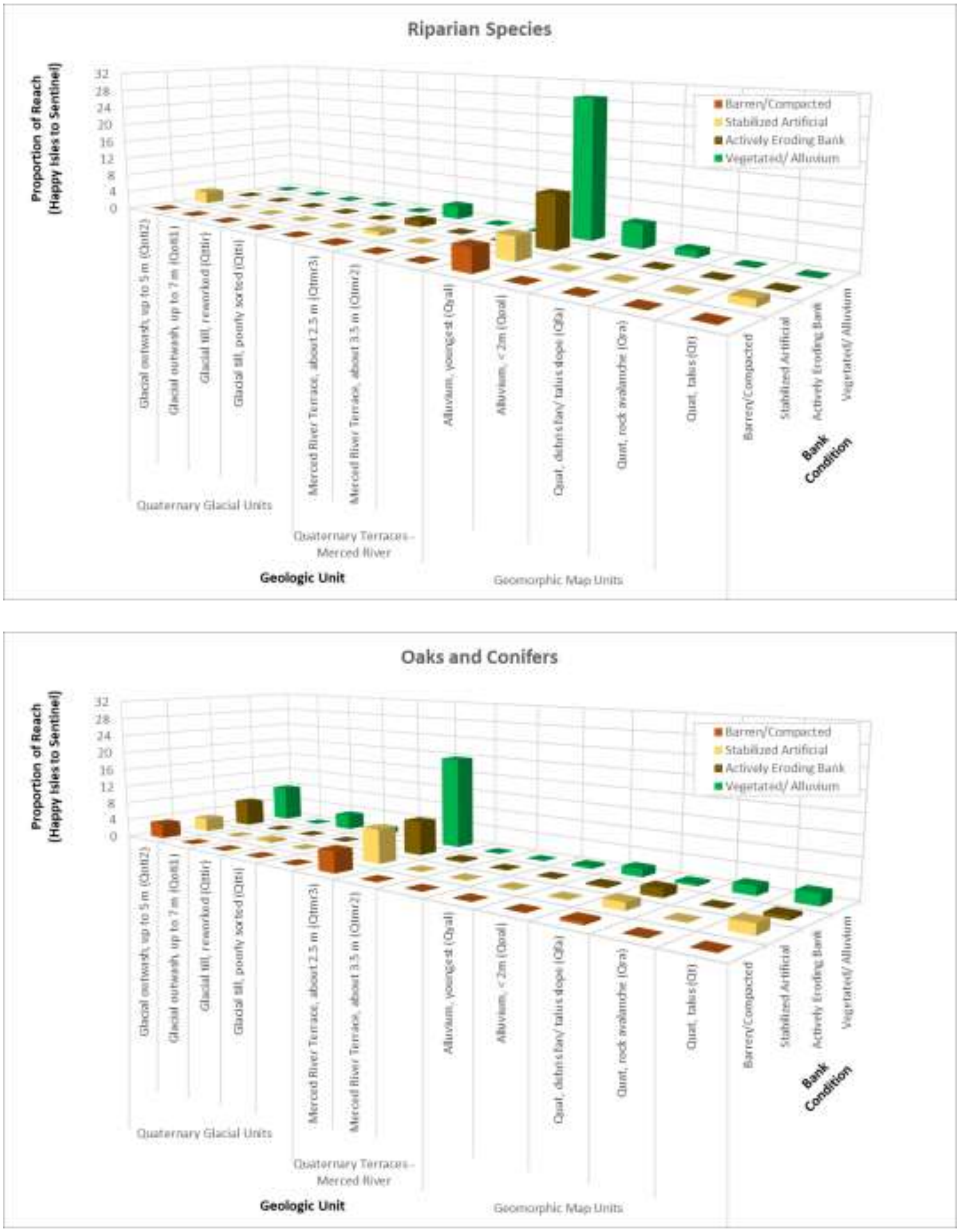


Figure 4-5. Comparison of the distribution riparian species (top) and oaks/conifers (bottom) in relation to geologic map unit and bank condition. Barren/compacted – banks with barren compacted soil due to human impact; Vegetated/Alluvium included both vegetated, deformable bank and alluvium and naturally barren banks due to geomorphic process.

Table 4-1. Proportion of total bank length vegetated by species in relation to geologic map unit and bank condition.

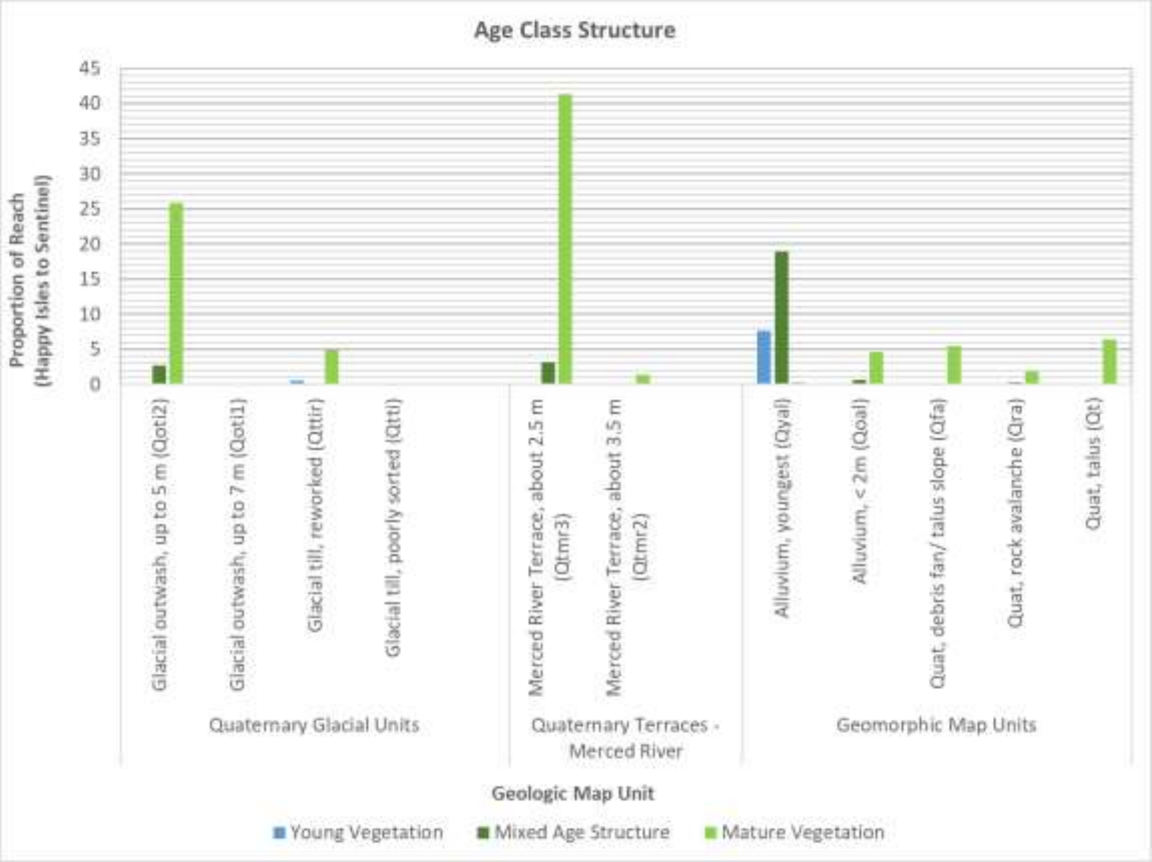
Species and Geologic Map Unit	Proportion of Total Bank Length			
	Bank Condition			
	Actively Eroding Bank	Barren/ Compacted[1]	Stabilized Artificial	Vegetated/ Alluvium[2]
Alder	**6.78**	**3.22**	**5.59**	**14.58**
Quaternary Glacial Units				
Glacial outwash, up to 5 m (Qoti2)	--	--	2.71	--
Geomorphic Map Units				
Alluvium, youngest (Qyal)	6.78	3.22	1.53	12.20
Alluvium, < 2m (Qoal)	--	--	--	1.02
Quat, debris fan/ talus slope (Qfa)	--	--	--	1.36
Quat, talus (Qt)	--	--	1.36	--
Alder/Willow	**0.51**	**1.02**	**--**	**--**
Geomorphic Map Units				
Alluvium, youngest (Qyal)	0.51	1.02	--	--
Cottonwood	**1.53**	**--**	**0.85**	**3.90**
Quaternary Terraces - Merced River				
Merced River Terrace, about 2.5 m (Qtmr3)	0.68	--	--	0.34
Geomorphic Map Units				
Alluvium, youngest (Qyal)	0.85	--	0.85	0.85
Alluvium, < 2m (Qoal)	--	--	--	2.71
Cottonwood/Alder	**0.85**	**0.85**	**1.69**	**5.59**
Quaternary Terraces - Merced River				
Merced River Terrace, about 2.5 m (Qtmr3)	0.17	0.17	0.85	--
Geomorphic Map Units				
Alluvium, youngest (Qyal)	0.68	0.68	0.85	5.59
Cottonwood/Alder/Willow	**1.53**	**--**	**0.85**	**6.95**
Geomorphic Map Units				
Alluvium, youngest (Qyal)	1.53	--	0.85	6.95
Cottonwood/Willow	**1.36**	**--**	**0.68**	**4.41**
Quaternary Terraces - Merced River				
Merced River Terrace, about 2.5 m (Qtmr3)	0.51	--	--	2.20
Geomorphic Map Units				
Alluvium, youngest (Qyal)	0.85	--	0.68	2.20
Willow Riparian	**--**	**--**	**0.17**	**2.88**
Quaternary Terraces - Merced River				
Merced River Terrace, about 2.5 m (Qtmr3)	--	--	--	0.34
Geomorphic Map Units				

