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Drought year changes in streambank profiles on incised streams in the Sierra Nevada Mountains

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Abstract

After streams incise, they evolve through channel widening and adjustment of bank angle and bank shape. The rate of bank erosion and the influence of vegetation on the processes of adjustment on bank morphology are not well understood. To evaluate the role of vegetation in streambank changes, this study included monthly measurements of bank movement along incised streams during a drought. Data were collected throughout one year along four streams in the Sierra Nevada Mountains. Streambank shape varied among five classes: vertical, boomerang, "L", short-cliff, and constant slope. Each shape included similar profile segments: top-bank, cliff, mid-slope, and toe-slope. The bank shapes did not follow location-for-time substitution models and erosion was not related to stream velocity. Relationships among profile shape, profile segment, and vegetation apparently influenced bank erosion, deposition, and net change. Most deposition occurred on vegetated, moderately steep slopes. Conversely, most erosion occurred on steep, bare banks. Rhizomatous plants retarded erosion, whereas forbs often grew in depositional areas.

1. Introduction

Streambank stability has long been a concern for land managers, but the processes involved are incompletely understood. Streams that have recently incised and degraded cause particular concern in the Sierra Nevada Mountains because these streams generally flow through meadows which provide abundant and valuable riparian habitat.

During droughts, low stream flows may allow bank sediments (which would normally be removed fluvially) to accumulate at slope toes (Carson and Kirkby, 1972). Consequently, vegetation may become established on the new substrate (Hupp and Simon, 1991). Once lower banks are stabilized by vegetation, and if the incised channel is wide enough to be near a dynamic equilibrium, streambank erosion along the active channel may decrease (Millar and Quick, 1993; Smith, 1976). This is an interactive process involving basal endpoint control (Carson and Kirkby, 1972) and vegetation growth (Hupp and Simon, 1991). The process is complex, however, and below normal precipitation may also stress upper bank vegetation (Stromberg and Patten, 1990) whose root mats reinforce the tensile strength of the soil (Thorne and Tovey, 1981; Kleinfelder et al., 1992).

Vegetation protects banks by creating a lower velocity buffer between the soil and the erosional forces of the main current (Hupp and Simon, 1991; Ree, 1949; Roberts and Ludwig, 1991). Dense roots can reinforce and protect banks in a rip-rap like fashion (Smith, 1976; Kamyab, 1991; Dunaway et al., 1994). Furthermore, plant cover reduces frost susceptibility (Bohn, 1987), and thereby increases soil stability (Broms and Yao, 1964; Kok and McCool, 1990).

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Overall rates of bank retreat are controlled by fluvial processes. Removal of previously failed bank material keeps the banks vertical and subject to more failure (Carson and Kirkby, 1972). Failure of the upper banks, however, is not directly fluvial but essentially results from gravitational forces (Carson and Kirkby, 1972; Harvey and Watson, 1986; Schumm, 1977; Thorne and Lewin, 1979; Thorne and Tovey, 1981). Non-fluvial types of bank erosion include slumps (Carson and Kirkby, 1972), cantilever failure (Thorne and Tovey, 1981), expansion crack and failure (Thorne and Lewin, 1979), dry ravel (Thorne and Lewin, 1979), and trampling (Elmore and Beschta, 1987).

Carson and Kirkby (1972) suggest that slope profiles may indicate different stability stages with ultimate stability attained when the bank is at an angle of repose. Harvey and Watson (1986) discuss location-for-time-substitution as a model of channel evolution. The model describes five consecutive conditions ranging from total disequilibrium, just downstream of a nick-point, to a new state of dynamic equilibrium, farther downstream. The model assumes that the distance downstream from a nick-point is related to the increased passage of time and, hence, increased channel widening and stability.

This study focuses on the role of vegetation in streambank retreat and deposition along incised and variably entrenched streams during a drought. The study also investigates vegetation as associated with different bank profiles and the amount of bank change which takes place at various heights on the bank. Because the study was conducted during the sixth year of drought, fluvial erosion was atypical and is specifically identified in the text where it occurred.

2. Study areas

Four streams in the eastern Sierra Nevada Mountains that were similar in character and accessible throughout the winter were selected: 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, 65, 44, and 39 square kilometers, respectively. The streams range from 1525 to 2100 meters in elevation and flow through broad meadows. Bank materials consist of loam, with thin lenses of courser and finer material ranging from clay-loam to gravel.

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. Channel forms vary in width/depth ratio from 3 to 15. However, the 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, the channels are sinuous, narrow, deep, low gradient, and have wide easily accessible floodplains (E4 in the classification of Rosgen, 1994). 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 to 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 indicate that the streams are currently in the process of recovery (Hupp and Simon, 1991). The upstream and downstream study reaches are separated by several active headcuts. The eroding, high banks caused by degradation and lateral cutting into the old floodplain provided the similarity needed for this study.

