Changes on Streambanks in the Sierra Nevada Mountains: Perspectives from a Dry and a Wet Year

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Abstract

We summarize the findings of a two-year study of vegetation and streambank erosion on incised streams. We conducted the first year of the research during the sixth year of a drought. During the second year of study, precipitation totals ranged from normal to 200% of normal. The focus of the study was to determine if vegetation established on a bank affects the erosion of or deposition on that bank. During the drought year, most banks showed relatively little change. During the high water year, 27% of all vegetated and 32% of all bare lower banks retreated more than 250 mm. This similarity between vegetated and unvegetated banks indicates that, on the streams studied, vegetation had little effect on bank erosion. Bank retreat was not related to near-bank velocities or to bank steepness. It is possible that herbaceous vegetation showed no effect on the incised streams because the streams were too far from a new dynamic equilibrium. The energy of the hydraulic system may have been greater than the vegetation could withstand.

Introduction

Healthy stream-side vegetation is vital to riparian ecosystems. Vegetation provides fish and wildlife habitat, helps to keep water temperatures low by providing shading, provides bank protection, and enhances stability. Over the past decade, much attention has been given to vegetation as a bank stabilizer. Willow and poplar cuttings are often planted as part of stream restoration and erosion-control measures. But revegetation measures must consider the stream morphology and dynamic state or energy of the stream.

Vegetation is an important component in some stream-bank stability. Plants protect banks by creating a lower-velocity buffer between the soil and the main current's erosional forces (Ree 1949; Hupp & Simon 1991; Roberts & Ludwig 1991). Dense roots can reinforce and protect banks in a rip-rap fashion (Smith 1976; Kamyab 1991; Dunaway et al. 1994). Root mats also reinforce the tensile strength of the soil (Thorne & Tovey 1981; Kleinfelder et al. 1992). Furthermore, plant cover reduces frost susceptibility (Bohn 1987), thereby increasing soil stability (Broms & Yao 1964).

During droughts, low stream flows may allow bank sediments to accumulate at slope toes. These sediments usually would be removed fluvially during normal flow years (Carson & Kirkby 1972). This vegetation may stabilize the bank toe or, in other words, provide basal endpoint control (Carson & Kirkby 1972). Consequently, vegetation may establish on the new substrate (Hupp & Simon 1991). Once lower banks are stabilized by vegetation, and if the incised channel is wide enough to be near a new dynamic equilibrium, streambank erosion along the active channel may decrease (Smith 1976; Millar & Quick 1993). This is an interactive process involving basal endpoint control (Carson & Kirkby 1972) and vegetation growth (Hupp & Simon 1991).

During wet years, the fluvial removal of previously failed bank material at the bank toe maintains a vertical bank that is subject to more failure (Carson & Kirkby 1972). If vegetation establishes at the toe of these banks and is resistant to fluvial forces, it may provide the basal endpoint control or bank-toe stabilization. This stabilization is needed for bank protection. The upper banks, however, may continue to erode until they reach an angle of repose (Carson & Kirkby 1972). Failure of the upper banks is not directly fluvial but is essentially due to gravitational forces (Carson & Kirkby 1972; Schumm 1977; Thorne & Lewin 1979; Thorne & Tovey 1981; Harvey & Watson 1986). Nonfluvial types of bank erosion include slumps (Carson & Kirkby 1972), cantilever failure (Thorne & Tovey 1981), expansion crack and failure (Thorne & Lewin 1979), dry ravel (Thorne & Lewin 1979), and trampling (Elmore & Beschta 1987). These processes will continue until a stable slope configuration such as angle of repose is attained (Carson & Kirkby 1972).

This study focuses on the role of vegetation in streambank retreat and deposition along incised and variably entrenched streams during a two-year study. We con-