Species and Geologic Map Unit	**Proportion of Total Bank Length**			
	Bank Condition			
	Actively Eroding Bank	**Barren/ Compacted[1]**	**Stabilized Artificial**	**Vegetated/ Alluvium[2]**
Alluvium, youngest (Qyal)	--	--	0.17	1.36
Alluvium, < 2m (Qoal)	--	--	--	1.19
Oaks and Conifers	**16.10**	**8.47**	**14.41**	**39.49**
Quaternary Glacial Units				
Glacial outwash, up to 5 m (Qoti2)	5.76	3.39	3.05	7.97
Glacial till, reworked (Qttir)	--	--	0.51	3.39
Glacial till, poorly sorted (Qtti)	--	--	--	1.36
Quaternary Terraces - Merced River				
Merced River Terrace, about 2.5 m (Qtmr3)	7.29	4.58	7.29	19.83
Merced River Terrace, about 3.5 m (Qtmr2)	0.34	--	--	--
Geomorphic Map Units				
Alluvium, youngest (Qyal)	--	--	--	0.51
Alluvium, < 2m (Qoal)	0.34	--	--	1.69
Quat, debris fan/ talus slope (Qfa)	1.69	0.51	1.53	0.51
Quat, rock avalanche (Qra)	--	--	--	1.86
Quat, talus (Qt)	0.68	--	2.03	2.37

[1] Barren, compacted soil due to human impact

[2] Includes both vegetated, deformable bank and alluvium and naturally barren banks due to geomorphic processes

Age structure diversity of all vegetation communities along the Merced River is strongly influenced by fluvial geomorphic processes (Figures 4-3 and 4-6). Younger vegetation occurred on alluvial surfaces, with limited recent recruitment on higher and older surfaces that have limited lateral connectivity to the channel, as well as on impacted stream banks (Figures 4-6 and 4-7). Mature communities were mapped on several geologic map units but were primarily mapped on the youngest Merced River terrace surfaces positioned about 2.5 meters above the active channel and on glacial outwash comprised of poorly sorted glacial conglomerate with boulders up to five meters above the active channel. Recent recruitment was minimal along stream segments with revetments, eroding banks, and compacted soils.



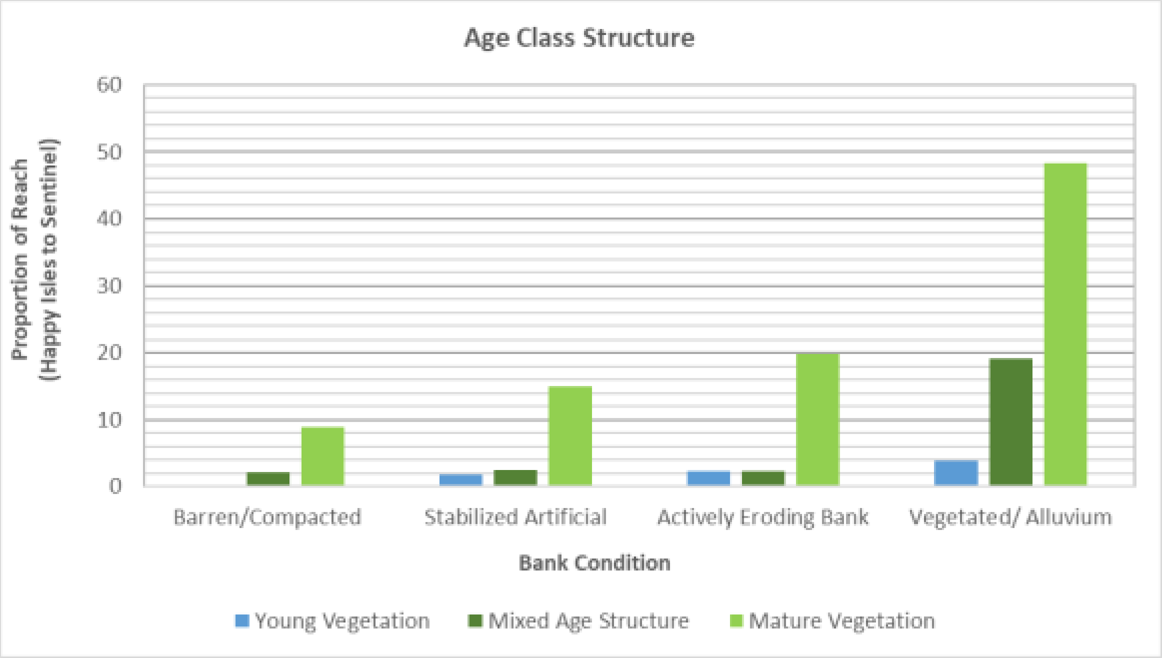


Figure 4-6. Comparison of age class structure in relation to geologic map unit (top) and bank condition (bottom). Barren/compacted – banks with barren compacted soil due to human impact; Vegetated/Alluvium included both vegetated, deformable bank and alluvium and naturally barren banks due to geomorphic processes.