A representative 1.5 km of each stream was selected for study. Within these sections specific study sites were selected along the outside of both sharp and gentle meander bends on banks less than two meters high (for

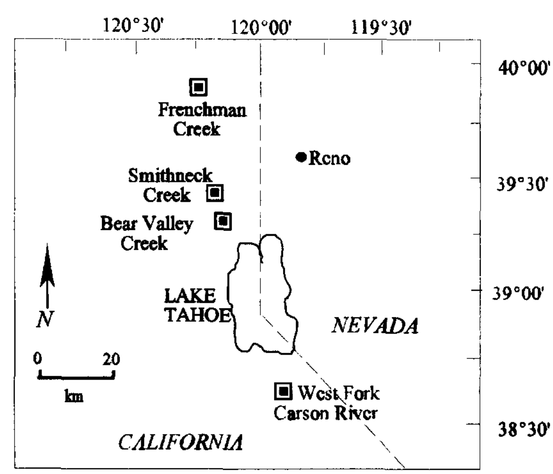

Fig. 1. Location map of study areas.

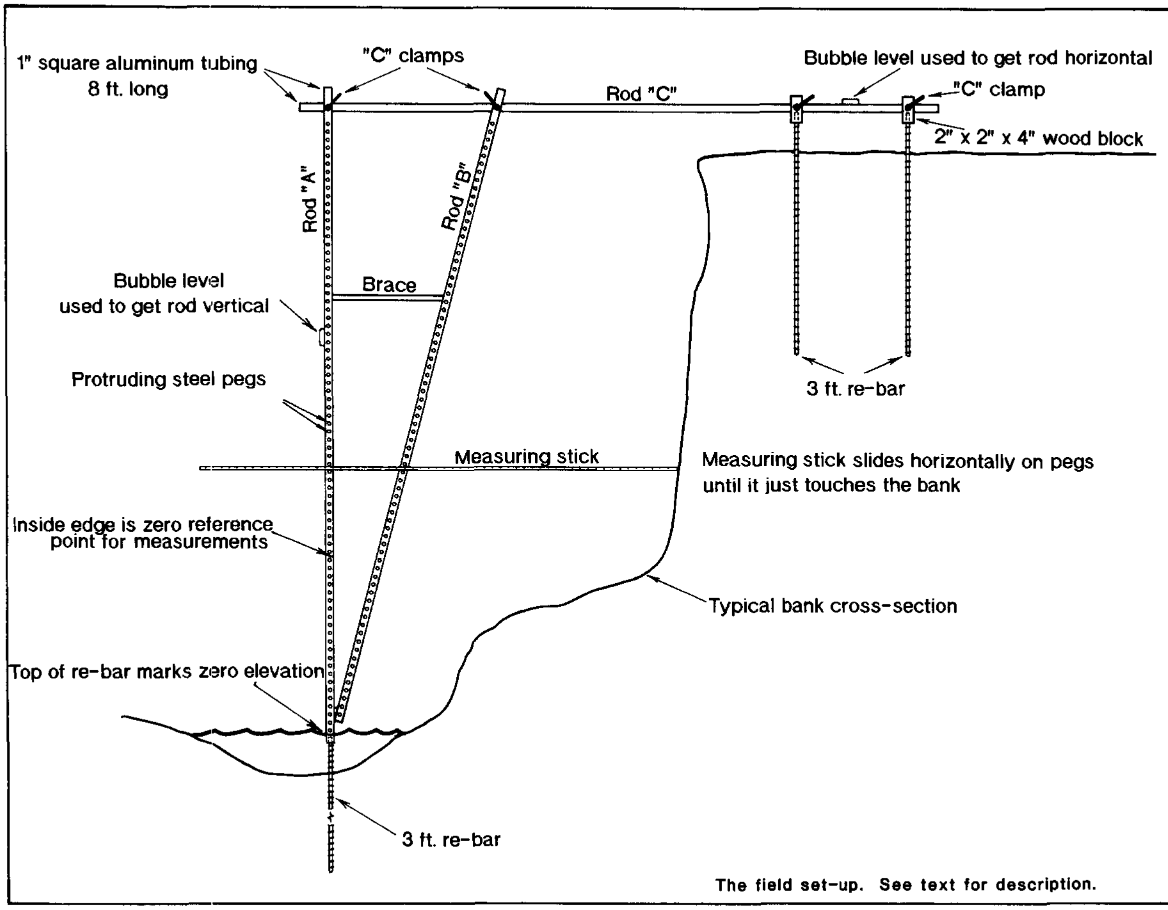

Fig. 2. The moveable frame set up.

practical reasons). At the start, 42 sites were selected but only 41 persisted for analyses. The sites were selected from stream reaches to be no less than three meters apart and to include a variety of vegetation types, stream velocities, and aspects. To avoid influences because of differing site boundary conditions, specific sites were selected so that the areas immediately adjacent to the sites were similar in vegetation, soil, and shape.

The land adjacent to all stream reaches has a history of grazing that dates back to the late 1800s. Smithneck and Bear Valley Creek pastures were grazed by dairy cows until 1975. Since then, these areas were hayed and grazed in late summer until 1990, when grazing ceased because of a change in land owners. Grazing from mid-summer to early fall still occurs at Frenchman Creek, but ceased in 1989 along the West Fork of the Carson River.