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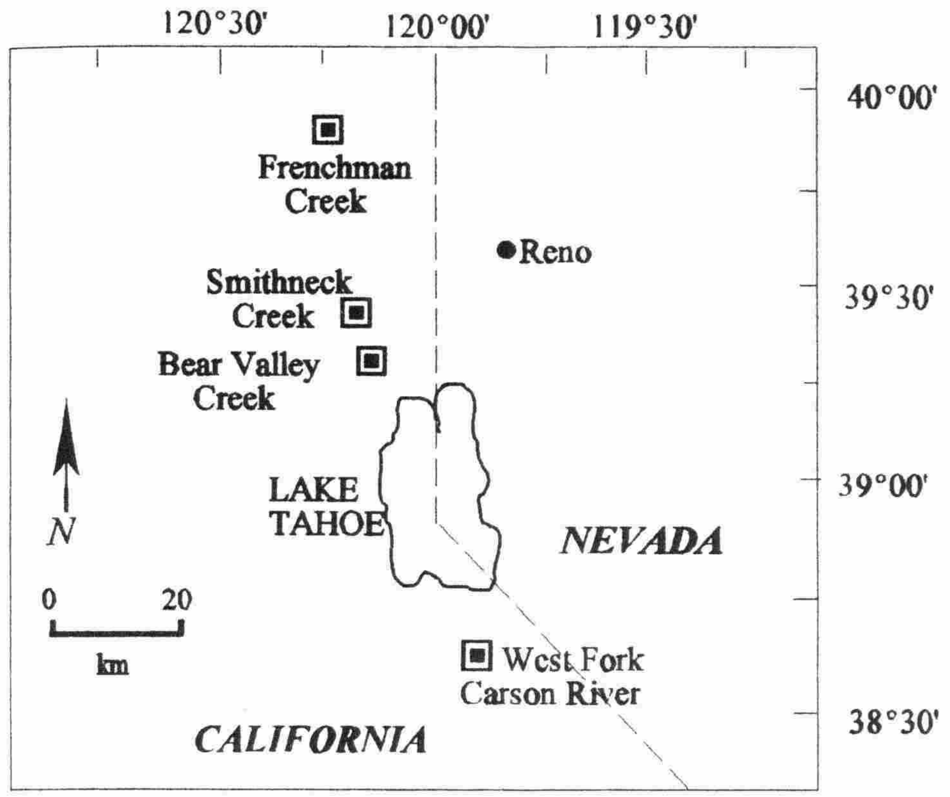


Figure 1. Stream locations.

ducted the first year of the study during the sixth year of a drought and the second year during an above-average precipitation year. Specifically, we tested the following hypotheses: (1) the type of vegetation affects bank erosion or deposition; (2) vegetation influence varies with different bank sections; (3) bank steepness, location, and near-bank velocity affect bank erosion and deposition.

Study Areas

Four streams in the eastern Sierra Nevada Mountains that were similar in character and accessible throughout the winter were selected for study: Smithneck, Bear Valley, and Frenchman Creeks in the Feather River Basin, and the West Fork of the Carson River in Hope Valley (Fig. 1). These creeks drain catchments of 137, 44, 39, and 65 km^2, respectively. The streams range from 1525 to 2100 m in elevation and flow through broad meadows. Bank materials consist of loam, with thin lenses of coarser and finer material ranging from gravel to clay-loam.

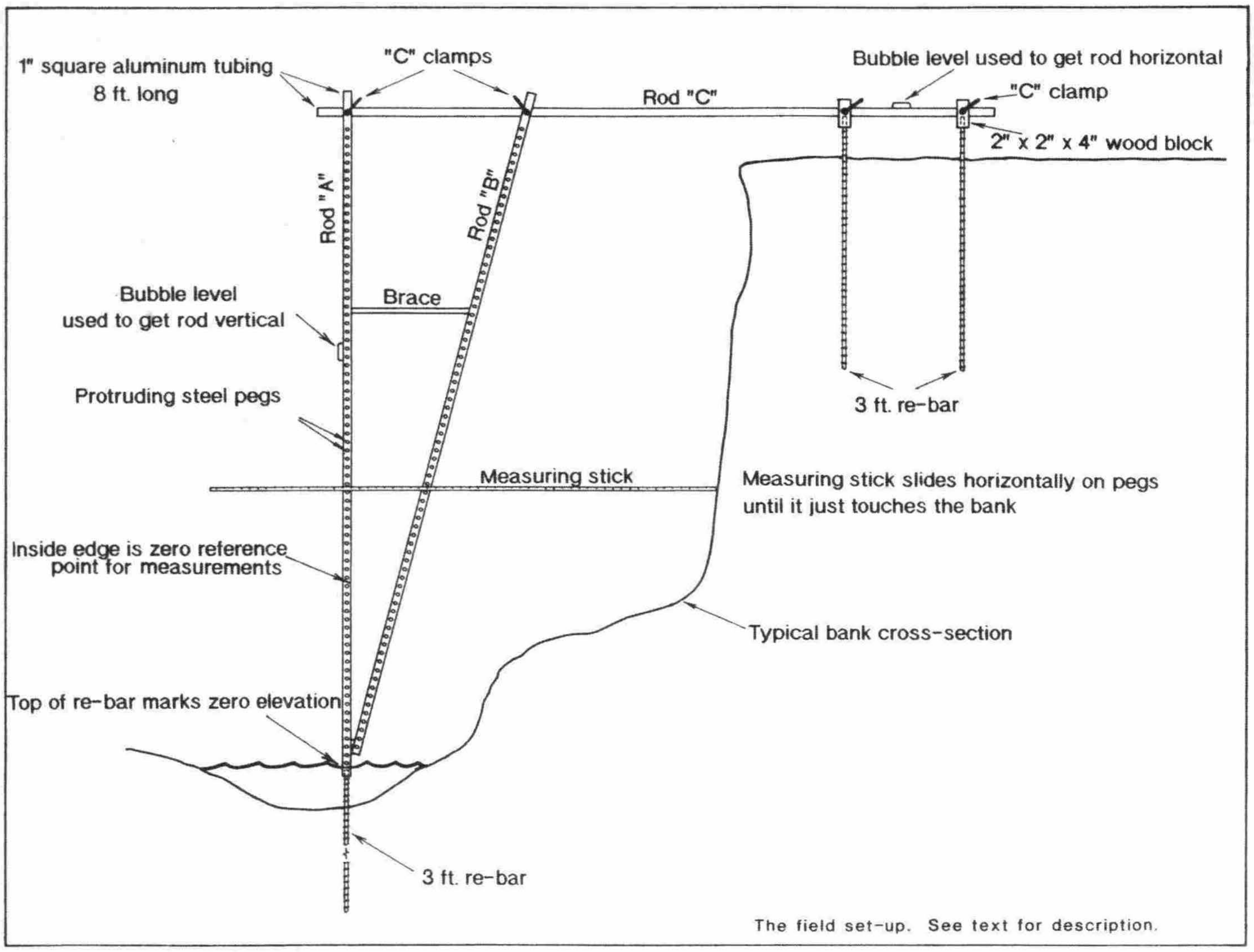
Bed sediments in the stream channels vary from gravel with substantial sand, silt, or clay, to cobble with much less gravel. Some stream sections are locally armored. Active channel forms vary in ratio of width to depth from 3 to 15. But their moderate sinuosity, 1.2 to 1.5, and low gradient, 0.009 to 0.014, suggest that the streams were essentially similar prior to entrenchment. Upstream of the sections studied, three of the four channels are sinuous, narrow, deep, and low in gradient, and they have wide, easily accessible floodplains (E4 in Rosgen's [1994] classification). Currently, stream sections studied are in various stages of transition as C4 (slightly entrenched and wide, with width:depth > 12), G4c (well entrenched and narrow, with w:d = 3–5), F4 (well entrenched and wide, with w:d > 12), or B3c (moderately entrenched, with a partially formed flood plain inside the gully walls and a cobble bed). Young vegetation along the banks indicates that the streams are currently in the process of recovery from a period of accelerated downcutting or widening to a more stable channel configuration under the current conditions (Hupp & Simon 1991). Several active headcuts separate upstream reaches from the downstream study sections. The eroding, high banks caused by degradation and lateral cutting into the old floodplain provided the similarity needed for this study.

