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RESEARCH ARTICLE

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Opportunities and challenges for restoration of the Merced River through Yosemite Valley, Yosemite National Park, USA

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Abstract

Successful river restoration requires understanding and integration of multiple disciplinary perspectives, including evaluations of past and ongoing watershed processes, local geomorphic response, and impacts unique to human activity. Nowhere is this more apparent than along the Merced River in Yosemite National Park, USA, where both an outstanding natural landscape and the consequences of over a century of human disturbances continue to interact. An intact upstream watershed highlights the importance here of local impacts on geomorphic response. Incision and the resulting decoupling of the channel from its adjacent late-Holocene floodplain are consequences of reduced channel roughness, likely from de-snagging the river, and instream gravel mining in the 19th and early 20th century. Riparian-zone disturbance by visitor use has damaged riparian vegetation and soils, inducing channel widening. Revetments and channel-spanning bridges, the latter being visible and oft-cited impacts to fluvial processes, have distorted the natural evolution of meanders and induced local channel narrowing. The historical rate of sediment export from Yosemite Valley has greatly exceeded replenishment from upstream and lateral sources, creating a deficit that now inhibits recovery via passive restoration of more natural channel form and function. Climate change may amplify now-diminished fluvial processes but also exacerbate the rate of sediment export. These conditions, reflecting a complex intersection of geologic history, modern geomorphic processes, and human interactions, demonstrate how a limited influx of sediment coupled with intensive human use can have long-term consequences for riverine conditions, restoration opportunities, and social engagement with the riverine landscape.

KEYWORDS
incision, riparian, river restoration, sediment supply, Yosemite National Park

1 | INTRODUCTION

1.1 | Study area

The Merced River flows through the heart of Yosemite Valley in Yosemite National Park, USA (Figure 1), one of the most iconic and recognizable landscapes in the world. Its headwaters lie along the crest of the Sierra Nevada, comprising three main branches (Tenaya Creek, Illilouette Creek, and the Upper Merced River) that descend from nearly 4,000 m elevation to join at the upstream end of Yosemite Valley. The mainstem Merced River enters the Valley with a drainage area of nearly 600 km^2 of protected and now largely undisturbed wilderness.

Once the Merced River emerges from its high-elevation reaches, it rapidly transitions to become a low-gradient meandering alluvial

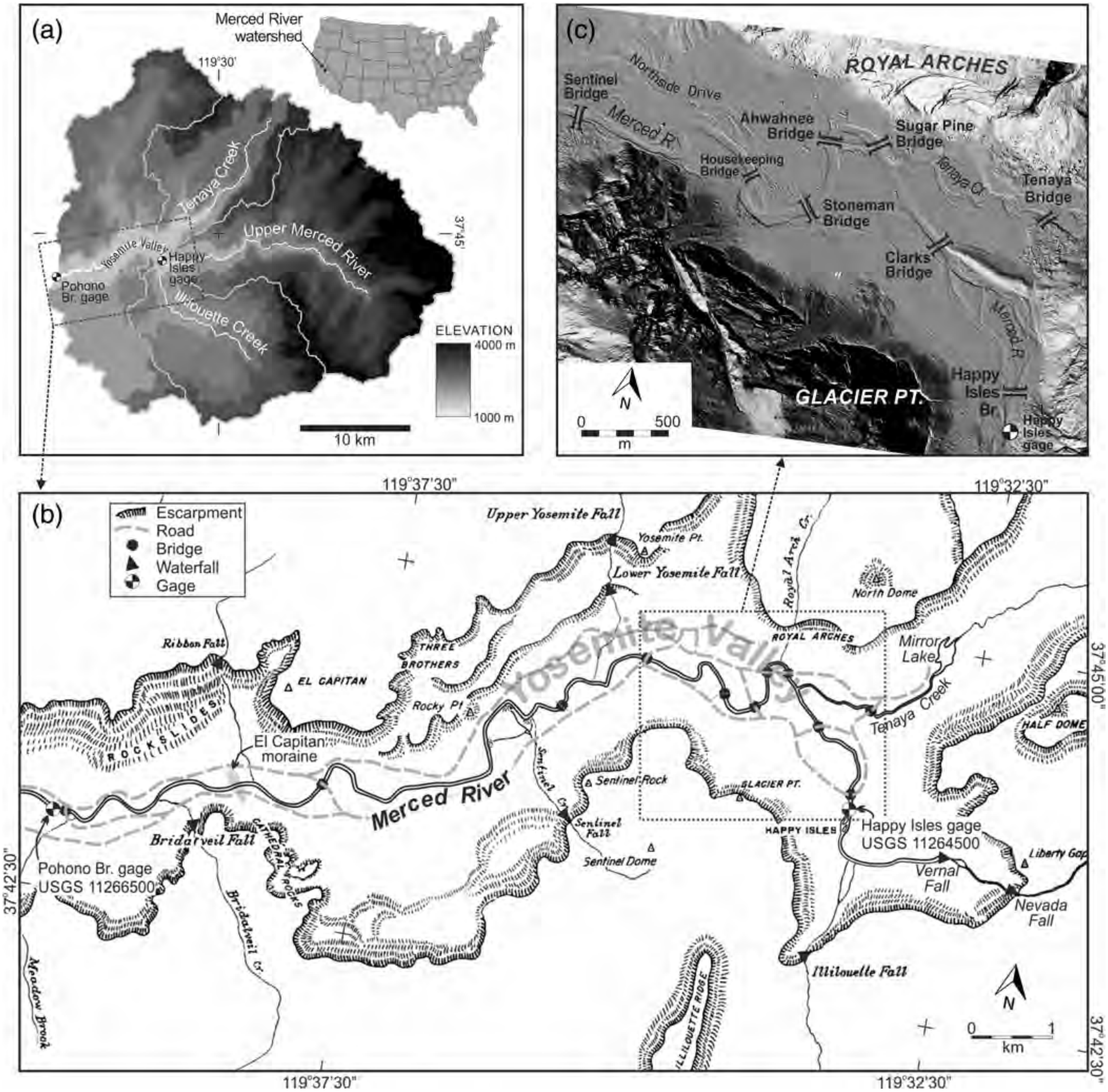

FIGURE 1 Index map of the Merced River watershed (a), Yosemite Valley (b), and the present Study Area (c). The drainage areas of the three major tributaries are 121 km^2 (Tenaya Creek), 159 km^2 (Illilouette Creek), and 469 km^2 (Merced River at Happy Isles gage #1264500)

river in Yosemite Valley. Here the river crosses beneath 10 pedestrian and automobile bridges over the next 14 km (Figure 1b) through the most intensively developed portion of Yosemite Valley (Figure 1c). The 5-km reach of the river between Happy Isles Bridge and Sentinel Bridge, which constitutes our "Study Area," includes segments flanked both by minimally impacted riparian zones and by severely impacted banks, armored with riprap or trampled by some of the 4 to 5 million visitors who visit the Park every year.