3. Methods

The device to measure bank profiles, described in detail by Zonge and Swanson (1994), measured the streambank profiles (Fig. 2) at 127 mm (5 inch) intervals nine times (approximately every month) between October 1991 and September 1992. Additional measurements were taken at intermediate heights as needed to fully define bank irregularities (Table 1). Because this method obtained 487 point measurements, only area (not volume) changes could be calculated. Photographs were taken each time a site was measured (Fig. 3).

For analyses, the streambank slopes were divided into four morphologic "profile segments": toe-slope, mid-slope, cliff, and top bank (Fig. 4). The toe-slope, the bottom portion of the bank, is generally wet or moist and subject to fluvial forces during most of the year.

Table 1
An example of data collected with the moveable frame and how the variables of deposition, erosion and net change are calculated

Site	Height	Profile measurements (mm) on the following dates[a]:						
	(mm)	18 Oct	07 Jan	02 Feb	04 Apr	Deposition[b]	Erosion	Net change[c]
FMC-A1	0	83	76	76	73	9	0	9
	127	121	143	197	210	0	−89	−89
	254	235	205	254	241	43	−19	24
	381	305	346	432	419	13	−127	−114
	508	584	524	616	588	89	−92	−3
	635	724	706	708	673	53	−2	51
	762	n/a	737	722	689	47	0	47
	889	737	737	737	759	0	−22	−22
	953	749	749	759	762	0	−13	−13

[a]The measurements listed in this table are in reference to a vertical line in front of the stream bank (see Fig. 1).
[b]In order to calculate the total deposition for the entire year, a program was written which looks at the difference between consecutive measurements. If the value on 18 Oct is > 07 Jan, then the difference is deposition. Similarly, if the measurement on 18 Oct is < 07 Jan, then the difference is erosion. The difference between each consecutive measurement is calculated and then totaled to determine the final value for that height on the bank.
[c]The variable net change = deposition + erosion.

The mid-slope is generally drier, and less vegetated than the toe. Cliff segments vertically cut into upper banks and do not usually grow vegetation. The top bank comprises the several upper centimeters of the bank, and is usually over-hanging because of an abundance of dead and a few live roots from plants on the abandoned floodplain.

Composite graphs of monthly profile measurements helped to visualize changes in the bank profiles at each site. Visual examination of the graphs indicated that 40 of the 41 sites measured could be grouped into five distinct "profile shapes" (Fig. 4): vertical, boomerang, "L", short cliff, and constant slope. Vertical profiles have greater than 80 degree slopes (100 degrees from the water surface) for the majority of bank height. In boomerang profiles, the toe- and mid-slopes are similar and range from 25 to 39 degrees, the top and cliff segments are greater than 80 degrees, and the contact between the mid-slope and cliff is abrupt and distinct. "L" shaped profiles have toe-slopes greater than 55 degrees and the mid-slopes are less than 35 degrees. On short cliff profiles the toe- and mid-slopes (5 to 70 degrees) have sharp contacts to the cliff (70 to 140 degrees), and the length of the cliff profile segment is much less than the length of the toe- and mid-slope. Constant slope profiles are not constant as the name implies but have indistinct contacts between the mid-slope (35 to 40 degrees) and the cliff (45 to 80 degrees).

During peak annual biomass in early July 1992, vegetation was surveyed within 0.3 m wide strips (0.15 m 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. Banks were divided vertically into horizontal sections from the bank top to the edge of the water according to obvious changes in vegetation type or density. Vegetative canopy cover was later visually combined into six 'vegetation groups': grass-likes (*Carex* and *Juncus*), grasses, forbs (other non-woody vegetation), bare (less than 50% cover), exposed roots, and litter. These groups were generally associated with different bank positions and, therefore, composed natural groupings.

Soils were classified in the field by texture, structure, and consistency using standard methods (Soil Conservation Service, 1975). Samples were taken vertically at different sites. Because the methods involved destructive sampling, soils were classified at the end of the field season and a meter away from each actual measuring site. Loam was the predominant soil at all sites.

Velocity measurements of near-bank flow were taken in March 1992 using a Marsh–McBurney flow meter during peak run-off. Because of the drought conditions, stages were less than bank full. Readings were taken approximately twenty mm away from the bank at 0.8 and 0.5 times the depth and just below the water surface.

The monthly profile measurements were combined to produce three bank movement variables: erosion, deposition, and net change. Erosion is the net retreat of the bank, deposition is the cumulative bank advance, and net change is the difference between the first and last measurements of the year. Three variables are presented because some bank positions did not consistently show erosion or deposition from month to month. Because of plant growth, tension fractures, or shrink/swell, the bank would often show expansion before erosion took place.

Variables related to profile movement (deposition, erosion, and net change) within each profile section were averaged. Combining the 487 data point measurements by this method reduced the number of data points to 154.