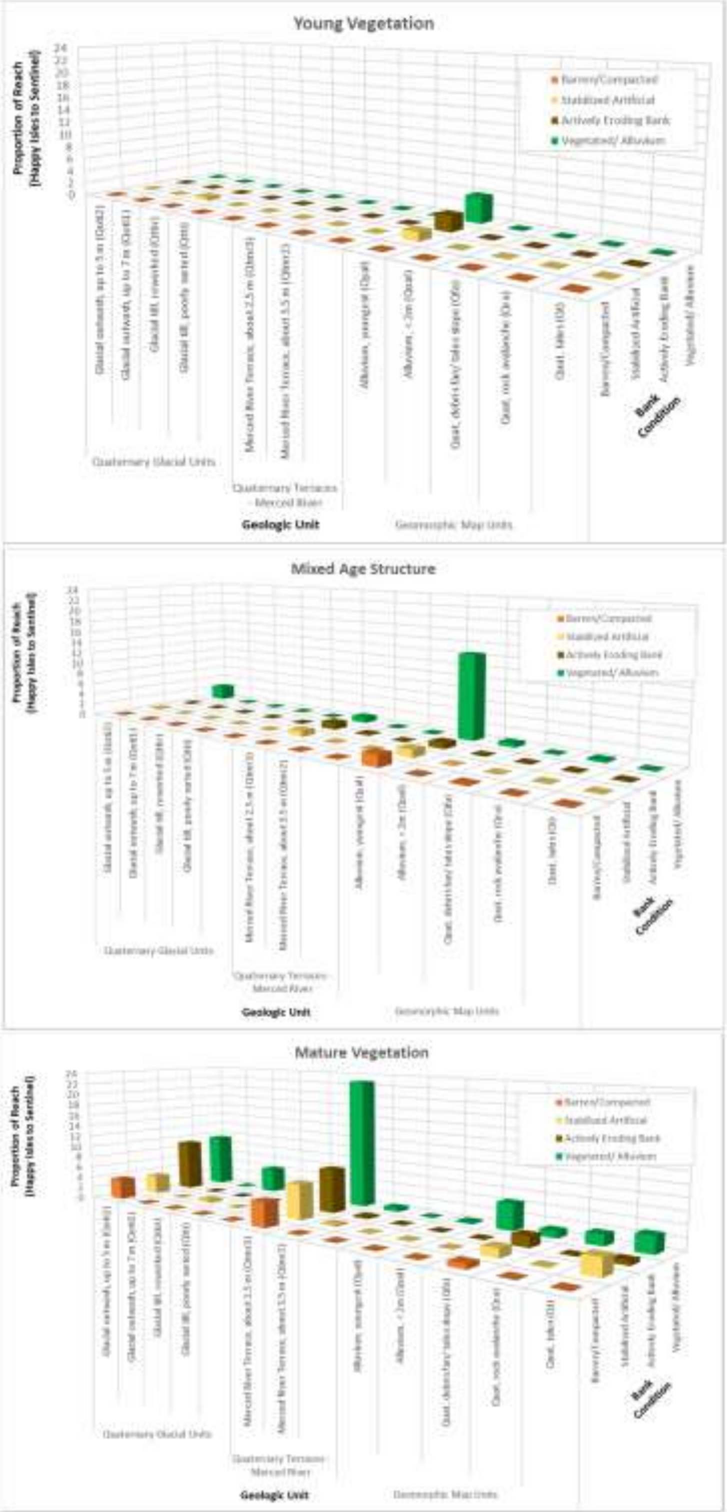


Figure 4-7. Comparison of the distribution young (top), mixed age classes (middle), and mature (bottom) vegetation in relation to geologic map unit and bank condition. Barren/compacted – banks with barren compacted soil due to human impact; Vegetated/Alluvium included both vegetated, deformable bank and alluvium and naturally barren banks due to geomorphic processes.

4.4 Discussion

Identification and categorization of reaches with potential for enhancement and expansion of the riparian corridor considered the underlying geology and fluvial geomorphic processes interacting with the life history strategies of the dominant species that largely determine the vegetation characteristics of the corridor. Geology constrains the potential for enhancement along some sections of the river. In some areas, recruitment of woody riparian species is limited by past and ongoing impacts to the banks, such as revetments and high recreation use. Alluvial surfaces with bank conditions that can be addressed are recommended for higher potential for enhancement. Banks identified as low potential for enhancement include those that are high terraces and lack alluvial surfaces; as well as those along which it may be difficult to remove revetments or reduce recreation use due to protection of infrastructure and proximity to recreation facilities and roads. Based on information collected from the field inventories, the potential for enhancement and expansion within the reach were categorized into four groups (Figures 4-8 and 4-9), as follows:

Category	**Characteristics**
High potential for enhancement and expansion	Alluvial surfaces and lower elevation surfaces with the potential to improve lateral connectivity, remove bank revetments, or reduce recreation use.
Moderate potential for enhancement and expansion	Primarily young inset terrace positioned about 2.5 meters above the active channel; with potential to enhance lateral connectivity and reduce bank erosion.
Moderate-low potential for enhancement	Primarily segments lower elevation surfaces on glacial outwash; with potential to enhance the corridor through reduced recreation use to minimize continuing compaction and erosion, and remove bank revetments.
Low potential for enhancement	High terraces, lack of alluvial surfaces, high bank revetments, high recreation traffic

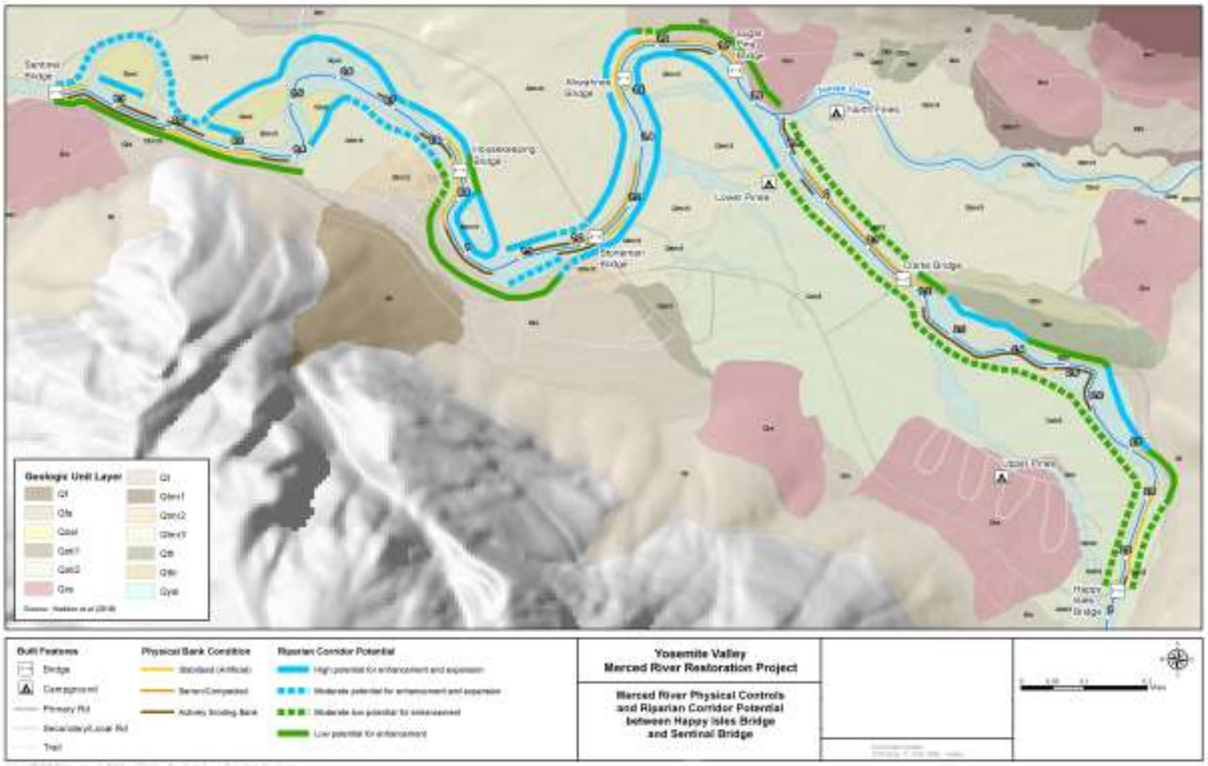


Figure 4-8. Merced River physical controls and riparian corridor potential between Happy Isles Bridge and Sentinel Bridge.

