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The role of vegetation and bed-level fluctuations in the process of channel narrowing

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Abstract

A catastrophic flood in 1965 on Plum Creek, a perennial sandbed stream in the western Great Plains, removed most of the bottomland vegetation and transformed the single-thalweg stream into a wider, braided channel. Following eight years of further widening associated with minor high flows, a process of channel narrowing began in 1973; narrowing continues today. The history of channel narrowing was reconstructed by counting the annual rings of 129 trees and shrubs along a 5-km reach of Plum Creek near Louviers, Colorado. Sixty-three of these plants were excavated in order to determine the age and elevation of the germination point. The reconstructed record of channel change was verified from historical aerial photographs, and then compared to sediment stratigraphy and records of discharge and bed elevation from a streamflow gaging station in the study reach. Channel narrowing at Plum Creek occurs in two ways. First, during periods of high flow, sand and fine gravel are delivered to the channel, temporarily raising the general bed-level. Subsequently, several years of uninterrupted low flows incise a narrower channel. Second, during years of low flow, vegetation becomes established on the subaerial part of the present channel bed. In both cases, surfaces stabilize as a result of vegetation growth and vertical accretion of sediment.

1. Introduction

Stream-channel narrowing can occur as a response to flood-induced widening (Schumm and Lichty, 1963; Burkham, 1972; Osterkamp and Costa, 1987), climate change (Schumm, 1969; Gottesfeld and Johnson Gottesfeld, 1990), construction of upstream dams (Williams, 1978; Williams and Wolman, 1984), changes in land management (Nadler and Schumm, 1981), introduction of exotic riparian plant species (Hadley, 1961; Nevins, 1969; Turner, 1974; Graf, 1978) or as part of a cyclic, autogenic process (Patton and Schumm, 1981; Nanson, 1986). Vegetation contributes to channel narrowing (Schumm and Lichty, 1963; Williams and Wolman, 1984; Hupp, 1992) by increasing sediment deposition and bank stability (Smith, 1976; Hickin, 1984). Where arid conditions limit plant growth rate and stem density, fluctuations in channel width are relatively large and rates of channel narrowing are relatively slow (Baker, 1977; Wolman and Gerson, 1978).

In arid and semi-arid regions, floods can increase the width of perennial alluvial streams by an order of magnitude (Schumm and Lichty, 1963; Burkham, 1972). Such a change is usually followed by a period of narrowing lasting for decades. Several authors have hypothesized that this narrowing is initiated by establishment of vegetation on the former channel bed during a period of relatively low flow that lasts several years. Subsequent high flows deposit sediment around the vegetation, forming a new stable surface adjacent

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to a narrower channel (Schumm and Lichty, 1963; Burkham, 1972; Nadler and Schumm, 1981; Osterkamp and Costa, 1987). Similar processes have been proposed to explain channel narrowing downstream of dams (Williams and Wolman, 1984) and following introduction of non-native shrubs (Hadley, 1961; Graf, 1978).

In most cases the role of vegetation has been inferred by examination of aerial photographs and repeated measurements of channel geometry. Such observations often show that vegetation establishment and channel narrowing occurred at about the same time, but the order of these events is difficult to determine because tree seedlings are too small to observe on aerial photographs and because aerial photographs are generally not taken frequently enough. Therefore, this approach cannot rule out the possibility that vegetation becomes established on pre-existing surfaces that were formed by some other process.

One factor that could contribute to channel narrowing is fluctuation in bed-level, a phenomenon that is particularly common in sandbed channels (Osterkamp and Costa, 1987). We propose that as the bed-level falls, relicts of former channel bed could be left behind at a relatively high elevation. Vegetation might eventually become established on these surfaces but would play no role in their formation. If this process was important, the rate of channel narrowing would be in part determined by the sequence of bed-level fluctuations in the years following a flood. Schick (1974) argued that terraces along ephemeral desert streams can be formed as a result of flow-related fluctuations in bed-level. No investigations of the role of bed-level fluctuations in the narrowing of perennial-stream channels have been undertaken.

In this study we used a dendrogeomorphic approach (Sigafoos, 1964; Hupp, 1988, 1992) to compare the influence of vegetation and fluctuations in bed-level on the process of channel narrowing following a catastrophic flood. We related the date and elevation of establishment of woody plants to the record of change in bed-level and discharge. If narrowing has occurred by establishment of vegetation on the channel bed, then the establishment elevation of existing trees and shrubs should be equal to the bed elevation. If narrowing has occurred as a result of fluctuations in bed-level, then the establishment elevation of trees and shrubs should be above the present bed-level and the date of establishment should follow a historic peak in bed-level.

