RESEARCH

Analysis of Bank Erosion on the Merced River, Yosemite Valley, Yosemite National Park, California, USA

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ABSTRACT / Channel changes from 1919 to 1989 were documented in two study reaches of the Merced River in Yosemite National Park through a review of historical photographs and documents and a comparison of survey data. Bank erosion was prevalent and channel width increased an average of 27% in the upstream reach, where human use was concentrated. Here, trampling of the banks and riparian vegetation was common, and banks eroded on straight stretches as frequently as on meander bends. Six bridges in the upper reach constrict the channel by an average of 38% of the original width, causing severe erosion. In the downstream control reach, where human use was minimal, channel widths both decreased and increased, with a mean increase of only 4% since 1919. Bank erosion in the control reach occurred primarily on meander bends. The control reach also had denser stands of riparian vegetation and a higher frequency of large woody debris in channels. There is only one bridge in the lower reach, located at the downstream end. Since 1919, bank erosion in the impacted upstream reach contributed a significant amount of sediment (74,800 tonnes, equivalent to 2.0 t/km^2/yr) to the river. An analysis of 75 years of precipitation and hydrologic records showed no trends responsible for bank erosion in the upper reach. Sediment input to the upper reach has not changed significantly during the study period. Floodplain soils are sandy, with low cohesion and are easily detached by lateral erosion. The degree of channel widening was positively correlated with the percentage of bare ground on the streambanks and low bank stability ratings. Low bank stability ratings were, in turn, strongly associated with high human use areas. Channel widening and bank erosion in the upper reach were due primarily to destruction of riparian vegetation by human trampling and the effect of bridge constrictions on high flow, and secondarily to poorly installed channel revetments. Several specific recommendations for river restoration were provided to park management.

Yosemite National Park is one of the most well known and highly visited parks in the United States. Yosemite National Park's 1980 General Management Plan (GMP) addressed high visitation issues (USDI 1980). The plan contained several proposed actions, including allowing natural processes to prevail in Yosemite Valley: "The primary objective of natural resource management programs will be to restore and perpetuate the natural processes of the park's ecosystems . . . In areas that have been disturbed by man's activity, natural processes will be allowed to restore the scene." The Merced River is a dominant feature of the valley, and natural river processes include occasional flooding, bank erosion, and sediment deposition. The GMP did not address relationships between river and floodplain use and river processes, and additional information on river dynamics was necessary for management decisions. Because bank erosion by the Merced River was perceived to be a threat to campgrounds and bridges in Yosemite Valley, the National Park Service funded a study to investigate the process of bank erosion, its causes, and possible solutions.

Bank erosion along meandering rivers is a natural process. In an undisturbed state, if a river is in equilibrium, the amount of material eroded from banks will be approximately balanced by the amount of new sediment deposited on point bars as the river migrates

KEY WORDS: Bank erosion; Trampling; Streams; Channel changes; Channel stability; River restoration; Riparian vegetation

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across its floodplain. However, several factors may cause the river regime to change, accelerate bank erosion, and initiate channel widening or deepening. An increase in the forces acting upon the banks or a decrease in bank resistance can increase rates of bank erosion. Accelerated bank erosion that is not balanced by sediment deposition can result in net channel widening, and push the system into disequilibrium.

Bank stability is an important control of channel equilibrium (Richards 1982). The river disequilibrium signaled by channel widening is frequently indicative of societal pressures in a watershed. Destruction of riparian vegetation is common in alluvial rivers throughout the world, although the causes of such destruction vary. Knighton (1984) discusses man-induced changes affecting streambanks and riparian vegetation, including grazing, logging, construction of dams and flood control levees, channelization, river gravel extraction, urban development, and agricultural practices. As populations grow, use of riparian and aquatic resources increases, and rates of landscape alteration also increase. The combination of these factors has led to an increasing concern with environmental problems, and a need for knowledge of processes controlling change and influencing equilibria. The techniques and recommendations based on our present study of channel stability should be applicable to other rivers where riparian vegetation and streambanks are threatened or damaged.

Bank erosion on the Merced River in the Yosemite Valley is not a new concern. In 1881, the commissioners in charge of Yosemite Valley were appalled at the "destructive currents" of the Merced River, and they initiated plans for stream control to "prevent future defacement of Valley lands and loss of real estate." (cited in Milestone 1978). Matthes (1936) of the US Geological Survey (USGS), presented an overview of bank erosion in Yosemite Valley. It is obvious from his report that park management was concerned about bank erosion over 50 years ago and had already installed bank protection devices. The debate of protecting the resource versus protecting the process is still active in the National Park Service. In theory, the latter is expounded as policy; in practice the former sometimes prevails.

The objectives of this study were: (1) to document historical channel changes, including the location, timing, and magnitude of bank erosion in Yosemite Valley, (2) to evaluate possible causes of bank erosion and channel widening, and (3) to recommend management and restoration options in Yosemite Valley.

Yosemite National Park covers 3080 square kilometers of the upper portion of the western slope of the Sierra Nevada, California. Bedrock in the park is primarily part of the Sierra Nevada granitic batholith. Granitic domes and cliffs form some of the most dramatic scenery in the park. Yosemite Valley, the focus of the present study, ranges from 1160 to 1280 m in elevation.

Two major rivers, the Merced and the Tuolumne, flow through glaciated canyons that are deeply incised into the surrounding forested uplands. Three stages of mountain glaciation, perhaps four (Wahrhaftig 1962), significantly altered the character of the Merced canyon. Glacial lake deposits up to 600 m deep underlie the valley floor. Most soils in Yosemite Valley formed on glacial deposits.

The Merced River drains a basin 469 km^2 in size at the Happy Isles gauging station, and 831 km^2 at Pohono Bridge (Figure 1). Major tributaries to the Merced, including Tenaya, Yosemite, and Bridalveil Creeks, enter within Yosemite Valley.

Documentation of River Channel Changes

Channel changes that occurred during the last 100 years were evaluated through: a search of historical manuscripts and photographs to document land use and channel changes; aerial photographic interpretation, surveying, and mapping present river conditions in two study reaches of the Merced River; and comparison of recent surveys to old maps.

Although Yosemite Valley has been under federal management for over a century, natural processes in the valley have been radically altered. Since Euroamericans entered the valley in 1851, many land-use activities have changed. These include: grazing, row crops, planted pastures, haymaking, construction of corrals, roads, campgrounds, garbage dumps, sewage plants, a slaughterhouse and powerhouse, barrow pits, drainage tiles, buildings, water development, utility lines and pipes, removal of trees and smaller vegetation, and fire suppression. All these uses can directly or indirectly affect channel and floodplain processes by inducing changes in erosive forces, such as water discharge, or in resisting forces, such as streambank resistance.