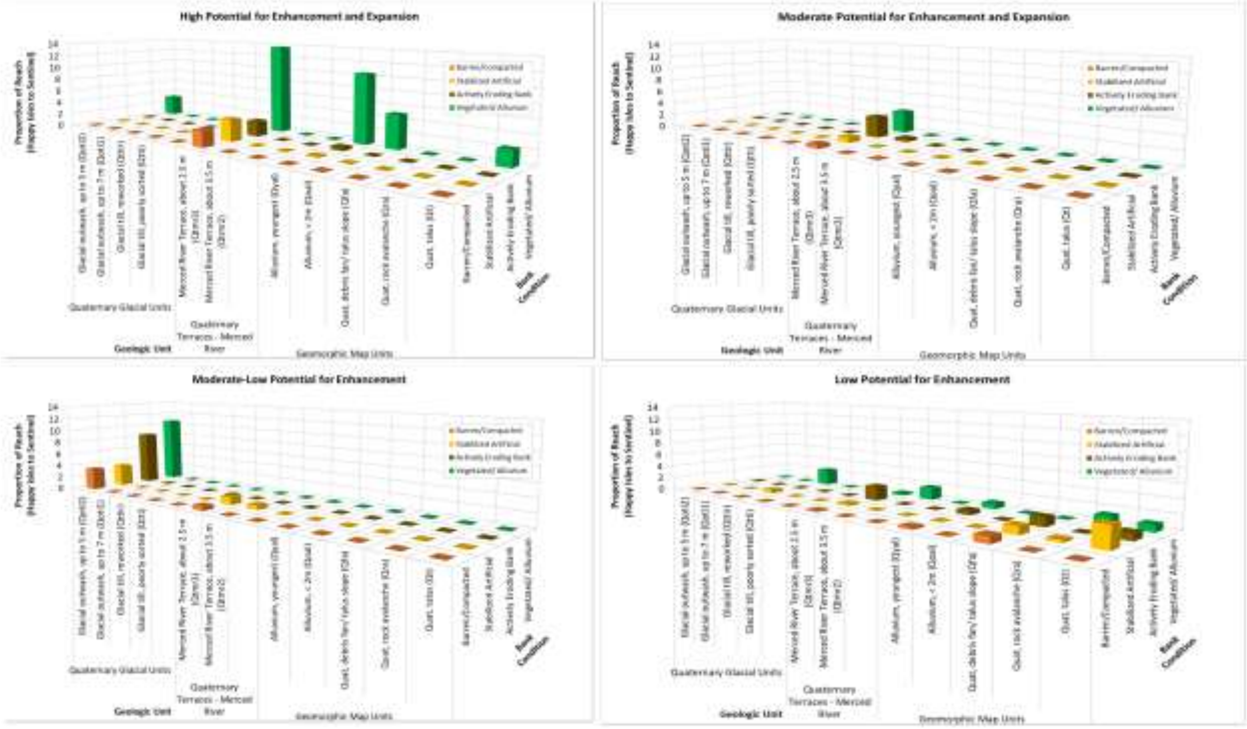


Figure 4-9. Potential for riparian enhancement and expansion: high potential (top, left), moderate potential (bottom, left), moderate-low potential (top, right), and low potential (bottom, right) in relation to bank condition and geologic map unit. Barren/compacted – banks with barren compacted soil due to human impact; Vegetated/Alluvium included both vegetated, deformable bank and alluvium and naturally barren banks due to geomorphic processes.

4.5 Measures of Success

Four metrics are recommended to measure success of ongoing and future river management actions to improve the geomorphic conditions of the Merced River and the ecological functionality of the riparian corridor. These metrics focus on documenting improvements of bank conditions along the river segments identified with high potential for enhancement and expansion, with includes alluvial surfaces and lower elevation surfaces that support woody riparian species, and include:

- Length of vegetated, deformable banks without increases in length of excessive bank erosion,
- Length of barren, compacted soils,
- Length of artificially stabilized banks, and
- Areas with potential suitable substrate for riparian regeneration.

5 CHANNEL MIGRATION MODELING

5.1 Introduction

Alluvial rivers tend to migrate laterally over time. Meander migration, which consists of bank erosion on the outside bank of curved channels and point bar and floodplain-building on the inside bank, is a key process for many important ecosystem functions (Malanson 1993; Florsheim et al. 2008). Examples of those key processes include 1) vegetative establishment for the riparian forest, 2) floodplain creation through progressive meander migration, 3) habitat creation (i.e., bank erosion for terrestrial and aquatic habitat), and 4) the creation of off-channel habitats (e.g., oxbow lakes, side channels, and sloughs) by progressive migration and cutoff processes. In addition, knowing the potential migration pattern is essential for planning purposes, particularly in assessing potential conflicts with infrastructure.

The meander migration process is a function of flow, channel form, and bank characteristics. In certain areas, the channel and banks of the Merced River through the Study Area have been restrained from migrating. To develop effective strategies for the conservation and restoration of key river and ecosystem functions, and for effective planning in relationship to infrastructure, it is important to understand the role that meander migration plays in relationship to these functions. Furthermore, it is critical to understand how the changes in channel form and bank erosion characteristics (through both natural and man-made causes) will alter the physical processes of channel migration.

This section presents the results of a meander migration study for the Merced River through eastern Yosemite Valley. This study is one of several components to document how habitats in the riparian corridor have been affected by anthropogenic activity, and to provide information for restoration opportunities.

The current meander migration study was designed to satisfy the following main objectives:

Objective 1: To understand the future migration tendencies with current conditions

Objective 2: To understand the future migration tendencies if the current restraints were not in place.

Objective 3: To investigate a method for predicting channel avulsion (cutoff).

Through previous research efforts, a predictive meander migration model has been developed (Micheli and Larsen 1997, Larsen et al. 2007) and applied (Larsen et al. 2006, Larsen 2007, Micheli and Larsen 2011) to a number of rivers. The model calculates channel migration using a simplified form of equations for fluid flow and sediment transport developed by Johannsson and Parker (1989). This model, which is freely available for public use, was developed and applied to the present Study Area along the Merced River.

5.2 Methods

5.2.1 Study area

This section describes the segment of the Merced River where the meander migration was applied for meander migration modeling. the choice of this segment was based on discussions with members of the study team. the meander migration study encompasses reaches 1-10, rm 0 to 3.1 (**Error! Reference**

source not found.), with an additional about a half-mile extending downstream from sentinel bridge (rm 0.0). additionally, migration was modeled with different bank restraint patterns from rm 0.3 to rm 0.5.

Figure 5-1. Study reach used for meander migration modeling.

5.2.2 Model input (see Appendix C)

The model requires the following six input values, reflecting the hydrology of the watershed and the hydraulic characteristics of the channel:

1) initial channel planform location,
2) characteristic discharge,
3) reach-average median particle size of the bed material,
4) width,
5) depth, and
6) slope

The reach-average width and depth are determined at the characteristic discharge, and slope is the average water surface slope for the reach. For the purposes of modeling, the “bankfull” values are used for the width, depth, and slope. The characteristic discharge was estimated as the 2-year recurrence interval discharge. Using these data, the model calculates other parameters required to predict channel migration (for a detailed description of the calculation process, see Johannesson and Parker 1989).

5.2.2.1 Channel centerlines

A 2016 channel centerline was digitized from Google Earth. A kmz file of the centerline was used as input into the model. For GIS and modeling purposes, all data were projected in NAD 83/ UTM Zone 11N.

5.2.2.2 Flow data

Flow data from the gaging station for the Merced River at Pohono Bridge were analyzed, and the 2-year recurrence interval flow was found to be 4750 cfs. This station was chosen because a review of the locations and magnitudes of tributary inputs suggested that these flow data were most appropriate for the majority of the study reach.

5.2.2.3 Width, depth, slope

Width and slope, which are required as model input, were taken from data in Cardno (2012). The depth was estimated using the other values, estimating a velocity, and back-calculating a depth.

5.2.2.4 Particle size

The particle size was estimated based on various reports (e.g., Madej, Weaver et al. 1994) that include reference to bed surface grain sizes. Recent information (Minear and Wright 2013; this study) suggest that the particle size that was used in the current model (10 mm) is smaller than exists on site (more commonly 20 to 60 mm). however, output results are not sensitive to bed particle size, and so model scenarios were not rerun with alternate grain sizes. A sensitivity analysis shows that the model results (done for a single case) change very little when the particle size varies from 10 mm to 50 mm (**Error! Reference source not found.**).

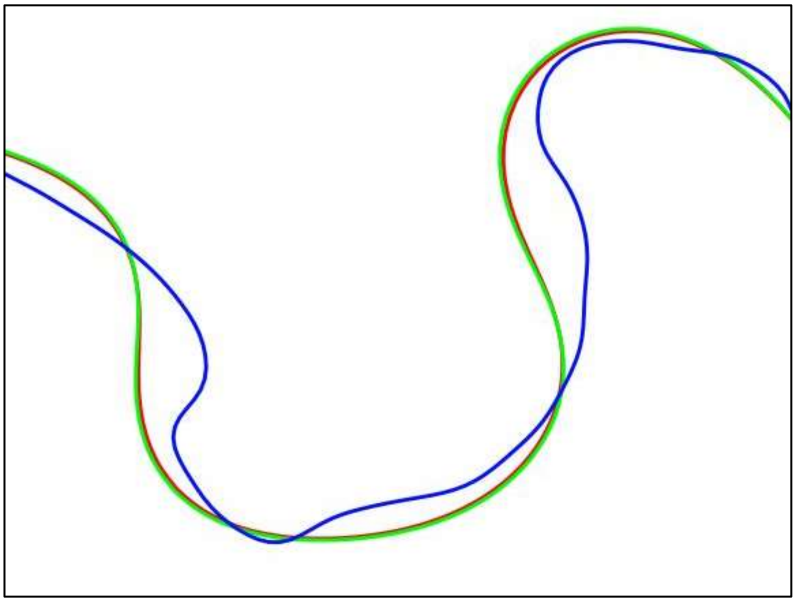


Figure 5-2. Sensitivity of model output to input bed particle size. Blue line shows initial condition. Red line shows output with 10 mm after “50 years” (see text for discussion of time periods). Green line shows output with 50 mm after “50 years,” and is virtually identical.

