RESTORATION STRATEGY FOR THE MERCED RIVER THROUGH YOSEMITE VALLEY
June 2019

UC Santa Barbara Project Team

Derek B. Booth (UC Santa Barbara)
Katie Ross-Smith (Cardno, Inc.)
Eric Larsen (UC Davis)
Virginia Mahacek (Cardno, Inc.)
Elizabeth Haddon (US Geological Survey)
Tom Dunne (UC Santa Barbara)

INTRODUCTION

The following discussion articulates the vision that is guiding ongoing efforts to restore the Merced River through Yosemite Valley, and explains the scientific rationale for the measures being pursued to achieve that vision. The purpose here is to provide the scientific context for these restoration measures so that stakeholders, practitioners, managers, and the general public can understand the basis for *what* is being undertaken, and *why* they these actions are being done.

For guidance on the vision of the Merced River and its management by the National Park Service, the Merced River Plan offers clear direction:

> "The overall goal of the Final Merced River Plan/EIS is to provide for public use and enjoyment of the river resource while protecting and enhancing the values for which the Merced River was designated a Wild and Scenic River," values that include "the river's free-flowing condition, water quality, and outstandingly remarkable values, collectively referred to as river values." Such rivers and their immediate environments are to be protected for the benefit and enjoyment of present and future generations. (MRP, pp. ES-1 and 1-3)

The Plan further refined this overarching vision to specify four goals specific to Yosemite National Park (MRP, p. 1-3):

- Protect and Enhance Ecological and Natural Resource River Values
- Provide Opportunities for Direct Connection to River Values
- Establish a User Capacity Management Program
- Determine Land Uses and Associated Developments

Only the first of these goals is directly addressed by the ongoing program of river restoration work being planned and implemented, but that work is occurring within a broader context that includes visitor access and experience, and the acknowledgement of other activities that may not directly involve, but must nonetheless support, the "natural and cultural river values today and into the future."

A host of restoration efforts are planned or already being implemented along the Merced River, and they are being informed by a variety of prior and ongoing studies. The U.S. Geological Survey made a first systematic survey of the extent and causes of bank erosion in the early 1990's, documenting the clear association of high visitor use with riverbank erosion and also pointing out potential problems with unnecessary bank armoring, bridge placement, and the systematic removal of large logs from the channel. A follow-up study in 2012 by the consulting firm Cardno Entrix documented similar conditions and identified the same suite of causal agents, noting that the 1997 flood of record had a particularly significant effect on both bank erosion and the introduction of large logs (from bank-eroded trees) into the channel. A survey of visitor preferences by Confluence Research and Consulting, also conducted in 2012, found broad support for controlling river access in ecologically sensitive areas but also a strong preference for maintaining the overall accessibility and use of the river for all.

Other, more recent technical studies have been completed or are presently underway. The U.S. Geological Survey developed a hydraulic model of the Merced River through Yosemite Valley in 2013, which by itself provides no particular guidance for restoration or identification of impacts but provides a critical tool for evaluating the likely efficacy of any future restoration alternatives. A research team led by the University of California Santa Barbara (UCSB) is currently synthesizing and updating the prior information on the river, integrating that river-specific information within both the physical environment of the Merced River watershed and the social context of visitor experience and stakeholder preferences. A component of that UCSB-led effort is the design and implementation of a set of site-specific riparian restoration projects, with three projects constructed in the summers of 2016, 2017, and 2018. Other products of the research team include a synthesis of the physical condition and trajectory of the river and its watershed; a range of restoration alternatives that could improve physical, ecological, and aesthetic conditions throughout the river corridor through Yosemite Valley; and, presently under development, an evaluation of conditions and alternative restoration measures in the vicinity of Sugar Pine Bridge, a study component specifically called for in the final Merced River Plan.

As a centerpiece of Yosemite Valley, the Merced River is at the heart of the visitor experience (Figure 1). It benefits from having a nearly pristine watershed, wholly contained within Yosemite National Park and largely protected in perpetuity by its wilderness status. The river itself is not unimpacted, but the watershed processes that support it are intact. These processes, most critically the delivery of water and sediment from the watershed to the river, are commonly compromised by upstream dams, logging, roads, agriculture, or urbanization. In such watershed settings, treatment of the channel itself my yield cosmetic benefits but they cannot be sustained without constant re-intervention. Where the only impacts have occurred from local manipulation of and to the channel, however, then reversing those local effects is the correct fundamental approach to restoration. Such efforts should be successful, and they should persist, because the river is allowed to heal itself (Beechie et al., 2010; Kondolf, 2011) and its intact watershed can sustain such an outcome. This overarching principle—reversing past damage to the river itself to allow natural watershed processes to reassert their influence—constitutes the fundamental guidance for the restoration of the Merced River in Yosemite Valley.

Figure 1. Upstream-looking view of the Merced River and Stoneman Bridge; Half Dome in the background.

The Society for Ecological Restoration (www.ser.org) defines ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed." They go on to note that the value of restoration lies not only in the repair of ecological damage but also in its ability to improve the human condition. As such, it requires the integration of nature and culture, drawing from both science and practice. This duality has been long-recognized in past efforts to identify and address the ecological impacts to the Merced River, and it continues to guide the current initiatives being pursued through Yosemite Valley today.

CONDITIONS INFORMING RESTORATION OF THE MERCED RIVER

As documented by the UCSB research team, a set of conditions along the Merced River have direct consequences for the degradation that has occurred, and significant implications for opportunities for reversing these effects through active restoration:

1. The river is largely disconnected from its once-active floodplain, such that adjacent upland areas that once flooded almost annually now require significantly larger, less frequent flows to be occupied. This has the dual effects of altering the biota of the floodplain, affecting both vegetation communities and water-dependent biota, and amplifying erosive forces within the channel by confining flows within its banks. The underlying causes are most likely the historical de-snagging the river of its large woody debris, reducing roughness and so enhancing the efficiency of flows to transport sediment, and historical gravel mining of the bed of the river, poorly documented but noted by prior studies. An additional factor may be long-term changes in climate patterns that have increased the relative frequency of high-magnitude winter rain-on-snow floods relative to more moderate (and less competent) snowmelt-dominated floods.

2. The channel has widened substantially through the historical period, with increases averaging more than 25% throughout much of the Valley. The locations of greatest widening align well with areas of high visitor access and use; more pervasive channel expansion likely results from the increased in-channel containment of high flows resulting from incision (see #1 above). The only exceptions to this pattern are the localized constrictions of the channel in the immediate vicinity of the stone bridges.

3. The sediment supply to the Merced River through Yosemite Valley is limited by the river profile through Nevada Fall and Vernal Fall, which trap virtually all coarse sediment from the upper watershed. The load transported through the valley is limited to that delivered downstream of these sediment blockages by Illilouette Creek and local rockfalls, as supplemented by bank erosion from channel widening (see #2 above). Comparison of the historical loss of coarse sediment (from incision and channel erosion) with the modern flux of coarse sediment through the reach suggest that more than a century of natural sediment delivery would be required to fully recover the losses that have occurred. Thus, restoration that relied primarily on natural processes to rebuild a natural channel form would require great patience.

THE RESTORATION STRATEGY

The overarching goal of restoration of the Merced River is to protect and enhance the values for which the Merced River was designated a Wild and Scenic River, while providing for present and future public use and enjoyment of those river values. Given its intact watershed setting, restoration of the river through Yosemite Valley can focus, virtually exclusively, on the local impediments to the natural expression of reach-scale hydrologic and geomorphic processes. These reach-scale processes include:

- The localized erosion, transportation, and deposition of sediment, and the expression of these processes in the form and shape of the river channel itself;
- The input, transport, and retention of organic material, particularly large wood;
- The lateral inputs of water and sediment from upland runoff and tributary streams; and

- The hydrologic and sedimentologic interactions between the channel and its adjacent floodplain, in the form of overbank flows and side-channel occupation.

Although a river with intact watershed processes “should” trend over time towards a fully functional, restored state, not every human impact can be easily reversed by natural processes alone. Other impacts may be reversible but can require decades, centuries, or more to change. Finally, Yosemite Valley itself is not a pristine landscape, and meeting other goals (such as visitor access and enjoyment, or protection of cultural resources as well as natural resources) requires a balance amongst potentially competing goals. These considerations suggest that the most successful outcomes will only be achieved through directed interventions, rather than simply “letting nature take its course.”