The most significant human influences on the Merced River have been the installation of bank protection structures, bridge construction, flow diversion, human destruction of riparian vegetation, and removal of organic debris. In addition, from 1877 to 1977 more than 15,000 m^3 of sand and gravel was excavated from the Merced River (Milestone 1978). To drain the floodplain of the lower valley, in 1879 a

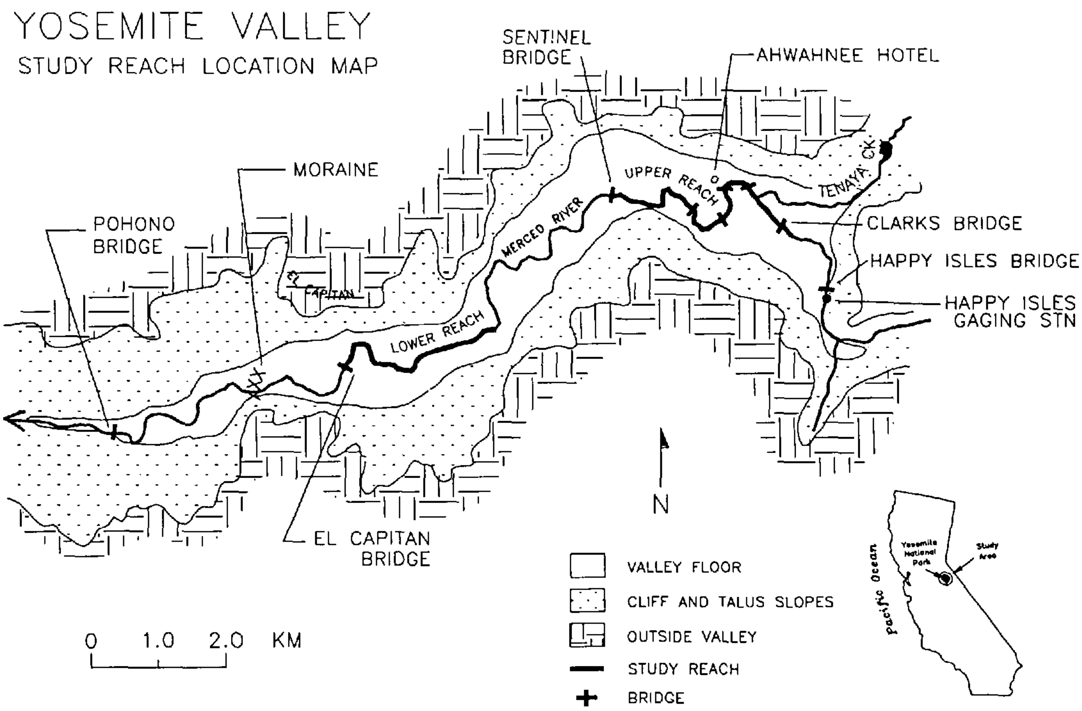

Figure 1. Location map of the Merced River, Yosemite Valley, Yosemite National Park, showing the location of the two US Geological Survey gauging stations, the two study reaches (upper and lower), and eight major bridges. Campgrounds are concentrated between Sentinel and Clarks bridges; none are along the lower reach.

moraine across the Merced River downstream of El Capitan meadow was blasted and caused localized downcutting up to 1.2 m (Milestone 1978).

Yosemite National Park is fortunate to have a large collection of historical photographs and paintings, many of which include the Merced River as part of the view. A survey of photographs from the late 1800s to the present was useful in documenting channel conditions through time. We can make several generalizations of past conditions based on this survey. Banks were steep and well vegetated, except on the outside of meander bends or where humans already had concentrated their activities. Active bank erosion was occurring on the outside of meander bends, with deposition on point bars. Large woody debris was common on banks and in the channel. Overhanging trees and undercut root masses provided shade and cover for fish.

A review of park documents, unpublished memoranda, and letters revealed that streambank erosion was a concern throughout the 1900s. Some concerns were with aesthetics, whereas others expressed concern about threats to park developments and resources. Workers in Yosemite observed bank erosion in the 1930s and attributed it to the force of the river and to the effects of human trampling. The common response was to construct more bank protection devices along the Merced, and by 1978 4.4 km of revetment had been installed in Yosemite Valley (Milestone 1978).

To quantify the degree of erosion and document the location and timing of erosion, we chose two stream reaches for intensive study. The reaches were selected to evaluate the possible impacts of human use on bank erosion in a highly used reach, and contrast it to a similar reach having much less intense human use. The high use area encompassed all major campgrounds in the valley, from Clarks Bridge to Sentinel Bridge (Figure 1). As is true in many river studies, an actual control reach with all the same characteristics of the impacted reach did not exist. Instead, a reach downstream of the high use area was selected, which had only scattered day use areas. It is called a control in this article, although we recognize it is influenced by water and sediment generated from the upstream impacted reach and by localized disturbance as well. Table 1 lists the characteristics of the two study reaches.

A range of drainage areas for each study reach reflects the influence of tributaries entering the

Table 1. Description of study reaches

	Upstream (impacted)	Downstream (control)
Drainage area (km^2)	460–596	725–777
Channel length (km)	3.5	2.6
Channel gradient (m/m)	0.0016	0.0005
Average channel width (m)	52	57
Sinuosity	1.48	1.31
Length of banks with active bank erosion (%)	39	17
Length of banks with channel revetment (%)	25	2

reach. Tenaya Creek (104 km^2) is the major tributary entering the upper reach, whereas the downstream reach has several smaller tributaries joining the main river.

The Merced River's appearance changes on its route downstream. From Happy Isles to Clarks Bridge (just upstream of the upper study reach), the channel bed is bouldery, and banks are also coarse (cobbles and boulders). Stream gradient is steep (1.08%). Visitor use impacts are minimal, and river conditions are stable (Figure 2). This reach represents the transition from a high-gradient mountain stream to a low-gradient valley stream.

In the upper study reach, from Clarks Bridge to Sentinel Bridge, the stream gradient is an order of magnitude less than the Happy Isles reach (only 0.16%). The bed material varies, with cobbles, pebbles, and sand. Streambanks comprise finer-grained material and are more susceptible to bank erosion. This reach has the heaviest visitor use, especially associated with six major campgrounds and six bridges. Figure 3 shows bank erosion near Clarks Bridge. Downstream from Clarks Bridge, revetment, groins, and bridge constrictions strongly control river morphology. Bed and bank materials become finer, channel gradient is gentler, and the intensity of human activity and bank erosion increases. Figure 4 shows the typical fine-grained, unvegetated banks in the campground areas. Stumps of former streamside trees are common features in this reach, but woody debris is mostly absent from banks and within the stream channel.

The downstream study reach extends from 3.5 km downstream of the Sentinel Bridge to the El Capitan Bridge. Here visitor use is locally heavy, but is limited to a few isolated day use areas (picnic areas, streamside trails, etc.) Bed material is fine grained, mostly sand and small pebbles. Stream gradient is lower (0.05%). Lateral bank erosion and channel migration is evident. Channel revetment and one bridge affect local areas on the river, but to a much lesser degree than in the upper reach. Riparian vegetation is denser and woody debris is more abundant in the downstream reach (Figure 5).

In 1919, the US Geological Survey produced a 1:2400 topographic map of Yosemite Valley with 0.6 m (2-ft) contour intervals on the flat valley floor and 1.2 m (4-ft) intervals on the steeper talus slopes. The maps contained considerable detail on ephemeral drainages, gravel bar locations, roads, channel bed elevations, oxbows, etc. Such map detail permitted remeasurement of channel widths in 1986 and 1989 and a comparison to widths shown on the 1919 topographic map. Figure 6 is an example of the 1919 map for a portion of the Merced River. By measuring from known features such as road junctions, we could field check the scale and accurately locate measurement sites. We measured channel widths of the Merced River with a tape at those places where there was good control from the topographic maps.

Twenty-four cross sections were measured in the upper reach in 1986, and in 1989, 21 cross sections in the downstream reach. The number of cross sections located in straight reaches and on meander bends was about equal. The floodplain/channel boundary was commonly distinct on the topographical maps, and channel width was measured from the top of the break-in-slope between the floodplain and the river banks. The top of the banks corresponds to a flow with a recurrence interval of <10 years, based on gauging records and a staff plate at Sentinel Bridge.

Results of channel width measurements show distinct differences between the upper and lower reaches (Figures 7A and B). In the upper reach (Figure 7A) channel widening occurred at 23 of the 24 cross sections. Channel widths increased up to 117%, and the average change in channel width was an increase of 27%. Sites with large channel width increases also had abundant field evidence of bank erosion, including trees and stumps presently located on the active channel bed, unvegetated banks, undercut banks, and bank collapse. The one cross section that was narrower in 1986 was a site where a mid-channel bar present in 1919 had become attached to the bank by deposition in the overflow channel at the base of the former right bank.

