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WOODY VEGETATION AND RIPRAP STABILITY ALONG THE SACRAMENTO RIVER MILE 84.5-119[1]

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ABSTRACT: Stability of vegetated and bare riprap revetments along a Sacramento River reach during the flood of record was assessed. Revetment damages resulting from the flood were identified using records provided by the U.S. Army Corps of Engineers and verified by contacts with local interests. Vegetation on revetments along a 35.6-mile reach was mapped using inspection records and stereo interpretation of aerial photos taken shortly before and after the flood. A follow-up field inspection was conducted in September 1989. Revetment age, material, bank curvature, vegetation, and damage were mapped from a boat. Mapping results from both 1986 and 1989 were placed in a data base. About 70 percent of the bank line of the study reach was revetted. About two-thirds of the revetment was cobble; one-third was quarry stone. Revetment vegetation varied from none to large (> 50-inch diameter) cottonwoods. About 10 percent of the revetted bank line supported some type of woody vegetation. Damage rates for revetments supporting woody vegetation tended to be lower than for unvegetated revetments of the same age located on banks of similar curvature. Chi-squared tests indicated damage rates were greater for older (pre-1950 construction) revetments, but were unable to detect differences based on vegetation or bank curvature. Research is needed to generate design criteria and construction techniques to allow routine use of woody plants in bank protection structures.
(KEY TERMS: riprap; streambank protection; riparian zone; vegetation; flood control; hydraulics; sedimentation; Sacramento River; remote sensing.)

INTRODUCTION

Stone blankets, also called riprap revetments, are widely used for streambank protection throughout North America. Sediment often deposits in riprap interstices and sometimes on top of the stone blanket. If the revetments are not maintained (e.g., mowed or sprayed with herbicide) these deposits are rapidly colonized by brush and pioneering woody plant species such as willow (*Salix* spp.) and cottonwood (*Populus deltoides*) (Figure 1) (U.S. Army Corps of Engineers, 1981; Webb and Klimas, 1988; Dennis *et al.*, 1984). Periodic maintenance of revetment vegetation reduces woody species richness as well as plant cover and numbers (Finn and Villa, 1979; Forbes *et al.*, 1976).

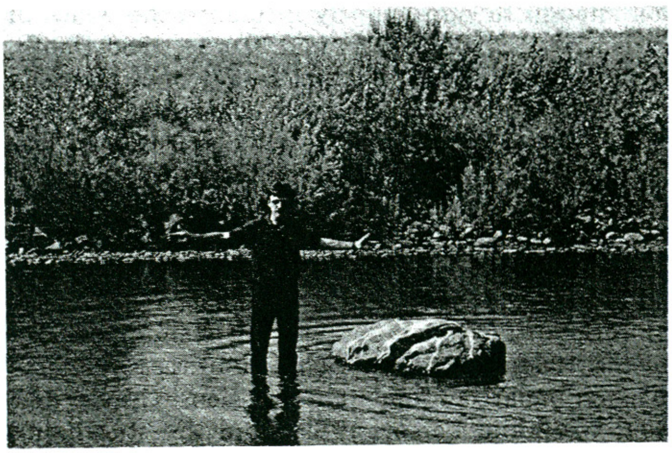

Figure 1. Invasion of Riprap Revetment by Pioneering Woody Species.

Riprap revetments are designed without consideration of sediment deposits or woody vegetation, and engineers often differ in their opinions of effects of woody vegetation on revetment performance. Application of federal regulations governing maintenance of flood protection works (Code of Federal Regulations, Title 33, Section 208.10) to maintenance of revetment vegetation varies regionally (Shields *et al.*, 1990). The purpose of this paper is to describe results of an empirical study of a particular river

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reach that may prove helpful to engineers who wish to advance the state of the art of riprap design to include vegetative factors.