The origin of Yosemite Valley was first described by Matthes (1930), who documented multiple glacial advances and retreats in this part of the Sierra Nevada range that ultimately carved the present-day topography. Upon this geologic template, human activity has imposed other influences on the river, particularly in Yosemite Valley where the majority of visitors congregate and infrastructure has been most developed. Correcting the consequences of those activities on the Merced River requires not only characterizing their expression, but also understanding the constraints and opportunities afforded by the Valley's geologic history and the resulting landforms and deposits, vegetation communities, and the river's geomorphic responses. Ignoring either dimension—the biophysical context or subsequent human impacts—will preclude successful restoration (Naiman, 2013).

1.2 | Historical manipulations of the Merced River

Nearly two centuries of recent human activity has severely impacted both the channel form and the geomorphic processes within the fluvial environment of Yosemite Valley. The modern-day channel has incised to a level where its adjacent floodplain is inundated only infrequently; long segments have been armored on one or both banks by riprap or constrained by bridges; and where not armored, the channel has widened with indistinct channel boundaries flanked by damaged riparian zones. The result is an "ecologically simplified" river (Piepoch et al., 2015), one where the complexity of the riverine landscape has been compromised by extensive, ongoing impacts.

Prior workers have documented multiple dimensions of these human impacts. Milestone (1978) identified five significant riverine impacts, based on historical records and photographs:

- The El Capitan moraine (Figure 1b), which controls the river's local base level in western Yosemite Valley, was breached with explosives in 1879 to reduce seasonal flooding (see also Huber, 2007). This lowered the base level by about 1.5 m, with declining influence for the next 6–7 km. This effect is virtually imperceptible, however, at Sentinel Bridge, 8 river km upstream and the downstream limit of our Study Area.
- Instream gravel was mined extensively in the late 19th and early 20th centuries (15,000 m^3 recorded, with presumably much more actually removed).
- Logs and stumps were aggressively cleared from the channel, leaving a simplified, unobstructed river as of 1899 in contrast to reports of abundant log jams as late as 1877. These efforts apparently continued as established Park policy through at least the mid-20th century, and they continue to the present day in more limited fashion in reaches frequented by rafters.
- Trampling of river banks adjacent to riparian-zone campgrounds was noted in 1964, when annual visitation was barely one-third of today's numbers.
- Confinement of the river by bridge crossings was documented by comparing "unconstrained" channel widths (defined as the measured width several tens of meters upstream of a bridge) with the narrower opening of the bridge immediately downstream. Confinement was more than 50% for Stoneman Bridge and nearly as great for Clarks, Sugar Pine, Sentinel, and Pohono bridges (see Figure 1).

Madej, Weaver, and Hagans (1991) compared measurements of channel width made in 1986 and 1989 with USGS topographic maps from 1919, documenting both pervasive channel widening, particularly in areas with much bare ground associated with high human use, and channel constrictions associated with the bridges. More recently, Cardno (2012) inventoried channel and riparian conditions throughout the Valley. They documented a steady increase in channel width throughout the second half of the 20th century and little change in overall channel planform, and they reiterated that the primary stressors to the geomorphic functioning and ecological health of the river are human use of the riparian zone and structural confinement from infrastructure and revetments. In addition, a detailed hydraulic model was developed by Minear and Wright (2013) to explore the hydraulic effects of the existing bridges.

1.3 | Study motivation and purpose

Multiple challenges face efforts to restore the Merced River to more natural conditions. Prominent among them are (a) the geologic setting of Yosemite Valley and the Merced River watershed, wherein slow rates of sediment delivery attenuate the river's response to changes in its alluvial regime; (b) the magnitude and persistence of anthropogenic manipulations associated with high visitor use and valley-bottom infrastructure, but which does not include any type of flow regulation; and (c) constraints imposed by other, non-geological "outstandingly remarkable values" (ESA Inc., 2012), such as those associated with scenic viewpoints or cultural resources, which motivate additional (and sometimes contradictory) management objectives.

The purpose of this study is to characterize the nature and underlying causes of river impairment, and to use that characterization to guide a restoration program to reverse those impacts over time. This requires understanding of the "process drivers" of fluvial form and process, particularly geology, climate, and land use (Buffington, Woodsmith, Booth, & Montgomery, 2003); how these process drivers are expressed in the age, morphology, and composition of floodplain and channel sediments; and the response of the river over time to episodic floods, to long-term shifts in climate, and to impacts from human activity. The restoration guidance here results from the findings that the Merced River is locally impacted but lies within a broader watershed in which supporting hydrologic and geomorphic processes remain virtually intact. Reversing those local impacts should achieve the oft-stated goal of allowing a river to "heal itself" (Beechie et al., 2010; Kondolf, 2011). However, we seek more specificity to this overarching principle to advance restoration of the Merced River in Yosemite Valley.

2 | METHODS

2.1 | Field investigations

We surveyed the physical condition of the stream channel, banks, floodplain, and terraces between Happy Isles Bridge and Sentinel Bridge during multiple visits in summer and autumn from 2015 through 2018, supplemented with information from earlier reports and unpublished materials. Bank conditions measured at 20-m intervals included bank shape, bank sediments, and relative degrees of bare, armored, and vegetated surfaces. We identified human-impacted areas by bank-stabilizing rock or having barren, compacted soils from pedestrian traffic (or both).

Terrace heights relative to the low-water surface and/or channel bed were recorded at approximately 200-m intervals and wherever notable change occurred. These measurements were supported by analysis of 2006 and 2010 aerial LiDAR surveys of the entire Valley. We also traversed the channel network upstream of the Study Area to identify the dominant sources of bedload-sized sediment being delivered to the Merced River.

We determined the types and ages of geologic materials, particularly the variety of terraces surfaces, through multiple field visits to examine surficial materials, natural outcrops, and shallow hand-dug test pits. Determining terrace ages was judged essential to distinguish natural postglacial fluvial adjustments from more recent responses to anthropogenic disturbance. Organic material for radiocarbon dating was collected in the field and dated using accelerator mass spectroscopy (AMS) by International Chemical Analysis Inc., Miami, FL, USA. All radiocarbon ages were converted into calibrated ages with OxCAL using the IntCal13 calibration curves (Reimer et al., 2013). Samples for optically stimulated luminescence dating (OSL) were collected with an auger and hand-packed into opaque PVC tubes for delivery to the US Geological Survey Luminescence Laboratory in Denver, CO. Samples were processed following Murray and Wintle (2000).

We assessed vegetation throughout the riparian zone through mapping of the dominant woody species and age classes within 30 m of the river channel. 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) (Table 1).

2.2 | Channel locations

We characterized the size and position of the past and (projected) future Merced River channel through multiple means. Channel widths between 1919 (the first USGS topographic map) and 1977 were compiled by Milestone (1978), with an additional decade of data added by Madej et al. (1991). Channel positions through 2011 were compiled from old maps and airphotos by Cardno (2012) into GIS; both widths and positions were subsequently updated by additional airphotos through 2018 for the present study.