Four broad categories of restoration approach stand out as having the best opportunity to correct the critical impacts to the river through Yosemite Valley. They are listed in overall priority ranking, in recognition that direct impacts to the riparian zone and channel banks are not only the most pervasive throughout the Valley but also the most easily and inexpensively corrected. Those restoration approaches that require more extensive in-channel work, or that would require extensive modifications to adjacent floodplain areas, will demand a higher level of engineering design support and impose greater (albeit temporary) disturbance to both the landscape and visitors alike. Therefore, they are lower-priority approaches and are not yet as fully developed as to conceptual design or identified potential localities for implementation.

1. **Restoration of the riparian zone** (Figure 2), including the reconstruction of streambanks trampled by unrestricted visitor access and reestablishment of a more diverse, native-species riparian vegetation community. Natural processes of vegetation succession and geomorphic adjustment would eventually achieve many of these goals, but the period of recovery without active intervention would likely extend for many decades or centuries.

Figure 2. Views of degraded riparian zones and associated bank erosion. Clockwise from top left: downstream of Clarks Bridge, between Stoneman and Housekeeping Camp bridges, along lower Tenaya Creek, and upstream of Sugar Pine Bridge.

2. **Encouragement of more frequent overbank flooding and off-channel flows** (Figure 5), supporting a more natural and diverse assemblage of riparian plant species and thus improved riparian habitat for birds, amphibians, and mammals. This approach works in consort with others: overbank flooding encourages the development and expansion of tributary channels, and a dynamic river will invariably leave some areas more prone to overbank flows at lower discharges. Therefore, this approach is also subject to the same types of constraints to achieve a balance between expression of natural riverine processes and their enjoyment by visitors.

Figure 5. Existing side channel off the mainstem Merced River, just upstream of Sugar Pine Bridge.

3. **Restoration of dynamic river and tributary channels in Yosemite Valley,** important to allow the development of diverse, complex riparian habitats supporting successional vegetation in multiple stages. While processes such as channel migration and development of cut-off channels and meander belts undoubtedly affected the entire valley in prehistoric time, they no longer have unfettered access to the entire landscape. The current constructed constraints on river-channel activity (e.g., armored banks), however, are more severe than strictly required by limitations of infrastructure, and they compromise unnecessarily the natural form and function of the river (Figure 3).

Figure 3. Bank armoring adjacent to Housekeeping Camp (river flow is towards the camera).

4. **Creation of more complex in-channel habitat**, increasing the quality of aquatic habitat and therefore supporting an increased diversity of in-stream and riparian species. The natural shifting of channels and recruitment of large wood will tend to achieve this outcome regardless of further intervention, but the rate of natural improvement can be orders of magnitude slower than with well-directed restoration efforts. Thus, a passive approach would support a vision of "future" enjoyment but would preclude any "present" benefits. In some locations, the magnitude of human-constructed constraints and associated channel simplification (Figure 4) may defy restoration by natural processes even over the (very) long term; for these, improvement will almost certainly require intervention through active restoration.

Figure 4. View downstream along the Merced River below Clarks Bridge, displaying a long reach of homogenous channel form.

The following table summarizes the restoration approaches and specific types of actions that are recommended for implementation along the Merced River.

Restoration approaches	Actions
1. Restoration of the riparian zone	• Revegetate riparian zone to increase channel roughness, induce sediment deposition, and promote the natural succession of native species • Fence off or otherwise impede access to bank areas vulnerable to trampling, and direct visitor usage to more resilient portions of the river • Remove unnecessary riprap, or failed riprap that causes increased erosion • Redirect flows to minimize bank erosion caused or exacerbated by bridges
2. Encouragement of more frequent overbank flooding and off-channel flows	• Increase in-channel roughness; narrow excessively widened channel reaches through riparian restoration and bank structures • Restore ditched and graded meadows, and remove structures diverting groundwater • Enhance existing or abandoned side channels to encourage more frequent reoccupation • Regrade selected floodplain areas to permit floodwater access at lower discharges
3. Restoration of dynamic river and tributary channels	• Remove riprap in non-essential locations, and/or replace with bioengineered bank protection structures • Place large wood structures along channel bank to reestablish a more natural channel width, limit bank erosion, and promote revegetation • Revegetate banks • Add large wood or engineered large wood structures to the river channel • Redirect flows near bridges
4. Creation of more complex in-channel habitat	• Retain large wood that naturally falls into the river; reposition, but not remove, wood between Clarks Bridge and Sentinel Beach where recreational rafting occurs • Add large wood or engineered large wood structures in the mainstem Merced River channel to increase habitat complexity and induce localized scour and sediment deposition • Revegetate the riparian and near-channel zone

EXAMPLE RESTORATION ACTIONS

A variety of restoration techniques and actions can be used to achieve the desired outcome for each of the approaches outlined above. These actions almost always require site-specific designs, but some pictorial examples can nonetheless characterize how each of these approaches is commonly implemented and visualize the kinds of outcomes that can be anticipated.

1. Restoration of the riparian zone (Figure 6)

Full or partial riprap removal and vegetation replanting to create a more diverse riparian zone:

Figure 6. Diagrammatic view of vegetative bank reinforcement, with or without initial removal of existing riprap.

2. Encouragement of more frequent overbank flooding and off-channel flows (Figure 7)

Bank lowering to allow for reactivation of historical side channels through low-use areas, actions that would create significant temporary disturbance and potential long-term consequences for visitor access, and so subject to significantly more analysis than anywhere yet conducted along the river:

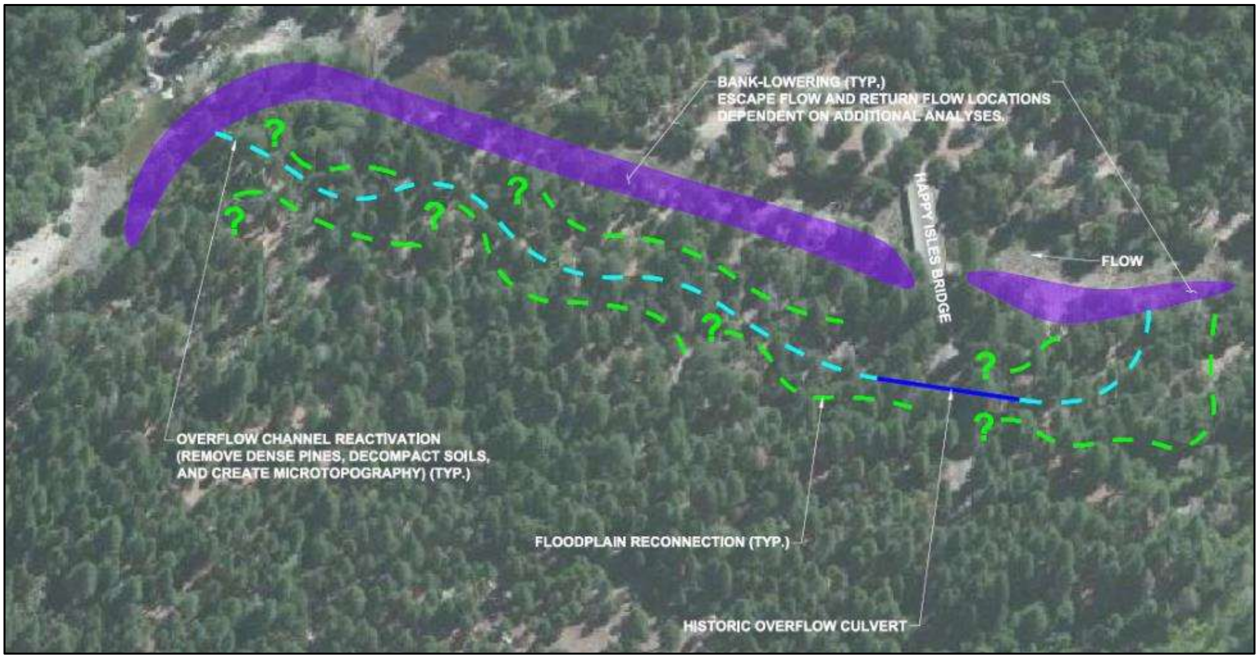

Figure 7. Example paths for reactivated off-channel features, for which either raising of the river bed or lowering of the floodplain would be required for non-extreme-flood occupation.