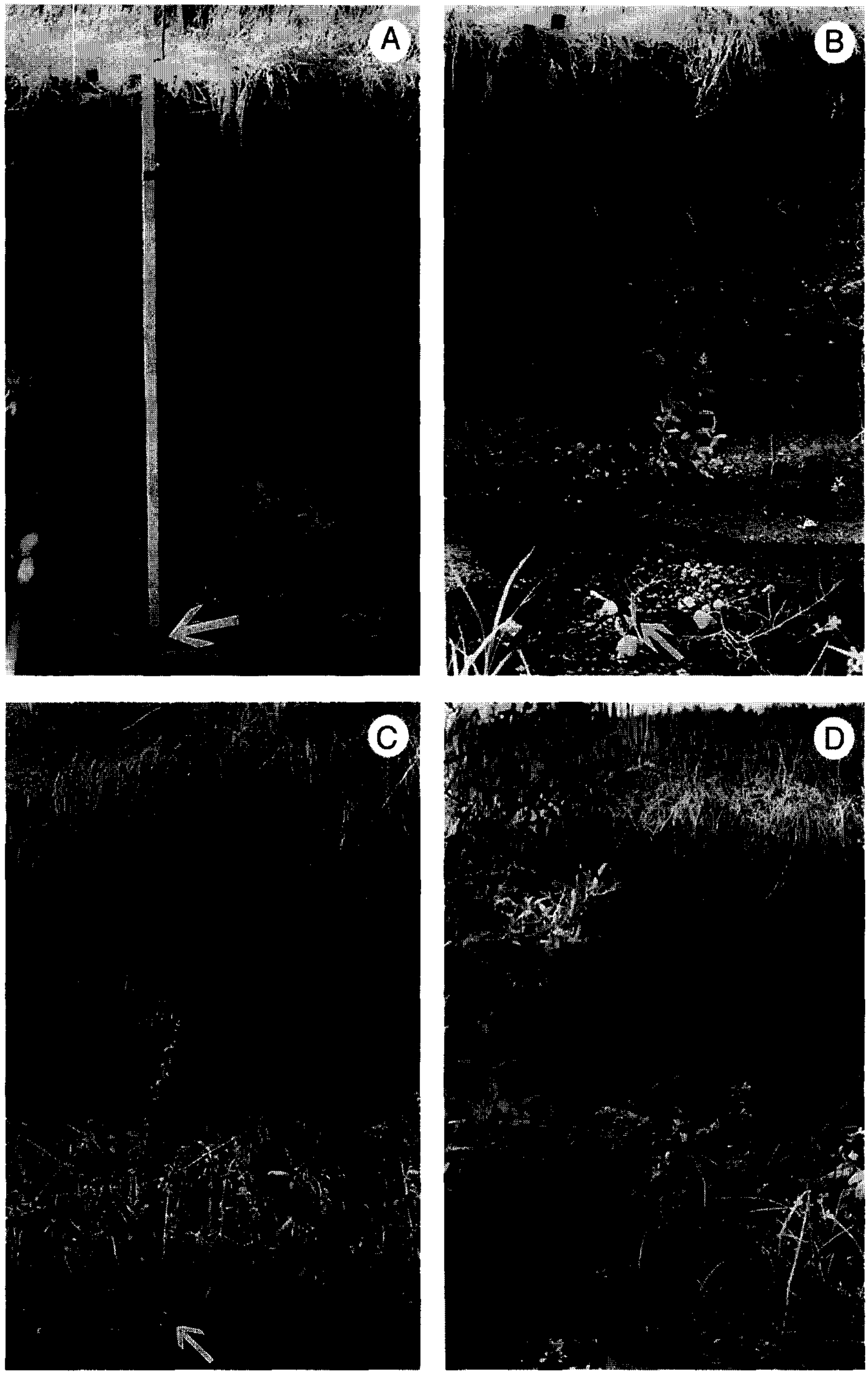

Fig. 3. Examples of measured banks. Site LBV-G4 is shown in the fall (A) and spring (B). The base re-bar is shown by the arrow. The toe slope was eroded 48 cm, while the upper banks showed little change. Site LBV-G2 is located 10 m upstream of LBV-G4 and is shown in the fall (C) and the spring (D). The base re-bar shown in (C) (arrow) was covered by the collapsed block in (D). The top bank changed little while the mid- and toe-slopes expanded more than 30 cm when the bank collapsed and the material was not removed.