2. Study area

Plum Creek is a sandbed stream in the Colorado Piedmont Section of the Great Plains physiographic province (Fenneman, 1931; Madole, 1991). From the confluence of East and West Plum Creeks near Sedalia, Colorado, Plum Creek flows north for 14 km along the base of the Rocky Mountains, and joins the South Platte River in Chatfield Reservoir south of Denver (Fig. 1). The Plum Creek valley is approximately 1 km wide and consists of Quaternary alluvial terraces, frequently inundated alluvial deposits, and eolian deposits (Scott, 1963). Pleistocene terraces and the channel bed are dominated by coarse sand. Most Holocene terraces are dominated by sand and silt.

Our project focused on a 7-km reach of Plum Creek from Sedalia downstream to Louviers. The watershed has an area of 782 km^2 at Louviers and includes areas

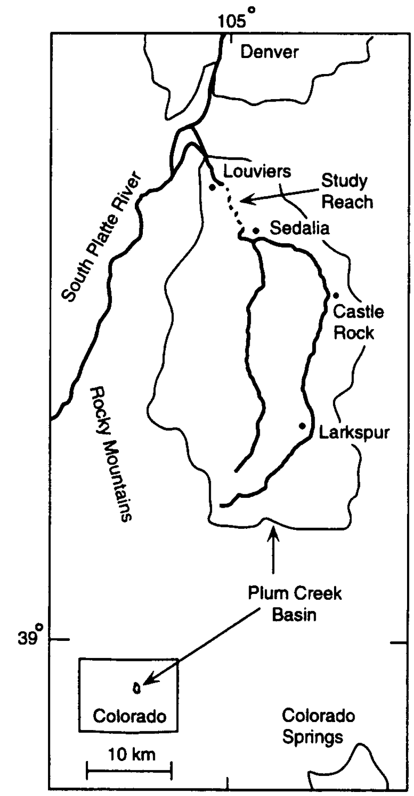

Fig. 1. Map of Plum Creek basin and vicinity, redrawn after Osterkamp and Costa (1987).

of granite and Tertiary sandstone and siltstone. Elevation within the study reach ranges from 1702 to 1745 m. Stream gradients measured in 1991 ranged from 0.0063 to 0.0071. Mean annual precipitation in Sedalia is 445 mm (Colorado Climate Center, no date). Plum Creek, gaged since 1947, has a median discharge for water years 1958 through 1990 of 0.382 m^3/s at Louviers (Ugland et al., 1991). In most years the highest flow is sustained for several weeks in March, April or May as a result of snowmelt, especially in the basin of West Plum Creek (Table 1). Less often the peak annual flow is a flash flood resulting from thunderstorms between mid-May and September.

On the afternoon of June 16, 1965, as much as 360 mm of rain fell in 4 hours on the watershed of Plum Creek (Matthai, 1969). The resulting peak discharge at Louviers was 4360 m^3/s, and the valley floor was inundated for 2.5 hours (Matthai, 1969). The recurrence interval for this flood has been estimated at 900 to 1600 years on the basis of mixed-population flood-frequency analysis and examination of terrace flood deposits (Osterkamp and Costa, 1987). The high recurrence interval indicates that this flood was exceptional for Plum Creek; however, similar floods have been reported on several streams draining Palmer Divide east of Plum Creek (Follansbee and Sawyer, 1948; Matthai, 1969). For example, Middle Bijou Creek at Deer Trail has a smaller watershed (492 km^2) than Plum Creek at Louviers, but a larger proportion of that watershed is in an area susceptible to intense rainfall (Hansen et al., 1978). This location experienced floods of 4070 and 4110 m^3/s in 1935 and 1965 (Follansbee and Sawyer, 1948; Matthai, 1969).