These results contrast sharply with measurements made in the lower reach (Figure 7B), where channel widths increased at only 10 of 21 cross sections, and the average change in channel width was an increase of 4%. In the upper reach, 39% of the banks showed active erosion, whereas in the lower reach only 17% of the banks displayed active erosion (Table 1).

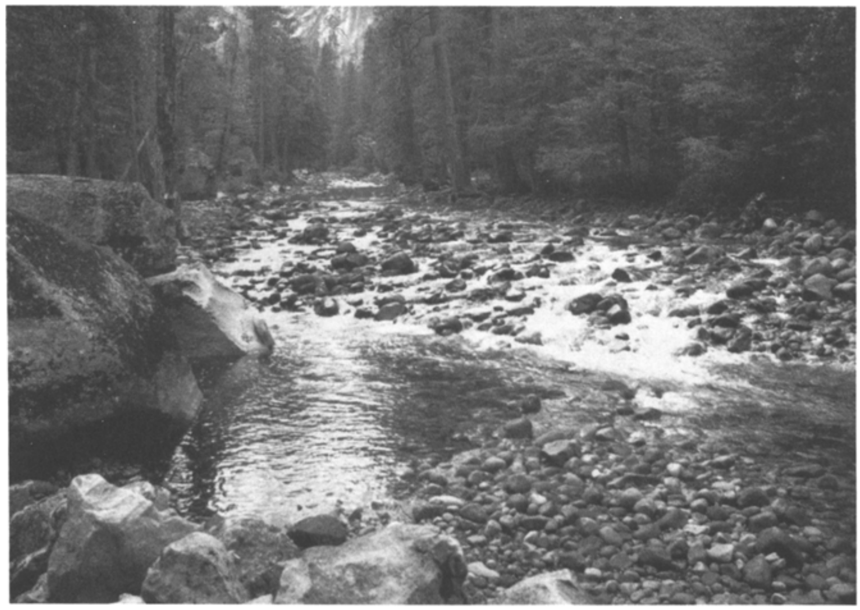

Figure 2. The Merced River downstream of Happy Isles Bridge exhibits a steep, coarse channel bed and bouldery, well-vegetated banks.

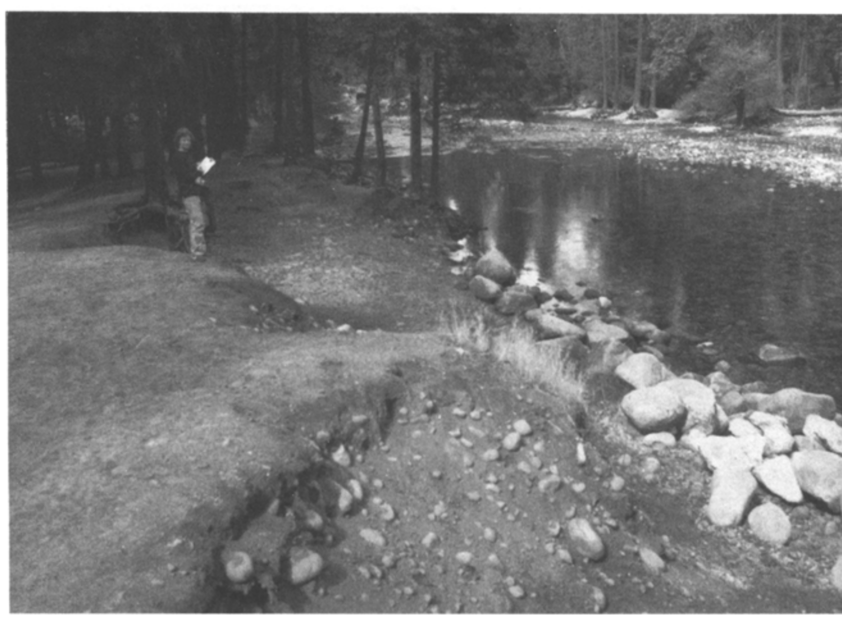

Figure 3. Looking downstream at the Merced River near Clarks Bridge. Erosion is occurring on the left bank both behind low riprap and in areas without channel revetment. Riparian vegetation is sparse, the floodplain has little organic litter or ground cover, and the soil is compacted.

The upper reach of the Merced River differed from natural channel behavior in two major ways. First, streambank erosion was greater than deposition, resulting in a net increase in channel width. Second, streambanks eroded as commonly on straight stretches as on bends, and four of the five highest increases in channel width were in straight reaches (Figure 8A). In contrast, the largest channel width change in the lower reach occurred on a meander (Figure 8B).

The lower reach, with minimum human impact, exhibited the expected pattern of streambank erosion with corresponding point bar deposition. Interestingly, in the lower reach, even where the Merced River migrated 45 m across the floodplain since 1919, channel width remained about the same.

In contrast to large changes in channel width, channel gradient in the upper reach scarcely changed over a 60-year period. We compared channel bed elevations from 1919 maps and 1981 National Park Ser-

Figure 4. Erosion of left bank in the upper study reach. Fine-grained unvegetated banks have eroded, leaving stumps of former streamside trees within the present active channel.

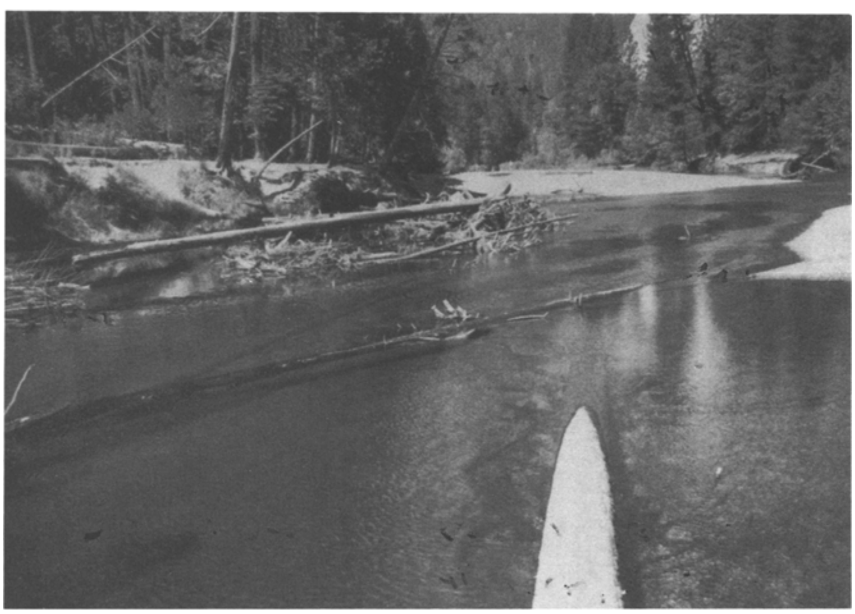

Figure 5. View looking downstream at the lower study reach showing abundant woody debris lying both on streambanks and in the active channel.

vice maps. Overlapping data sets were only available for the upper study reach. A comparison of the longitudinal profiles in the upper study reach in 1919 and 1981 showed little change in channel gradient through time (Figure 9). The apparent changes in the channel bed upstream of Clarks Bridge were probably an artifact caused by sparse survey points from the 1981 mapping. Downstream changes, in contrast, were probably real. The biggest differences were at two major bridges, Stoneman and Sentinel bridges, where deep scour holes formed due to channel constriction caused by the bridges.