Potential detrimental effects ascribed to vegetation include reduction of channel conveyance, impairment of revetment visibility for inspection, hindrance of flood-fighting activities, and adverse effects on revetment durability. Potential effects of vegetation on durability involve several hypothetical mechanisms. For example, flow around large stems and the debris they trap may locally scour riprap. Discontinuities in rock blanket created by growth or uprooting of large trees by wind or water flow have also been suggested as potential hazards. Anecdotal evidence is frequently cited for piping through earthen levees induced by woody plant roots (Gray *et al.*, 1991). This paper does not deal with effects of vegetation on levees.

Potential beneficial effects of volunteer woody vegetation on revetment stability, channel conveyance, and environmental resources have also been recognized. Woody riparian vegetation controls bank erosion enough to significantly influence the width of smaller river channels (Hey and Thorne, 1986; Smith, 1976; Odgaard, 1987) but not larger ones (Nanson and Hickin, 1986). Bank height and angle possibly control vegetative influence on bank erosion, with less vegetative control for high, steep banks. Woody vegetation planted on banks, either alone or in combinations with structures, has been widely proposed and used for streambank protection (Schiechtl, 1980; Gray and Leiser, 1982; Fridl and Demetrious, 1982; Bowie, 1982; Schultze and Wilcox, 1985; Henderson and Shields, 1984; Henderson, 1986). Plant roots reinforce soils and impart an "apparent cohesion" (Gray *et al.*, 1991; Gray and Leiser, 1982), and the stabilizing influence of volunteer woody vegetation on riprap has also been recognized (U.S. Army Corps of Engineers, 1981). The value of grass as a component in dam spillway lining composed of layers of geotextile and concrete blocks with cells filled with soil and turf has been quantified (Hewlett *et al.*, 1987). Shade from bank vegetation can prevent invasion and partial obstruction of the channel by terrestrial and aquatic plants.

In some cases, revetment can foster and promote development of riparian vegetation (DeBano and Heede, 1987). Since revetment vegetation occurs along riparian corridors, its habitat value per unit area is greater than similar vegetation in blocks away from waterways. Riparian corridors are used for avian migration routes through developed areas (Decamps *et al.*, 1987) and influence avian population density and diversity in adjacent agricultural fields (Henke and Stone, 1978). Although a vegetated revetment is not as valuable as natural riparian zones, it does provide surrogate habitat more valuable than bare riprap (Dennis *et al.*, 1984). Forbes *et al.* (1976), found vegetated Willamette River revetments supported 2.6 times as many birds and 1.4 times as many bird species as recently cleared revetments. Woody vegetation on revetments close enough to the water to provide shade and detritus benefits aquatic habitats. Visual resources of the river corridor are generally improved when revetments are vegetated.

Civil engineers often lack expertise in developing designs that use planted or volunteer vegetation (Bache and Coppin, 1989). Indeed, expertise for using woody species is often beyond the state of the art, although qualitative, conceptual guidance is provided by Seibert (1968) and Schiechtl (1980) among others. Quantitative design criteria for streambank protection works composed wholly or partially of woody vegetation are needed to assist designers in selecting species, prescribing construction and plant establishment techniques, and specifying operation and maintenance procedures. Limited research is underway to address some of these concerns (Bowie, 1982; personal communications, A. J. Bowie, U.S. Agricultural Research Service, and H. H. Allen, U.S. Army Engineer Waterways Experiment Station, 1990). In the absence of research results, judgment, observation, and empirical study are useful. This paper describes an empirical study performed using data from the Sacramento River to assess the validity of stated concerns regarding volunteer woody vegetation and revetment durability.

STUDY AREA

Observations of revetment durability and vegetative conditions were made along a 35.6-mile reach of the Sacramento River in northern California (Figure 2). The Sacramento River basin occupies about 26,300 square miles and consists of a flat valley flanked by abruptly rising mountain ranges. Average discharge at Sacramento is about 25,000 cfs. Prior to European settlement, Sacramento River flood overflowed through gaps in natural levees that flanked the channel and inundated huge expanses of low basins that occupied much of the floodplain. Existing flood control works, which have evolved from efforts initiated over 100 years ago (Kelley, 1989), include storage reservoirs in the headwaters, bypass channels that occupy much of the area of the old basins, rather fragile levees that flank the river and floodway channels, and weirs that convey main channel overflow into the floodways (Mifkovic and Petersen, 1975). Floodway capacity is an order of magnitude greater than river channel capacity. Integrity of the levees, weirs, and other system components is safeguarded by extensive riprap revetment along the river banks. Construction of the flood control system has allowed extensive agricultural and urban development of the floodplain; riparian vegetation occupies only a tiny fraction of the area it previously covered (King, 1984; Frayer *et al.*, 1989).