3. Restoration of dynamic river and tributary channels (Figure 8)

Channel-narrowing treatment along trampled banks:

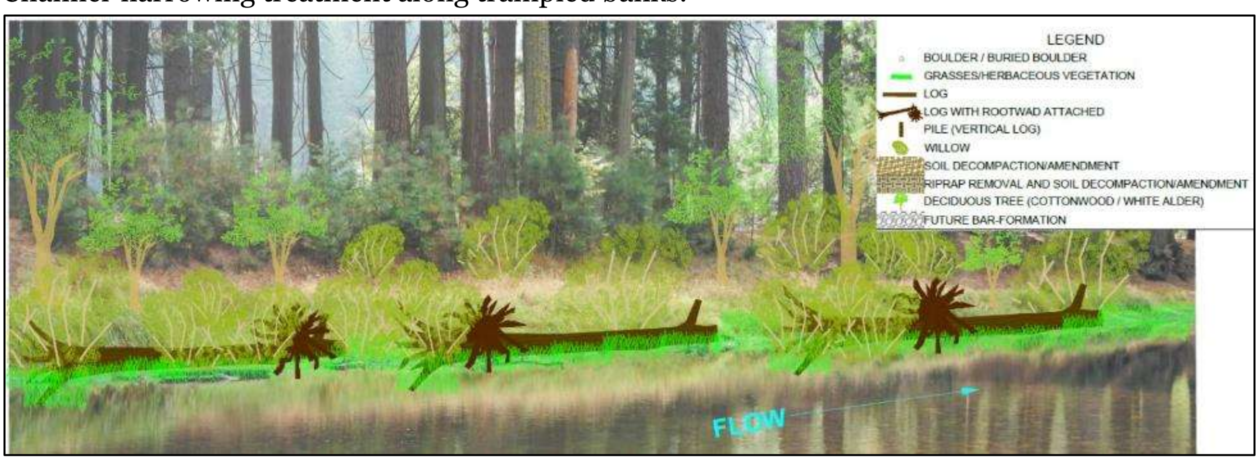

Figure 8. Reinforcement and rebuilding of trampled banks, plus riparian vegetation replanting within and above the bank structures.

4. Creation of more complex in-channel habitat (Figure 9)

In-channel large wood structures to create habitat diversity:

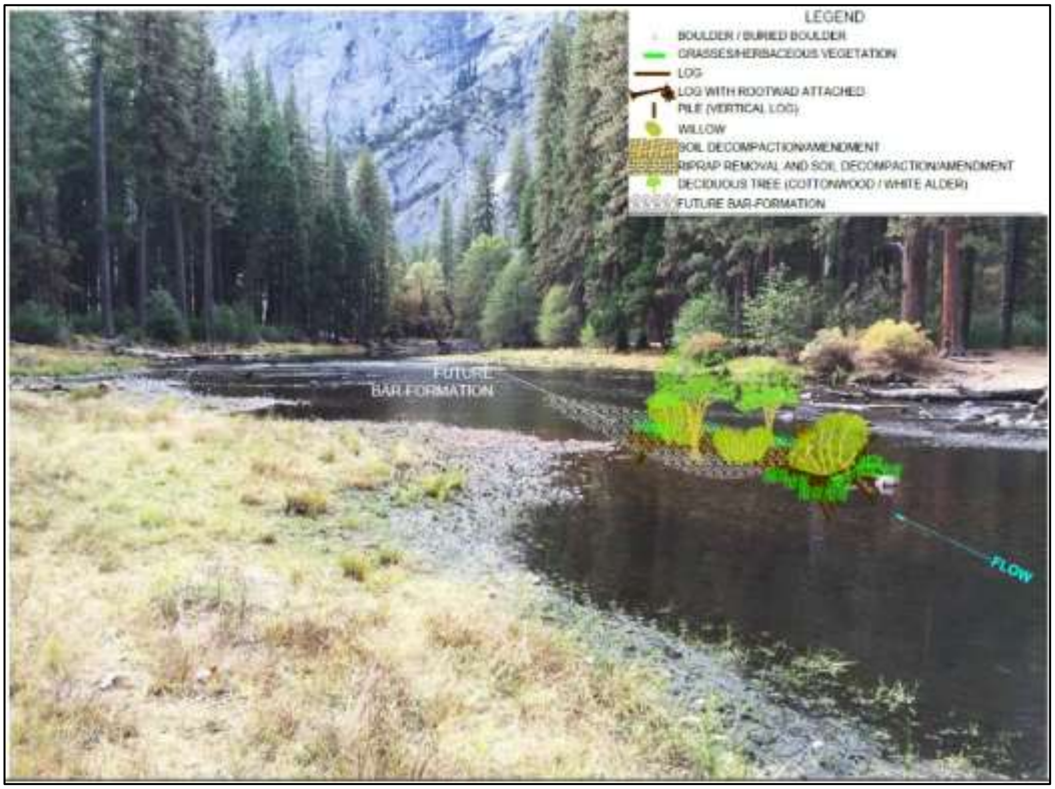

Figure 9. Construction of in-channel engineered log structures increase physical habitat diversity and recover a more complex channel form.

REACH-BY-REACH CONDITIONS, OPPORTUNITIES, AND RECOMMENDATIONS

The three miles of the Merced River, between Happy Isle Bridge and Sentinel Bridge, present a wide variety of impairments to the river through the most intensively used portion of Yosemite Valley. They also highlight opportunities for different types of restoration treatments discussed above, and where they are most likely to be effective. At many sites, even a visual reconnaissance has proven sufficient to make firm recommendations for restoration design and implication; at other sites, the complexity of conditions or the risk to infrastructure will require more detailed analysis before firm recommendations can be made.

The following discussion summarizes and updates the findings of prior reports prepared as part of the present project: the initial project examples identified in *Merced River Riparian Corridor Restoration in Yosemite Valley* (Cardno, 2016)*;* the June 2018 UCSB evaluation of riverine conditions, *Restoration of the Merced River through Yosemite Valley, Yosemite National Park* (Booth et al., 2018); and the draft *Reach 6 Restoration Concept Designs* (Cardno, 2018). Also invaluable has been prior work on the Merced River, including the Master's thesis of Milestone (1978, notated "Ms" where referenced), the US Geological Survey reports of Madej (1991, notated

“Mj”) and Minear et al. (2013, notated “Mr”), and the earlier river and riparian-zone assessment of Cardno (2012, notated “C12”).

The description of prospective, recommended, and constructed restoration actions in the following reach descriptions references the project numbering framework defined in Cardno (2016) and Cardno (2018). They are references as, for example, “5-3” and “2-1”. The first digit is the reach number (Figure 10) and the second digit identifies individual projects within that reach in approximate downstream-to-upstream order.

Figure 10. Index map of Merced River reaches (purple numbers) discussed in the text. River miles are shown by the circles (in 1/10th-mile increments), measured upstream of Sentinel Bridge.

Reach 10 (downstream of Happy Isle Bridge; RM 2.95–2.71)

This reach is most upstream and steep within the Study Area, as the Merced River emerges from the rangefront between Glacier Point and Grizzly Peak. The average channel gradient through this reach is about 2% but is nearly twice as steep just upstream of Happy Isles Bridge, and less than half as steep as it descends through Clarks Bridge and Sugar Pine Bridge farther downstream. Thus, sediment sizes on the bed of the river are coarse (Figure 10.1) but rapidly decline in caliber. Such a reduction in grain size implies a zone of sediment deposition, because the coarsest component of the load is left behind and accumulates as the river loses competence; but because the overall sediment supply is so low, this tendency for aggradation is overwhelmed by the loss of in-stream structure that favors enhanced sediment transport. Thus, the coarsest sediment continues to be deposited, but the bed of the river has been winnowed of a far greater volume of finer material, resulting in net incision and a modern river level well below the level of the adjacent terrace that presumably once formed its active floodplain. This terrace is best developed along the left (west) bank of the river; the right bank is constrained by talus slopes off of Grizzly Peak over most of this reach, which the river has been largely ineffectual in modifying, and by two short sections of bank armoring to protect Happy Isles Loop Road.