Evaluation of Causes of River Channel Changes

To determine the possible causes of the bank erosion and channel widening documented in the upper reach, we assessed several hydrologic and physical factors, including trends in precipitation, runoff and

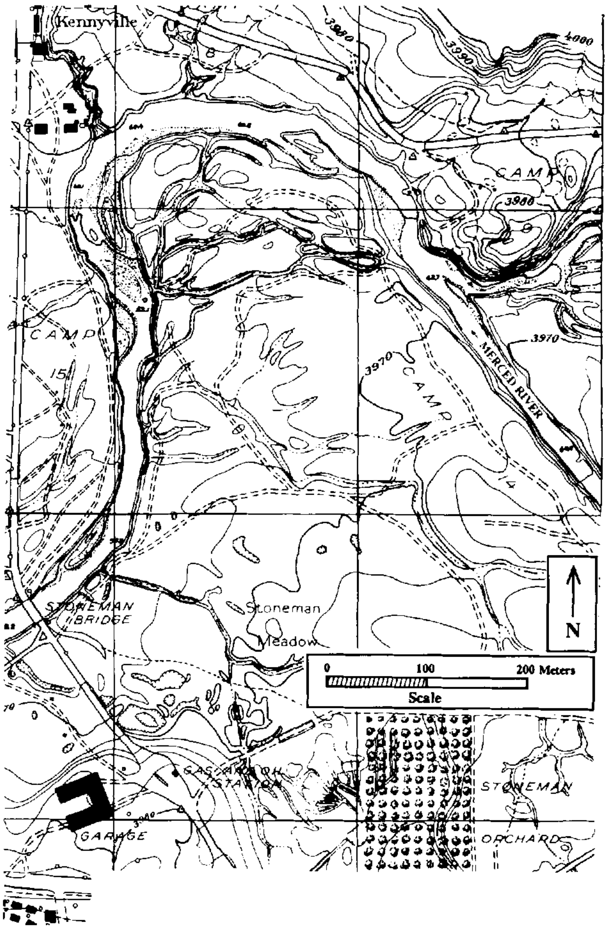

Figure 6. Reduced copy of 1919 USGS topographic map of Yosemite Valley and the Merced River. Two major bridges now present on the meander were not yet built. The original maps are at a 1:2400 scale, and they show well-defined channel boundaries, locations of ephemeral streams, roads, gravel bars, and spot channel bed elevations. Many small channels are shown on the sharp meander, whereas presently one greatly enlarged cutoff channel exists there.

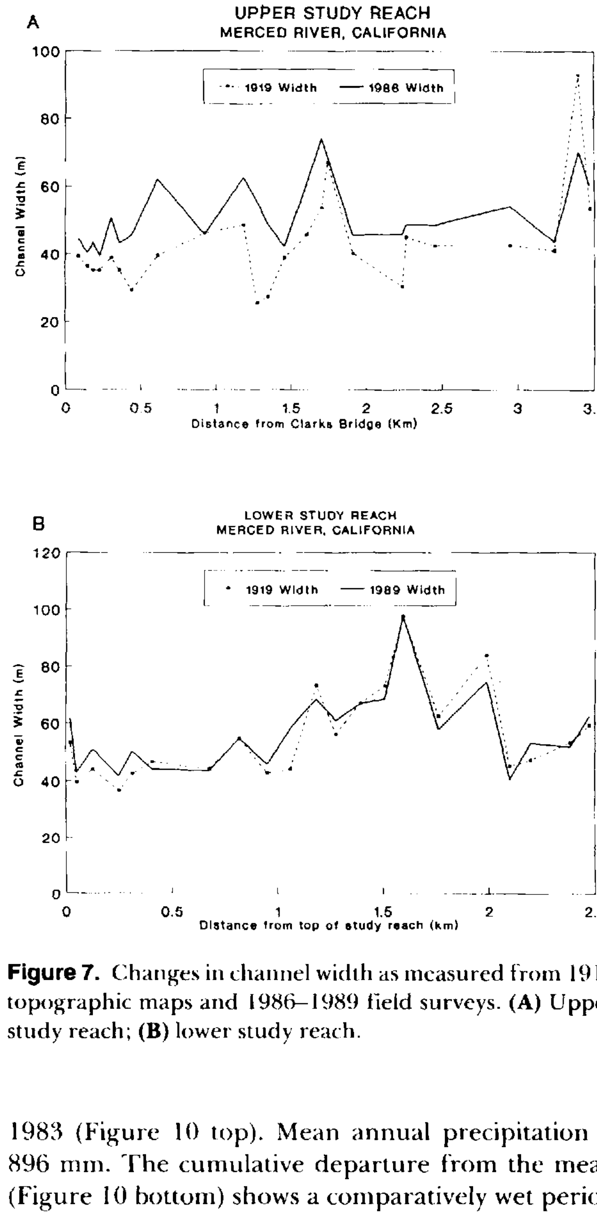

Figure 7. Changes in channel width as measured from 1919 topographic maps and 1986–1989 field surveys. **(A)** Upper study reach; **(B)** lower study reach.

peak flows, soils, large woody debris, riparian vegetation, human trampling, and man-made structures. River flow affects channel stability in several important ways. High flows do most geomorphic work by transporting sediment, eroding banks, and reshaping channels. Low flows govern the extent and vigor of riparian zones and limit summer aquatic habitat. Water flow in the Merced, in turn, is dependent upon rainfall and snowmelt.

Precipitation has been measured near Yosemite Park Headquarters in Yosemite Valley since 1905 (California Department of Water Resources 1981, NOAA 1990). Annual precipitation varies widely, from a low of 292 mm in 1977 to a high of 1751 mm in 1983 (Figure 10 top). Mean annual precipitation is 896 mm. The cumulative departure from the mean (Figure 10 bottom) shows a comparatively wet period in the early part of the century, followed by a prominent series of drier-than-average years in the 1920s and early 1930s. Since then, there have been several fluctuations between wet and dry years. Most recently, droughts occurred in 1976–1977, and seven of the last eight years have been below average in precipitation; however, precipitation trends alone would not account for increased bank erosion in the upper reach.

In 1916, the USGS established two gauging stations in Yosemite National Park to monitor the Merced River. The gauging station at Happy Isles Bridge (Merced at HI, station 11264500, drainage area = 469 km^2), provides a daily record of water discharge and temperature and periodic records of water quality

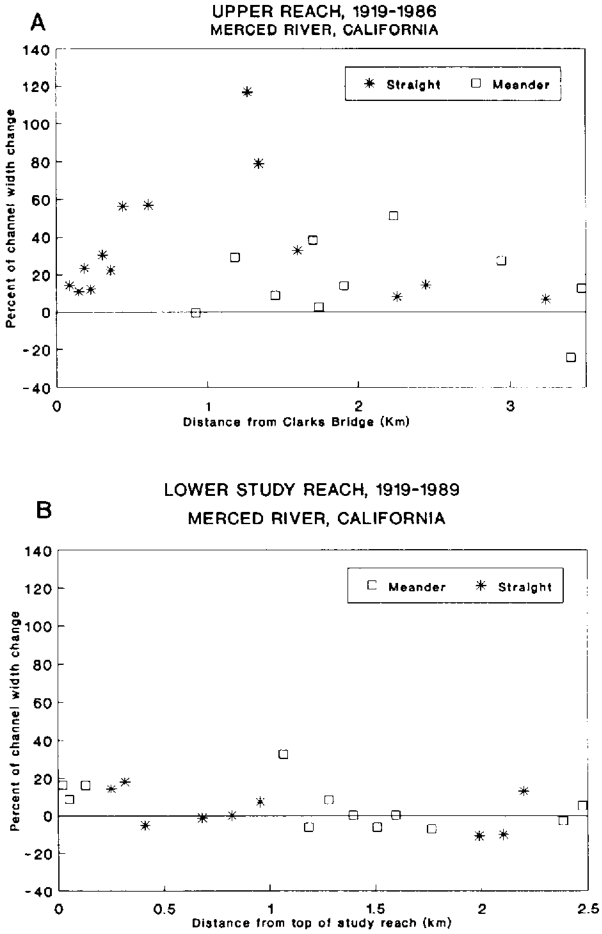

Figure 8. Channel width changes in relationship to channel pattern. (**A**) Upper study reach; (**B**) lower study reach.