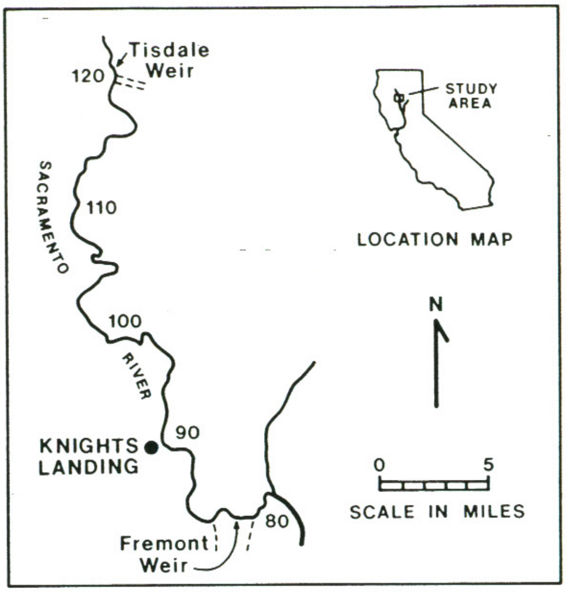
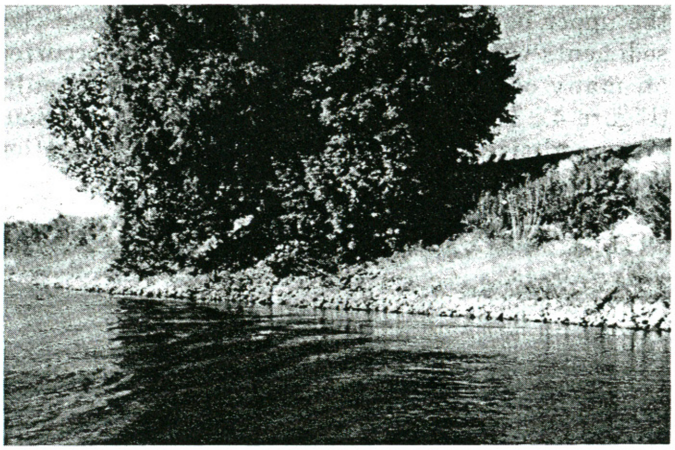


Figure 2. Map of Study Reach. Study reach extended from Fremont Weir to Tisdale Weir. Numerals are river miles.

The study reach extended from River Mile (RM) 84.5 to RM 119 (Figure 2). Reach endpoints were two major overflow weirs, and there were no inflows or outflows during floods. The channel was closely flanked by earthen levees on both sides. A berm ranging from a few tens to several hundred feet wide was between the riverside levee toe and the top of the river bank. Revetments composed of river cobble and angular quarry stone riprap were common on both convex and concave river banks. Most river cobble revetments were constructed prior to 1974; quarry stone revetments were generally more recent. Cobble revetments were placed at a 1V:3H slope and with a blanket thickness of 12 inches above low water elevation and 15 inches on lower elevations. Cobble revetment extended channelward for 10 feet past the bank toe; no toe trench was constructed (U.S. Army Corps of Engineers, Sacramento District (Sacramento District), 1957). The more recent quarry stone revetments were steeper (1V:2 or 2.5H) and thicker (18 inches) below low water, and toe trenches were frequently used (Sacramento District, 1974). Stone size gradations have varied slightly during the period of construction, with maximum sizes generally 70-200 lbs. (12-15 inches screen size) and median sizes ranging from 25 to 75 lbs. (Sacramento District, 1974).