Figure 10.1. Coarse sediment forming the bed and near-channel terrace deposits, about 500 feet below Happy Isle Bridge.

Three main issues provide the focus for restoration here: locally eroding, unstable streambanks associated with downcutting; simplified vegetation structure; and abandonment of previously occupied left-bank side channels. Because the sediment is so coarse the streambanks here are not as susceptible to the impacts of visitor traffic as farther downstream (any revegetation, however, would nonetheless require protection from visitors); instead, bank erosion appears to be primarily a consequence of enhanced sediment transport and associated downcutting, augmented by the resulting confinement of high flows within the main channel. Happy Isles Bridge also appears to offer some hydraulic constriction at high flows, with a modest narrowing of the flow (about 12%[(Ms)]) and an oblique orientation to the channel that enhances downstream deposition on the left bank, in the lee of the bridge, and more directed flow and thus erosion downstream along the right bank (Figure 10.2).

Figure 10.2. Just downstream of the right abutment of Happy Isle Bridge showing localized bank erosion, likely induced by bridge orientation and flow constriction.

The primary restoration opportunity in this reach is for reactivation of high-flow channels still visible as relict swales across the left bank terrace. Although these channels do not cross areas occupied by Upper Pines Campground, providing high-flow access to them by floodplain lowering would involve substantial earthwork activity (treatment 10-5), and so additional river modeling and engineering design would be required to inform any such design. In addition, one of these channels originates just upstream of Happy Isles Bridge and crosses the path of Happy Isles Loop Road (treatment 10-4); it passes beneath the road in a culvert that may lack sufficient capacity if it were more fully engaged during high flows. The goal of reactivating this portion of the floodplain could also be advance by increased roughness along the main channel, installing engineered log structures to raise water levels and begin the process of channel (re)aggradation.

In addition to these major prospective projects, the right bank immediately downstream of Happy Isles (Figure B) and elsewhere along this side of the river would benefit from selective riprap removal and revegetation (10-1, 10-2, 10-3).

Reach 9 (upstream of Clarks Bridge to Clarks Bridge; RM 2.71–2.18)

This reach continues many of the patterns established immediately upstream: channel gradients (and thus sediment sizes) continue to decline, much of the right bank is again confined by difficult-to-erode geologic landforms (here, a moraine built by the glaciers that once emerged from the valleys to the east), and the side channels that originate in (and just above) Reach 10 return to the main channel across a broad terrace now stranded just a few feet above the active floodplain. The widening of the valley has allowed for a greater degree of channel migration and sediment deposition throughout this reach, with several broad gravel bars deposited along inside bends of the river. This migration has, in turn, cut into the opposite bank on the outside of the bend, particularly along the high left bank terrace (Figure 9.1). Net channel migration, however, has still be minimal over the last century except within a limited zone extending for several hundred yards above Clarks Bridge (Figure 9.2).

Figure 9.1. Active erosion into the terrace bounding this reach.

Although the developed portion of Upper Pines Campground directly abuts this reach only at the downstream end, visitor traffic across the terrace is evident, and the vegetation around areas of low streambanks has been impacted. Ironically, point bars are one of the most resilient landforms of a river system and are fairly common along this reach, but they are predominately along the right bank where visitor access is much less direct.

Despite the incision of the channel and local human activity, a combination of active sediment deposition and a wider valley has produced a number of zones where fluvial processes are relatively intact. They offer examples of what restoration the Merced River might achieve, at least in these upper reaches of the Study Area (Figure 9.2).

Figure 9.2. View upstream from Clarks Bridge, showing a diverse multi-thread channel with a near-intact riparian zone. This segment of river, not far downstream of that shown in Figure 9.1, displays many of the restoration outcome sought for the Merced River elsewhere in Yosemite Valley.

Issues within this reach include eroding streambanks and a riparian corridor with reduced structural complexity, species diversity, and functionality. Milestone (1978) found that Clarks Bridge narrowed the channel by about 40%, but Madej (1991) believed that the steep channel slope minimized the impacts of this constriction on the river. Potential treatments to improve overall conditions would seek to reduce foot traffic within the riparian corridor and along the banks, particularly along the left bank of the river at the upper and lower ends of this reach (treatments 9-1 and 9-3). Also beneficial would be the removal of the Upper Pines Dump Station (also proposed in the MRP, and for which bank erosion in 2018 has necessitated emergency repairs). Restoration here would require soil decompaction, regrading, and vegetation planting (treatment 9-2).

Reach 8 (Clarks Bridge downstream to above Tenaya Creek; RM 2.18–1.97)

This relatively straight reach threads between North Pines and Lower Pines campgrounds, situated on paired terraces about 8–12 feet above river level. Within the narrow band of more recently deposited alluvium adjacent to the river, the channel has maintained its position almost without discernable shifts for more than 60 years, despite a near-absence of bank armoring except in the immediate vicinity of Clarks Bridge. The absence of significant variations in the planform and a lack of woody material in the channel has resulted in a near-homogenous channel form (Figure 8.1). This geomorphic setting, which lacks both steep banks on the outside of bends (which would discourage foot traffic) and active point bars along inside bends (which turn over frequently and so are resilient to transitory disturbances), results in a homogenous straight reach whose margins are neither inaccessible nor resilient. Thus, this reach displays some of the clearest evidence throughout the Study Area of visitor activity (Figure 8.2). Channel widening since 1919 is typically modest (<30%) but ubiquitous[(Mj)], although the downstream-most cross section in this reach had nearly doubled in width between 1919 and 2007[(Mr)].

Figure 8.1. Homogenous channel form, looking downstream from Clarks Bridge.

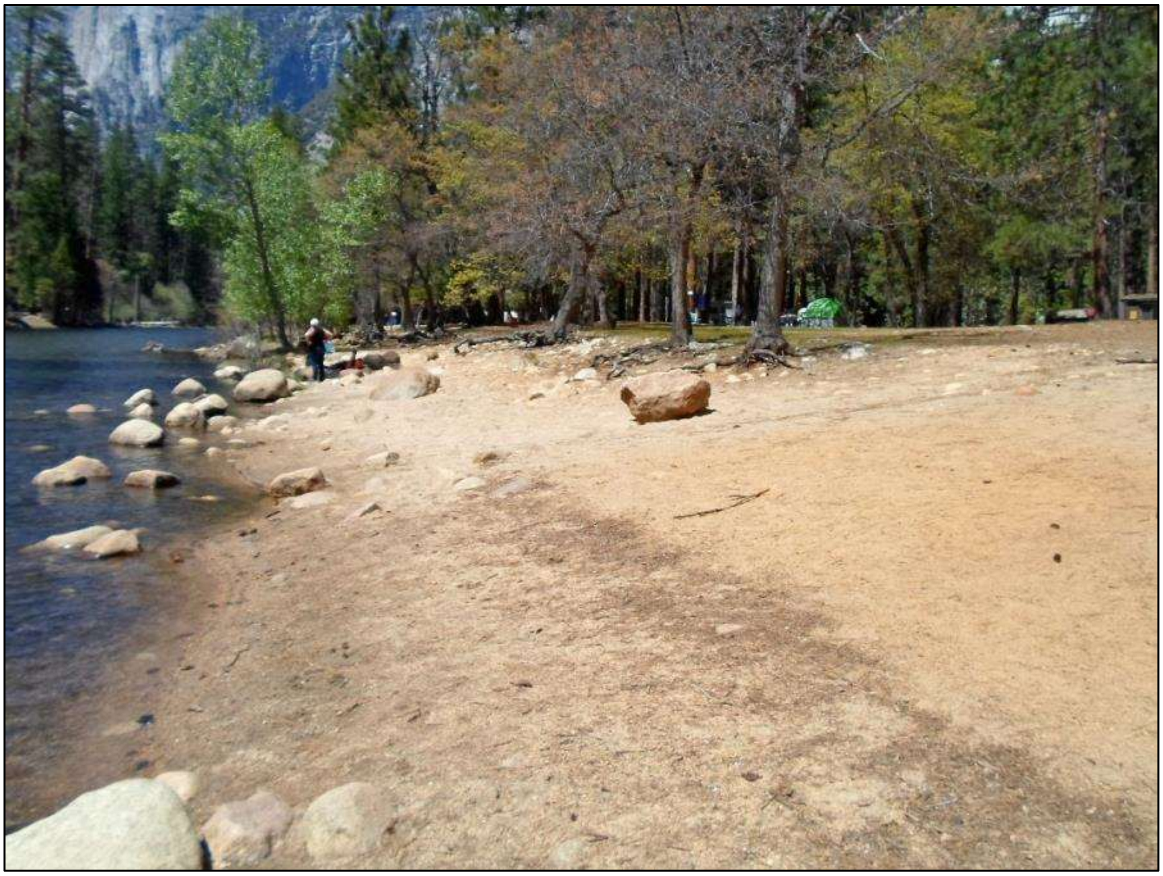

Figure 8.2. Extensive bank trampling adjacent to North Pines campground.