Several factors could account for the current configuration of the streams. The overall hydrology of the stream watersheds has changed through time, possibly due to logging and grazing practices. The watersheds were intensively logged from the late 1800s to the early 1900s and are currently logged. The streams also have a history of grazing that dates back to the late 1800s. Smithneck and Bear Valley Creek pastures were used by a dairy until 1975, after which these areas were hayed and grazed in late summer until 1990, when grazing ceased due to a change in land owners. Grazing ceased in 1989 along the West Fork of the Carson River. Grazing from mid-summer to early fall still occurs at Frenchman Creek. Local residents from the Frenchman Creek area have stated that other streams in the vicinity that are now dominated by sagebrush communities due to stream incision once supported meadow communities and successful dairy farms.

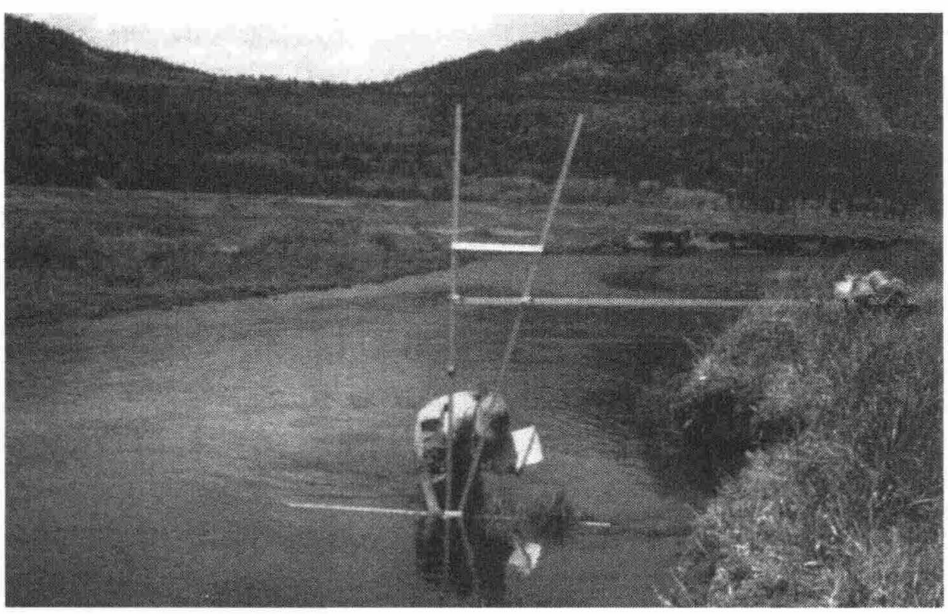
Besides overall changes in watershed hydrology, other more localized disturbances may also have affected the stream dynamics and energy. Local roads and culverts, although fairly distant from the study reaches, could have had far-reaching effects on stream gradients. Lowering of the water table due to diversions or domestic pumps can promote stream incision. Beaver dams can also affect the stream gradient. There are currently no beaver dams along the stream reaches studied and, although beavers could have inhabited the basins, no evidence was found to indicate past beaver occupation.