Revetments were maintained by groups of landowners ("local interests"), ostensibly to comply with standards that were prescribed by the Sacramento District (1955). Standards for maintenance of levee and revetment vegetation have been a point of controversy for years (Carter and Anderson, 1984). These standards have historically been interpreted as requiring regular removal of all woody vegetation. Although most of the revetments were maintained free of woody vegetation by manual cutting or application of herbicide, a wide range of woody vegetation types, sizes, and densities were present (Figure 3) because compliance with maintenance standards varied.



a. Sacramento River Mile 109.25.

b. Sacramento River Mile 92.6.

Figure 3. Range of Vegetative Cover Found on Study Reach Revetments.

Reach geomorphology was described by Harvey *et al.* (1989). Channel sinuosity was 1.6, and planform has been extremely stable for many decades. Approximate channel slope was 0.0001, channel width ranged from about 300 to 500 ft., and channel depth from about 27 to 34 ft. Infrequent point bars of sand and finer sediments occurred on a few of the convex banks. Stage-dependent eddies were observed just downstream of point bars.

The river bed was composed of fine sand, while bank sediments were composed of point bar deposits, abandoned channel fill, ancient meander belt deposits, and flood basin deposits. Point bar deposits were stratified materials of varying erosivity. Abandoned channel fills were erosion-resistant silts and clays. Flood basin deposits often occurred as erosion-resistant, impermeable, cohesive strata at the bank toe and seepage on the upper surface of this material sometimes resulted in rotational failures of the upper bank. Longitudinal berms of silt and clay sediments with wedge-shaped cross-sections occurred on many of the revetted and unprotected banks (Figure 4). These deposits were colonized by various types and sizes of herbaceous and woody vegetation (Fischer *et al.*, 1991).

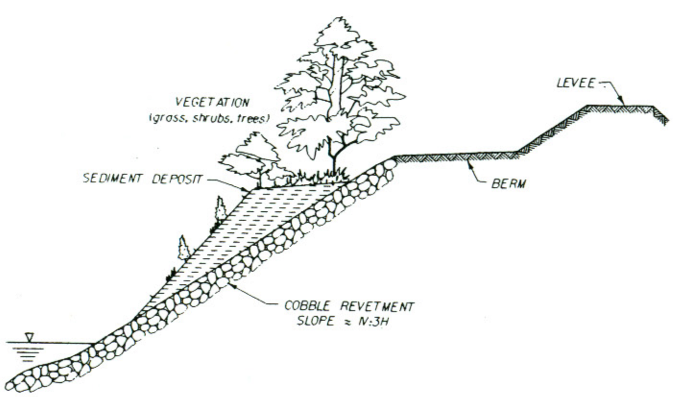


Figure 4. Schematic of Longitudinal Sediment Berms Found in Study Reach (from Shields *et al.*, 1990).

The design capacity of the leveed river channel in the study reach was 30,000 cfs (Sacramento District, 1957). Annual peak discharges have varied little during the period of record (1939-present), and typically approach or slightly exceed the design flow (Figure 5). Low flows are also confined to a rather narrow range. The uniformity of the annual hydrograph reflects the influence of the upstream storage reservoir that augments low flows, and the diversion weir at the upper end of the reach, which limits maximum flows. The highest mean daily discharge during the period of record (32,700 cfs) occurred in February 1986 (Sacramento District, 1987). The Sacramento District (1957) reported maximum point velocities for three cross sections within the study reach of 3.0, 4.2, and 4.4 fps for discharges of 27,000, 27,000, and 23,900 cfs, respectively. Estimated mean velocity at RM 117.6 for the February 1986 peak discharge was 4.2 fps (Shields *et al.*, 1990).

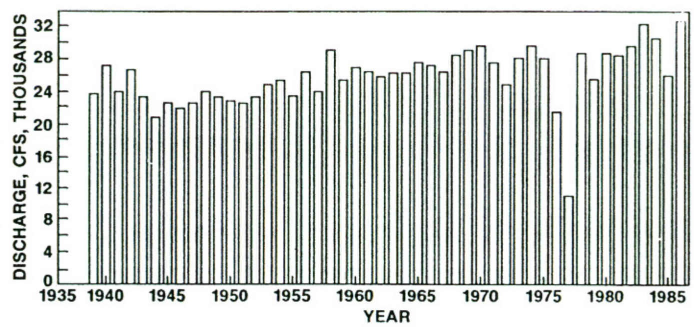


Figure 5. Annual Peak Discharges, Sacramento River at Wilkins Slough, California, Calendar Years 1938-1989.