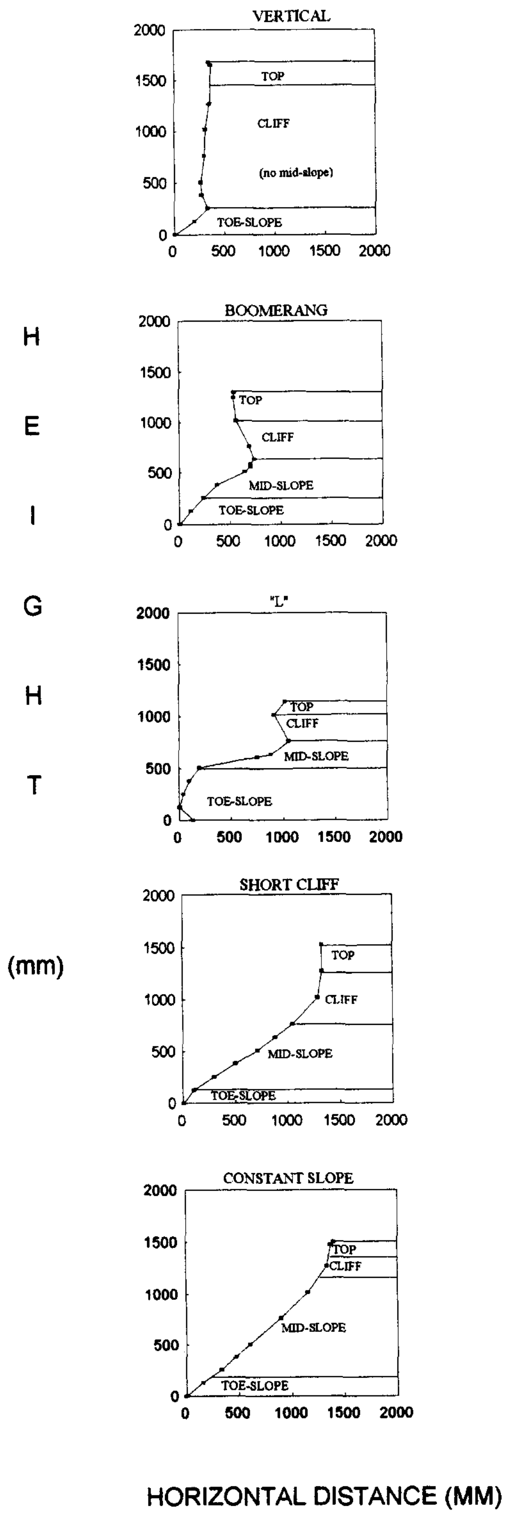

Fig. 4. Profile shapes and segments.

Analysis of variance (ANOVA) by the method of multiple regression with indicator variables (Neter and Wasserman, 1985) allowed us to accept or reject geomorphological relationships between the three variables for bank movement and various combinations of: vegetation group, profile segment, profile shape, bank aspect, and near-bank velocities. Where ANOVA identified significant differences between groups, we examined differences among categories by sequential comparison with each omitted category, using a two tailed t-test at $p = 0.05$. This significance value was used because it seemed the most reasonable for the data sample size and variance.

4. Results and discussion

4.1. Profile shapes and segments

Overall erosion, deposition, and net change were not significantly different among shapes (Table 2). Values for net change show that on most shapes, most of the eroded material was not deposited on the banks. Because erosion and deposition exceed net change, much of the recorded deposition represents expansion and contraction or deposition and subsequent removal through wind or fluvial erosion.

The profiles held the same general shape over the course of one drought year. Profile shapes and data for overall net change, however, suggest differing rates or processes of erosion and deposition among segments. A small positive net change for mid-slopes flags them as depositional, whereas cliff and top-bank segments eroded 49 and 60 mm, respectively.

The difference between erosional and depositional segments is most dramatic on the constant-slope shape. There, net erosion from the top-bank and cliff averaged 106 mm, whereas 60 mm of soil deposited on the mid- and toe-slopes. Furthermore, net change on the toe-slope varied significantly among profile shapes because of the large positive net change on constant-slopes. Whereas, short-cliff, boomerang, and vertical profile toes were eroded fluvially.

The mean values of overall erosion did not vary significantly among shape or segment. The boomerang toe, however, eroded more than the "L" or constant-slope toe or any other boomerang segment and the boomerang top-bank eroded less than the constant-

Table 2
Mean values of erosion, deposition, and net change (in mm) for bank shapes and segments