Before 1965, Plum Creek was a single-thalweg, irregularly meandering stream with steep, wooded banks. The flood sheared off or uprooted half of the trees on the bottomland, removed much of the silt and clay, and transformed Plum Creek into a wider, straighter, and steeper braided channel (Table 2; Osterkamp and Costa, 1987). A discontinuous layer of coarse sand was deposited on top of the lower-Holocene terraces. The decrease in vegetative cover and fine sediment reduced bank stability, allowing continued widening of the stream during the minor high flows of 1969 and 1973 (Table 2; Osterkamp and Costa, 1987). Channel narrowing began after 1973 (Fig. 2). At present Plum Creek is still wider and straighter than it was before the 1965 flood, and most of the study reach is

Table 1
Peak instantaneous annual discharge by water year at U.S. Geological Survey gaging stations on Plum Creek, Colorado. Locations of measurements are: 1945 and 1991–1992, Sedalia; 1948–1956 and 1990, Titan Road, 4 km downstream of Louviers; 1957–1989, Louviers

Year	Month	Day	Discharge (m^3/s)
1945	8	8	220
1948	3	14	14.7
1949	6	13	26.8
1950	4	16	1.24
1951	7	30	6.29
1952	5	27	7.22
1953	7	29	76
1954	7	21	110
1955	5	20	11.5
1956	8	1	54.9
1957	7	13	22.7
1958	5	9	6.09
1959	4	28	8.50
1960	5	24	31.7
1961	8	2	48.7
1962	4	22	6.09
1963	9	19	8.21
1964	3	18	8.21
1965	6	16	4360
1966	7	17	51.0
1967	7	7	17.3
1968	5	11	3.88
1969	5	8	125
1970	4	29	6.97
1971	5	5	6.68
1972	6	16	6.57
1973	5	6	110
1974	4	27	20.3
1975	6	11	16.0
1976	4	26	2.10
1977	8	10	10.7
1978	5	17	11.4
1979	4	25	11.4
1980	5	10	23.1
1981	5	28	5.30
1982	7	29	8.64
1983	7	23	73.9
1984	8	24	80.1
1985	5	1	20.3
1986	4	10	3.71
1987	5	7	37.9
1988	5	27	10.9
1989	7	30	1.90
1990	7	30	9.03
1991	6	13	2.10
1992	4	17	5.75

Table 2
Changes in width, gradient, and sinuosity of a 4.08-km reach of Plum Creek near Louviers, Colorado, from 1964 into 1983 (from Osterkamp and Costa, 1987)

Date of aerial photography	10/4/64	6/27/67	8/7/71	6/24/75	7/8/78	7/9/80	10/5/83
Mean channel width (m)	26	68	72	116	70	54	47
Channel gradient	0.0053	0.0063	0.0062	0.0064	0.0064	0.0063	0.0063
Sinuosity	1.22	1.03	1.04	1.01	1.01	1.03	1.03

still braided. The sediment load carried by Plum Creek is greater than 90% bedload (W.R. Osterkamp, unpubl. data). The flood contributed to this exceptionally high percentage by replacing bottomland fines with easily entrained sand and gravel.

The dominant woody plants at Plum Creek are five members of the willow family (Salicaceae): plains cottonwood (*Populus deltoides* subsp. *monilifera*), peachleaf willow (*Salix amygdaloides*), crack willow (*Salix fragilis*), sandbar willow (*Salix exigua*) and yellow willow (*Salix lutea*) (Friedman, 1993). These species produce abundant seeds almost every year at about the time of peak snowmelt discharge (Scott et al., 1993). The seeds can germinate immediately, but remain viable for only a few weeks (Ware and Penfound, 1949; Van Haverbeke, 1990). Because seedlings have high requirements for light and moisture, successful establishment is limited to recently disturbed sites including flood deposits and portions of the former channel bed (Scott et al., 1996). Stands of these species are usually even-aged because the high light requirement of seedlings prevents establishment under existing trees or herbs (Johnson et al., 1976; Friedman, 1993).

3. Methods

3.1. Cross-sections and plots

In 1991 we established eight cross-sections in the 7-km study reach. Four were sites of previous U.S. Geological Survey measurements of channel morphology. The other four were chosen to ensure a representative sample of geomorphic conditions at Plum Creek. We located cross-sections on straight reaches, bends, reaches with single-thalweg flow, reaches with divided flow, and a reach downstream of a tributary junction. Two of the cross-sections were in areas grazed by cattle, two were in areas grazed by horses, and the remaining four were in areas that had experienced varying amounts of herbivory by beavers in the previous decade. Deer were observed occasionally throughout the study site. The cross-sections ranged in length from 150 to 208 m, encompassing the entire width that has been inundated since 1965, as well as about 80 m of the lower adjacent terrace. We installed six staff gages and eight crest-stage gages within the study reach. We carried out a rod-and-level survey to determine the relative positions of the cross-sections, staff gages, and crest-stage gages.