METHODS

Pre- and post-flood vegetative cover on all revetments located in the study reach was mapped using records of semiannual inspections conducted in the fall of 1985 and spring of 1986 by the California Department of Water Resources, and enlargements of aerial photos taken in 1984-1985 and in 1986-1987. Vegetation presence and size from each time interval and data source were mapped onto a series of overlays to base maps. The base maps were enlarged 1986 photomosaics showing the location and construction date of all revetments. The size of woody plants was assessed using crown size, length of shadows, texture, and stereo interpretation. Vegetation was classified and mapped according to size without regard to density. Three size classes were used: type 1 was bare rock or soil or very low (less than 4 ft. high) herbaceous growth, type 2 included woody vegetation roughly 4-12 ft. high; and type 3 was woody vegetation larger than type 2. Revetment vegetation was also observed and mapped onto a separate overlay during the September 1989 visual inspection of the study reach from a boat. During the field inspection, ten trees growing on revetments located between RM 88.2 and 140.3 were cored and diameters were measured to obtain sizes and age estimates for typical individuals.

Public Law 84-99 authorizes the U.S. Army Corps of Engineers to perform emergency repairs of certain flood control works at federal expense when requested by local interests (U.S. Army Corps of Engineers, 1989). Study reach revetment performance during the 1986 flood was assessed using data from Sacramento District files containing records of requests for flood damage repair from local interests. Results of the file screening were verified by contacting representatives of local interests with revetments in the study reach. Revetment condition in the study reach was also assessed by visual inspections from boats in April (Harvey *et al.,* 1989) and September 1989. A liberal, but repeatable definition of damage (any area of displaced stone larger than about 10 sq. ft.) was used for the September 1989 visual inspection. No attempt was made to screen out damage due to slope failure (geotechnical factors) rather than flow forces (hydraulic factors), since the intent of the study was to detect any association between vegetation and revetment damage, even if causation could not be proved. Revetment damage locations from files and from each visual inspection were separately mapped onto clear mylar overlays to the aforementioned base maps showing locations of all revetments.

A digital database was constructed using the aforementioned base maps and overlays. Revetted bank lines were divided into 100-ft-long segments (hereinafter, "segments") running parallel to the channel; each record in the data base represented a segment. Data base fields included spatial location, bank curvature, construction date, revetment material (cobble or quarry stone riprap), vegetation type from pre- and post-flood inspections, vegetation type from pre- and post-flood aerial photos, and revetment condition (damaged or undamaged). Informal revetments constructed using construction rubble were not included in the data set. Bank curvature was not recorded as a continuous variable; instead, curvature was classified as straight, convex, or concave. Vegetation entries were based on the largest individual plants occurring within each segment. The digital data base was analyzed using graphical techniques, summary statistics, and cross-tabulation.

RESULTS

About 65 percent of the bank line (46.6 of 71.2 miles) in the study reach was covered by revetment at the time of the 1986 flood, and about 67 percent was revetted in September 1989 (Figure 6). About 70 percent of the revetment was composed of cobble, and about 30 percent was quarry stone. The aerial photography showed that about 11 percent of the revetted segments supported woody vegetation types 2 or 3 prior to the flood, but only 9 percent after the flood. perhaps some vegetation was scored away by the flood or removed by maintenance activities intermediate to the photo dates. Both photo coverages showed slightly more type 2 vegetation than type 3. Data from the 1989 visual inspection revealed that about 6.3 and 3.7 percent of the revetted segments supported vegetation types 2 and 3, respectively. The 10 cored trees had diameters ranging from 0.3 to 51.3 inches and estimated ages ranging from 2 to 60 years. Older revetments were more likely to support woody vegetation. Relative to aerial photos, state inspection records under-reported revetment vegetation by about 80 percent, indicating only 3 and 2 percent of the revetted bank line was vegetated before and after the 1986 flood, respectively.