The reason for the current condition of the streams was not the focus of this study, but it appears that the streams have gone through a hydrologic change and are currently recovering to a more stable configuration. The main question then is whether or not vegetation helped in the recovery process.

We studied a representative 1.5-km reach of each stream. We selected 42 specific study sites along the outside of both sharp and gentle meanders on banks less than 2 m high (for practical reasons), but only 41



a.



b.

Figure 2. (a) The moveable frame set-up used to measure the stream-bank profiles. (b) The moveable frame on the West fork of the Carson River in May 1992.

persisted for analyses. We selected sites at least 3 m apart with a variety of vegetation types, stream velocities, and aspects. To avoid the influences of differing site-boundary conditions, we selected specific locations so that the areas immediately adjacent to the measurement sites were similar in vegetation, soil, and shape.

Methods

We used the device described in detail by Zonge and Swanson (1994) to measure the streambank profiles (Fig. 2) at 127-mm intervals. Additional measurements were taken at intermediate heights as needed to fully define bank irregularities (Fig. 3). This method obtained point measurements along a plane at each site so that changes in cross-sectional area (not volume) were calculated. For this study, we used measurements made during the fall of 1991, 1992, and 1993. We photographed sites at each visit.

During peak annual biomass in early July 1992, we surveyed vegetation within 0.3-m-wide strips (1 foot on either side of each measured streambank profile). Forty-four genera and 67 species provided more than a trace of cover at one or more sites. We divided banks vertically into horizontal sections from the bank top to the water's edge according to obvious changes in vegetation type or density. Vegetation canopy cover was later visually combined into five vegetation groups: monocots (grasses and *Carex–Juncus* species), forbs (other nonwoody, broad-leafed vegetation), bare (less than 50% cover), litter, and exposed roots. These groups were generally associated with different bank positions and therefore composed natural groupings. Likewise, less than 50% cover was used to define bare banks because this was a natural split for the data (Rogers & Schumm 1991).

We classified soils in the field by texture, structure, and consistency using standard methods (Soil Conservation Service 1975). Because the methods involved destructive sampling, soils were classified at the end of

		Profile measurements (in.)*				
Site	Height (in.)	Sept. 91	Sept. 92	Sept. 93	Net Change 91-92 (in)	Net Change 92-93 (in)
LSN-B4	0	7.25	6.50	7.00	0.75	-0.50
	5	8.35	8.10	6.00	0.25	2.10
	10	18.75	13.80	25.50	4.95	-11.70
	15	24.50	22.50	30.50	2.00	-8.00
	20	27.22	28.10	32.50	-0.88	-4.40
	23	28.37	28.50	33.30	-0.13	-4.80
	25	27.00	28.50	34.00	-1.50	-5.50
	30	24.88	25.30	36.30	-0.42	-11.00
	35	21.50	22.50	41.30	-1.00	-18.80
	40	20.69	21.00	43.30	-0.31	-22.30
	47	16.31	17.30	43.30	-0.99	-26.00
	48	16.75	17.50	43.30	-0.75	-25.80
	49	17.50	17.50	44.80	0.00	-27.30

* The measurements listed in this table are in reference to a vertical line in front of the stream bank (see Figure 2).

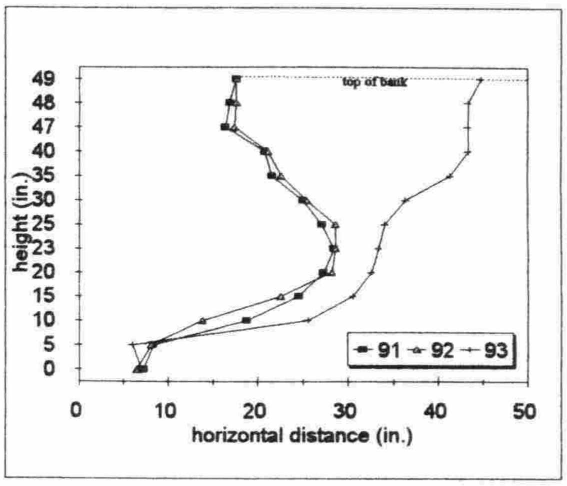


Figure 3. An example of the data collected using the moveable frame in both table and graph form (see Fig. 2).

the field season and a meter away from each actual measuring site. Loam was the predominant soil at all sites.

We measured near-bank velocity in March 1992 during peak run-off using a Marsh-McBurney flow meter. Readings were taken approximately 20 mm away from the bank at 0.8 and 0.5 times the depth and just below the water surface. Due to drought conditions, stages were less than bank full.