3.2. Tree excavation and calculation of changes in bed-level

The bottomland at Plum Creek consists of discrete, relatively flat surfaces separated by breaks in elevation. This feature made it possible to subdivide the eight cross-sections into surfaces (Fig. 3). Except on terraces, we excavated the oldest woody plants on each surface, and cut transverse sections of each plant at the germination point as indicated by the lowest root flare (Sigafoos, 1964; Hupp, 1988). The 63 excavated woody plants were mostly plains cottonwood and sandbar willow, but included a few peachleaf willow and leadplant (*Amorpha fruticosa*). We shaved plant sections with a sharp knife (Phipps, 1985) and counted rings in the laboratory using a hand lens or dissecting microscope. We defined the age of a surface as the age of the oldest woody plant occupying it. In most cases, we excavated several stems per surface. We verified the ages of surfaces in three ways. On surfaces younger than 5 years, we counted the number of winter bud scars on the oldest woody plants. On older surfaces we counted the number of rings in cores taken from an additional 66 trees. Cores were collected with an increment bore less than 30 cm above the ground. Finally, we verified surface ages using historical ground-level

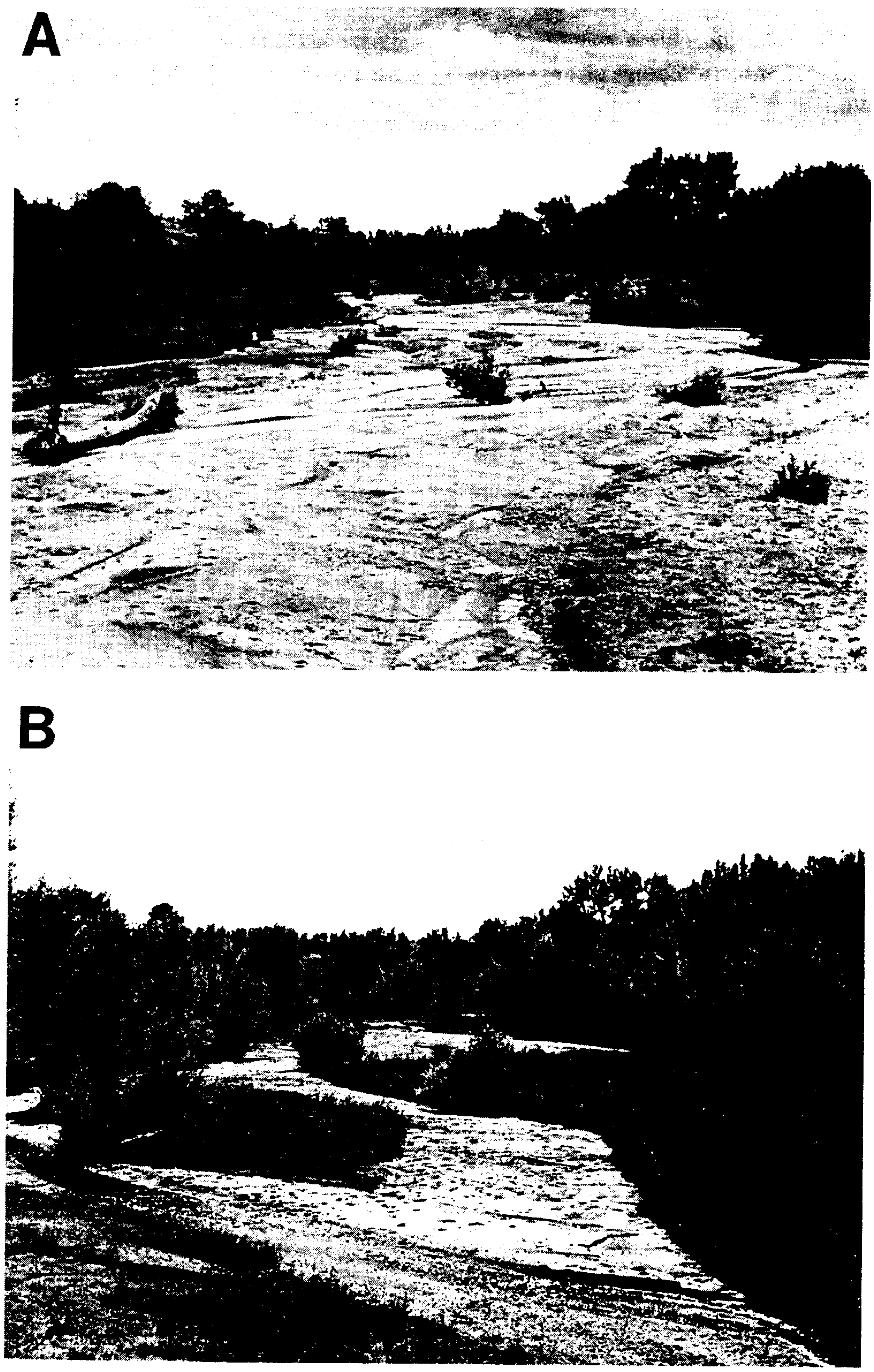

Fig. 2. Matching photographs illustrating channel narrowing by formation of stable bars along Plum Creek, Louviers, Colorado, (A) September, 1981, (B) September, 1991. The view is upstream; shrubs in the channel in the later photograph are about 2 m high.

and aerial photography. We surveyed the elevation of the root flare of all excavated trees relative to the water surface at the cross-section on April 16, 1991. We also surveyed the elevation of the channel bed at 3-m intervals along all eight cross-sections.

If a surface is older than the oldest woody plants occupying it, then the germination point of the oldest plants may overestimate the initial elevation of the surface. Therefore, we also examined the stratigraphy at each excavated tree and measured the elevation of the lowest sediment layer that was less coarse than channel sediment. Because patches of silt are occasionally deposited on the channel bed, this method may underestimate the initial elevation of a surface. The true elevation of a surface at the time it was formed should be between the results produced by the two methods.