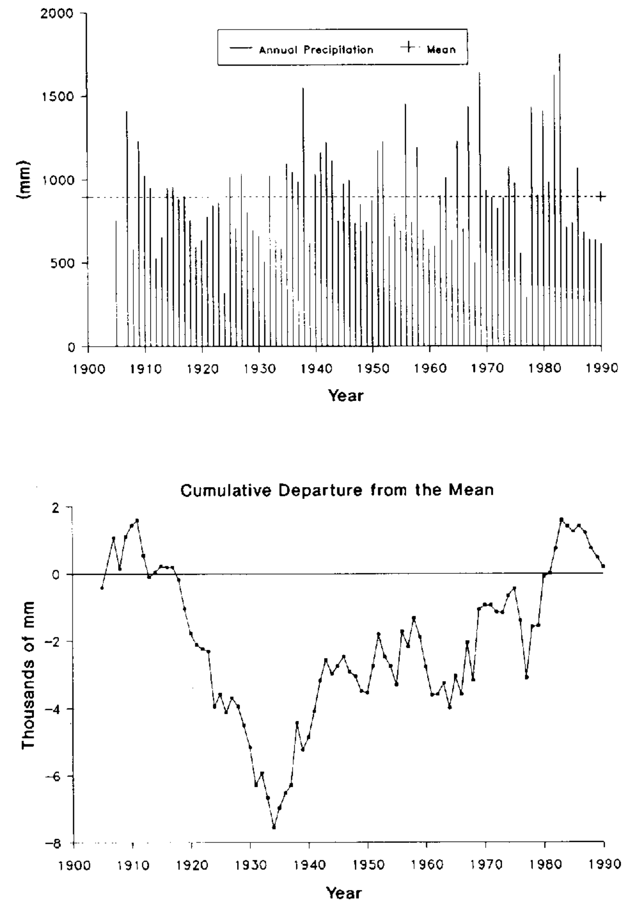

Figure 10. Annual precipitation (top) and cumulative departure (bottom) from the mean measured in Yosemite Valley, Yosemite National Park.

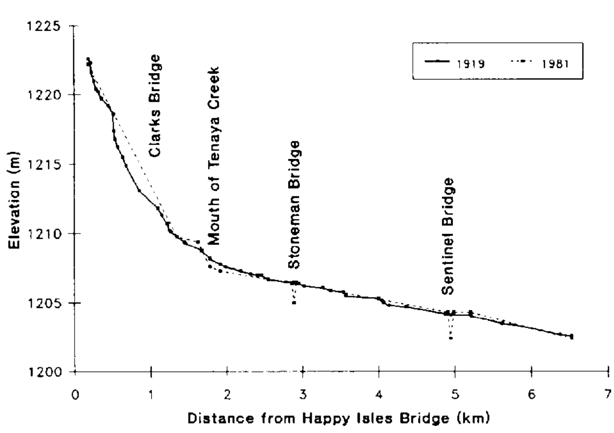

Figure 9. Comparison of 1919 and 1981 longitudinal profile surveys of the upper reach of the Merced River.

characteristics and suspended sediment. Another station, Merced River at the Pohono Bridge (Merced at PO, station 11266500, drainage area = 831 km^2), provides a daily record of water discharge.

The amount and duration of streamflow is strongly influenced by the amount of snowpack, its water content, rate of snowmelt, and rainfall. Average annual discharge is 9.9 cm at Merced River at HI, and 17.4 cm at Merced River at PO. Low flow commonly occurs in September or October, and averages 0.2 cm at Merced at HI and 0.6 cm at Merced at PO. In contrast, high flow may occur anytime between November and June, depending on patterns of rainfall and snowmelt. Maximum discharges on record were 279 cm on 23 December 1955 for Merced at HI, and 663 cm for Merced at PO on the same date.

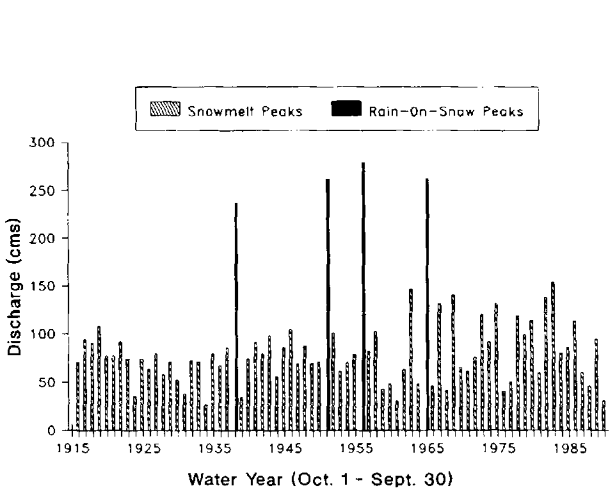

Figure 11. Annual peak flows measured on the Merced River at Happy Isles (1916–1990). Snowmelt peaks are more common but are significantly lower than those produced from rain-on-snow events.

Anecdotal evidence indicated that most bank erosion and damage to occurred during large floods. Annual peak flows ranged from 26.5 cm in 1934, to ten times higher, 279 cm in WY 1956 (Figure 11). Three mechanisms generate peak flows in the Merced River: snowmelt, rain-on-snow, or rain alone. Snowmelt floods generally occur from 15 April through July. From 1916 to 1990, 95% of the peak flows occurred in response to snowmelt. Rain-on-snow events occurred from September through about 15 April and caused the four highest floods on record. In addition, historical accounts describe large floods in December 1867 and December 1871 (before the gauging stations were established) as rain-on-snow events. The third type of mechanism, due to rain alone, caused the February 1963 flood, the sixth highest flood on record.

Based on the 75 years of record at the Happy Isles gauging station, the period 1916–1923 had above-average values, followed by a drought. Nine of the 13 highest peak flows occurred in a 20-year period (1963–1983). Although bank erosion has been a concern for half a decade, there may have been an increase in the incidence and magnitude of bank erosion in the last 20 years associated with the several large floods during this period. Nevertheless, no long-term trend of increasing discharge or peak flows is apparent.

From the early 1900s to 1985, the park diverted an average of 0.05 cm from upstream of the Happy Isles gauging station for visitor use (Walsh 1980). This diversion represented an average of 20% of the low flow at Merced at HI and up to 54% of the low flow during dry years. Although diversions may have had a negative impact on aquatic habitat, water diversions alone could not account for the degree of bank erosion in the upper reach.

Because changes in the hydrologic regime could not account for the bank erosion and channel widening in the upper reach, physical factors were also evaluated. Bank erosion can be initiated by changes within the stream channel or the banks themselves. The quantity and size of sediment a stream carries, the filling in or scouring of a streambed, the type of soil forming a streambank, man-made structures, and changes in riparian vegetation can all influence bank stability.

The quantity of sediment transported by the Merced River is germane to the bank erosion problem in several ways. First, if a river's available sediment load decreases significantly, while discharge remains the same, net bed scour and bank erosion may increase. Alternatively, if sediment loads increase significantly, in-channel deposition may occur, which also can lead to bank erosion. Watershed changes may alter sediment transport patterns, which in turn may affect channel stability. Because no sediment transport measurements were made in the study reaches, we used several methods to estimate probable sediment yield (both the suspended load and bedload) in the Merced River.