Issues here are similar to but even more severe than along Reach 9, particularly associated with the adjacent campgrounds. Success of any potential treatments to rebuild the riparian zone would need to exclude and redirect river access to specified locations. Some initial work, mainly installation of split-rail fencing in 2006 to encourage natural revegetation[C12], reflects the long-standing recognition of restoration needs in this area. More active revegetation and brush layering could enhance the riparian corridor, reestablishing a more natural degree of bank stability that could begin to counteract the widening that has occurred over the past century (treatments 8-1, 8-2, 8-3).

Reach 7 (above Tenaya Creek to Sugar Pine Bridge; RM 1.97–1.74)

This reach, forming the approach of the river to Sugar Pine Bridge, reflects a variety of underlying geologic conditions and human influences. The left (west) bank terrace is a younger, lower surface than farther upstream, sufficiently so to allow flood inundation during extreme events (including that of 1997, which led to the abandonment of the developed campground in this area). Detailed topography of this area (also visible on the 1919 topographic map) reveals several high-flow channels, hinting at a once more-active surface that carried significant flow even during moderate floods. The most prominent of these channels now parallels the road embankment that connects Sugar Pine Bridge to Ahwahnee Bridge; it almost certainly owes its size and position in part to the presence of that embankment, which diverts to the west all overland discharge. Madej (1991) expressed concern that this channel might someday capture of the entire flow of the river; the subsequent 1997 flood formed a large log jam at the inlet to this channel, however, which has apparently has limited its expansion since that time.

The right bank hosts the confluence of Tenaya Creek, a moderately sized tributary area that contributes flow but little additional coarse sediment, by virtue of its flat lower reach and the presence of Mirror Lake not far upstream. Immediately downstream of the confluence, the steep and erosion-resistant riverbank formed by the 12,000-year-old Sugar Pine Bridge rock avalanche confines the valley bottom along its eastern edge, limiting both channel migration and the formation of an extensive floodplain or terrace. Across the river, several of the north and northeast sites in North Pines campground are situated on the same lower terrace.

From 1919 to 1989 the channel widened by almost 50%[(Mj)], resulting in a near-featureless channel (Figure 7.1) that is grossly oversized with respect to both its natural form and the downstream opening beneath Sugar Pine Bridge that it must pass (Figure 8.2). A subsequent resurvey in this reach in 2007 also suggests that the channel has shallowed by nearly three feet, in addition to having widened[(Mr)].

Figure 7.1. Widened channel between the Tenaya Creek confluence (in middle distance, opposite the figures on the gravel bar) and Sugar Pine Bridge.

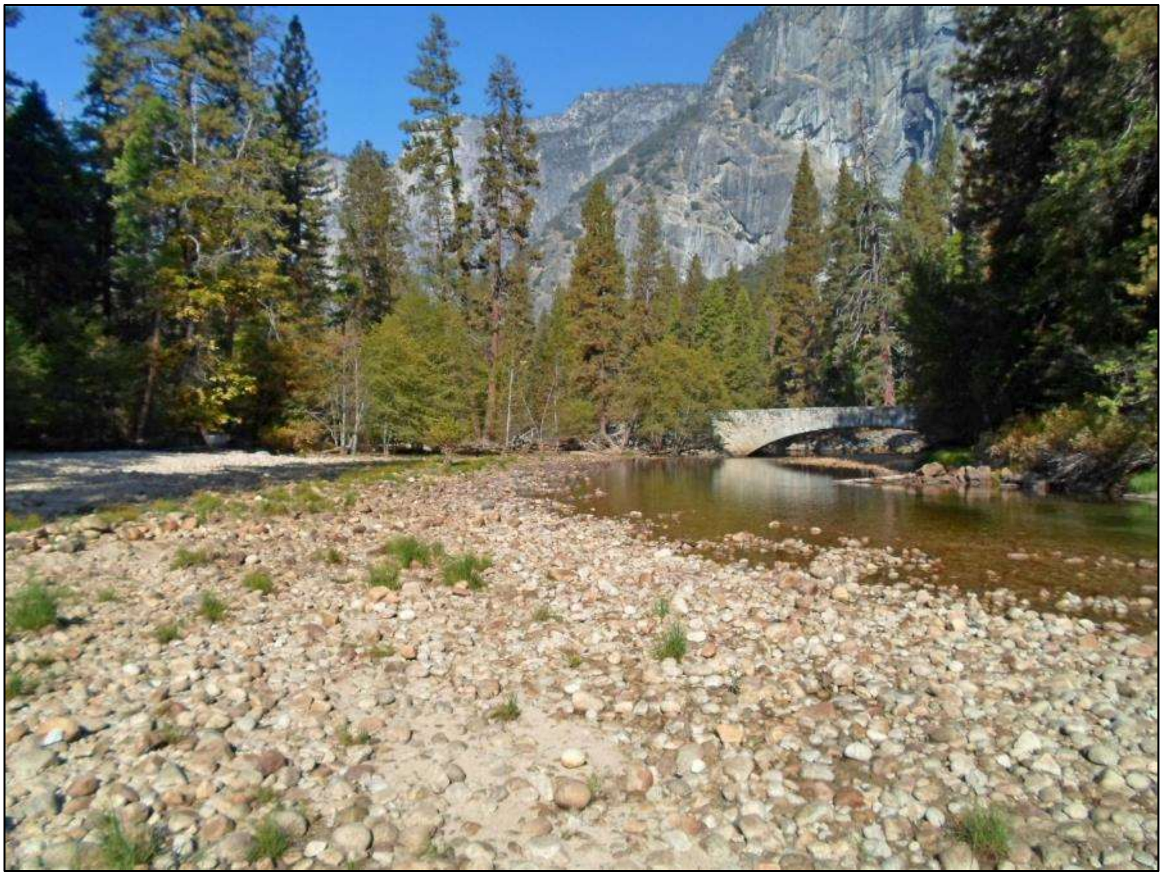

Figure 7.2. View downstream from opposite the Tenaya Creek confluence towards Sugar Pine Bridge, showing the offset in the bridge relative to the main direction of flow.

The primary issue in this reach is the extreme widening of the channel, primarily a function of visitor access from Lower Pines campground. Although removal of the lower loops following the 1997 flood has surely reduced the rate of visitation, trails from the still-active campground down the river are ubiquitous and well-worn, and many areas along the left side of the river have almost no defined streambanks at all. The prominent left-bank gravel bar in the middle of the reach (with visitors on it in the middle distance of Figure 7.1) could offer a fairly resilient access point to the river, but its very existence is anomalous—it is on the *outside* of a bend, not the inside, and owes its development to the widening of the river, likely coupled with the backwater effects of the abrupt narrowing of high flows imposed by Sugar Pine Bridge.

Potential treatments to address channel widening and bank instability (7-1, 7-4, 7-5, 7-6, 7-7) are similar to those recommended upstream. They are central to the broader restoration goal of reducing impacts to the river from the present configuration of Sugar Pine Bridge, and their success will require a level of engineering design that has not yet been completed. They will also require attention to limiting visitor access to reconstructed and replanted areas (all treatments in this reach) with at least as much vigor as the actual restoration itself. Reactivation of historic swale features on the left floodplain, engineered in-channel features to direct flows, and floodplain lowering are additional measures that represent progressively more intensive efforts that could help redirect high flows into overbank areas, reducing the degree of hydraulic constriction from the downstream bridge while enhancing floodplain function and conditions along the riparian corridor (treatments 7-2, 7-3). Their prospective locations and design are only conceptual at present; development of more detailed assessments await the application of hydraulic modeling and further discussion with the National Park Service and stakeholders.