All surfaces other than terraces and channel bed supported woody vegetation. Because many of the terraces did not, a different method was necessary to date these surfaces. We used aerial photographs with an image scale of 1:6000 from 1956, 1965, 1976, and 1986 to divide terrace surfaces into two groups: those that were 26 years old and those that were older than 26 years. Terrace surfaces 26 years old were formed during the flood of 1965. In the 1956 aerial photos, these areas were occupied by channel bed or low, unwooded bars. Most of the 26-year-old surfaces were on bends in the creek that were abandoned and filled with coarse sand during the 1965 flood. Terrace surfaces older than 26 years were already terraces before the flood.

We reconstructed the history of change in bed elevation at Plum Creek by calculating changes in the stage-discharge relation as indicated by rating tables and shift records for the gaging station at Louviers for water years 1966 through 1990 (Williams, 1978). Many of the rating tables for the Louviers station do not extend down to 0 discharge. Therefore, we calculated changes over time in the stage of the median discharge, and assumed that the difference between this stage and the stage of 0 discharge has not changed. This procedure assumes that all changes in the stage at median discharge can be attributed to a change in bed elevation. The assumption is reasonable for a wide sandbed stream like Plum Creek, where stage is always controlled by the bed and the median flow does not cover the entire bed. The resulting graph is an extension of the work of Osterkamp and Costa (1987). When we used the stage corresponding to a discharge of 5, 10, or 90% duration, instead of the median discharge, the result was essentially the same. We were not able to extend the record to years before 1965 because the flood destroyed all of the reference marks at the gaging station. Our record ends in 1990, when the station was moved from Louviers to Sedalia.

4. Results

4.1. Fluvial surfaces

Each cross-section at Plum Creek included 10 to 47 m of channel bed—a bare or sparsely vegetated surface of recently deposited channel sediment (Fig. 3). Channel sediment is a poorly sorted mixture dominated by gravel and sand. At high flow the channel bed is completely inundated; however, during most of the growing season, this surface is only partly inundated by the shifting anabranches of Plum Creek. The channel bed ranges in relative elevation from −0.20 to 0.14 m, although a point in the thalweg of a tributary at the confluence with Plum Creek had an anomalous elevation of −0.63 m (Fig. 4).

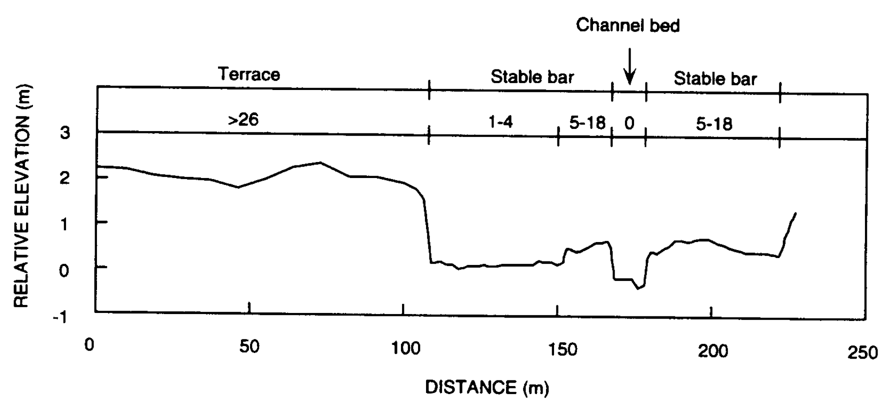

Fig. 3. Sample cross-section of Plum Creek, in Sedalia, Colorado, on June 18, 1991. Elevation is relative to the water surface on April 16, 1991. Fluvial surfaces and the ages in years as of 1991 are indicated above the cross-section.