From 1975 to 1989, the USGS collected periodic suspended sediment samples at the Happy Isles station, which is upstream of the documented bank erosion sites. The watershed monitored by this station is primarily designated as wilderness and has no evidence of land-use changes or changes in sediment load during the last few decades. Combining the sediment rating curve of the Happy Isles station with a flow duration curve, we estimated annual suspended sediment transport at the Happy Isles station to be 2.7 t/km^2/yr. This suspended sediment data set was limited for two reasons. First, the highest discharge samples was 75.3 cm, which corresponds to a two-year flow. Sediment transport during large floods is important to quantify, but no information on sediment concentrations during floods is available. Secondly, less than 30 points were available for constructing the sediment transport curve. More data points may cause revision of the curve. Finally, no bedload data were available, yet bedload may make up much of the total load in the Merced River. For these reasons, we used several independent methods to check the plausibility of the estimated suspended sediment yield.

Based on a literature search (Table 2), low sediment yields are common in Sierran streams, and the estimated yield for Merced River at HI is not unrealistic. This is to be expected in an undisturbed water-

Table 2. Annual sediment yield estimates of Sierran streams

	Drainage area (km^2)	Suspended sediment ($t/km^2/yr$)	Bedload ($t/km^2/yr$)
General Creek (1984–1987) (Hill and Nolan 1990)	19.2	9.1	1–1.4
Sagehen Creek in 1983 (Andrews and Erman 1986)	27.2	—	2.9
Merced River at HI (1975–1989) (USGS records)	468	2.7	—
Refilling of excavation on Camp 16 point bar, Merced River (Milestone 1978)	572	—	0.9
Refilling of excavations on point bars, Merced River (Kondolf and Cook 1986)	648	—	0.5
Deposition at Cascade Diversion Dam on Merced River (Kondolf, personal communication, Blodgett 1989)	842	—	0.7

shed that has little erodible material available for transport. The low quantities of sediment transported by the Merced River suggest channel erosion and deposition were balanced upstream of Happy Isles, and no major channel scour or bank erosion was occurring. Field surveys showing a stable channel in that reach supported that conclusion.

To compare the importance of the contribution of bank erosion to the annual sediment load, we made a rough estimate of how much material entered the Merced River along the upper study reach from bank erosion during the period 1919–1986. We used a double-end area method, taking the average change in channel width between two consecutive cross sections and multiplying it by the average height of banks and the length of stream between cross sections. The volume of material eroded was significant, (74,800 t), equivalent to a sediment yield of about 2.0 $t/km^2/yr$. This volume includes both fine material that would be carried as suspended load and the coarser sediment that would be carried as bedload.

Zinke and Alexander (1963) classified and mapped soil types in Yosemite Valley, and the US Soil Conservation Service updated the survey in 1992 (USDA 1992). Streambanks in the upper and lower study reaches comprise similar soils. The most common soils, Sentinel and Leidig, are coarse, loamy, mixed, mesic Vitrandic Xerumbrepts. The soils formed on glaciolacustrine or alluvial sediments, contain some volcanic ash, and have 0%–18% clay. They have a high content of very fine sand, they are friable when moist and loose when dry, and they exhibit low cohesion. The soils have good drainage, but are susceptible to lateral erosion by the Merced River. The inherent erodible nature of streambank material for most of the length of the Merced River in Yosemite Valley makes the banks very susceptible to changes in bank resistance or erosive forces.

Man-made structures, such as revetments, diversion ditches, wing walls, groins, pipe dams, and bridges affect river flow and channel morphology and are apparent in many places along the Merced River. Effects of such structures range from the positive (providing clear resource protection) to the negative (accelerating erosion and threatening both developments and natural resources).

Several foot and vehicle bridges cross the Merced River in Yosemite Valley. Many of these bridges are decades old, and eight are listed on the National Register of Historic Places. In a natural river channel, the streambanks are either vertical or sloping back away from the stream, so that as flows increase, channel width and cross-sectional area also increase. However, the situation is reversed at many bridges on the Merced River. The arched bridges confine the flow, and actually produce a narrower channel at higher flows (Figure 12). Six bridges in the upper reach are an average of 38% narrower than the unconstrained channel immediately upstream of them (Milestone 1978). Bridge constriction causes several problems. First, flow velocity increases at the constriction, resulting in scour at the bridges. Deep scour holes and scour around bridge abutments were both evident at bridges with constrictions. Second, if all flow cannot be conveyed under the bridge at high discharge, water can become backed up behind the bridge. Low-lying areas or overflow channels can become flooded by the backwater. The release of backwater through overflow channels has caused locally severe erosion problems in Yosemite Valley. One overflow channel, at Sugarpine Bridge, widened from 4 to 17 m since 1919, and presently threatens roads, campsites, and the bridge itself. Sediment scoured from bridge sites was deposited in mid-channel bars downstream of the bridges, and streamflow was directed against the streambanks, causing widespread erosion.

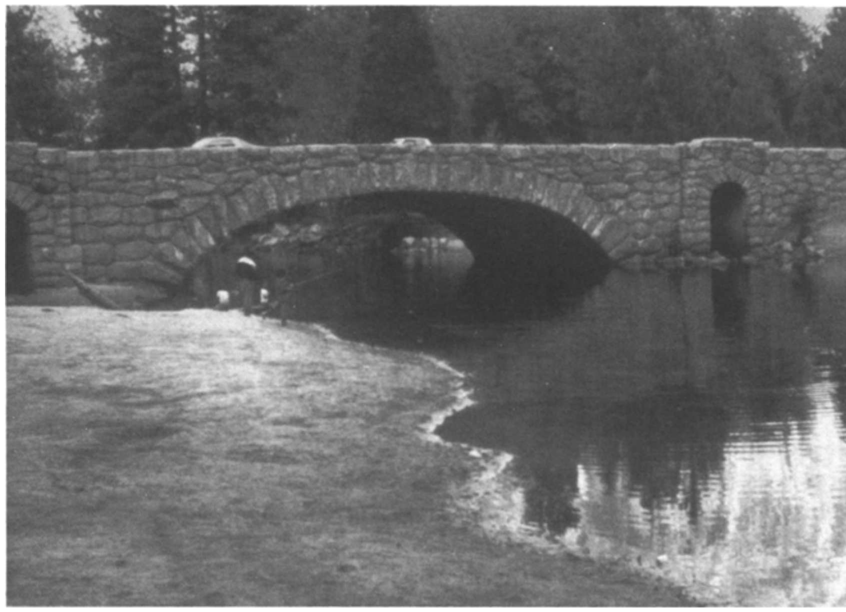

Figure 12. View looking upstream at Stoneman Bridge showing arched design and bridge abutments in active channel, both of which constrict flow at high discharges. Channel widening has caused walkways at side to presently be within active channel.

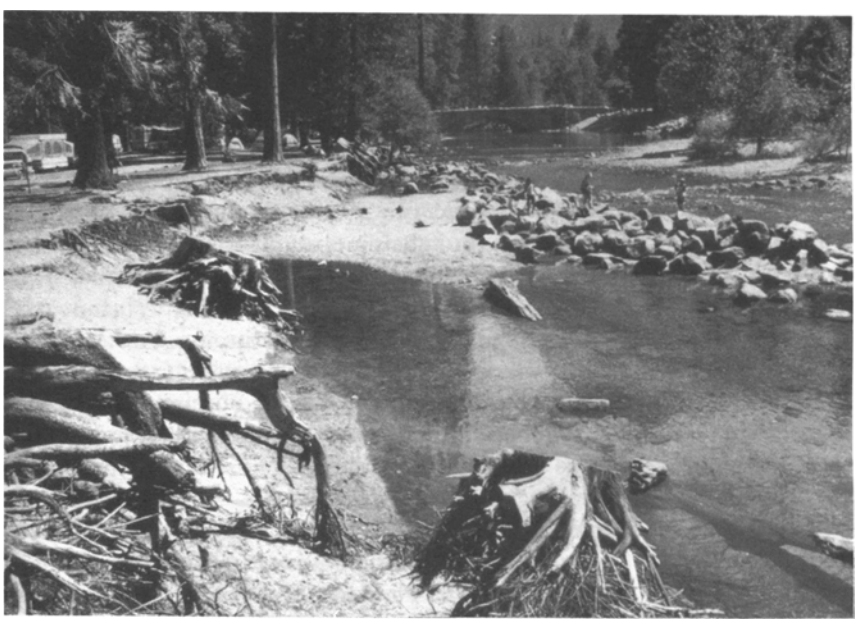

Figure 13. View upstream of Merced River in the upper study reach. Right bank has eroded 25 m since 1919, and riprap formerly on the bank is now in mid-channel. Trees undercut by bank erosion were cut down to reduce threats to visitors, leaving stumps in channel.