Because banks were different heights, we divided them into four morphologic profile segments to allow for bank comparisons: toe-slope, mid-slope, cliff, and top-bank (Fig. 4). The toe-slope comprises the bottom portion of the bank, which is generally wet or moist and subject to fluvial forces during most of the year. The mid-slope is generally drier and less vegetated than the toe. Cliff segments cut into the upper bank are relatively steep or overhanging and do not usually grow vegetation. The top bank comprises the several upper centimeters of the bank and is usually overhanging due to an abundance of dead and a few live roots from plants on the abandoned floodplain.

After banks were divided into segments, we grouped data to account for varying sample point numbers between banks. We averaged data if there was more than one point measured within a segment or vegetation group on a particular bank. We used graphs and simple regression equations to compare bank change with various bank characteristics. The correlation values for these comparisons are summarized and discussed in the following section.

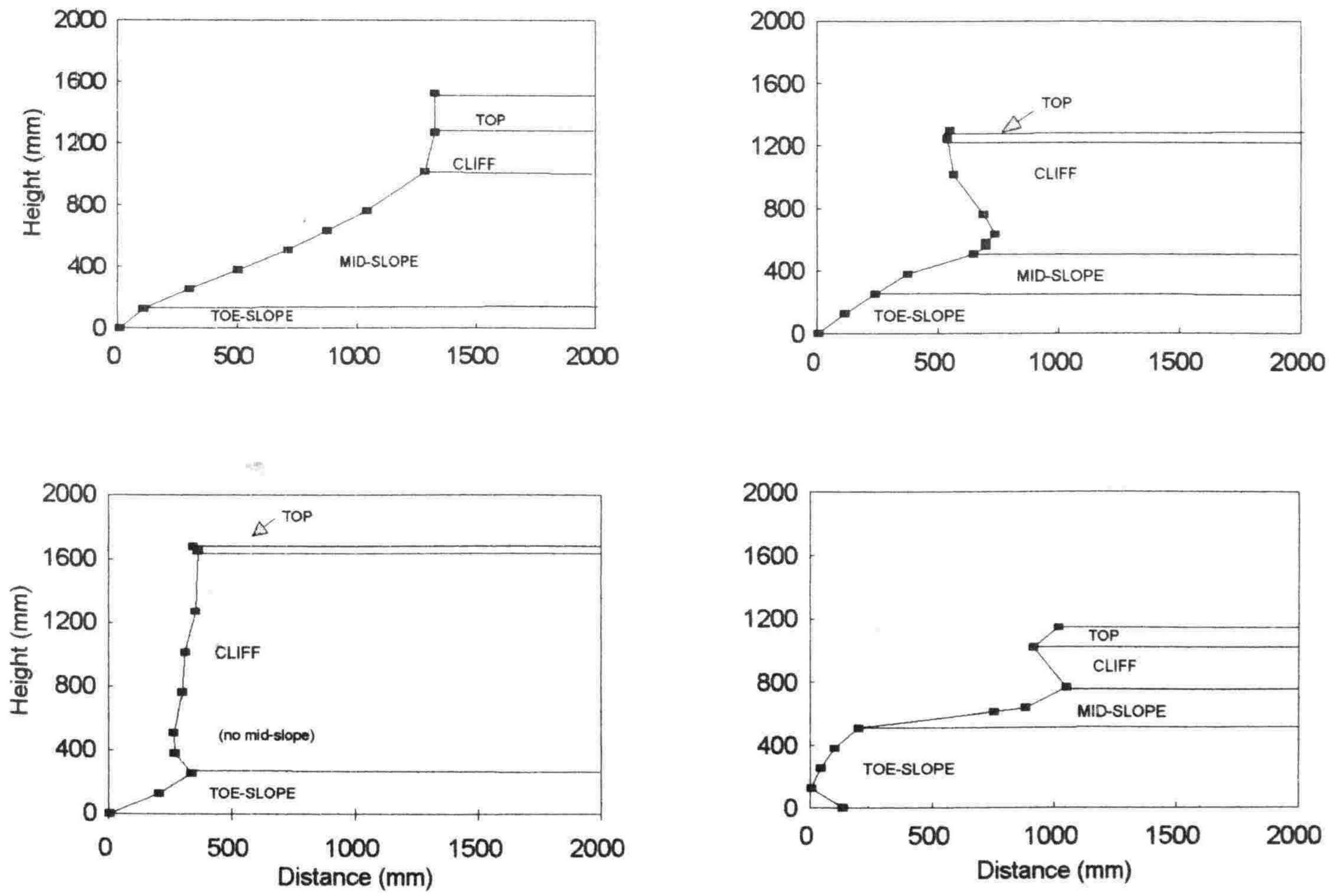


Figure 4. An example of the four types of bank profiles studied and the associated bank segments. The 0 point on the graph is the base of the bank near the water's edge.