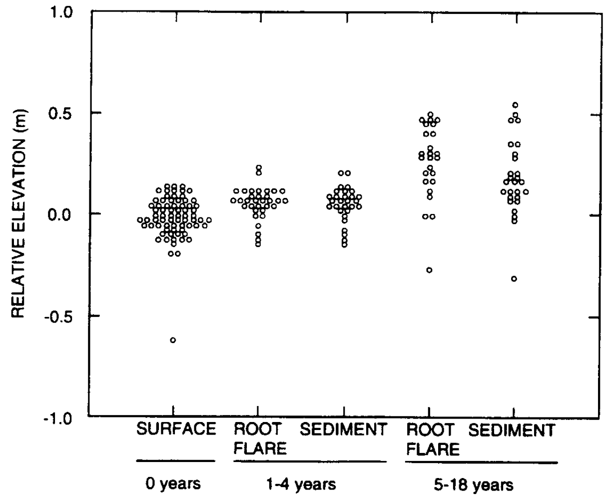

Fig. 4. Elevation of the channel bed surface (age 0), the root flare of woody plants growing on surfaces aged 1 through 4 and 5 through 18 years, and the bottom of overbank sediment deposits adjacent to the excavated plants. Ages are in years before 1991. Elevation is relative to the water surface on April 16, 1991.

Adjacent to the channel bed are stable bars that have been deposited since the onset of postflood narrowing, and that now occupy from 43 to 104 m of the cross-section (Fig. 3). These surfaces consist of channel sediment covered by several layers of well-sorted overbank sediment ranging from silt to sand. In a few cases channel sediment occurs between two layers of overbank sediment. Stable bars are sparsely to densely vegetated and range in elevation from −0.14 to 0.79 m. The stable bars and channel bed are dotted by streamlined islands formed downstream of woody debris at high flow (Osterkamp and Costa, 1987). Beyond the stable bars is a steep slope up to a terrace 0.94 to 3.41 m above the channel bed (Fig. 3).

4.2. *Excavation of root flares*

The elevation of the germination point of excavated trees was strongly related to the age of the associated surface. All but two of the 33 root flares of woody plants excavated on surfaces aged 1 through 4 years were within the range of elevations occupied by the present channel bed (Fig. 4). Similarly, all but two of the 29 pits that were dug around these root flares revealed an elevation for the bottom of overbank deposits that was within the range of elevations occupied by the present channel bed (Fig. 4). This evidence supports the hypothesis that surfaces now aged 1 through 4 years were created by establishment of vegetation on the present channel bed (Schumm and Lichty, 1963). An average of 4.2 cm of silt has been deposited around these plants since establishment.

Twenty of the 25 root flares of woody plants that were excavated on surfaces aged 5 through 18 years were above the range of elevations of the present channel bed (Fig. 4). Similarly, 15 of the 27 pits that were dug around these root flares revealed an elevation for the bottom of overbank deposits that was above the range of elevations occupied by the present channel bed. This evidence contradicts the hypothesis that surfaces now aged 5 through 18 years were initiated by establishment of vegetation on the present channel bed. Some other process raised the elevation of these surfaces before vegetation became established. An average of 14.7 cm of sediment has been deposited around these plants since establishment.

4.3. *History of fluctuations in bed-level*

Since the 1965 flood, bed-level has fluctuated over a range of 0.8 m in response to variation in discharge (Fig. 5). Bed-level has risen during periods of high flow, especially in 1969, 1973, 1983, and 1984, and fallen during periods of sustained low flow. Although the period of record is short, the data suggest that fluctuations in bed-level have decreased in magnitude over time since the flood (Fig. 5).