The presence of revetment is common along the banks of the Merced River and some of its tributaries. Installation of revetment reached its peak during the 1930s and reflects many different methods. It varies from small (20 cm) hand-placed rocks to large (60- to 100-cm) boulders dumped along the bank by heavy equipment. If well designed, channel revetments can protect streambanks; however, poorly designed structures caused localized scour and lateral erosion in several locations in the upper study reach (Figure 13).

Historical photographs show that large and small woody debris was a common occurrence on the banks and in the channel of the Merced River in the late 1800s and early 1900s. Sources of woody debris are lateral erosion and local slumping of banks, causing the toppling of trees, shrubs, or clumps of grass. As trees on eroding streambanks become undercut, they eventually fall and either get lodged on the banks or bed or float downstream to other locations. Small detritus (leaves and twigs) also comes from the riparian zone.

In the past, the National Park Service perceived woody debris, especially fallen trees, to be a problem for many reasons. Woody debris can be trapped on bridges at high flows, leading to damage or failure of the bridge. Debris jams can back up water and cause localized flooding. They pose a drowning danger to boaters and swimmers on the river. For these reasons, until 1989, it was park policy to remove woody debris from high use areas along the Merced. Woody debris was removed informally as well. For many years, firewood collection was allowed in the campgrounds. In high use areas the streambanks were denuded of all woody debris, large and small, for this purpose.

Woody debris plays an important role, however, in the aquatic ecosystem and in controlling local channel processes (Sullivan and others 1987). Small organic debris provides nutrients for aquatic organisms, which is especially important in this low sediment yield river. Fallen trees and stumps provide cover and shade for fish. They cause local scour in the streambed to form pools. Trees lying parallel to the flow at the base of banks can provide natural protection from eroding forces of the river. Accumulations of debris at the base of banks can also discourage humans from using those areas as easy access routes to the river, and thus protect the bank from trampling.

There is a striking difference in the abundance of large and small woody debris between the two study reaches. We mapped pieces of debris >25 cm in diameter in the river channel in the study reaches. The upper reach had 12 pieces/km of river, and the lower reach had 29 pieces/km. The value for the lower reach is a minimum because not all woody debris in deep pools was counted. Kisanuki and Shaw (1992) showed that 54% of the average total cover for fish habitat in the downstream reach was due to woody debris, whereas only 21% of total cover in the upper reach could be attributed to woody debris.

Besides contributing woody debris to channels, riparian vegetation is also important to stream channel stability by its contribution to flow resistance. The abundance of riparian vegetation has diminished significantly during this century, especially in campgrounds that were established in the 1930s (Gibbens and Heady 1964):

> Before campgrounds were established the river banks supported a thick cover of shrubs and herbaceous plants; today, herbaceous plants are gone and the remaining azalea clumps have been broken by people . . . An indication of what would happen in the present campgrounds if people were excluded was furnished by the temporary closing of campgrounds 7 and 15 during 1943, 1944, and 1945 . . . Tree seedlings appeared and herbaceous plants recovered rapidly, especially near protected spots and guard rails at camp boundaries where the seed source was located. Several campgrounds, abandoned for sanitary reasons soon after 1906 and still not in use as campgrounds, now show no evidence of past trampling.

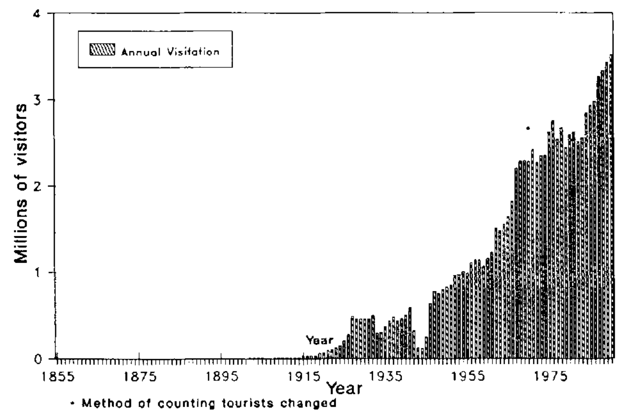

Figure 14. Number of tourists visiting Yosemite National Park (1855–1990). Current visitation is over 3,500,000 people per year.

Trampling by cattle can severely damage streambanks and riparian vegetation (Platts and Nelson 1985), but the effects of human trampling on streambank stability have not been quantified. Impacts depend on the type of trampling, soil type, and type of vegetative cover. In a study of the effects of human trampling on subalpine vegetation in Yosemite National Park, Holmes and Dobson (1976) broke trampling into several categories: shearing, crushing, toe/heel gouging, grinding, and ripping. Although the study was in a subalpine environment rather than the mixed conifer forest typical of Yosemite Valley, several generalizations probably are applicable to conditions in the valley. Solitary plants were vulnerable to gouging, especially when soil was soft and sandy. Defoliation and breakage of vegetation resulted from shearing and crushing. Moist peaty soils had the most resistant plants. Plant survival decreased with slope, because there was more gouging and less soil moisture. Layered and mixed communities had higher resistance to damage by trampling than pure stands of the same species. Soil structure itself changed with trampling and exhibited an increase in bulk density and a decrease in percent water content. Foster and Samson (1992) also reported higher bulk densities on heavily used campsites in Yosemite Valley than in low use sites and that compaction is a limiting factor for vegetative growth in heavily used areas.

The intensity of human use increased simply during this century, especially in the upper reach. Figure 14 shows the dramatic increase in tourist travel since

1920; in 1991 Yosemite National Park had over 3.5 million visitors. Although no figures are available for the number of people actually walking on the banks of the Merced River, the National Park Service estimates that 90% of the tourists coming to Yosemite National Park visit Yosemite Valley (near the upper study reach). Over 1000 campsites are within 500 m of the Merced River's upper study reach, and these frequently fill during peak visitation months. In addition, a large but unquantified number of rafters uses the upper study reach of the Merced River. Trampling at raft put-in and take-out locations is especially severe.

Human trampling damages or destroys riparian vegetation, thereby reducing bank stability. To evaluate bank stability, we used a procedure developed by the US Bureau of Land Management to rate riparian sites, which considers both physical and vegetative characteristics. Streambanks are first rated separately for soil stability and percent vegetative cover, then ratings are averaged to obtain a value for mean bank stability for right and left banks. Banks were not rated if they were artificially stabilized by channel armor.

The first rating, described by Platts and others (1987), is a streambank soil alteration rating in which streambanks are evaluated on the basis of how much the banks are physically altered and eroded. The presence of large tree roots and grain size of the streambank material also influences the ratings because a bank with many cobbles or thick roots is less erodible than a sandy bank. Ratings range from a value of 4, where streambanks are stable and less than 25% of the bank along a transect line is eroding, to 1, where streambanks are severely altered and over 75% of the streambank is eroding.

The second assessment used, a vegetative bank protection rating (Pfankuch 1975), is based on vegetative cover and the presence of a continuous rootmat. A rating value of 4 means a combination of trees, shrubs, grass, and forbs covers more than 90% of the ground. Growth is vigorous, with a deep, dense root mat present. The lowest rating value of 1 is given where less than 50% of the ground is covered, trees are absent, growth and reproduction vigor are poor, and root mats are discontinuous and shallow. Many transects in Yosemite Valley displayed 0% ground cover.