Reach 6 (Sugar Pine Bridge to Ahwahnee Bridge; RM 1.74–1.51)

This is the most constrained reach in the Study Area, by virtue of both natural and anthropogenic features. More than half of the right bank is bounded by the Sugar Pine Bridge rock avalanche and adjacent talus and alluvium shed from Royal Arches. Riprap is ubiquitous along nearly all of the right bank, and the two bridges anchor the position of the channel at their present locations. Immediately downstream of Sugar Pine Bridge on the left bank, a large and persistent sand-and-gravel point bar (Figure 6.1) provides direct access to the river by visitors from the road between Ahwahnee and Sugar Pine Bridges; a somewhat smaller bar is also present at the inside bend just upstream of Ahwahnee Bridge. Direct visitor access to the river from the right bank is largely precluded by steep, rock-armored banks, including a robust structure that protects the eponymous sugar pine tree from flows guided by the modestly mis-oriented Sugar Pine Bridge (Figure 6.2).

Figure 6.1. Point bar immediately downstream of Sugar Pine Bridge, formed on the inside bend of the river and in the lee of the bridge and road abutment.

Figure 6.2. Downstream view of Sugar Pine Bridge from immediately upstream. Rock armoring of the sugar pine tree is evident through the bridge opening.

Prominent issues in this reach related to the confinement of high flows by the limited opening of the bridge, the extensive bank armoring between the two bridges, the misalignment of Sugar Pine Bridge relative to the current position of the mainstem river, and the obstruction of overbank flows by channel incision and (for those flows that do overtop the banks) the left-bank roadway embankment. Nearly half of the natural channel width is constricted by Sugar Pine Bridge[(Ms)]; Madej (1991) considered its potential consequences the most severe in the Study Area because of the perceived potential for the channel to avulse across the left bank, abandoning its present course under the bridge altogether. Immediately downstream of the bridge, much of the existing bank armoring is likely unnecessary for limiting significant additional channel migration, because the underlying substrate is coarse sediment shed from the adjacent valley walls and the ultimate position of the river is fixed by the two bridges at each end of the reach. Direct impact to the river from heavy visitor use along the right bank, likely associated with the proximity of the Ahwahnee Hotel, is also modest, given the steep outer bank of the bend that constitutes this reach of the river. Here, the major restoration needs associated with this activity pertain to the well-trafficked upland forest and meadows.

The greatest restoration challenge in this reach is posed by the historical efforts to preserve the sugar pine tree itself (visible in the center of Figure 6.2, through and above the bridge opening). Given the concentration and orientation of flows through the bridge, only robust artificial bank armoring is likely to preserve this tree (Figure 6.3); without it, erosion would have likely toppled the tree long ago.

Phot

Figure 6.3. View upstream; the Sugar Pine tree and associated rock armoring visible in the left foreground, with Sugar Pine Bridge about 60 feet beyond.

Restoration actions in this reach exemplify the trade-offs needed in balancing a variety of management objectives. Preservation of the sugar pine tree requires artificial bank protection, and although some greater degree of “naturalization” of that armoring may be possible (treatment 6-4), a fully bioengineered structure is likely not feasible. Preliminary evaluation of the stresses imposed on the bank and the bridge-imposed limitations on structures built into the present course of the channel indicate that only a well-hardened structure is likely to persist over time. Downstream of this locality, however, the consequences of future outer-bank erosion are not likely to be severe even with riprap modification or outright removal (treatments 6-1, 6-2, 6-3). Infrastructure is minimal in this area, and the magnitude of unconstrained channel migration into the upland terrace will be modest. Some reduction of the now-myriad visitor trails through this area would improve overall riparian conditions, but the processes of river–floodplain interaction in this reach currently are most active along the opposite (left) bank, where visitor access (and thus impacts) are substantially less.

Reach 5 (Ahwahnee Bridge to Stoneman Bridge; RM 1.51–1.22)

The river moves away from the valley wall into the center of the valley as it enters this reach, and so the adjacent uplands flanking the channel are exclusively floodplain deposits. Once inundated by flows of the 2- to 5-year recurrence flood, these surfaces now require much larger flows that occur only one-quarter as frequently. Nonetheless these surfaces retain many of the features of natural floodplains, including flat topography and easily erodible soils. Thus, they have experienced heavy visitor traffic seeking river access, and they have lost much of their riparian understory vegetation and the bank resistance that was once imparted (Figure 5.1). Even more that with Reach 7, Reach 5 has experienced a substantial degree of widening over the last century, with increases locally up to 100' and an overall expansion of nearly 60%[(Mj)], particularly (but not exclusively) along the left bank where adjacent to the now-abandoned sections of Lower Pines campground. The outside bends have been armored by riprap both downstream of Ahwahnee Bridge (left bank) and upstream of Stoneman Bridge (right bank). Constriction of the natural channel by Ahwahnee Bridge has occurred but is relatively modest relative to other crossings in the Study Area (here, about 25%[(Ms)]); the equivalent measure for Stoneman Bridge is substantially larger[(Ms)] but more difficult to evaluate given subsequent widening of the channel downstream.

Figure 5.1. Trampled, denuded banks on both sides of the river just downstream of Ahwahnee Bridge. Project 5-5 was built in 2017 just downstream of this photograph; Project 5-4 was built in 2018 across the river just out of view to the right.

Migration modeling has identified this reach as having some of the greatest potential for "unrestrained" (i.e., with no bank armoring or revetments) migration, and a moderate potential for movement even with the existing bank armoring (Figure 5.2, left). This tendency, however, has been confounded by the extreme widening that has occurred along the left (i.e., east) bank

(Figure 5.2 right), likely a consequence of visitor use during the pre-1997 period when Lower Pines campground extended into this area.

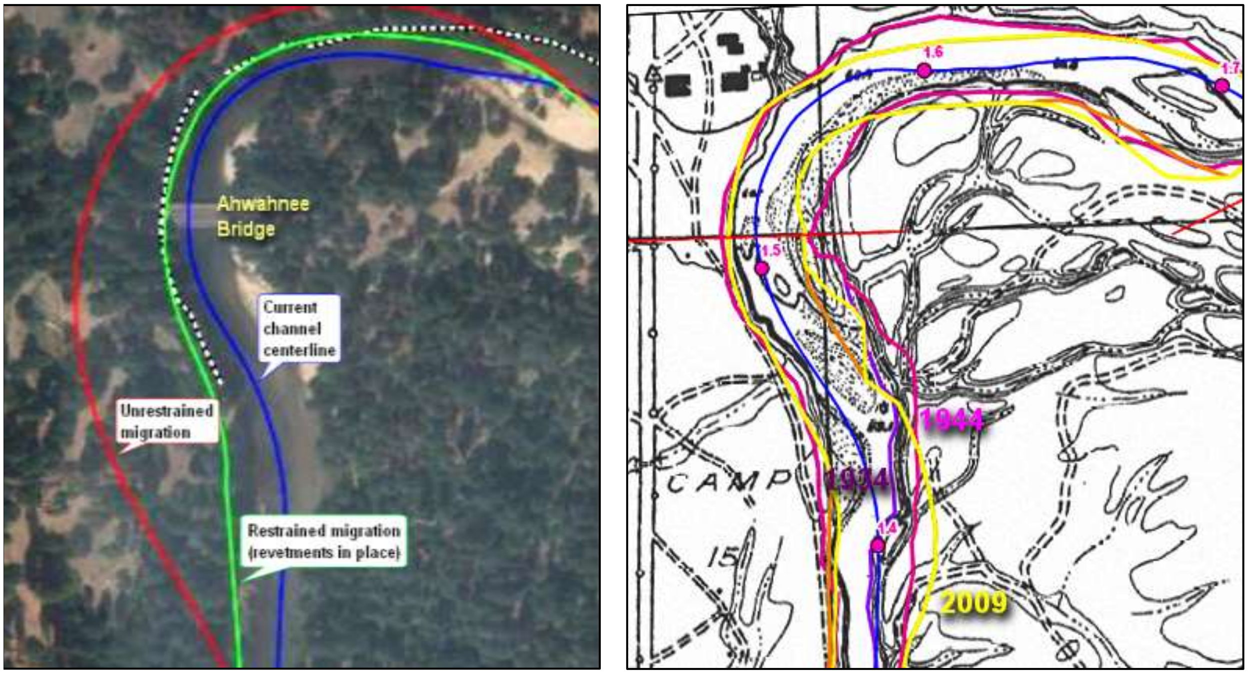

Figure 5.2. Modeled (left) and historical (right) patterns of channel migration downstream of Ahwahnee Bridge. This locality shows the greatest disparity between the “unrestrained” and “restrained” model simulations (red and green channel centerlines in the left panel); and, in fact, the actual changes in channel boundaries (right panel) have been even more strongly influenced by widening due to visitor use. Note the abundant, now-relict swales crossing the peninsula of land between Reach 7 and Reach 5 on the 1919 topographic base of the right panel.