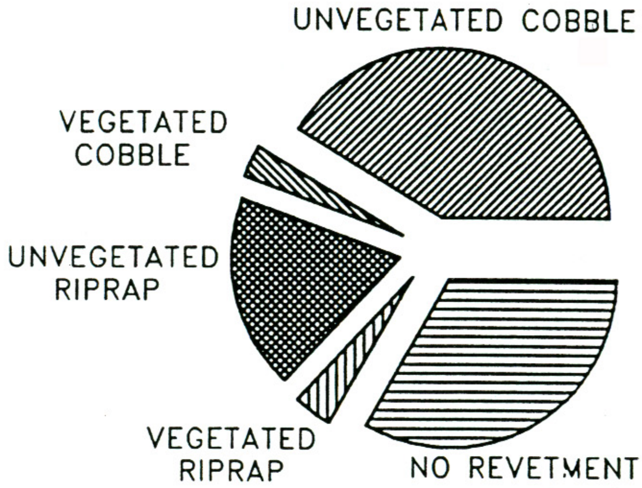


Figure 6. Distribution of Bank Cover Types in Study Reach, September 1989.

Review of the PL 84-99 request files revealed five instances of revetment damage attributed to the 1986 flood in the study reach (Table 1). None of the five sites supported woody vegetation before or after the flood. Only one site had been repaired by 1989, and although displaced stone was clearly visible at the other sites, bank stability was not threatened. Three of the five sites were on convex banks of unusually sharp bends, and damage evidently resulted from flow separation from the point bar and associated turbulence that occurred at high stage as described by Bagnold (1960).

Additional, but slight revetment damage was observed during the September 1989 field inspection. About 2.9 percent of the revetted bank line segments

TABLE 1. 1986 Flood Damages to Revetments, Sacramento River Miles 84.5-119.

River Mile	Material	Date of Construction	Length of Damage (ft)	Remarks
84.6	Cobble	1944	1,000	Rock displaced vertically downward to expose 1 to 3 ft. of bank at waterline.
92.6	Quarry Stone	1979	40	Convex bank. Small point bar has formed just downstream.
94.0	Quarry Stone	1985 (repair)	160	Convex bank. Small point bar has formed just downstream.
99.2	Quarry Stone	1985	120	Slip failure visible as large, semicircular arc in rock blanket.
99.5	Quarry Stone	1979	140	Convex bank. Has failed and been repaired repeatedly.

were classified as damaged. In no case did the stability of banks or adjacent structures appear threatened. Sixty-eight percent of the damaged segments were cobble; 63 percent of the damaged segments were constructed before 1970. Several types of damage were observed, but the most common type consisted of vertical downward displacement of the lower portion of cobble revetment, resulting in exposure of 1 to 3 ft. of near-vertical, cohesive bank just above the normal low-water elevation. Exposures were often periodic, with wavelengths of several feet. Harvey *et al.* (1989), suggested that this pattern was due to heterogeneity of sediments in the underlying banks. Selective erosion of sand-dominated units separated by cohesive units results in local stone displacement. The absence of filter materials and revetment toe trench may have also promoted this type of damage. Local scour of stone blanket downstream of tree trunks was not observed.

To examine relationships between damage rates and the presence of woody vegetation, the data base was divided into 18 subset pairs (Table 2). Each pair contained a subset for unvegetated (type 1) and vegetated (types 2 or 3) revetments. The 18 classifications were based on revetment age (three classes), bank curvature (three classes – straight. concave, or convex), and material types (cobble or quarry stone). Damage rates, defined as the number of damaged segments divided by the total number of revetment segments, were computed for each subset (Table 2). Only 15 of the 18 paired subsets contained data for both vegetated and unvegetated revetments, and some of the categories contained very few segments. For example, the damage rate of 60 percent given for cobble revetments constructed since 1970 on convex banks represents three of only five segments. Damage rates were higher for unvegetated revetments in nine of the 15 instances, higher for vegetated revetments in four instances, and zero for the remaining two subset pairs. In other words, damage rates for revetments supporting woody vegetation tended to be lower than for unvegetated revetments of the same material and age located on banks of similar curvature.