5.2.2.5 Revetment coverages

The effect of revetment on channel migration was investigated by using a GIS coverage of existing revetments. Of the currently existing revetments in the study reach, four discreet areas appeared to predominately restrain the existing channel. A GIS coverage was developed that included only these four areas (**Error! Reference source not found.**.) To explore the impact of this revetment on channel migration, migration was modeled with, and without, revetments.

Figure 5-1**.** Selected revetments (white dashed lines) used for modeling migration.

The final hydraulic input parameters are given in Table 5-1.

Table 5-1. Input parameters for the Merced River modeling.

Q (m^3/s)	**Width (m)**	**Depth (m)**	**Slope**	**Particle size (mm)**
134.5	53.6	1.7	0.0009	10

5.3 Cutoff simulation

The meander migration model has the capability of modeling channel cutoff. This was explored at a location where modeling a potential cutoff would be most promising, from RM 0.3 to RM 0.5 where an existing overflow chute is already present.

The meander migration model can model cutoffs in two ways, or in a combination of the two. The first is based on a hydraulic and geomorphic analysis that matches cutoff occurrence to empirically derived quantities. The second method is to use a “cutoff potential path” derived from digital elevation information of the floodplain that exists between the two limbs of the bend. For this cutoff simulation, the first method was used based on typical values from previous experiences (Micheli and Larsen 2011), using values specific to the Merced River.

5.4 Model calibration

Historical channel locations from 1870, 1883, 1934, 1944, 1987, 2005, 2009, and 2016 were used to evaluate model calibration. We focused analyses on areas where the channel movement was determined by those factors which the meander migration model was designed to model (e.g. areas that were likely to have been formed by fluvial processes). These include channel locations that show fluvially-formed channel curvature and terrestrial resistance to bank migration. In essence, the modeling sought locations and time sequences where the migration appeared to be regular, where it appeared to be determined by channel curvature, and where the bank resistance looked relatively uniform.

In many areas of the study reach, there was so little or no migration between 1987 and 2009 that one might wonder if it wasn’t copied incorrectly. In addition, there seems to be very little movement between 1934 and 2016. This suggests that there is either very little movement or it is entirely constrained (and has been for many decades). This makes calibration, which is difficult even with good data, even more of a challenge.

The final calibration was done with centerlines from 1870 and 1883. This calibration utilizes 13 years, during which time the flows were not investigated. A longer time period over which to average the migration rate might be more effective. Therefore, the *migration rate* determined with these values may be different, but the *pattern* of migration should be representative. This is true of all meander migration modeling, because the annual patterns of flow and storm events are not predicable. The meander migration model simulated a nominal 50 years of migration. However, the patterns should be relied on more than the specific duration of time—no one can say for certain “where” or “when” a channel will migrate to a specific location.

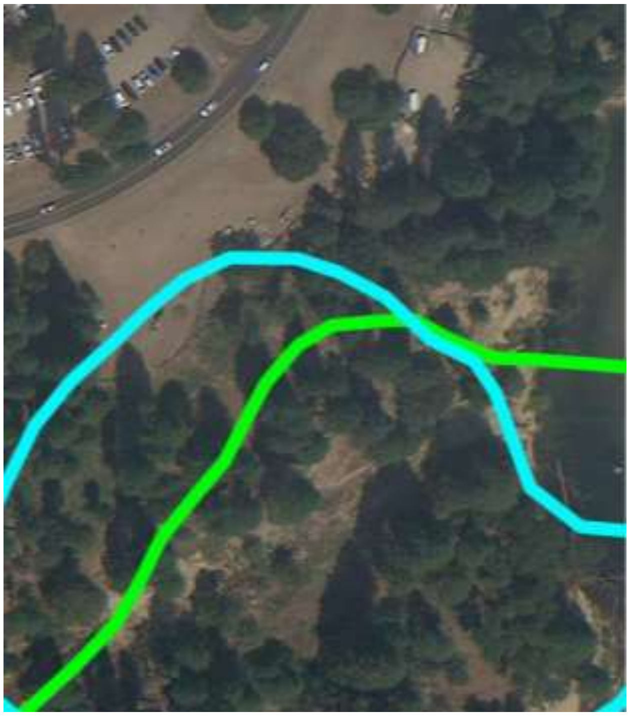


Figure 5-2. Historical progressive migration 1870-1883 at RM 0.3 to 0.4. The channel migrated from green to blue.

Figure 5-3. Calibrated 13-year migration at RM 0.4 to 0.5. The channel migrates from green to blue in this simulation.

5.5 “Area reworked” defined

The area of land reworked during a given time period is calculated by intersecting centerlines of channels from the beginning and end of the time period. The area between the two curves is calculated and called the area of land reworked (Figure 5-4).

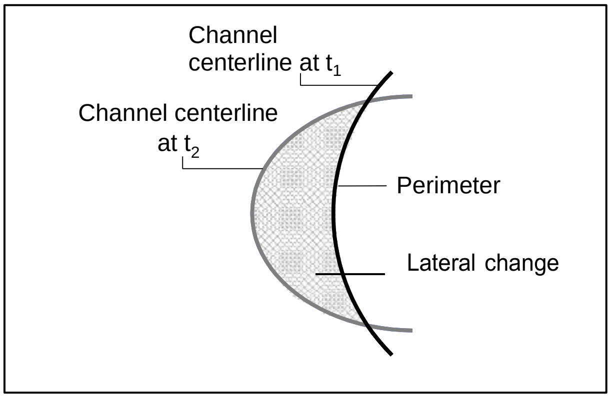


Figure 5-4. Definition of “area reworked” polygon.

5.6 Results

5.6.1 Modeled migration with and without revetments

Model outputs show modeled channel centerlines in yearly time steps, for 50 years into the future, superimposed on a background map (i.e., **Error! Reference source not found.**). From these centerlines, the area reworked was calculated.

Error! Reference source not found. shows the channel migration from 2016 to 2067 (a modeled 50 years) in one-year increments with the selected revetments in place. In contrast, **Error! Reference source not found.** shows the migration with the selected revetments removed. The meander migration patterns are similar for areas where there are no modeled revetments because all conditions were assumed the same in those locations for both simulations.