We applied a meander migration model (Larsen, Girvetz, & Fremier, 2006; Micheli & Larsen, 2011) to predict the general configuration and trajectory of future channel positions to better understand the river's natural and constrained patterns. The model is based on simplified forms of equations for fluid flow and sediment transport developed by Johannesson and Parker (1989), whose results are determined by the initial channel planform location and five reach-averaged input parameters: a single "characteristic" discharge (Q_2 at the Pohono Bridge gage [see Figure 1b], presumed to adequately integrate the geomorphic work accomplished by all flows), the median particle size of the bed material (10 mm, from Madej et al., 1991), and key channel parameters (width, depth, and slope, averaged from data by Madej et al., 1991 and Minear & Wright, 2013). Measured changes in channel position over time, needed for model calibration, were derived from maps from 1870 and 1883, an interval with no bank armoring or other known migration restraints. This period was unfortunately brief in duration, but the model-predicted spatial trends in bank erosion rates and resulting bend migration based on this calibration should be representative of the long-term patterns. Model runs with and without extensive artificial revetments evaluated the potential consequence of these constraints on the future trajectories of channel position.

TABLE 1 Vegetation categories used in the riparian-zone mapping

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

3 | FINDINGS

3.1 | Geology of Yosemite Valley

Geologic history and processes set the physical template for the river corridor, reveal the undisturbed pre-anthropogenic behavior of the river, and help to anticipate the river's response to future manipulations and climate change. The modern landforms of the Yosemite Valley floor are primarily created through two processes—the lateral delivery of sediment from the steep bedrock walls, contributed primarily by episodic rockfalls and debris-flow fans built by the tributary channels (e.g., Wieczorek & Jäger, 1996); and the downvalley transport and deposition of sediment by the Merced River. The river emerges from the primary influence of coarse-grained 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 valley-wall deposits (Figure 2).

Dated fluvial sediments and landforms in the Study Area (see Haddon et al., 2017) document mainly aggradation during the late Pleistocene, characterized by a stratigraphic sequence of valley-bottom glacial till overlain by mass-wasting deposits, fluvial sand and gravel, and localized lacustrine silts. The predominantly depositional

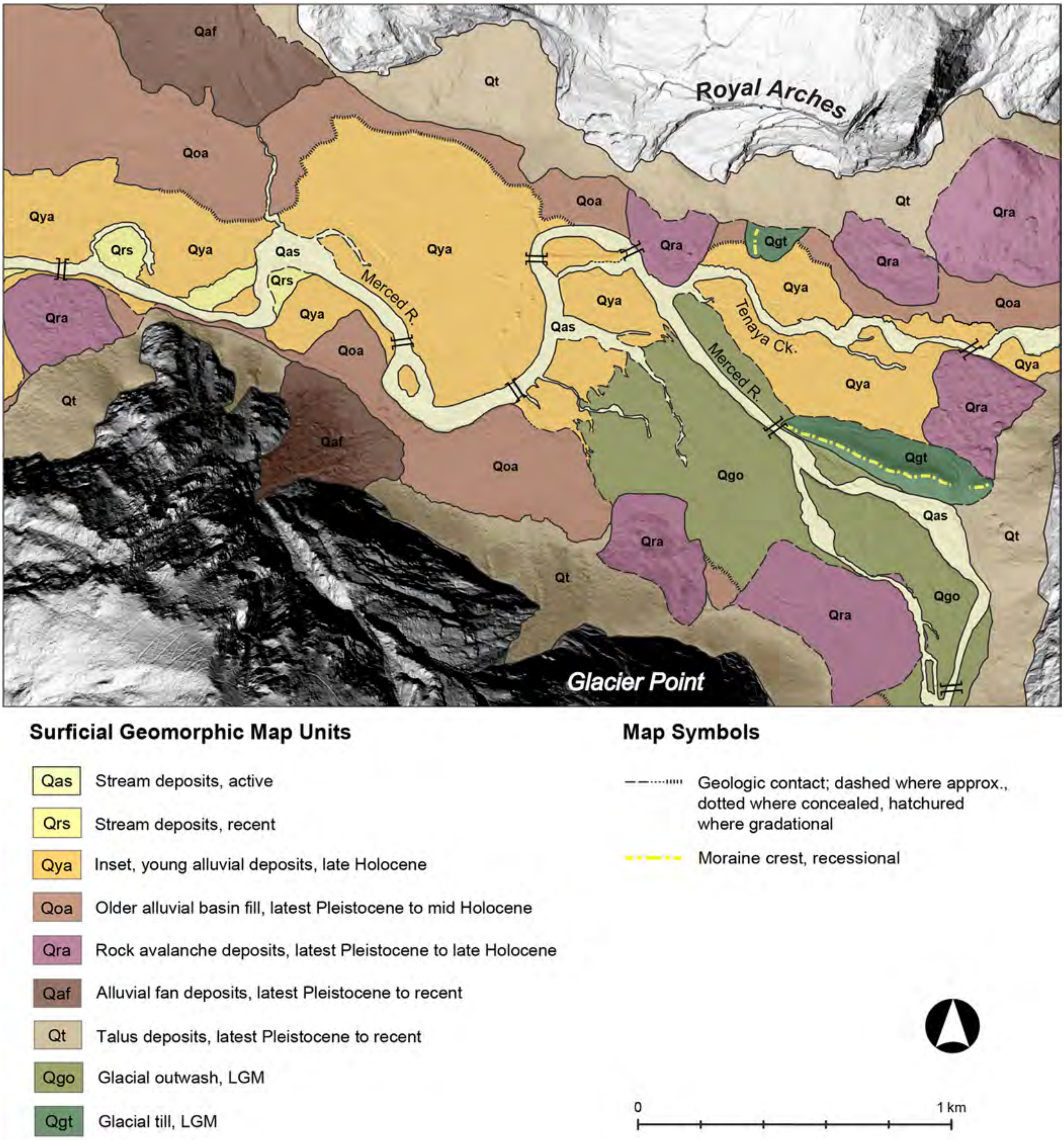

FIGURE 2 Geologic map of the Study Area (simplified from Haddon, Stock, & Booth, 2017) [Color figure can be viewed at wileyonlinelibrary.com]

regime shifted to incision in the first half of Holocene, with subsequent cycles of fluvial incision leaving a flight of terraces across the valley bottom, with the modern river inset by up to ~9 m. Although some of these periods of incision likely record changes in local base level within Yosemite Valley itself associated with glacier retreat and terminal moraine incision, well-developed outwash terraces also present below the maximum downvalley extent of glacier ice suggest that the temporal variability of incision has a more widespread underlying cause (likely climatic).

The most prominent, widespread valley-bottom feature is a terrace of fluvial sand and gravel with a surface typically 2–2.5 m above the modern summertime baseflow of the river through the Study Area (unit Qya of Figures 2 and 3), and on which most of the Valley's iconic meadows have developed. This surface is still a zone of active deposition, at least episodically. The oldest date from this sediment is 4.65 ± 0.36 ka (preliminary quartz OSL age; S. Mahan, USGS, pers. comm. 2020) from a sample at a depth of 1.8 m below the surface, along the south bank just downstream of Sentinel Bridge; the youngest sediment dates to the late 19th century (AMS) from a depth of 0.72 m, also along the south bank about 2 km downstream of Sentinel Bridge. This surface has thus been a persistent feature of the fluvial landscape, almost certainly its active floodplain for much of at least the last several thousand years, but more recently removed from regular inundation by virtue of increased channel–terrace relief.