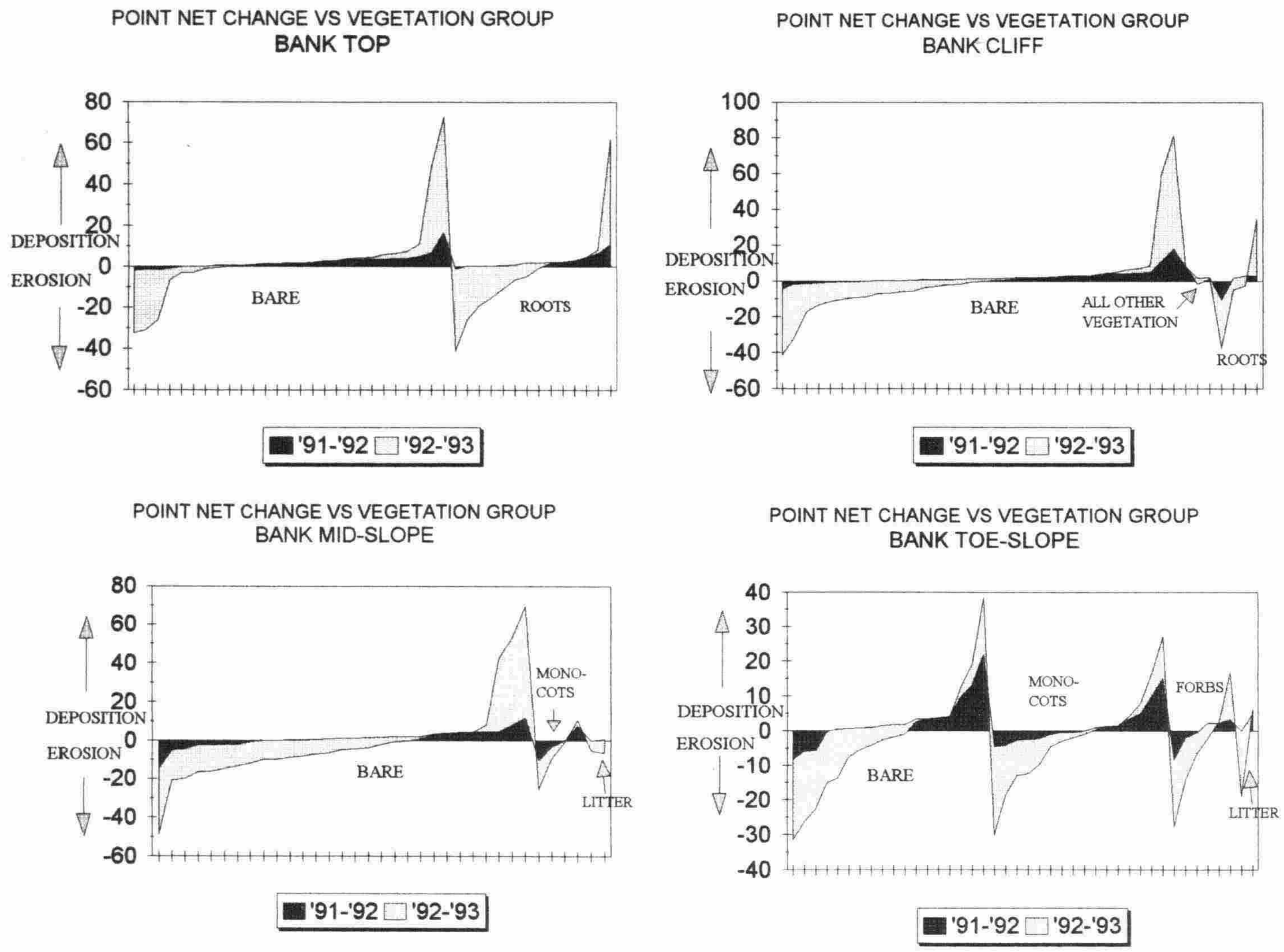


Figure 5. Point net changes versus vegetation type for each bank segment. The graphs represent collective data from all streams studied.

Results and Discussion

The majority of bank segments were dominated by the bare vegetation group (Fig. 5). Vegetation was most abundant on bank toes, probably due to water availability, There were no vegetated sites other than roots in the top segments and too few vegetated sites in the cliff segments for analyses. Both bare and vegetated lower banks (toe- and mid-slope) showed erosion. The percentage of vegetated lower banks that retreated more than 25 cm is very similar to that of bare banks (Table 1). This similarity is contrary to the findings of other authors (Hupp & Simon 1991; Kleinfelder et al. 1992; Dunaway et al. 1994) and indicated that other influential factors are involved, as discussed below.