	Vertical $N=5$	Boomerang $N=9$	"L" $N=9$	Short cliff $N=12$	Constant slope $N=5$	Overall $N=40$	Significance $p=$
Erosion							
Top-bank	$-171_{0.43}$	$-83^{A}_{0.51}$	$-114_{0.56}$	$-129_{0.94}$	$-158_{0.81}$	$-125_{0.75}$	0.05
Cliff	$-67_{0.34}$	$-122^{A}_{0.57}$	$-109_{0.84}$	$-95_{0.64}$	$-164_{0.89}$	$-102_{0.74}$	0.66
Mid-slope	-117^{*}	$-107^{A}_{0.55}$	$-141_{0.80}$	$-144_{0.63}$	$-125_{0.56}$	$-132_{0.64}$	0.88
Toe-slope	$-150^{ab}_{0.76}$	$-205^{Bb}_{0.82}$	$-83^{a}_{0.71}$	$-143^{ab}_{0.85}$	$-73^{a}_{0.46}$	$-132_{0.88}$	0.05
Overall	$-129_{0.65}$	$-115_{0.84}$	$-112_{0.75}$	$-127_{0.78}$	$-131_{0.81}$	$-122_{0.77}$	0.67
Significance $p=$	0.20	0.01	0.68	0.18	0.20	0.46	0.18
Deposition							
Top-bank	$+152^{Bb}_{0.31}$	$+31^{a}_{1.02}$	$+51^{a}_{0.71}$	$+64^{a}_{0.88}$	$+68^{Aa}_{0.76}$	$+65_{0.86}$	<0.01
Cliff	$+40^{A}_{0.24}$	$+71_{0.71}$	$+41_{0.92}$	$+60_{0.67}$	$+42^{A}_{0.85}$	$+53_{0.74}$	0.03
Mid-slope	$+19^{*}$	$+113_{0.46}$	$+157_{0.69}$	$+131_{0.48}$	$+178^{B}_{0.29}$	$+136_{0.55}$	0.02
Toe-slope	$+55^{Aa}_{0.24}$	$+124^{ab}_{0.82}$	$+73^{a}_{0.76}$	$+106^{ab}_{0.80}$	$+139^{Bb}_{0.53}$	$+101_{0.77}$	<0.01
Overall	$+78_{0.74}$	$+81_{0.85}$	$+80_{0.97}$	$+90_{0.76}$	$+104_{0.73}$	$+87_{0.80}$	0.60
Significance $p=$	<0.01	0.21	0.53	0.43	<0.01	<0.01	0.01
Net change							
Top-bank	$-19_{2.18}$	$-53_{0.77}$	-630.96	$-65_{1.24}$	$-90^{A}_{1.82}$	$-60^{A}_{1.38}$	0.46
Cliff	$-27_{0.81}$	$-13_{3.15}$	-681.45	$-35_{1.96}$	$-123^{A}_{1.38}$	$-49^{A}_{1.88}$	0.84
Mid-slope	-98^{*}	$+5_{7.53}$	$+15_{5.87}$	$-13_{8.66}$	$+53^{B}_{1.72}$	$+4^{B}_{2.09}$	0.44
Toe-slope	$-95^{a}_{1.15}$	-81^{a}	$-9^{ab}_{1.52}$	$-37^{a}_{4.29}$	$+66^{Bb}_{1.12}$	$-30^{AB}_{3.92}$	<0.01
Overall	$-50_{1.42}$	$-34_{2.07}$	$-31_{2.50}$	$-37_{2.93}$	$-27_{5.61}$	$-35_{2.03}$	0.98
Significance $p=$	<0.01	<0.01	0.27	0.02	<0.01	0.03	0.07

Note: Different upper case letters indicate means that differ ($p=0.05$) among bank segments (down columns) and different lower case letters indicate means that differ ($p=0.05$) among shapes (across rows). The * indicates a mean that cannot be compared because of insufficient observations ($n=1$). Subscripts are coefficients of variation (sd/mean).

slope top-bank. Perhaps boomerang shapes occur early in bank stabilization, before toe-slopes become as well reinforced as "L" or constant-slope toe-slopes.

Relative rates of erosion and deposition suggest future bank shape. Although overall deposition varied significantly among segments, analyses focused on vertical and constant-slope profiles because of the significant interaction with shape. Constant-slope deposition clearly varied from low rates on top-banks and cliffs to higher deposition on mid-slopes and toe-slopes. These bank shapes have steep profiles (50 degrees average), which readily transmit eroded soil to the toe. We found similar values for deposition on boomerang and short-cliff toe-slopes. Perhaps drought water conditions (shallow, low velocity) allow a basal endpoint control that will gradually allow slope reduction as upper bank material collects on lower banks.

Among toe-slopes, constant-slope deposition exceeded both vertical and "L" toe-slope deposition. These toe-slopes are quite steep (55–90 degrees and 90 degrees, respectively). The vertical profiles have deep pools below the toes, hence soil cannot accumulate there because fluvial processes remove it. On the "L" banks, the distance between the toe and cliff is large. Soil that accumulates on the relatively flat-lying mid-slope is not transmitted to the toe.

The vertical top bank deposition of 152 mm exceeds any other top-bank or vertical segment. Although the vertical top-bank appeared depositional, it, like most other top-bank and cliff deposition features, must instead indicate pre-erosion expansion (crack widening, swell, etc.). Soil could not possibly accumulate on these vertical surfaces.

Expansion fractures (Thorne and Tovey, 1981; Thorne and Lewin, 1979) develop parallel to the bank face. These fractures, important features in the erosion process, opened as wide as twenty millimeters prior to failure. The fractures varied in depth from thirty millimeters to the entire bank height. Erosion in the cliff segment shows that non-fluvial processes are effective

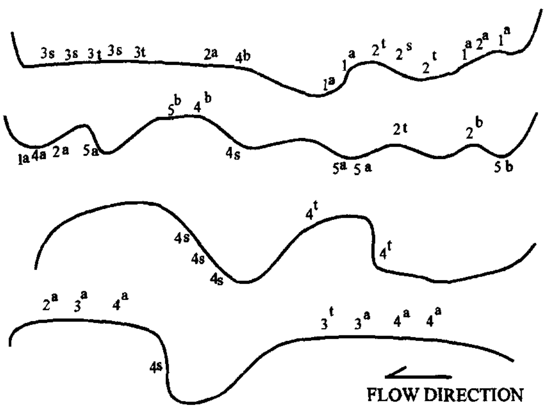

Fig. 5. Stream planviews and locations of study sites.

in eroding steep, unvegetated banks. This finding corresponds with the work of others (Thorne and Lewin, 1979; Carson and Kirkby, 1972).