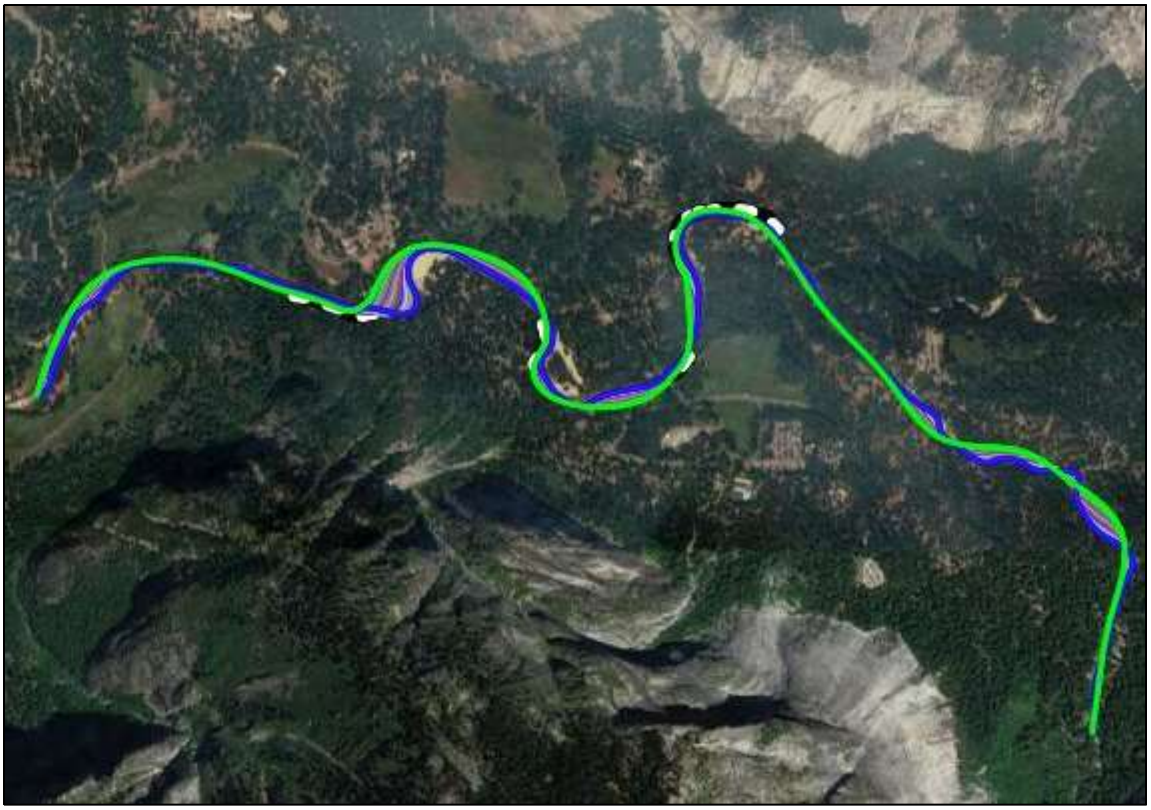


Figure 5-7. Channel migration 2016 to 2067 with revetments in place. The blue line represents the channel centerline in 2016; the green line represents the channel centerline in 2067 modeled with revetments.

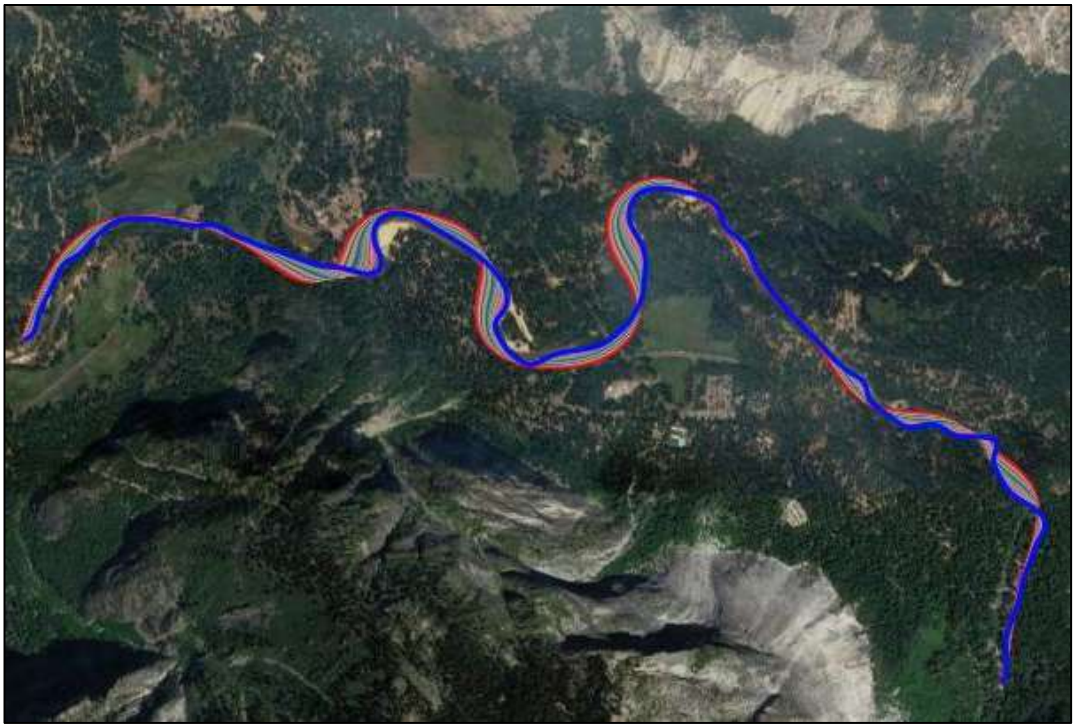


Figure 5-5. Channel migration 2016 to 2067 without revetments in place. The blue line represents the channel centerline in 2016; the red line represents the channel centerline in 2067 modeled with no revetments.

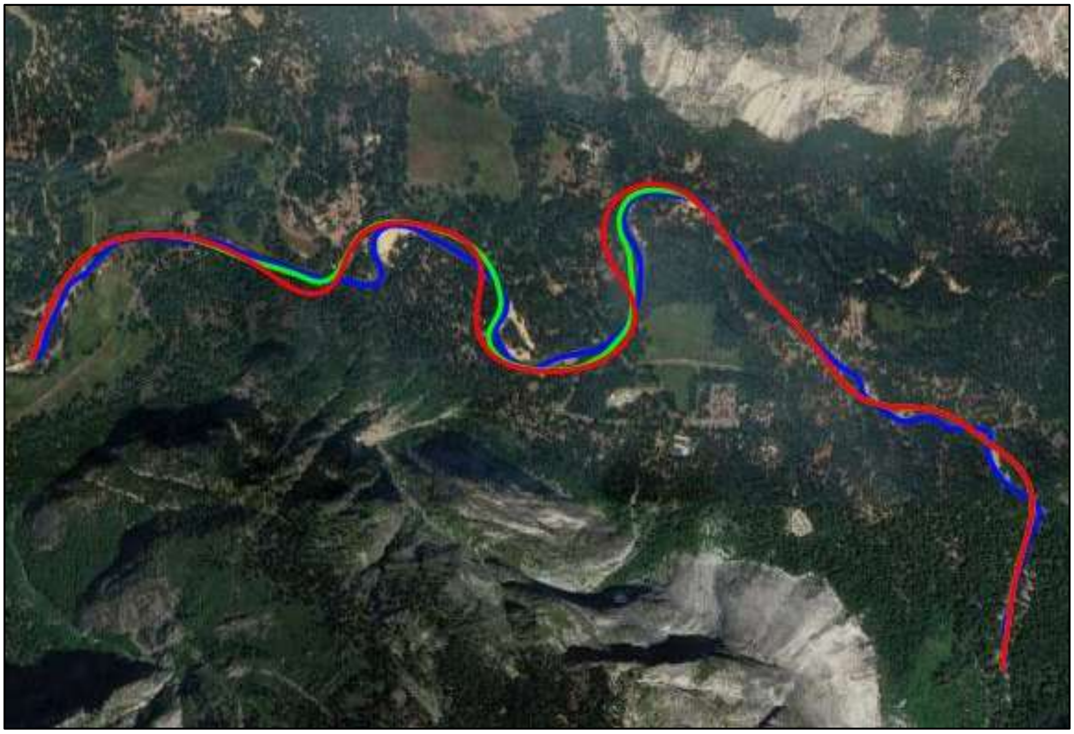


Figure 5-6. Channel migration patterns with and without revetments. The blue line represents the channel centerline in 2016. The green line represents the channel centerline in 2067 modeled with revetments; the red line represents the channel centerline in 2067 modeled with no revetments.

The main difference in migration patterns occurs at locations where the revetment has been modeled to be removed, resulting in a difference in the total magnitude of area reworked for each scenario (**Error! Reference source not found.**.) The calculation of area reworked was non-dimensionalized to emphasize that the exact migration rate is an estimate based on a simple method of calibration. The *relative* magnitudes, which are given here, and which are based on the migration patterns, are more instructive. There is about 50% more area reworked with the revetments removed (Table 5-2 and **Error! Reference source not found.**.)

Table 5-1. Total area reworked along the Study Area.

With revetments:	Area (m^2):	118,190
Without revetments:	Area (m^2):	161,260
Percent of area reworked, without/with:		149%

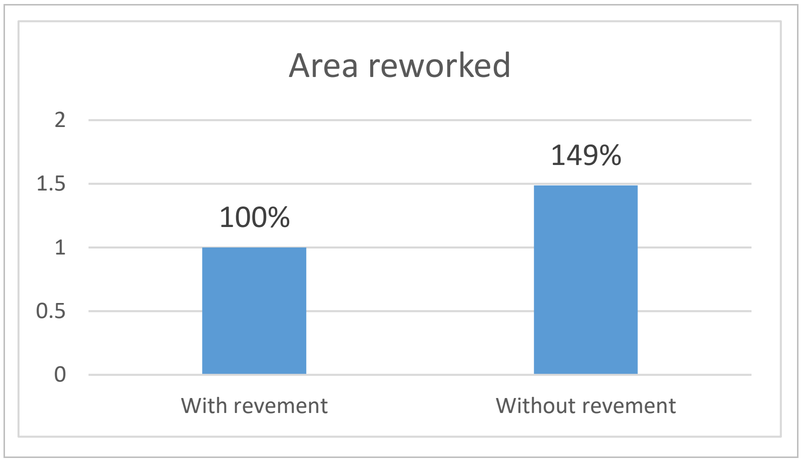


Figure 5-7. Total area reworked with and without revetments.