On the toe- and mid-slopes, monocot-dominated banks were eroded considerably (Fig. 5), contrary to the findings of other authors (Smith 1976; Kleinfelder et al. 1992), probably due to steep bank erosional processes rather than a lack of vegetation strength. Many bank toes originated as collapsed vegetated material from upper banks. During low-flow years, these vegetated mounds of collapsed material were not washed away and were incorporated into the bottom of the bank (Fig. 6). These mounds may have constricted the stream channel during normal- or high-flow periods and were consequently eroded away, as suggested in Figure 5. Note that toe-slope deposition was higher than erosion during the 1991–1992 year and vice versa during the 1992–1993 year.

It is surprising that mid-slopes showed considerable erosion (Fig. 5). As Figure 3 shows, mid-slopes generally have gentle slopes that would be likely locations for soil deposition from the upper banks rather than erosional sites. These data may reflect the common occurrence during the course of the field data collection in which the entire bank eroded. Bare mid-slope sites showed higher deposition than vegetated mid-slopes (Fig. 5). Quite possibly, the bare mid-slope banks were too active to support vegetation (Hupp & Simon 1991).

Note in Figure 5 that the cliff and top segments show "deposition." This is not actually deposition but bank expansion due to crack widening and swelling (Thorne & Tovey 1981). It was quite common to see vertical

Table 1. Percentage of each vegetation group that eroded more than 250 mm during 1992–1993.

Bank Segment	*Bare*	*Monocots*	*Forbs*	*Litter*	*Roots*	*All Vegetation**
Toe- and mid-slopes	32	25	29	33	na	27
All segments	24	25	25	25	35	27

* Monocots, forbs, litter, and roots.

Figure 6. An example of a collapsed vertical bank on Smithneck Creek in May 1992. The grass at the toe of the bank originated at the top of the bank. The collapsed bank material is restricting stream flow and will probably be fluvially removed during higher flows.

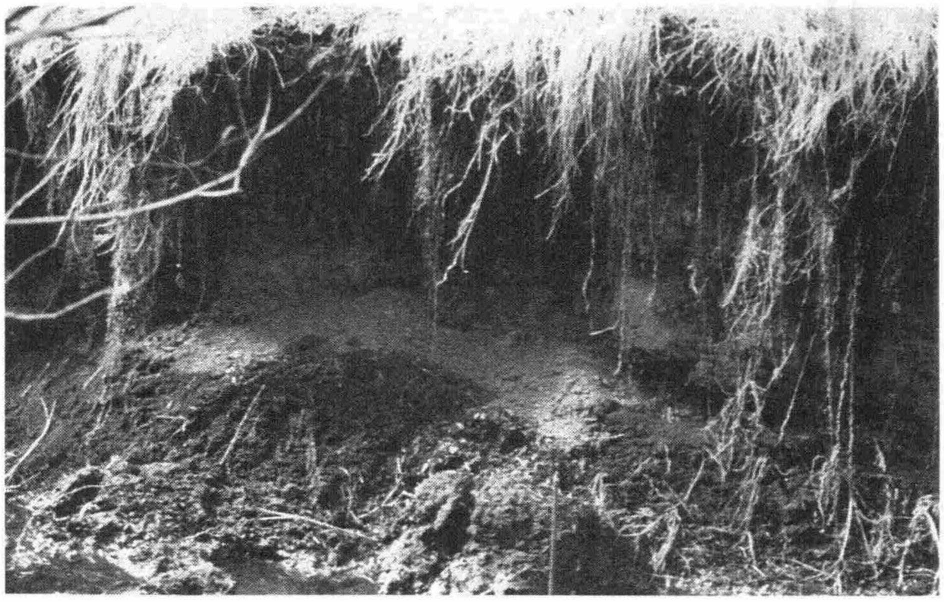


Figure 7. Typical roots exposed in the top-bank on Little Valley Creek in March 1992. Dry roots no longer hold soil.

cracks (sometimes up to 20 mm thick) develop in bare and rooted cliffs parallel to the bank surface, prior to bank collapse. This phenomenon appeared to skew the data more for the dry year than the wet year because there was very little upper-bank erosion during the dry year. Although roots may bind the soil and attenuate upper-bank erosion, once the fine roots are exposed to air and dry soil they become brittle, are no longer able to hold soil, and thus provide little bank protection (Fig. 7).

The wet 1992–1993 year showed considerably more bank change than did the dry 1991–1992 year (Fig. 5). This is a reasonable finding because fluvial forces shape streams (Leopold et al. 1964) and because wet banks are more susceptible to frost action and are thus much more easily eroded (Wolman 1959). There was, however, no statistically significant relationship between bank change and near-bank velocities (Table 2). Near-bank velocities can change dramatically with stream stage, and velocity measurements were taken at flows lower than the formative bank-full flows. Bank-full velocity measurements would probably correlate better with observed bank erosion.

Carson and Kirkby (1972) suggest that bank-slope profiles may indicate different stability stages, with ultimate stability attained when the bank is at an angle of repose. Although no relationship was found when bank angle was plotted against bank erosion (Table 2), more than a third of the banks steepened during the wet year (Table 3). There was no correlation between bank angle and near-bank velocity.