3.2 | Floodplains and terrace surfaces

The alluvial deposits of the 2–2.5 m surface through the Study Area (unit Qya) require floods with recurrence intervals exceeding about 5 years to initiate inundation. One hundred years ago, however, they were activated more than twice as frequently (Minear & Wright, 2013; Figure 4, upper panels). Even this comparison understates the magnitude of change since pre-disturbance times, because significant impacts to the channel had already occurred by the time of the 1919 topographic map. Prior to any significant human disturbance this surface would have been even more active geomorphically, experiencing frequent (likely annual to biannual) inundation typical of temperate-latitude alluvial floodplains. Subsequent widening and incision have thus converted the 2–2.5 m surfaces into geomorphic features more akin to upland terraces than active floodplains. During the largest multi-decadal floods they continue to be inundated, however, and to approximately the same spatial extent as in 1919 (Figure 4, lower panels), indicating that morphological changes caused by such floods are largely limited to increased flood capacity in the channel and not widespread terrace aggradation.

3.3 | Sediment sources

Relative to continental and global norms, the sediment load of the Merced River is unusually low for a drainage basin of its size (e.g., Syvitski & Milliman, 2007) because of the resistant nature of Sierran granites to weathering and erosion, and because Pleistocene glaciers removed most weathering products from hillslopes and left only small deposits of loose glacial sediments. Unusual even among Sierran watersheds, however, much of the upper watershed is also disconnected from Yosemite Valley by the stairstep topography above the Study Area. Along the mainstem river, 3 km of near-zero-gradient channel through Little Yosemite Valley, above Vernal Fall and Nevada

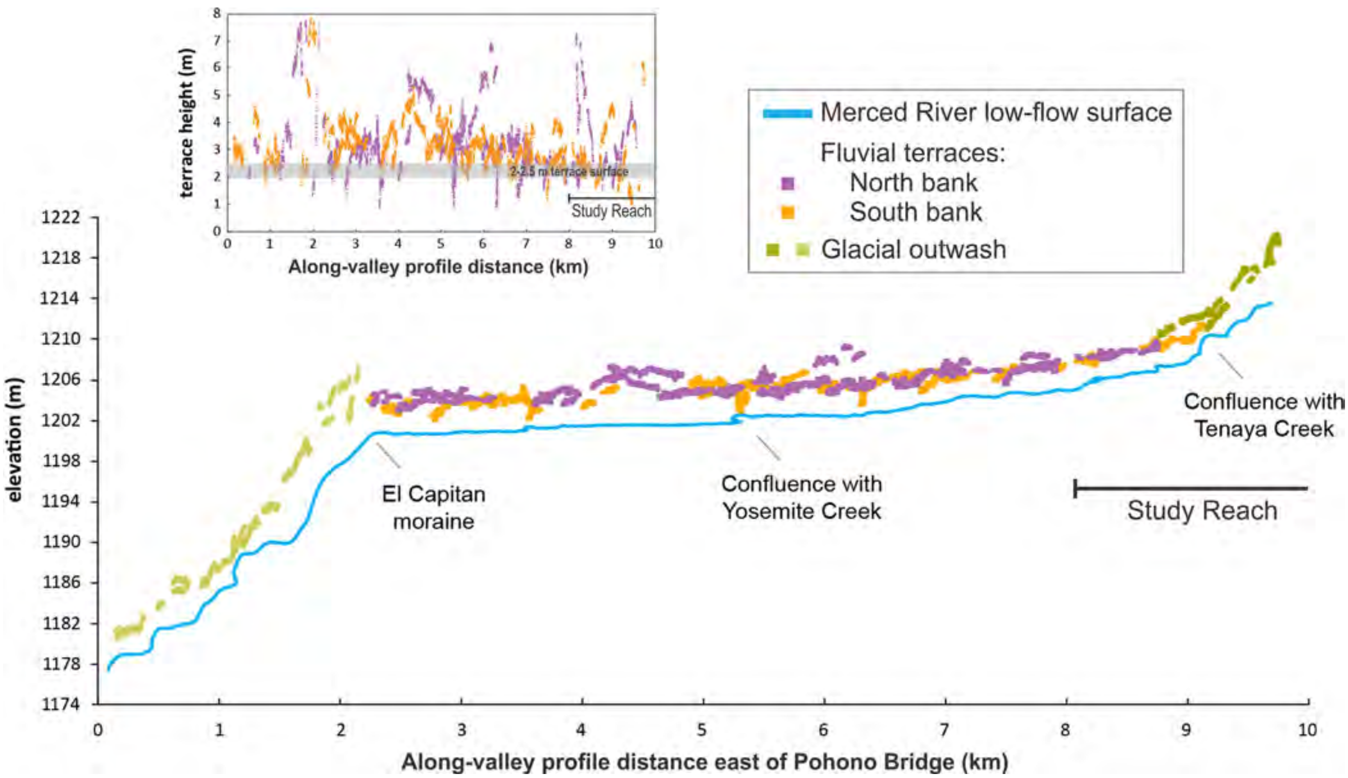

FIGURE 3 Terrace levels adjacent to the Merced River, from Pohono Bridge (left side of the graph) upstream to Clarks Bridge (simplified from Haddon et al., 2017). The x-axis measures distance along the valley axis (not along the river channel itself); the river profile (blue line) approximates the low-water surface when the LiDAR was flown in 2006. Below km 6.5, the "2-2.5 terrace surface" appears to lie at a consistently higher relative elevation, suggesting legacy expression of El Capitan moraine lowering [Color figure can be viewed at wileyonlinelibrary.com]