In order to display the difference in migration patterns more clearly, the bend from about RM 1.4 to 1.9 has been isolated and enlarged in Figures 5-11 through 5-13.

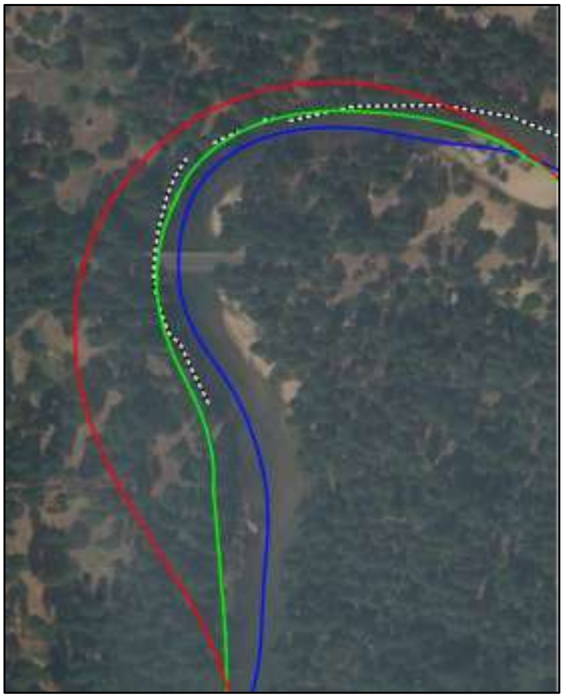


Figure 5-11. Modeled migration at RM 1.4 to 1.9 with and without revetments. The blue line represents the channel centerline in 2016. The green line represents the channel centerline in 2067 modeled with revetments; the red line represents the channel centerline in 2067 modeled with no revetments. Ahwahnee Bridge in upper right-center; Sugar Pine Bridge just off image to the right. Flow is from left to lower right.

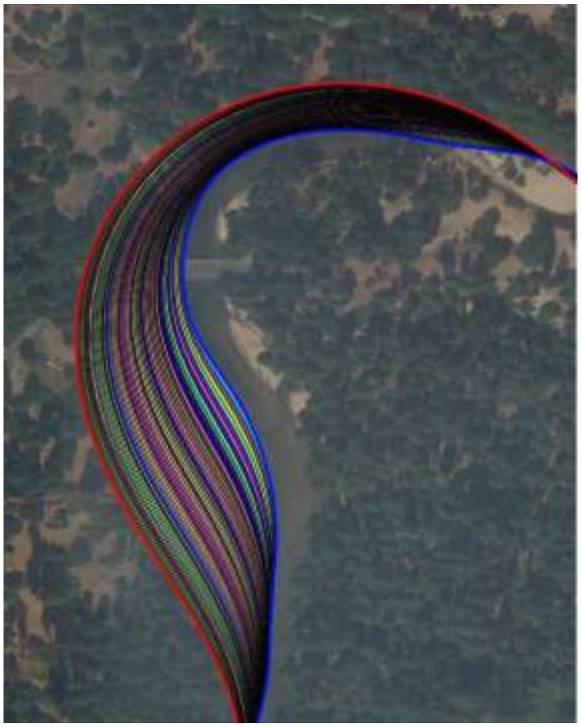


Figure 5-12. Modeled migration at RM 1.4 to 1.9 without revetments.

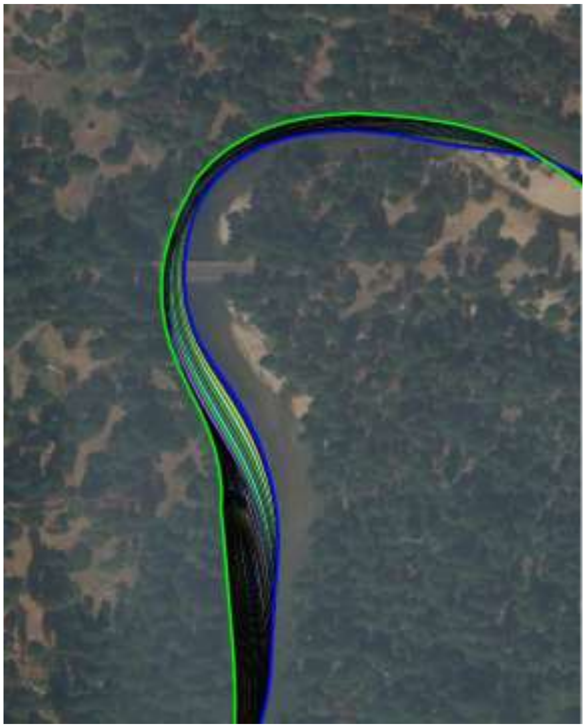


Figure 5-13. Modeled migration at RM 1.4 to 1.9 with revetments.

5.6.2 Modeled cutoff at RM 0.3-0.5

Figure 5-14 gives a large-scale view of the cutoff location at RM 0.3 to 0.5 (between Housekeeping and Sentinel bridges). Figure 5-15 and Figure 5-16 show the modeling of the potential cutoff at this location. The left-hand figure shows the migration of the channel in this bend if no cutoff were to occur, with the dark blue channel representing the initial channel centerline, and the light blue representing the final location after an estimated two or three decades of migration. The right-hand figure shows the potential cutoff, where the white dashes show the location of cutoff, going from the dark blue channel centerline to the dashed at cutoff, the light blue shows the location of the channel after the channel migrates subsequent to cutoff.

Figure 5-14. Location of cutoff modeling.

Figure 5-15. Progressive migration at RM 0.3 to 0.5. Current channel position is dark blue, migrated centerline is light blue.

Figure 5-16. Cutoff and migration at RM 0.3 to 0.5. White dashed line shows the path of the most probable cutoff; light blue line indicates the centerline of subsequent migration.

5.7 Discussion

In this study, a general meander migration model was specifically designed for, and tested on, the Study Area of the Merced River in eastern Yosemite Valley. Hydraulic and geomorphic factors characterizing the reach from Happy Isles Bridge to a point downstream from Sentinel Bridge were taken from published sources and used to tailor the model for this specific segment of the river.

To illustrate its effectiveness, and to test the Merced River model on this reach, we used the model to forecast future migration with the existing revetment in place. Then we used the model to forecast migration without the revetment. A comparison showed how planners can use the model to quantify the effect of the revetment in limiting the ecological benefits due to migration.

In the study reach there are three main rather large, “loopy” bends, where most of the meander dynamics occur (Figure 5-). Four key areas of revetment adjacent to the large bends were considered. The green line shows the location after migration with revetment in place, and the red line shows the location of migration if the revetment were removed. In the lower figure, the blue line shows the location of the channel at the initiation of migration modeling.

The comparisons show strong tendencies for migration on the downstream limb of the large bends.