This reach is well-suited to bioengineered treatments to stabilize banks and re-direct flows, with the goals of reversing the historical trends in channel widening, local bridge-induced scour, and simplified channel morphology. Although the predictions of the migration modeling and the lack of critical infrastructure or roads west of the channel would both encourage the removal of bank constraints in this area, these considerations are rendered moot by the extreme widening that has occurred here over the past century, involving erosion along both sides of the channel. To address this acute impact, two restoration projects have been recently constructed with the objectives of narrowing the channel and reinforcing the banks to allow riparian vegetation to reestablish more structurally diverse and robust margins. The first restoration project based on these recommendations was constructed along the right bank at RM 1.4 in 2016 (treatment 5-5); the second along the left bank in 2017 (treatment 5-4; Figure 5.3). Both are visible from Ahwahnee Bridge (Figure 5.4); a similar, third project that will also replace an extent of barren rock riprap is planned for the left bank just upstream of Stoneman Bridge in 2019 (treatment 5-3), with an additional site identified for future implementation where the floodplain swales from Reach 7 return to the mainstem channel (treatment 5-7). Other potential treatments include extensive riparian revegetation and management of visitor access (5-1, 5-2, 5-8), and more intensive efforts to increase in-channel diversity (5-6).

Figure 5.3. View downstream from the upper end of Project 5-4, one year after initial construction. Stoneman Bridge in the far distance, with the riprap to be replaced by Project 5-3 also visible just upstream.

Figure 5.4. View downstream from the left end of Ahwahnee Bridge. Much of Project 5-4 visible along the left bank of the river; the upstream end of Project 5-5 is also visible along the right bank.

Reach 4 (Stoneman Bridge to Housekeeping Camp footbridge; RM 1.22–0.85)

As with Reach 6, nearly all of this reach is bounded on one side (here, the left bank) by high terraces and talus shed off the northeast face of Sentinel Dome. The natural tendency for additional channel migration towards the outside of the broad bend that constitutes this reach is therefore geologically constrained, but the proximity of Southside Drive and Housekeeping Camp makes problematic even this limited migration potential. Immediately downstream of Stoneman Bridge, local scour at least 16 feet deep[(Mr)] and heavy visitor use has resulted in a broadly over-widened channel (Figure 4.1), with a downstream channel form whose expansion has led to a relatively featureless channel with some significant sand deposition along its margins (Figure 4.2). Along the right bank just downstream of Stoneman Bridge, the Lower River campground once occupied the adjacent terrace, requiring riprap bank armoring and encouraging visitor traffic throughout the riparian zone. Campground and riprap removal occurred in 1991, although channel expansion downstream of the bridge-induced constriction has continued to occur.

Figure 4.1. Downstream face of Stoneman Bridge, with a view of the heavily impacted left-bank river access area.

Figure 4.2. View downstream from Stoneman Bridge in a zone of substantial channel widening. The armored bank below Housekeeping Camp visible in the far distance.

Towards the downstream end of this reach, Housekeeping Camp sits above the steep outer (left) bank on talus and alluvial-fan deposits well above both the modern and historical floodplain. The inside of this bend is occupied by an extensive sand and gravel bar, well-trafficked by visitors but largely inundated and reworked by 5- to 10-year (and larger) floods. Meander modeling shows that this area is second only to Reach 5 in the tendency for the channel to shift position towards the outside of the bend, and so a robust rock riprap had been installed to protect Housekeeping Camp; it has been replaced by bioengineered bank protection (as of autumn 2018) to improve the condition of the riparian zone and near-bank channel conditions while maintaining protection for the infrastructure above (treatment 4-3; Figure 4.3).

Figurer 4.3. Upstream view of the Housekeeping Camp riprapped embankment in 2015 (left) and during construction of Project 4-3 in 2018 (right).

Overall, this reach has been substantially impacted by human activity, and so the restoration needs and opportunities are similar to, but more extensive than, many of the reaches farther upstream. These include improving a riparian zone that presently displays reduced structural complexity, species diversity, and functionality (treatments 4-2, 4-6); and the variety of active streambank erosion (treatments 4-1, 4-4, 4-5), substantial channel widening (treatment 4-7), and locally extensive riprap along the left streambank (treatment 4-1, 4-3, 4-8). Hardened river access could encourage recreation use with minimal riparian impacts in some areas close to roads and (particularly) Stoneman Bridge (treatment 4-8), an area that has already seen improvements in 2006 to focus visitor activity and protect the rest of the riparian zone[C12]. Along the right bank, well-established trails already provide access from the Housekeeping Camp footbridge to the large and relatively resilient point bar, although much of the right-bank riparian zone on either side of the bar is also impacted and would benefit from restoration. Regrading, pine tree removal, and replanting with native riparian species plantings within the floodplain would enhance the riparian corridor on the right streambank and floodplain; more intensive engineered structures along the left streambank have already been implemented to enhance channel and riparian conditions while protecting valuable infrastructure.

Reach 3 (Housekeeping Camp footbridge to Housekeeping Camp beach; RM 0.85–0.35)

In contrast to immediately upstream, this reach is presently among the least constrained through the Study Area, with no riprap and only limited areas of log-stabilized banks. It is also one of the most dynamic and well-connected with its modern floodplain, particularly at its downstream end as the river passes through an "S-bend" with a well-developed inner point bar (Figure 3.1) and frequently occupied side channels that allow significant off-channel flow. Meander modeling indicates that the larger of these channels is a favored location for future avulsion of the river.

This reach is not without its human impacts, however; the extension of Housekeeping Camp along much of the left bank has resulted in a broadened channel with a degraded riparian zone along the upper half of the reach (Figure 3.2). Although Housekeeping Camp footbridge does not dramatically narrow the channel[Mr], a rock sill beneath it has limited natural adjustment of the riverbed and resulted in a prominent downstream scour hole and likely interruption of downstream sediment transport. Immediately downstream of the footbridge, riprap once armored the right bank but was removed and replanted in 1992; an area of additional riprap removal on the left bank occurred in 1995[C12].