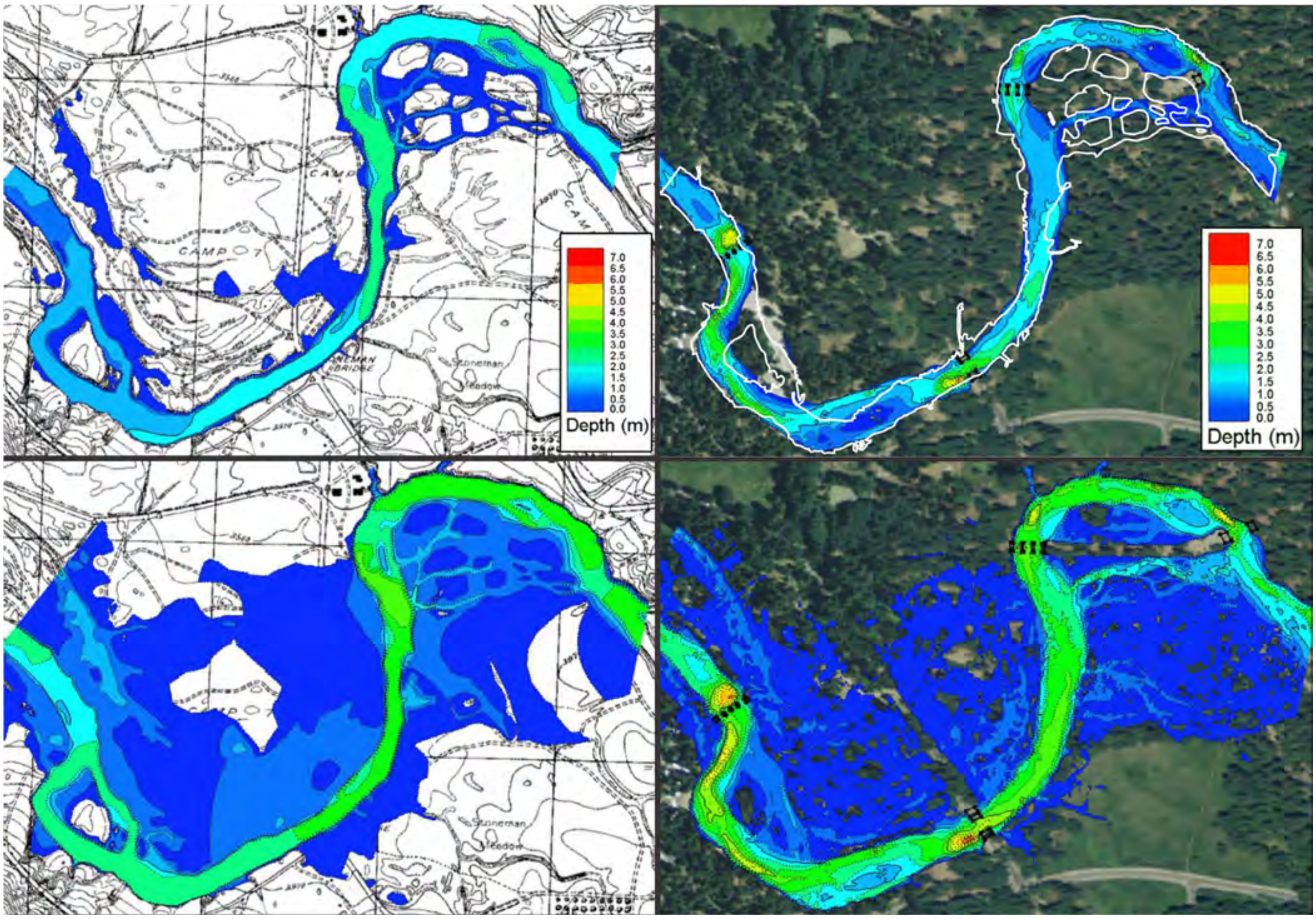

FIGURE 4 Hydraulic model projections (modified from Minear & Wright, 2013) of floodplain/terrace inundation. Top left, 2-year flood using the 1919 channel and floodplain geometry. Top right, near-equivalent inundation at a 5-year flood using modern topography (white outlines the extent of the 1919 2-year channel, from the left panel). The 5-year discharge is nearly 60% larger but it now inundates a similar area because it flows in a channel that averages 27% wider (Madej, Weaver, & Hagans, 1994) and about 20% deeper through this reach than in 1919. Bottom panels show floodplain/terrace inundation during the 20-year flood (about 70% greater discharge than the 5-year flood shown above), overlaying that discharge on the 1919 topography (bottom left) and the modern topography (bottom right). Except for the recent road fills, the extent of floodplain/terrace inundation is nearly identical, indicating that sufficiently large flows overwhelm any differences in channel capacity between the two scenarios [Color figure can be viewed at wileyonlinelibrary.com]

Fall, present a near-insurmountable barrier to the downstream transport of coarse sediment. Landslide-dammed Mirror Lake similarly traps coarse sediment along Tenaya Creek (Figure 1).

Just upstream of the Study Area, Illilouette Creek joins the Merced River and provides the first substantial input of coarse sediment as the river enters Yosemite Valley, marking an abrupt and dramatic change in river morphology and sediment delivery. Upstream of the confluence with Illilouette Creek, the river channel is nearly devoid of bed material, with the sediment load overwhelmingly composed of 1- to 4-m angular blocks delivered to the valley bottom by rockfalls; immediately downstream, abundant gravel-sized rounded clasts delivered from Illilouette Creek line the bed of the river channel and form extensive bars. The channel gradient changes dramatically across this confluence—upstream, the Merced River is descending at a gradient of about 2%; downstream, it steepens abruptly to about 8%. Downstream from this confluence through the full extent of the Study Area, the gradient of the river progressively flattens and the bed sediment sizes also decline monotonically (Figure 5), reflecting not only the declining competence of the river but also the lack of significant lateral inputs of sediment in the gravel-to-boulder range (including Tenaya Creek).

Despite this discrete source of coarse sediment, a sediment budget demonstrates that the reworking of Holocene floodplain and terrace deposits, through bank erosion and channel expansion, ultimately provides most of the river's bedload sediment load. Andrews (2012) quantified the suspended load entering the Study Area from upstream as 1,000 t/year, or only about 2 t/km^2/year—a very small value relative to most other rivers worldwide (Milliman & Meade, 1983). A plausible analog, that of a small granitic basin in northeastern France (Viville, Chabaux, Stille, Pierret, & Gangloff, 2012), had a measured bedload yield constituting one-third of the total sediment load; other compilations (e.g., Walling & Webb, 1987) suggest this may be an

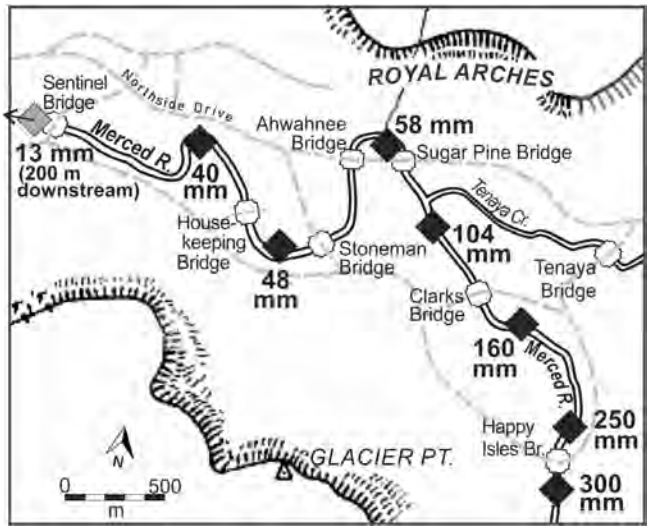

FIGURE 5 Median grain diameters (D_{50}) through the Study Area downstream of Illilouette Creek (black diamonds). All measurement sites located on the upstream low-water margin of point bars or mid-channel bars where clasts are most likely to reflect the active bedload during transport events (Kondolf, Lisle, & Wolman, 2003)

upper limit on the bedload fraction of the total load. Thus, Illilouette Creek (the primary upvalley coarse sediment source) likely has an order-of-magnitude bedload sediment contribution of ca. 200 t/year. This upstream source of coarse sediment dominates in the upper part of the Study Area but is progressively augmented by the 700 t/year of sediment contributed by widening and deepening of the river, of which a significant fraction is bedload-sized material that progressively exceeds the Illilouette Creek contribution downstream to Sentinel Bridge. From downstream measurements of bar deposition and reservoir infilling rates, Madej et al. (1991) calculated a net export of bedload-sized material out of Yosemite Valley of about 360 t/year (approximating modern-day coarse-sediment input rates).