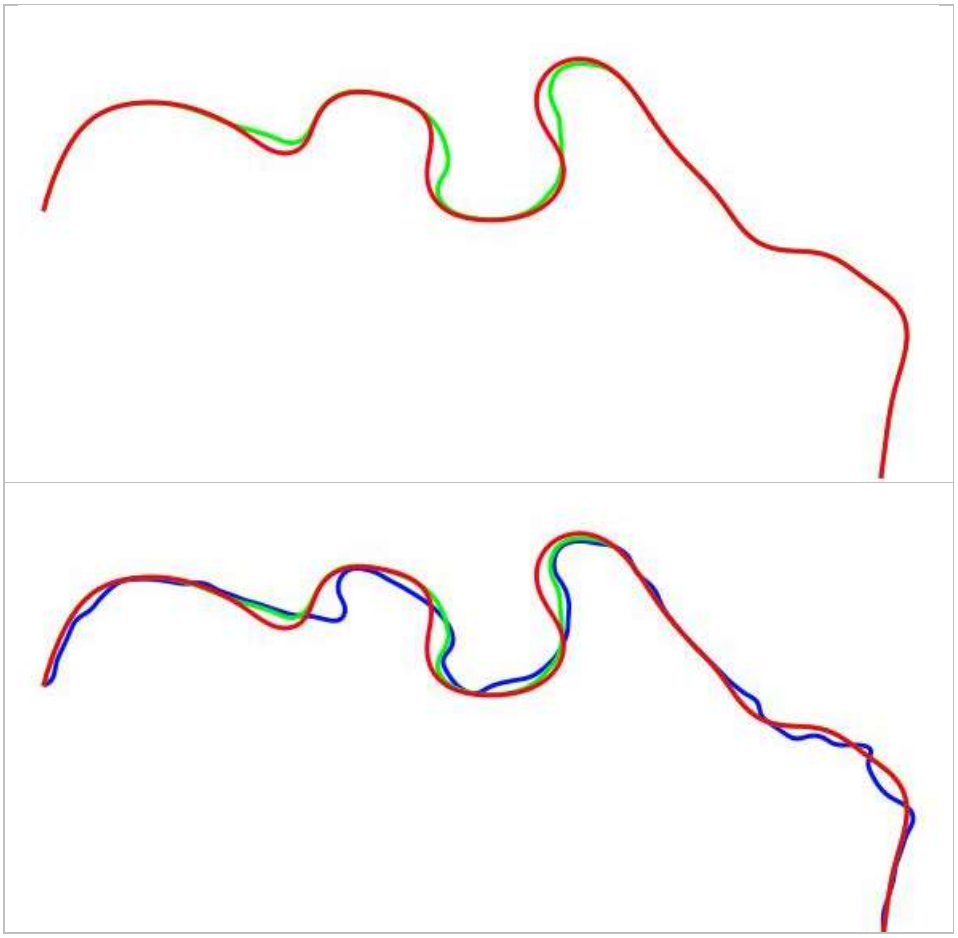


Figure 5-17. Study reach centerlines. The red line shows the migration with no revetments. The green line shows the migration with revetments in place; the blue line shows the channel at the initial time period. Flow is from lower right to left, with Happy Isles Bridge near the upstream limit of the view (lower right-hand corner); Sugar Pine Bridge is on the right flank of the first bend going downstream.

The forecasting of meander migration effectively shows tendencies and trends of a dynamic channel. Like all models, this model is effective in helping planners consider these tendencies. The channel will tend to migrate; *exactly* where and when it will migrate, however, is not clear. Therefore, modeling is most effectively used to consider the patterns. This model is quite effective in helping consider complex patterns of meander channel evolution, patterns that can sometimes be quite unexpected, even when considering past migration patterns.

The use of "area reworked" illustrated how this one simple-to-understand metric can illustrate the benefits and impacts of a range of ecological values. Over years of presenting complicated metrics representing separate ecological riparian and aquatic processes (e.g., vegetation succession, floodplain development, large wood recruitment), we have found that this one metric successfully represents the integrated benefits of many processes. It has proved to be an excellent way to communicate the benefits and impacts of meander dynamics quickly and effectively with the public and others.

On the study reach of the Merced River, the take-home message of the area-reworked graph (Figure 5-18) is that four areas of revetment are limiting an additional 50% of meander migration dynamics.

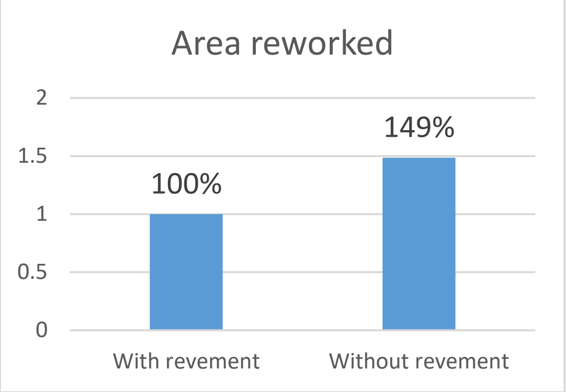


Figure 5-18. Area reworked.

These examples also illustrate how this approach can be used to model channel cutoff, by exploring a potential cutoff at RM 0.3 to 0.5, upstream from Sentinel Bridge (Figure 5-19). The cutoff algorithm in the model uses empirical information (i.e., how have cutoffs occurred in the past on this river?) linked with hydrodynamic modeling (i.e., what will the channel form and forces of water tend to do?) to forecast possible cutoffs and their shape and location. In our study example, we picked a location to inform our modeling where a high-water overflow chute already exists.

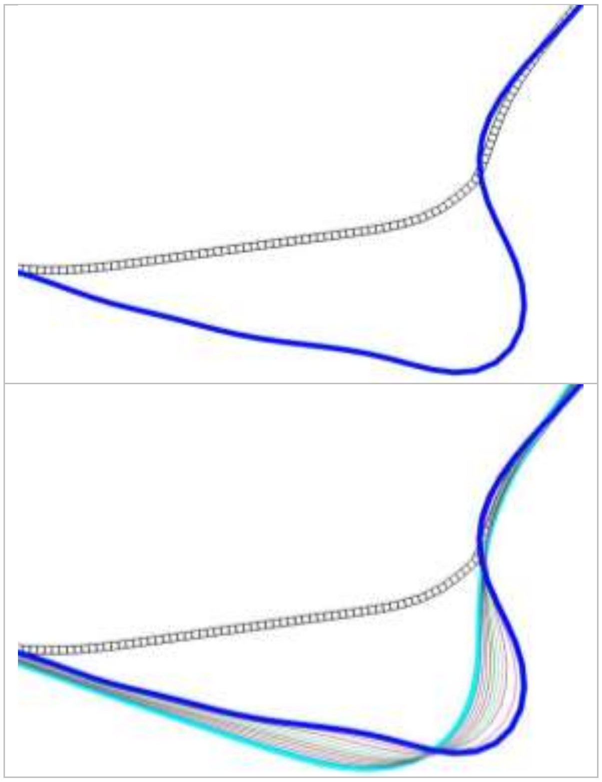


Figure 5-19. Cutoff modeling summary. The top image shows the path of the modeled cutoff channel (white dashed line); the lower image shows the migration assuming no cutoff and no revetments. Flow is from upper right to left; Sentinel Bridge is about 0.3 miles downstream.

The meander migration model has been found useful for a range of applications. The most obvious is as a planning tool. It can answer the question, “how is the river likely to behave to in the future?” When a river like the Merced River migrates, it interacts with infrastructure like parking lots and bridges; this is unavoidable. Foreseeing the interaction patterns of infrastructure with river meandering can reduce unexpected conflicts. Even when traditional planning is used to foresee river meander migration, these traditional plans often overlook the downstream consequences of localized measures to respond to (or to constrain) meandering. The hydrodynamic model used here clearly shows that what you do upstream has effects downstream.

Another benefit of the tool is the ease of use and the ability to quickly evaluate different scenarios. Planners can use the model to literally “think” about what might happen. The modeling often becomes a way of thinking. As model results reveal patterns that were unexpected, unexpected opportunities also reveal themselves. And equally important, the graphic quality of the output (the model can produce animations that show river movement over time) is a powerful communication tool. Users have found that they can communicate – without words – complicated patterns of river and infrastructure interactions. Comments from viewers are often similar to “oh, is that what you meant!”

In these examples, specific restoration scenarios related to cutoff were not addressed, and no direct design questions were evaluated. The current model was established for possible future use for these purposes. A benefit of the current meander migration model is that it is freely available for public use. This means that NPS employees, with minimal need for outside help, can use the model quickly and efficiently for planning and evaluation.

In many public environments like Yosemite, people have viewed the occurrence of meander migration as a surprise, or a nuisance, or as some combination of the two. The movement of the channel laterally and downstream is a natural occurrence, just like growing taller and wider is for a tree. You wouldn’t be surprised to see a tree get taller! The stigma attached to the natural progression of a meandering river can be felt when you hear or say the words “bank erosion.” These two words tend to conjure up an image of negative forces acting against us. But much of what falls under the subject of “bank erosion” is the natural growth of a healthy river in its native habitat. Understanding the patterns of river “growth” can make the river an ally in our planning processes. When you understand the processes of meander migration, you can work with them, and even make them a constructive part of your planning. The meander migration model described in this report, developed specifically for the Merced River, allows planners to work in collaboration with the migration of the river.

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