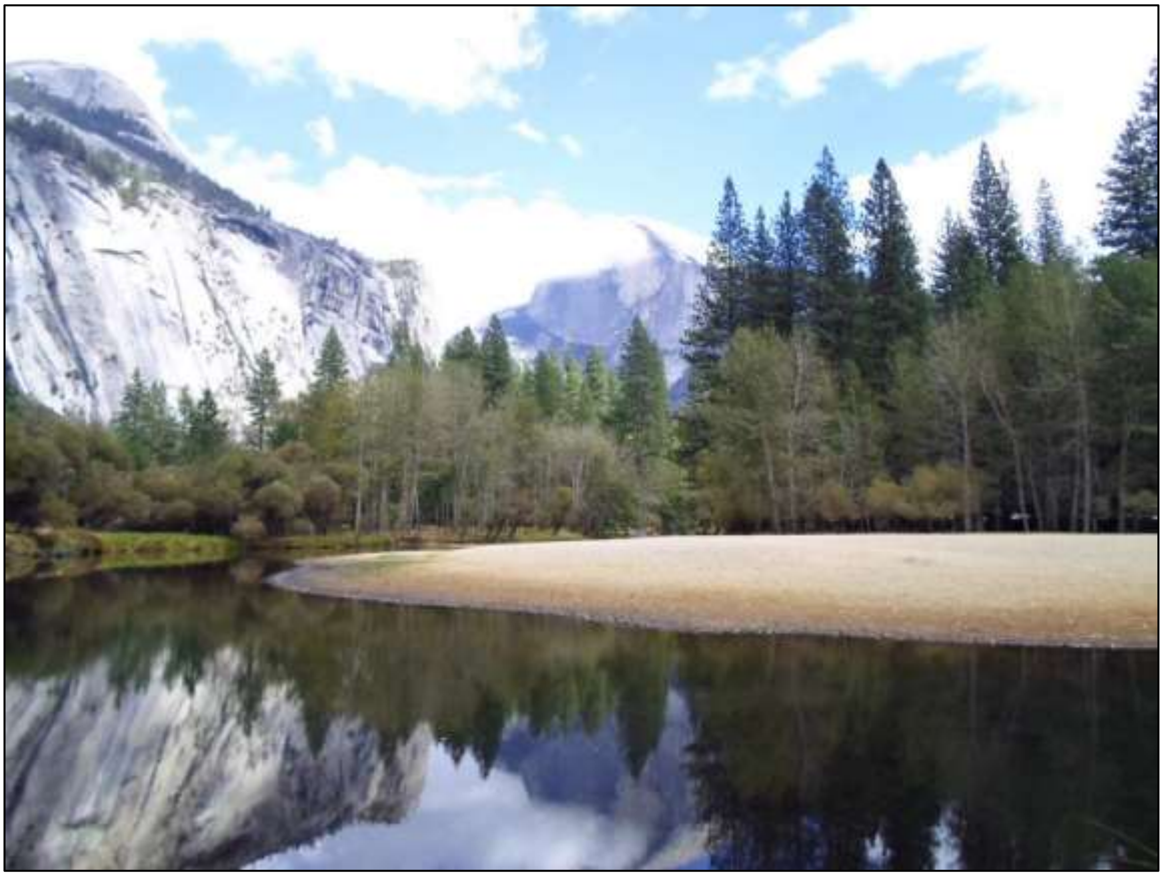

Figure 3.1. The informally named "Housekeeping Camp beach," located on the inside bend below the camp and well-used by visitors during much of the year.

Figure 3.2. View upstream towards Housekeeping Camp footbridge, displaying the widened and simplified channel upstream of the S-bend in the river.

Restoration needs within this reach result from localized streambank erosion from visitor use along the upper half of the reach, particularly along the left bank adjacent to Housekeeping Camp, and a partly disconnected floodplain. To address localized areas of bank erosion, bank reconstruction with vegetation plantings and access management would help stabilize them (treatments 3-1, 3-2, 3-6). Left-bank visitor traffic could be directed to the relatively resilient Housekeeping Camp beach (where most usage in this reach already occurs); right-bank traffic is lighter and could be even more restricted to allow riparian restoration to proceed, particularly where the river most closely approaches the main Village parking area (treatment 3-4).

Opportunities for extensive floodplain reactivation are present along the right bank at the downstream end of the reach, where high-flow side channels are currently active episodically (treatment 3-3). Migration modeling suggests that they may be future avulsion sites with or without additional management efforts, providing the potential expression of natural channel dynamics in an area where park infrastructure is sufficiently set back to run little risk of impact. An additional opportunity to reconnect a historical channel position, now a rarely inundated swale, is present mid-reach along the right bank (treatment 3-5).

Reach 2 (below Housekeeping Camp beach; RM 0.35–0.19)

The Merced River is moderately constrained throughout most of this reach, particularly along the left (south) bank by the steep north face of Sentinel Dome. On the right bank it has only locally carved into the same terrace that boarders the modern channel upstream to Tenaya Creek, and which also forms the surface now hosting the iconic meadows of Yosemite Valley. Formerly the active floodplain of the Merced River, channel incision has now rendered this surface too high above modern river level for frequent inundation. The channel through this reach has been virtually stable for the last 80 years, although meander modeling highlights the tendency of the channel to erode its left bank as it emerges from the S-bend of Reach 3, particularly if the potential upstream avulsion pathway were ever occupied. As a result, the Southside Road is protected by near-continuous armoring in this area (Figure 2.1), constituting the longest extent of continuous bank armoring in the entire Study Area[C12].

Figure 2.1. Riprap along the left bank of the river, adjacent to the Southside Road.

Issues within this reach include a riparian corridor along the left streambank with reduced structural complexity, species diversity, and functionality; stormwater runoff from the adjacent road that flow into the river channel, causing streambank erosion and reducing water quality; and prior fill placement along the right floodplain. Stormwater pretreatment would reduce localized erosion and improve water quality (treatment 2-3). Removal of non-native fill, re-contouring of the topography, and native vegetation planting along the right floodplain and streambank would enhance the quality of the riparian corridor (treatment 2-1), particularly where the overflow channel from Reach 3 reenter the mainstem river (treatment 2-2). Although the left streambank riparian corridor is also confined and degraded, the need to protect Southside Drive limits the degree to which additional benefits to river functions and ecology can be implemented to address impacts there (treatment 2-4).

Reach 1 (upstream of Sentinel Bridge; RM 0.19–0.00)

In this reach, the bedrock valley turns to the southwest while the river continues west, and so the Southside Road has room to recede from the river's left bank to provide some additional space for a riparian zone. Along the right bank, an extensive area of recently active floodplain forms several acres of low-lying ground, the site of a meander bend carved into the adjacent terrace (and then abandoned, some time prior to the 1919 topographic map). The active channel has further narrowed in this area since 1934, although just upstream the same style of channel widening from degraded banks, as seen throughout the Study Area, has also occurred here.

Figure 1.1. Upstream view, from 200 yards upstream of Sentinel Bridge. Road-protecting riprap of Figure 2.1 visible in the middle distance; low floodplain area expressed along the left-hand edge of the photograph.

Issues within this reach include unstable streambanks caused by visitor traffic, a locally widened channel, armored banks adjacent to Sentinel Bridge (which was replaced in 1994), and a riparian corridor with reduced functionality and structural complexity. To alleviate erosion caused by recreation use, limited river access and riparian buffer enhancement with fencing would reduce recreation access within this relatively fragile riparian zone (treatments 1-6, 1-8), particularly the low-lying right-bank floodplain area (treatment 1-3). Bioengineered protection of the bridge abutments would stabilize the streambank while enhancing the riparian corridor (treatments 1-1, 1-2); additional such treatments would be beneficial along much of the upstream left bank of the river in this reach (1-7). Improved in-channel complexity, lacking here and throughout these lower reaches of the Study Area, could be achieved through a combination of mid-bar-forming engineered log features and more extensive lowering of the right streambank to expand the area of floodplain reconnection (1-4, 1-5).

REFERENCES

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., Pollock, M.M. 2010. Process-based principles for restoring river ecosystems. BioScience, 60 (3), pp. 209-222.

Booth, D.B., Ross-Smith, K., Larsen, E., Mahacek, V., Haddon, E. and Dunne, T. 2018. Restoration of the Merced River through Yosemite Valley, Yosemite National Park. June 30th, 2018. Unpublished report, 51 pp.

Cardno, Inc. 2012. Final Report – Merced River and Riparian Vegetation Assessment: Yosemite National Park. Prepared for Yosemite National Park Division of Planning. June 2012. Unpublished report.

Cardno. 2016. Merced River Riparian Corridor Restoration in Yosemite Valley – Restoration Concept Designs. Prepared for The University of California, Santa Barbara, Californian Cooperative Ecosystem Studies Unit. March 2016.

Kondolf, G.M. 2011. Setting goals in river restoration: When and where can the river "heal itself"? Geophysical Monograph Series, 194, pp. 29-43.

Madej, M.A., W.E. Weaver, and D.K. Hagans. 1991. Analysis of bank erosion on the Merced River, Yosemite Valley, Yosemite National Park. National Park Service files, Yosemite National Park, CA. Unpublished report.

Minear, J. Toby, and Wright, Scott A. 2013. Hydraulic and Geomorphic Assessment of the Merced River and Historic Bridges in Eastern Yosemite Valley, Yosemite National Park, California: Sacramento, California, United States Geological Survey, Open-File Report 2013-1016, 74 pp.