Harvey and Watson (1986) discuss location-for-time substitution as a model of channel evolution. The model is based on observations of a headcut or nick point moving through a watershed from downstream to upstream reaches. The model describes five consecutive conditions ranging from total disequilibrium just downstream of a headcut to a new state of dynamic equilibrium further downstream from the headcut. The model assumes that after a headcut passes through an area the channel begins to recover through floodplain widening. Therefore, the areas farthest downstream of the headcut have had the longest time to recover and therefore should have the most stable channel configu-

Table 2. Chart of r^2 values for comparisons made during analyses.*

	Near-Bank Velocity	*Toe Vegetation*	*All Vegetation*	*Percent Vegetation Cover*	*Percent Bare*	*Bank Height*	*Bank Angle 1991*	*Bank Angle 1992*	*Bank Angle 1993*	*Bank Angle Change 1991–1992*	*Bank Angle Change 1992–1993*	*Upstream and Downstream Location*	*Bank Aspect*
1991–1992													
Total Net Change	0.02	0.001	na	0.001	0.001	0.001	0.04	0.001	0	0.066	na	0.001	0.02
Point Net Change	na	na	0.001	0.003	0.001	0.03	na	na	na	0.01	na	na	na
1992–1993													
Total Net Change	0.006	0.001	na	0.003	0.0001	0.0001	0.0001	0.04	0.003	na	0.26	0.003	0.027
Point Net Change	na	na	0.001	0.001	0.0001	0.0001	na	na	na	na	na	0.001	0.001
Toe Net Change	0.0003	0.001	na	0.001	0.0001	na	na	na	na	na	0.0001	0.0001	0.001
Point Slope	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	na	na	na	0.001	0.001	na	0.001
Velocity	na	0.001	na	na	na	na	na	0.02	0.04	na	0.001	0.001	na

* Total net change is the sum of all change on the bank. Point net change is the net change for each point measured on the bank. Point slope is the bank slope between adjacent points. Bank angle is the angle from the toe to the top of the bank. Aspect is the direction that the bank was facing.

Table 3. Percentage of the banks that changed to a different bank angle during 1991–1993.

	Flatter	*Steeper*	*Neither*
1991–1992	26	15	59
1992–1993	26	36	35

ration. This hypothesis did not hold true for any of the four streams in this study (Table 2). Perhaps the streams were not close enough to a new dynamic equilibrium to show a relationship.

The finding that vegetation was not associated with increased bank stability is contrary to findings of other authors (Hupp & Simon 1991; Kleinfelder et al. 1992; Dunaway et al. 1994). But many factors may have influenced the stream systems that were not accounted for in the analyses. These include entrenchment, width:depth ratios, stream-bed armoring, meandering dynamics of "C" type streams, and stream discharge versus vegetation (size, root structure, strength, etc.). Before stream restoration or revegetation measures are taken, basic stream data must be collected and understood, or time and energy may be literally washed downstream.

Entrenchment and width:depth ratios of stream cross-sections can provide useful stream information when used with bank-full discharge. Rosgen (1994) provides an excellent description of how and why these ratios are determined. The streams we studied were highly entrenched, with low width:depth ratios. When compared to bank full flows, the numbers indicated that the streams had lost accessibility to their floodplain and were in the process of channel-widening to accommodate bank-full flows. These values indicate floodplain accessibility for the stream and can indicate the relative stability of a stream reach. On streams with active headcuts, the area downstream of the headcut by definition has incised and may not have reached a new dynamic equilibrium. In this case, stream power may exceed the stabilizing capabilities of herbaceous and even woody vegetation (Swanson & Myers 1994).

Streambed armoring prevents streams from downcutting. Therefore, streams may erode laterally to accommodate larger flows, especially if the stream no longer has access to its floodplain. Lateral cutting and migration are also integral parts of "C" type streams (Rosgen 1994). When in dynamic equilibrium, these streams cut the outside of meanders as they deposit on point bars. In these cases, vegetation stabilization on the outside of meanders may be futile and hinder the natural "evolutionary" dynamics of the stream. Straight sections or areas high on point bars would be more suitable areas capable of sustaining planted vegetation.

Vegetation is vital to the ecology of riparian areas. It provides wildlife habitat and may help to stabilize soil and nutrients. However, results from this study indicate that the presence of vegetation alone may not be enough to stabilize a stream bank. Past research has suggested that vegetation can bind soil and provide bank protection. Streams are complex systems, however, and there are many factors which influence stream morphology. In some instances, the energy acting on stream banks may be greater than the strength of the riparian vegetation. Vegetation may 'choke' a stream during drought years and be removed during high flow years.

Re-vegetation measures must consider the many complex components of a stream system in order to design a successful stream restoration program. Vegetation plays an important role in restoring a stream channel but must be used with an understanding of the whole watershed including bank-full flows, channel geometries, channel and bank materials, and past and present land uses in order to obtain an effective and successful restoration project.

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