To compare bank stability with the degree of human use, an estimate of trampling intensity was needed. Because actual numbers documenting people walking on the streambanks were unavailable, we used a surrogate variable of whether the bank at the cross section transect was a high use or low use site,

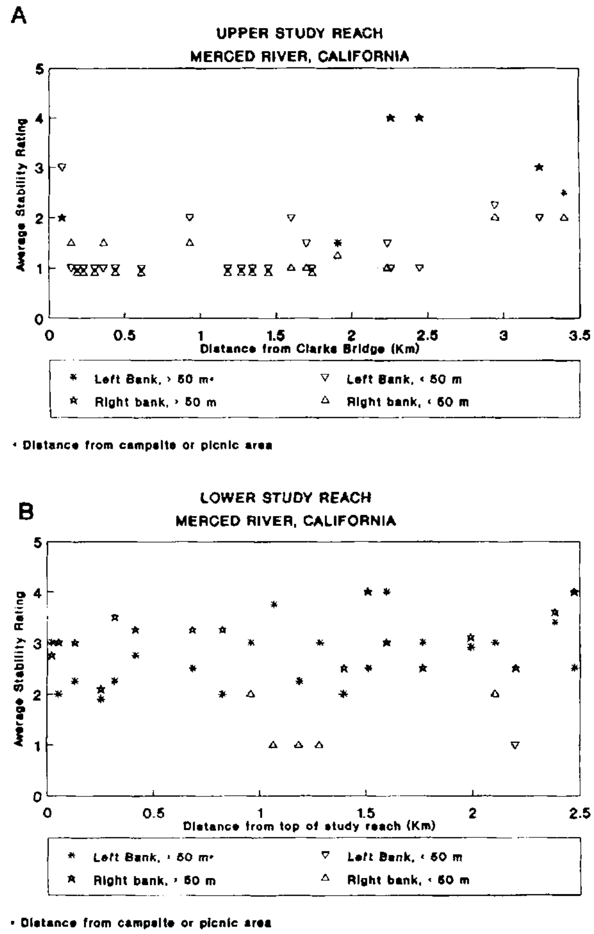

Figure 15. Streambank stability ratings versus intensity of visitor use in the upper and lower study reaches.

that is, greater than or less than 50 m from a campsite or picnic area, respectively.

Figure 15 shows the strong association of low bank stability ratings with high use areas. In the upstream study reach, 95% of the banks that rated ≤2 were high use sites, and 80% of sites rating >2 were low use sites. In the downstream study reach, 55% of the banks that rated ≤2 were high use sites, and 100% of sites rating >2 were low use sites. Currently, high use areas have much less vegetative cover and more actively eroding banks than low use sites, and all sites with 0% vegetative cover were high use areas.

In addition, the degree of channel widening was compared with bank stability ratings (Figure 16). In this case, left and right bank ratings were averaged for an overall rating at a cross section. There is a general inverse relationship between the amount of channel widening since 1919 (percent increase or decrease in channel width) and bank stability ratings (r = 0.59).

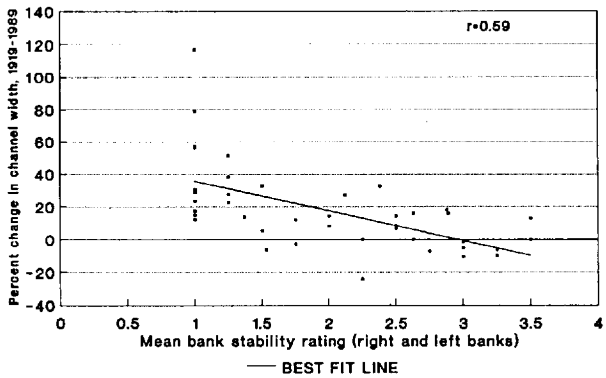

Figure 16. Percent change in channel width versus mean bank stability ratings for the upper and lower study reaches combined.

Furthermore, *all* cross sections that exhibited more than a 20% increase in channel width were in high use areas.

A limitation of this analysis is that present vegetative cover and soil stability may not reflect streambank conditions several decades ago when erosion may have occurred. For example, streambanks along an abandoned campground are now well vegetated, but the present channel width is still greater than the 1919 width.

Based on the work of Holmes and Dobson (1976), the Soil Conservation Service (USDA 1992), Foster and Samson (1992), and our field measurements, we believe human trampling accelerated bank erosion by its damage to vegetation and disturbance to soils. Once plants are damaged, they provide less protection to streambanks, and when the soil is disturbed, it is difficult for new vegetation to become established. Streambank material along the Merced River is friable and susceptible to gouging, especially where banks are moderately to steeply sloping.

Recommendations for Park Management

Based on the above results, several recommendations and pilot project descriptions were presented to park management to diminish the threat of bank erosion to park resources (Madej and others 1991). Human access and foot traffic need to be controlled in the riparian zone and could be directed to stable or depositional areas such as point bars, or onto hardened access points (such as wooden stairs). Problem bridges could be removed or replaced with better-designed structures. Problem revetment could be removed, and any remaining channel armor could be heavily planted. The riparian zone needs to be aggressively replanted with appropriate native plant material and carefully protected from further trampling. Biotechnical controls incorporating both structures and vegetation could be used to protect critical areas. Woody debris could be allowed to remain in the river channel wherever possible. River resources and management should be included in long-term planning goals, and the public should be informed of restoration goals. Finally, long-term monitoring of stream channel stability should be established.

Summary and Conclusions

Channel changes were documented in two study reaches of the Merced River in Yosemite Valley through a review of historical photographs and documents and a comparison of present channel widths and bed elevations to those surveyed in 1919. Since 1919 the Merced River has deepened only at bridge sites with channel gradient remaining about the same. However, bank erosion and channel widening have been rampant in the upper reach. Bank erosion and channel widening were especially prevalent in areas with concentrated human use, such as campgrounds. In the upper, heavily used reach, banks eroded on both straight and meandering reaches. The lower reach, with only localized day use, exhibited much less bank erosion, and banks only eroded on meanders. Woody debris was more common in the lower reach as well.

Possible causes of bank erosion were evaluated, including changes in precipitation, water yield and flood peaks, low flow diversions, change in sediment loads, man-made structures, and human trampling. No change in climatic or hydrologic trends could account for the degree of bank erosion that occurred since 1919. The degree of channel widening was inversely correlated with bank stability ratings. Low bank stability ratings were strongly associated with high human use areas. Trampling by humans and flow constriction by bridges, locally aggravated by revetment placement, were the most probable causes of the erosion problems.

Several possible actions to reduce future human-caused damage may be considered. Where bridges constrict flow, they cause localized erosion and should be replaced or removed. Where channel armor is nonfunctional or causing streambank erosion, it should be removed and banks need to be aggressively replanted. Biotechnical bank protection devices may be used in critical areas to provide a base for revegetation. Visitor access to the river should be focused onto point bars and pedestrian foot traffic should be actively discouraged across steep streambanks. Woody debris should be allowed to remain in the channel wherever possible. These steps to river restoration should be accompanied by vigorous education of the public, because without cooperation of the over three million visitors to Yosemite Valley each year, human trampling will continue to destroy riparian vegetation, allowing channel widening to continue.

Acknowledgments

We would like to thank the Resource Management staff, park forester, landscape architect, and park historian at Yosemite National Park for their help and information. Vicki Ozaki, Randy Klein, Dave Best, Carrie Jones, Kelly Helstrom, and Ray Alvarado provided assistance throughout many phases of the project. We are grateful to the reviewers whose comments helped strengthen this manuscript.

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