In summary, the Merced River carries the entire watershed's runoff, but only about one-quarter of that area contributes coarse sediment as the river enters the head of Yosemite Valley. Over the 15,000 years since deglaciation the river has adjusted to these low-sediment conditions, resulting in rapid declines in both channel gradient and sediment sizes in the upper portion of the Study Area, followed by much more gradual declines farther downstream. This limited flux of coarse sediment limits the rate at which channel morphology can adjust to restoration efforts, particularly those efforts that involve rebuilding of adjacent floodplain surfaces.

3.4 | Channel migration

The Merced River has historically displayed only limited migration that is likely a consequence of its low sediment load, encasing coarse glacial-age outwash terrace deposits, and only modest flood magnitudes ($Q_{100\text{-yr}}$ is less than four times $Q_{2\text{-yr}}$, among the lowest ratio of all Sierran rivers; Andrews, 2012, his table 3). In the eight decades following construction of bridges and revetments, the river's opportunities for migration have been limited to a few discrete localities. Migration modelling suggests that this historical pattern changes little in the future (Figure 6). With the main zones of armored banks remaining in place, only some limited channel shifting in the upper part of the Study Area and one potential avulsion site that already carries flood flows at modest recurrences are anticipated, severely restricting the area over which dynamic channel activity has any potential to create ecosystem benefits.

Only a subset of the stone bridges significantly restrict channel migration processes in the Valley (specifically, Stoneman, Ahwahnee, and Housekeeping bridges; Figure 6). Although Milestone (1978) identified Clarks, Sugar Pine, Stoneman, and Sentinel bridges as having the greatest effect on channel narrowing (all with >40% width reduction over upstream channel dimensions), of this group only Stoneman Bridge also shows a modelled measurable influence on future migration. Conversely, Ahwahnee and Housekeeping bridges are most

FIGURE 6 Channel migration patterns of the Merced River. Past changes shown by superimposing the 1934 channel position (top panel, yellow outline) on the 2015 Google Earth airphoto. Future changes from the channel centerline in 2016 (bottom panel, blue line) are modelled, with four main areas of existing revetments included (green line) and omitted (red line). The dominant mode of future change is downvalley meander migration where revetments have been removed (i.e., where the red and green lines diverge), with one location of anticipated avulsion between Housekeeping and Sentinel bridges [Color figure can be viewed at wileyonlinelibrary.com]

influential in restraining channel migration but have imposed width reductions of only 26 and 19%, respectively.

Neither the constrained nor unconstrained future scenarios suggest dramatic shifts in channel position or associated reworking of floodplain sediments over the next 50+ years. Thus, large-scale changes in channel position or migration rates, and the ecosystem diversification benefits that commonly accompany that geomorphic process, should not be among the goals of restoration. As a further consequence, the existing condition of low sediment flux as supported primarily by upstream and tributary inputs is likely to persist indefinitely.

3.5 | Riparian conditions

The general patterns and age structure of the existing riparian vegetation community reflect the interaction between watershed geology, river–floodplain connectivity, geomorphic processes, plant species' life history adaptations, and the direct and indirect effects of human activity. These relationships also indicate where riparian restoration is likely to be most successful. Different combinations of late seral species, including oaks, conifers, and incense cedar, dominate the riparian corridor, with shorter interspersed segments dominated by pioneer riparian species occupying recently flood-scoured areas (*Alnus rhombifolia* [white alder], *Populus trichocarpa* [black cottonwood], and *Salix* spp. [willows]). The majority of the corridor is composed of mature vegetation, with shorter segments expressing recent successful recruitment (i.e., stands with young vegetation).

Oaks (*Quercus* spp.) and conifers dominate on the older, higher terraces and glacial-sediment surfaces, even those that until recently represented the rivers active floodplain (Qya); whereas riparian species primarily occupy channel bars and alluvial floodplains within two meters above the active channel (Figure 7, upper panels). All vegetation types are most common on unimpacted alluvial banks; the various types of natural bank erosion and artificial bank stabilization have substantially less vegetative cover.

The age structure of the vegetation communities along the Merced River also is strongly influenced by underlying landforms and bank conditions (Figure 7, lower panels). Mature communities, almost entirely comprising mature trees with minimal age diversity, are most common on intermediate-height terrace surfaces, particularly the widespread relict floodplain now positioned about 2.5 m above the active channel (Qya). Younger riparian vegetation and communities with a diverse age structure are limited to the youngest, most actively flood-disturbed alluvial surfaces (Qas) but are rare or entirely absent on stream banks impacted by either human activity or natural erosion.

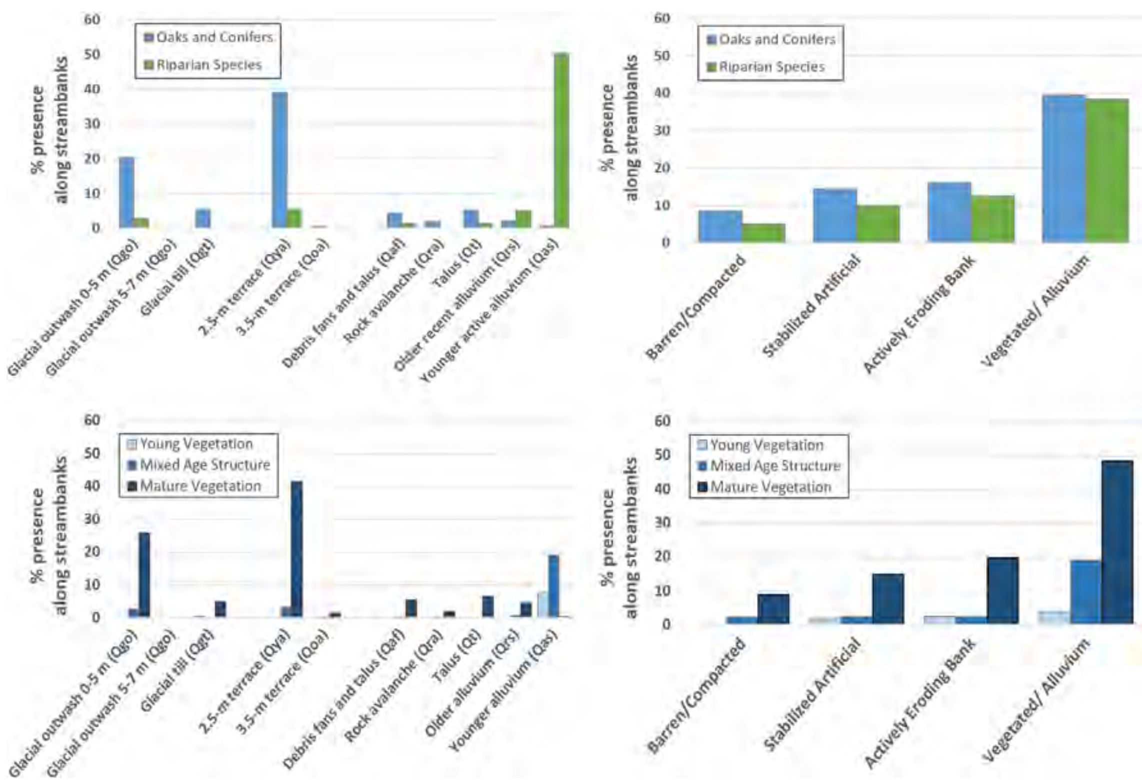

FIGURE 7 Comparison of the distributions of pioneer riparian species and oaks/conifers (upper panels) and age class structure (bottom panels) in relation to geologic map unit (see Figure 2) and bank condition. "Barren/compacted" and "Stabilized artificial" categories constitute the banks expressing human impact(s); the other categories include bank conditions resulting from natural geomorphic processes [Color figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