Most of the mean values listed in Table 2 do not differ statistically because of low degrees of freedom and high standard deviations. Results varied among sites within shapes, meaning that dramatic erosion or deposition occurred on only a few sites. For example, most erosion on toe-slopes appeared to be on the vertical-shaped profiles. These bare toes over deep pools on sharp outside bends in meanders experienced relatively high near-bank stream velocities. Much of the erosion, however, took place at one site where the toe retreated over 600 mm because of ice gouging between November and February. Close examination of the other vertical profiles shows that toe erosion was minor.

Study site locations were plotted (Fig. 5) and show that no location-for-time substitution model exists for bank shape or stability. Possibly a longer stream section is required for the model.

Although near-bank velocities during peak flows ranged from 0.03 to 0.75 m per second, velocity did not correlate to toe erosion or bank shape. Because peak flows were below the one to two year average events, they, therefore, did not represent formative flows.

4.2. Vegetation

Groups of vegetation are often associated with specific shapes and segments (Table 3). The bare group dominated the cliff segments of all bank shapes and the entire vertical shape. The toe and mid-slopes of "L" shaped banks are mostly covered by grass or grass-likes. The sloping toes and mid-slopes of boomerang, short cliff, and constant slope shapes, are dominated by the bare or forb group. These differences indicate that profile shape and characteristics of the toe segments may be influenced by vegetation. Conversely, substrate characteristics such as deposition rate, capillary rise, and time in place alter habitat suitability for plants. The top banks generally form overhangs, apparently held together by dense root systems. After being exposed to air and dry soil, the roots eventually die, become brittle, and the overhang collapses (Thorne and Tovey, 1981).

Toe-slopes dominated by the grass group have specific characteristics. The toes are steep (80% have slopes greater than 50 degrees) and showed low deposition (25 mm) and erosion (23 mm). Grass was dense (at least 100 percent cover), rhizomatous, and had dense rooting characteristics that may allow the

Table 3
Bank shapes and segments with the percent of the associated vegetation group. For example, 33% of all of the Boomerang bank shape toes are covered by forbs

Bank shape	*n*	Bare	Forbs	Litter	Grass	Grass-likes	Roots
n		95	19	10	8	18	14
Vertical	5						
Top cliff		100					
Cliff		100					
Mid-slope		100					
Toe slope		100					
Boomerang	9						
Top cliff		67					33
Cliff		89	11				
Mid-slope		33	33	33			
Toe slope		33	33	33			
"L"	9						
Top cliff		67					33
Cliff		100					
Mid-slope		11		33	55		
Toe slope					22	78	
Short cliff	12						
Top cliff		33					63
Cliff		76	8	8			8
Mid-slope		31	23	7	7	15	
Toe slope		31	23	15	7	23	
Constant slope	5						
Top cliff		100					
Cliff		100					
Mid-slope		80	20				
Toe slope		20	60		20		

toe-slopes to hold a steep angle (Kleinfelder et al., 1992).

The grass-likes group is also associated with steep toe-slopes, however, this vegetation group allowed substantial erosion on five out of eight toe-slopes. This may be contrary to the findings of other authors (Kleinfelder et al., 1992; Smith, 1976), because some *carex*- and *juncus*-dominated community types have dense root mats (Manning and Padgett, 1992) that resist erosion (Dunaway et al., 1994). Three sites showed continuous erosion and two sites showed abrupt erosion during low water flows (between June and July). Two toes, dominated by non-rhizomatous *Carex subfusa* plants were eroded the most dramatically. One of these collapsed because of undercutting and the toe lost 380 mm. It was a heavily vegetated mound at the bank toe that had at some prior time been part of the top bank.

The forb and bare groups occupied moderate to gentle toe and mid-slopes (30 to 40 degrees). Toes dominated by the forb group showed the highest deposition at (180 mm versus 50 mm for bare, $p=0.03$). The difference between the two groups may be that the forbs act as collection points for loose falling soil. Whereas, on bare slopes, nothing held the soil in place when it fell. Carson and Kirkby (1972), Leopold et al. (1964), and Schumm (1977) stated that forbs also protect banks from rain splash erosion.

Vegetation groups, comprising at least 50 percent cover, were used in these analyses. The percent cover was used with vegetation group in two-way ANOVA analyses and was found to have no relationship to erosion or deposition within shapes or segments.

Accumulated errors in measurement, can possibly influence the observed mean values. The margin of error on measured values is ± 1.5 mm which is within acceptable limits for the data collected. The moveable frame method gives the most accurate data when used for steep banks with firm soils (Zonge and Swanson, 1994).