Chi-squared statistics (Neville and Kennedy, 1964) were used to test hypotheses that damage rates were not significantly different for revetment segments grouped by vegetative cover, age, bank curvature, and material (Tables 3, 4, 5, and 6). Data base grouping for chi-squared tests was arranged to obtain expected frequencies greater than or equal to five. Finer subdivisions (such as those shown in Table 2) were not analyzed because of the small number of vegetated revetment segments. Damage rates appeared to be considerably greater for revetments constructed prior to 1950 than for more recent ones, but vegetation, bank curvature, and construction material did not appear to impact revetment durability.

The effect of vegetation on stability of nearby segments was studied by examining the overlays and by plotting a schematic of the entire reach showing damage and vegetation locations. Proximity of vegetation had no bearing on stability.

DISCUSSION AND CONCLUSIONS

Findings of this study regarding the extent of revetment and vegetation were consistent with limited works by others. Sixty-seven percent of the bank line of the study reach was revetted; revetment coverages of 41 (Harvey *et al.*, 1989) and 75 percent (Jones and Stokes Associates, 1987) were reported for

TABLE 2. Percentage of Revetted Bank Line Classified as Damaged, Sacramento River Miles 84.5 to 119, September 1989.

Material	Construction Date	Bank Curvature	Damage Rates: Unvegetated (percent)	Damage Rates: Vegetated (percent)
COBBLE	Pre-1950	Straight	12.00	10.00
		Concave	3.13	0.00
		Convex	23.08	13.33
	1950-1969	Straight	0.56	0.00
		Concave	3.42	0.00
		Convex	0.82	6.45
	1970-Present	Straight	5.45	0.00
		Concave	3.39	11.76
		Convex	0.00	60.00
RIPRAP	Pre-1950	Straight	None in Category	None in Category
		Concave	6.67	0.00
		Convex	33.33	None in Category
	1950-1969	Straight	28.57	0.00
		Concave	0.00	None in Category
		Convex	0.00	0.00
	1970-Present	Straight	1.45	0.00
		Concave	0.00	0.00
		Convex	4.46	9.09

TABLE 3. Contingency Table for Effect of Woody Vegetation on Revetment Durability, Sacramento River Miles 84.5-119, September 1989 (table entries represent classifications of 100-foot long revetment segments).

	Damaged	Undamaged	Totals
Unvegetated	62	2,195	2,257
Vegetated	12	241	253
TOTALS	**74**	**2,436**	**2,510**

Chi-Squared Statistic (corrected for continuity) **2.509**

Probability **0.1132**

We are unable to reject the null hypothesis.

TABLE 4. Contingency Table for Effect of Revetment Age on Revetment Durability, Sacramento River Miles 84.5-119, September 1989 (table entries represent classifications of 100-foot long revetment segments).

	Damaged	Undamaged	Totals
Pre-1950	15	174	189
1950-1969	32	1,266	1,298
1970-1985	27	996	1,023
TOTALS	**74**	**4,946**	**2,510**

Chi-Squared Statistic **17.31**

Probability **0.0002**

Reject the null hypothesis.

TABLE 5. Contingency Table for Effect of Bank Curvature on Revetment Durability, Sacramento River Miles 84.5-119, September 1989 (table entries represent classifications of 100-foot long revetment segments).

	Damaged	Undamaged	Totals
Straight	18	469	487
Convex or Concave	56	1,967	2,023
TOTALS	**74**	**2,436**	**2,510**

Chi-Squared Statistic (corrected for continuity) **0.8792**

Probability **0.3484**

We are unable to reject the null hypothesis.

TABLE 6. Contingency Table for Effect of Revetment Material on Revetment Durability, Sacramento River Miles 84.5-119, September 1989 (table entries represent classifications of 100-foot long revetment segments).