4.1 | Historical changes to the Merced River

Two primary changes to the Merced River through Yosemite Valley in modern times present significant challenges to its ongoing management and potential restoration. First, the channel has widened substantially over the last century, with increases averaging more than 25% throughout much of the Valley (Madej et al., 1991). The locations of greatest and most acute widening align well with areas of high visitor access and use. More extensive channel expansion likely resulted from the increased in-channel containment of (and consequent erosion by) high flows. The only exceptions to this pattern are the localized constrictions of the channel in the vicinity of the stone bridges.

Second, the river has become 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 effect of altering vegetation communities and amplifying erosive forces by confining greater discharges within the channel banks. We infer that the underlying causes are: first, the historical de-snagging of large woody debris from the river, reducing roughness, reducing in-channel bed sediment storage, and enhancing the efficiency of flows to transport sediment (Schanz, Montgomery, & Collins, 2019; Wohl & Scott, 2017); and, second, historical gravel mining from the bed of the river, poorly documented in historical records but noted by prior studies.

Comparing the historical export of coarse sediment (from instream-mining, incision, and channel widening) with the modern flux of coarse sediment suggests a primary challenge for restoration here: geomorphic processes are far too slow to support meaningful recovery over typical management timescales of years to decades. Two (partly) quantifiable sources of exported sediment, instream gravel mining and post-1919 channel expansion, highlight the magnitude of this difficulty. Milestone's (1978) minimum estimate of early-20th century gravel mining (15,000 m^3) is only a modest fraction of (and may be included in) the magnitude of sediment exported over the last century from just the 5-km-long Study Area, a consequence of channel widening (increasing from an average of about 42 m to more than 50 m, according to data in Madej et al., 1991) and channel deepening (averaging about 0.5 m, from reach-scale estimates of water depths; see Figure 4). Individually or in combination, these sediment exports are more than a hundred times the previously noted estimate of annual bedload-sized sediment flux through Yosemite Valley of about 360 t/year. Natural replenishment would thus occur far too slowly, even with optimal sediment retention within the valley, to meet expectations for any restoration action that included natural recovery of a smaller, more typical pre-disturbance channel form.

4.2 | Restoration strategy

Both the past disturbances to the Merced River and a variety of existing constraints, both natural and human, would challenge any restoration program (Dufour & Piégay, 2009). Given the context developed by our work, four broad categories of restoration have the best opportunity to correct the deleterious impacts to the Merced 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 corrected. 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 typically require design and implementation over longer (multi-year or decadal) time frames.

1. **Restoration of the riparian zone**, 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 even centuries.
2. **Encouragement of more frequent overbank flooding and off-channel flows** through creation or re-activation of side channels to support a more natural and diverse assemblage of riparian plant species and thus improved riparian habitat. This approach works in consort with others: overbank flows develop and expand tributary channels, and a dynamic river will invariably create some areas more prone to overbank flows at lower discharges. Therefore, this approach is subject to the constraints needed to balance the expression of natural riverine processes with their access and enjoyment by visitors.
3. **Restoration of dynamic river and tributary channels in Yosemite Valley,** important for promoting the development of diverse, complex riparian habitats, which in turn facilitates multi-stage plant succession. Channel migration and development of cut-off channels undoubtedly affected the entire valley throughout most of the Holocene, but these processes no longer have unfettered access to the entire landscape. Some existing constraints on river-channel activity (e.g., armored banks) are more severe than are required to protect infrastructure, and they unnecessarily compromise the natural form and function of the river (Piégay, Darby, Mosselman, & Surian, 2005).
4. **Creation of more complex in-channel habitat**, increasing the diversity of aquatic habitat and therefore supporting an increased diversity of in-stream and riparian species (Hafs, Harrison, Utz, & Dunne, 2014). The natural shifting of channels and recruitment of large wood will tend to achieve this outcome (if the large wood is allowed to remain in the channel) regardless of further intervention, but the rate of natural improvement can be orders of magnitude slower than with well-directed restoration efforts.

Some example actions associated with each of these categories, in part reflecting projects recently constructed within the Study Area and others under active design for future implementation, are listed in Table 2.

TABLE 2 Example actions associated with the four categories of restoration identified for the Merced River through the Study Area

Restoration approaches	Examples of potential actions
1. Restoration of the riparian zone	• Revegetate riparian zone to increase channel bank diversity 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 • Rebuild channel banks through wood structures along channel bank to reestablish a more natural channel width, limit bank erosion, and promote revegetation • Redirect flows to minimize bank erosion caused or exacerbated by bridges
• 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
• Restoration of dynamic river and tributary channels	• Remove riprap in non-essential locations; replace with bioengineered bank protection only where critical infrastructure is threatened • Revegetate banks • Add large wood or engineered wood structures to the river channel
• Creation of more complex in-channel habitat	• Retain large wood that naturally falls into the river; re-position, but not remove, wood where recreational rafting will continue to be permitted • Add large wood or engineered 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 to encourage long-term successional tree species that may ultimately contribute to large wood loading into the channel

The interaction of geology, landforms, geomorphic processes, infrastructure, and the life-history strategies of the dominant riparian species provide the best guide to promising restoration sites and actions. Terrace/floodplain elevations and sedimentary materials impose a fundamental constraint on recruitment of woody riparian species. For example, riparian zones identified as low potential for enhancement include those abutting high terraces and human infrastructure; those with higher potential for enhancement include active alluvial surfaces. Of course, the establishment of any vegetation can be compromised by past and ongoing impacts to streambanks, such as revetments or intensive recreational use.

Based on information collected from the field inventories, the potential for riparian enhancement and expansion within the Study Area was categorized into four groups. Those areas with the highest potential for enhancement and expansion comprise active alluvial surfaces and those lower elevation surfaces with the potential to increase the area and frequency of floodplain–channel interactions. In contrast, those areas with high terraces, lack of alluvial surfaces, high bank revetments, and/or high recreational foot traffic have the lowest potential. Other potentially promising restoration sites include the young terraces positioned no more than 2–2.5 m above the active channel, whereas revegetation of the older glacial outwash terraces surfaces could support valley-floor habitat diversity but have lower overall restoration potential or benefits.