4.4. *Local factors promoting establishment of vegetation on the channel bed*

During the summers of 1991 and 1992, we observed establishment of vegetation on relatively undisturbed areas of the channel bed (age 0). Such areas included locations that were relatively high, locations that were protected from scour by upstream debris islands or by irregularities in the channel bank, and locations that happened to be missed by the shifting anabranches of Plum Creek. All such surfaces along the cross-sections were disturbed by snowmelt, and possibly by ice scour (Johnson, 1994), during the winter and spring of 1992–93. Therefore, no surfaces aged 1 year occurred in 1992. However, matched aerial and ground-level photographs show that surfaces 1 through 4 years old in 1991 were channel bed in 1987 and 1988.

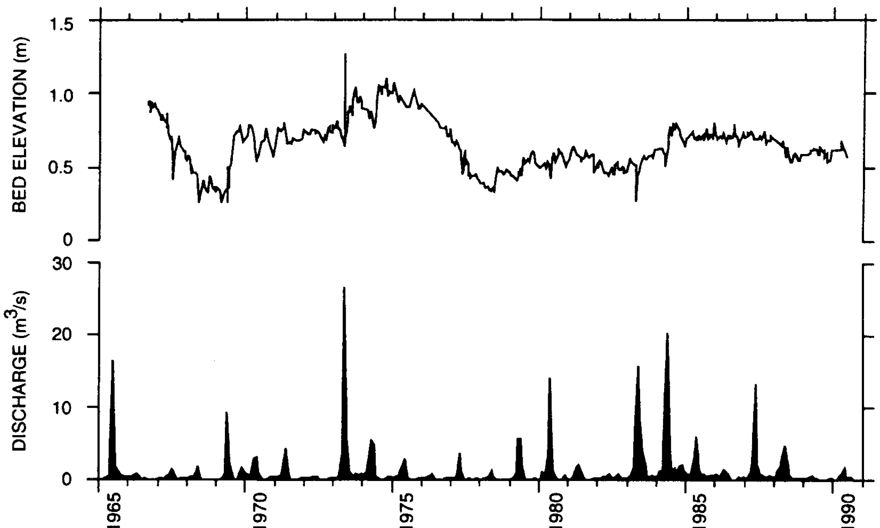

Fig. 5. Bed-level and mean monthly discharge at the U.S. Geological Survey gaging station on Plum Creek near Louviers, Colorado. Elevation is relative to the arbitrary datum of the gaging station.

Debris islands occupy a small proportion of the bottomland, but play an important role in channel narrowing by controlling lateral movement of anabranches and by influencing scour and deposition (Osterkamp and Costa, 1987). For example, the divided flow around an island may result in filling on one side, and the relatively high bedforms produced in this way are susceptible to establishment of vegetation. Many islands have become attached to the banks or to other islands in this way (Osterkamp and Costa, 1987).

5. Discussion

5.1. *Causes of bed-level fluctuations*

Plum Creek is a perennial stream with ephemeral tributaries. Sediment input occurs only during high flow, when tributaries are active and discharge is high enough to enable Plum Creek to erode laterally into terraces deposited or exposed by the flood of 1965. As a result, bed-level rises during periods of high flow; then, during periods of base flow, a narrower channel may be incised, leaving behind relatively high portions of the former channel bed (Fig. 5). These surfaces are available for colonization by vegetation. Fluctuations in bed-level appear to have been damped in recent years (Fig. 5), perhaps because vegetation has stabilized sediment deposited and exposed by the 1965 flood.

5.2. *Bed-level fluctuations and channel narrowing*

The bed-levels in 1974 and 1984 were, respectively, 40 and 15 cm above the present level (Fig. 5). The germination points of the woody plants excavated on surfaces aged 5 through 18 years were an average of 28 cm above the present bed-level. These results are consistent with the hypothesis that the oldest plants on surfaces aged 5 through 18 years were established on remnants of the channel bed from the mid-1970's and mid-1980's. This proposed mechanism for the development of new surfaces by fluctuations in bed-level is related to the mechanism proposed by Schick (1974) for formation of inset terraces along desert streams. However, in the desert streams studied by Schick base flow does not occur; bed-level rises during moderate floods and falls during catastrophic floods.