	Damaged	Undamaged	Totals
Cobble	50	1,617	1,667
Riprap	24	843	867
TOTALS	**74**	**2,436**	**2,510**

Chi-Squared Statistic (corrected for continuity) **0.0466**

Probability **0.8291**

We are unable to reject the null hypothesis.

overlapping and downstream reaches, respectively. Ten percent of the revetted bank line supported woody vegetation; others reported figures of 5 to 13 percent for downstream (DeHaven and Weinrich, 1988) and overlapping (Snow, 1987) reaches, respectively (Shields *et al.,* 1990). My data base indicated 2.9 percent of the revetted segments were damaged; Harvey *et al.* (1989), classified 2.4 percent of the revetted bank line in the same reach as damaged based on an April 1989 visual inspection. Segment-by-segment comparison of the two damage tallies revealed that the differences were almost entirely due to our more liberal definition of damage.

Woody vegetation did not impair study reach revetment performance during the 1986 flood. Although the damage rate for vegetated segments was roughly twice as high as for unvegetated segments, this was evidently due to the fact that vegetated revetments were generally older. In fact, when revetments of similar age, material, and location were compared, vegetated revetments were less likely to be damaged. Vegetation may have benefitted revetment stability by increasing bank soil shear strength and by deflecting higher velocities. Although the Sacramento River upstream of our study reach experienced higher velocities and also have substantial lengths of vegetated revetment, only one other instance of Sacramento River revetment damage was identified in the 1986 PL 84-99 request files. A quarry stone revetment at RM 187.1 was damaged, but vegetation was not involved because the revetment was constructed in 1985.

How applicable are the results presented here to other river channels? The findings of this effort would be more conclusive if the data set had contained records for a larger number of vegetated revetment segments. The stability of a given revetment during a given hydrologic event is a complex combination of many factors which vary widely in time and space. Therefore, blind application of these empirical findings to other sites is unwise. However, imposition of a uniform policy of vegetation removal to all sites is similarly unwise. Despite the frequency of objections to woody vegetation on revetments, documented cases of vegetation-induced failure or damage of bank protection works are extremely scarce. Spitz *et al.* (1990), inspected about 100 bank stabilization sites in four northwest Mississippi watersheds and observed sediment deposition and woody vegetation on many of the structures. Although they admitted the possibility that vegetation could be detrimental to structural stability, they reported that vegetation-induced failure mechanisms were not significant at the sites they inspected. Effects of volunteer woody vegetation on revetment durability is likely complex and cannot be classified as positive or negative without consideration of the type and density of vegetation, bank geometry and stratigraphy, and local hydraulic conditions (Thorne and Osman, 1988). Undoubtedly, woody vegetation promotes revetment stability at certain locations. Hewlett *et al.* (1987) presented experimental results showing the reinforcing effect of grass roots on geotextile and cellular concrete channel linings. Grass stems and roots enhanced block interlocking and increased the revetment shear and lift resistance. Similar data are needed for structural bank protection that incorporates woody species. Presumably such data would also define conditions, if any exist, where woody vegetation might be detrimental to revetments. Simple maintenance policies applied uniformly to all channels are unlikely to produce optimal resource management and conservation.

Vegetation maintenance policies for riprap protection on flood control channel banks must address coveyance issues as well as revetment durability. This study did not deal with conveyance, but a few observations are offered. First, revetment that will support woody species occupies only about 10-15 percent of the wetted perimeter of typical cross-sections in the study reach (both banks revetted). Revetment vegetation policy would therefore affect roughness of only a modest portion of the boundary, and trees could be cut to produce patterns of trunks that minimize flow obstruction (Li and Shen, 1973). Furthermore, in this particular situation, flow capacity in the river channel is tightly constrained, but some excess capacity is available in the floodway that receives flow from the diversion weir at the upper end of the reach. Making the reach rougher would probably tend to force more flow into the floodway. However, system response is complex, and careful observation of incremental changes in operation or maintenance policies should precede wholesale change.

Currently available theories are not adequate to predict effects of various bank vegetation maintenance policies on channel hydraulic roughness. Progress in this area is retarded by the difficulty of numerically or physically simulating the geometric complexity and flexibility of woody plants.

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