4.3 | Restoration project examples

A variety of river-enhancement projects designed to reduce prior impairments have been constructed by the National Park Service (NPS) over the past three decades, some of which predate this study whereas others were informed by our preliminary findings. Earlier projects emphasized removal of utilities and other infrastructure from the river corridor, and some new bank armoring with both rock and vegetation. More recent projects have replaced rock revetments with bioengineered slopes and have begun the process of narrowing the channel through log structures, visitor exclusion, and riparian revegetation. Although these latter projects have shown early success in both initiating riparian restoration and withstanding recent high-flow events without noticeable damage, they also demonstrate the challenges of rebuilding an overwide channel with an intrinsically low flux of coarse sediment (Figure 8). At any single project site, the volume of bank material needed to reduce the channel width to dimensions more closely approximating their historical values is of the same order as the entire annual bedload sediment flux; thus, truly systemic recovery of channel dimensions would require many decades to centuries' worth of natural coarse sediment recruitment without more active filling of channel-narrowing structures.

4.4 | Implications of climate change

The trajectory of river restoration here is likely to be complicated by long-term changes in climate. Andrews (2012) analyzed historical trends in flow data over the last 60 years, documenting a decrease in the fraction of the annual runoff discharged during springtime snowmelt (April through July) throughout the west slopes of the Sierra Nevada, a trend anticipated to continue with future increases in temperature (Roche, Bales, Rice, & Marks, 2018). Andrews found "no discernible trends in the magnitude of annual peak floods and mean annual runoff" over the

FIGURE 8 Photographs taken over a three-year period of the channel-narrowing and riparian-restoration project constructed about 200 m downstream of Ahwahnee Bridge along the right bank of the Merced River. Project consists of logs with root balls placed perpendicular to the bank, designed to trap bedload sediment and promote riparian vegetation growth. Image dates October 2016 (left, just after project installation), October 2017 (center), and April 2019 (right; higher discharge at this time, inundating the foreground sediment). Note the lack of significant sediment accumulation between the log structures. An additional project constructed September 2017 is visible cross-river in the last two images [Color figure can be viewed at wileyonlinelibrary.com]

past decades. However, modelling studies under future climate-change scenarios consistently report significant increases in maximum peak flows, particularly for those floods occurring during winter rain-on-snow events, which are significantly larger than late-season snowmelt-dominated floods. Model predictions also anticipate increases in storm magnitudes, storm frequencies, and numbers of days with more precipitation falling as rain and less as snow (Das, Dettinger, Cayan, & Hidalgo, 2011). The expected upward shift in snowline elevation will likely drive larger and more frequent floods (Davenport, Herrera-Estrada, Burke, & Diffenbaugh, 2019). Stewart, Ficklin, Carrillo, and McIntosh (2015) reported model predictions of increasing high flows for the winter and spring seasons, with little or no change in the occurrence of summer and fall high flows. They predicted increases of 150+% for the upper Merced River drainages, consistent with independent modelling results by Maurer, Kayser, Doyle, and Wood (2018).

These changes in flood magnitude are liable to increase the frequency of sediment-mobilizing events. Potentially, more frequent transport events could more effectively redistribute coarse sediment delivered to the mainstem Merced River by Illilouette Creek and other steep lateral tributaries, hastening the pace of natural channel reconstruction at restoration sites—but also increasing the rate of erosion along impacted banks, and potentially accelerating the export of sediment out of the Valley. These competing processes probably will not be expressed uniformly; Minear and Wright (2013), for example, reported a reduction in channel cross-sectional area (i.e., net deposition) upstream of Sugar Pine Bridge immediately following the 1997 flood of record, with re-expansion of channel dimensions occurring in the following years of lower peak discharges. Elsewhere, however, the same flood immediately induced greater bank erosion and damage to rock revetments (Cardno, 2012).

More frequent high flows should accelerate the recovery of natural riverine processes that are the fundamental goal of this restoration program, but riparian plantings may have less time to establish before experiencing potentially damaging, scouring overbank flows. High flows also can pose a direct threat to recreational opportunities and have already caused substantial damage to Park facilities, of which the total cost of recovery from the 1997 flood alone exceeded $250 M (National Park Service, 2013). Projected changes to the regional climate are thus likely to support various elements of river restoration but also to pose new and significant challenges to overall visitor and resource management.

5 | SUMMARY

5.1 | Causes of riverine damage

The Merced River through Yosemite Valley reflects the effects of more than a century of locally intensive human impacts, superimposed on a river whose contributing watershed remains largely intact. Intensive visitor activity along the riparian zone, gravel mining, and removal of large wood are the most severe, systemic impacts that have resulted in channel widening and partial disconnection of the channel from its historical floodplain through incision. Bank armoring and bridge crossings have further limited the expression of the natural riverine processes otherwise typical of alluvial channels.

5.2 | Challenges for restoration

Full understanding of the geomorphic context, and the history of both natural evolution and human disturbance, are needed before informed decisions on restoration priorities and specific actions can be made. The Merced River provides a valuable case study for this approach, in a setting where a truly outstanding natural landscape also is host to intensive human presence. The challenge posed by people is well-expressed by the near-doubling of annual Park attendance over the past 40 years, with more than 4 million visitors every year since 2015. The Merced River is a prime recreation attraction, but successful restoration requires redirecting that attention to more resilient parts of the river corridor without “limiting other uses that do not substantially interfere with public use and enjoyment of these [outstandingly remarkable] values” (section 10(a) of the Wild and Scenic River Act). Heavy visitor use and associated infrastructure is the most severe, ongoing impact to river conditions; it will continue to be a major challenge to implementing and sustaining future improvements (Dufour & Piégay, 2009).

The watershed itself presents a second challenge to restoration. Much sediment has been exported from the Yosemite Valley segment of the Merced River for more than a century. The rate of natural sediment replenishment from the upper watershed, however, is orders of magnitude too slow to support rapid recovery of a pre-disturbance channel form and size, even if in-channel and riparian measures are entirely successful in their intended goals. Resolution of this conundrum will require active replacement of the “lost” sediment, or else great patience, to achieve desired results.

5.3 | Anticipated outcomes

The current restoration program for the Merced River, with the first projects initiated in 2016, emphasizes the reconstruction of more natural channel form and functions through bioengineered riparian restoration, controlled visitor access to the river, retention of large wood, reactivation of floodplain channels and other overbank areas, and selective replacement of artificial bank hardening with wood-based floodplain-building channel margins. The support of an intact watershed and a strong management commitment to restoration suggest optimism in predicting river response; but the magnitude of legacy impacts and the sheer volume of visitor traffic preclude any certainty of success. The NPS has committed to “improv[ing] the visitor experience while ensuring that the river and Yosemite National Park are “protected for the benefit and enjoyment of present and future generations” (National Park Service, 2014), and our work has proceeded with the hope and expectation that these goals will be achieved.

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DATA AVAILABILITY STATEMENT

Those data that support the findings of this study are available from the corresponding author (DBB) upon reasonable request.

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