Bank aspect was not correlated with vegetation or bank movement. Capillary rise may have masked predicted differences because of variable duration of soil moisture usable to certain plants. Furthermore, drought-dry soil may have masked any aspect-related freeze–thaw frequency effects.

No statistically significant seasonal relationships were observed for bank movement. No visually significant changes in bank profiles occurred during or after spring runoff.

5. Summary and conclusions

This study found that during one drought year, steep upper banks changed measurably and this change was not related to fluvial processes. Unvegetated banks are eroded more than vegetated banks, especially those covered by rhizomatous grasses. Vegetation "trapped" and held loose, freshly deposited soil on gently sloping toes or mid-slopes. This, apparently, augmented bank recovery and stability. Vegetation was correlated with bank shape, but cause and effect was unclear and apparently variable. Hupp and Simon (1991) suggest that bank must attain stability before vegetation can become established. During drought conditions, low near-bank stream velocities may ease bank toe erosion so that vegetation can become established. Perhaps this will help to stabilize banks during higher flows, especially where management prefers rhizomatous species. Any vegetation, however, even annual forbs, may promote bank stabilization.

References

Bohn, C., 1987. Management of winter soil temperatures to control streambank erosion. In: R.E. Gresswell, B.A. Barton, and J.L. Kershner (Editors), Practical Applications to Riparian Restoration. Management and Educational Workshop, pp. 69–71.

Broms, B. and Yao, L., 1964. Shear strength of a soil after freezing and thawing. American Society of Civil Engineers Proceedings, Soil Mechanics and Foundations Division 90 (SM4).

Carson, M.A. and Kirkby, M.J., 1972. Hillslope Form and Process. Cambridge University Press, NY.

Dunaway, D., Swanson, S.R., Wendel, J. and Clary, W., 1994. The effect of herbaceous vegetation and soil texture on particle erosion of alluvial streambanks. Geomorphology, 9(1): 47–57.

Elmore, W. and Beschta, R.L., 1987. Riparian areas: perceptions in management. Rangelands, 9(5): 260–265.

Harvey, M.D. and Watson, C.C., 1986. Fluvial processes and morphological thresholds in incised channel restoration. Water Resour. Bull., 22(3): 359–368.

Hupp, C.R. and Simon, A., 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. Geomorphology, 4: 1–14.

Kamyab, I., 1991. Streambank stability prediction for C6 stream type reconstruction. PhD Thesis in Hydrology, Univ. of Nevada, Reno.

Kleinfelder, D., Swanson, S., Norris, G. and Clary, W., 1992. Unconfined compressive strength of some streambank soils with herbaceous roots. Soil Sci. Soc. Am. J., 56: 1920–1925.

Kok, H. and McCool, D.K., 1990. Freeze thaw effects on soil strength. Frozen Soil Symposium (proceedings), Spokane, WA, March 21–22.

Leopold, L.B., Wolman, M.G. and Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco, 522 pp.

Manning, M.E. and Padgett, W.G., 1992. Riparian community type classification for the Humboldt and Toiyabe National Forests, Nevada and eastern California. USDA FS Intermountain Region Symp.

Millar, R.G. and M.C. Quick, 1993. Effect of bank stability on geometry of gravel rivers, J. Hydraul. Eng., 119(12): 1343–1363.

Neter, J. and Wasserman, W., 1985. Applied Linear Statistical Models. 2nd ed. Irwin-Dorsey Limited, Georgetown, Ont., pp. 273–292.

Ree, W.O., 1949. Hydraulic characteristics of vegetation for vegetated waterways. Agric. Eng., April: 184–187.

Roberts, J. and Ludwig, J.A., 1991. Riparian vegetation along current-exposure gradients in floodplain wetlands of the River Murray, Australia. J. Ecol., 79: 117–127.

Rosgen, D.L. 1994. A classification of natural rivers. Catena, 22(3): 169–199.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York, 338 pp.

Smith, D.G., 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geol. Soc. Am. Bull., 87: 857–860.

Soil Conservation Service, 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. USDA-SCS Agric. Handbk. 436. US Gov. Print. Office, Washington, DC.

Stromberg, J.C. and Patten, D.T., 1990. Riparian vegetation instream flow requirements: A case study from a diverted steam in the Eastern Sierra Nevada, California, USA. Environ. Manage., 14(2): 185–194.

Thorne, C.R. and Lewin, J., 1979. Bank processes, bed material movement and planform development in a meandering river. In: D.D. Rhodes et al. (Editor), Adjustments of the Fluvial System. Annu. Geomorphol. Symp., 10, pp. 117–137.

Thorne, C.R. and Tovey, N.K., 1981. Stability of composite river banks. Earth Surf. Process. Landforms, 6: 469–484.

Zonge, K.L. and Swanson, S., 1994. A moveable frame technique for measuring changes in streambank profiles. In: Effects of Human-Induced Changes on Hydrologic Systems. Annu. Summer Symposium AWRA.