Surfaces aged 26 years were also formed by a fluctuation in the bed-level. As the 1965 flood subsided, sediment in transport was deposited in the channel. Two days later, a U.S. Geological Survey team observed a headcut 2 m high proceeding up Plum Creek within the study reach (M.S. Peterson, unpubl. flood measurements, 1965). This headcut, which is visible on aerial photographs taken the same day (Fig. 6), established the present channel location of Plum Creek. The rise and fall in bed-level were more rapid and greater in magnitude in 1965 than in 1973 through 1976. In addition, the agent of erosion during downcutting in 1965 was probably water draining from the

Fig. 6. Aerial photograph of Plum Creek at Louviers, Colorado, June 18, 1965. This photograph was taken 2 days after the flood. Flow is from bottom to top. The arrow indicates a headcut on the main channel.

sandy banks, not the sediment-poor base flow that caused downcutting after 1973. However, the pattern of bed aggradation during high flow and degradation during low flow is the same for both cases.

An additional process could help explain the high initial elevation of surfaces aged 5 through 18 years relative to the present channel bed (Fig. 4). The range in elevation of the channel bed at a particular time may be correlated with the range in discharge in the preceding months. The high peak flows in 1973, 1983, 1984, and 1987 (Table 1) may have produced higher bedforms than have been produced by the low flows since 1987.

Although vegetation was not responsible for the formation of surfaces aged 5 through 18 years at Plum Creek, the substantial amount of sediment deposition around the vegetation suggests that it may have helped to raise the elevation of these surfaces. Osterkamp and Costa (1987) found that the presence of fine sediment at Plum Creek was strongly associated with vegetation.

The elevation and abundance of surfaces that formed in different years can be explained in terms of the records of bed-level and discharge (Fig. 5). None of the surfaces examined in this study dated to 1965 through 1973. This is probably because the two highest flows since the 1965 flood were in 1969 and 1973. These flows apparently reworked any new surfaces that developed in that period. As a result of the high flow of 1973, bed-level peaked in 1974 (Fig. 5); subsequent incision of a narrower channel made available portions of the former bed for vegetation establishment. The high flows of 1983 and 1984 raised the elevation of pre-existing surfaces and formed new surfaces for colonization. Low flows since 1987 (Fig. 5) have allowed establishment of vegetation on the present channel bed. This is apparently why woody root flares on surfaces aged 5 through 18 years are higher in elevation than root flares on surfaces aged 1 through 4 years (Fig. 4). The difference between age groups in root-flare elevation is paralleled by clear differences in species composition (Friedman, 1993).

Five different age groups of surfaces at Plum Creek have been described in this paper: 0 years (channel bed), 1 through 4 years, 5 through 18 years, 26 years (deposits of the 1965 flood), and greater than 26 years. The initial elevation of each age group was a result of

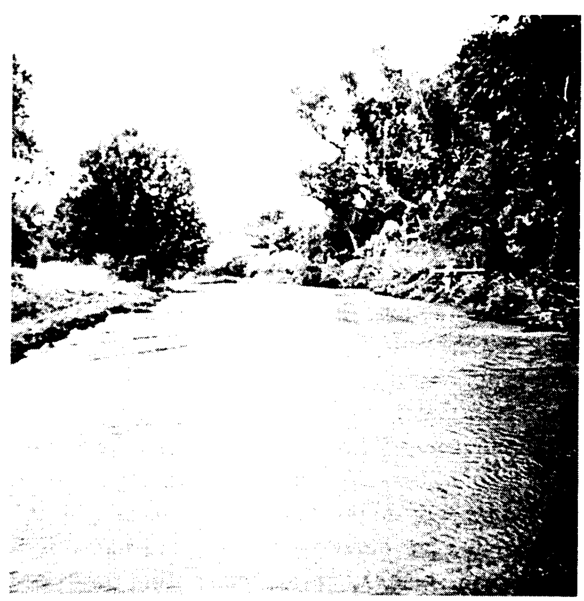

Fig. 7. Photograph of Plum Creek near Louviers, Colorado, July 31, 1953; note meter-high banks with abundant woody vegetation.

a specific sequence of high and low flows and the associated fluctuations in bed-level. Because the different age groups began at different elevations, the vegetation on these surfaces cannot be viewed as a successional sequence (Friedman, 1993). For example, moisture availability limits establishment of many wetland plants; therefore, the vegetation on newly exposed sites should depend upon elevation. Herbaceous species restricted to the low wet sites aged 1 through 4 years may never have occurred on surfaces that began at a higher elevation. The woody species that dominate surfaces aged 1 through 18 years have never become established on surfaces aged 26 years. Cottonwood seedlings have been observed on these high surfaces in some years (W.R. Osterkamp, unpubl. observation), but all have died, apparently because of stress from summer drought.

5.3. Future changes in channel geometry and vegetation

The developing flood plain at Plum Creek has not reached a steady-state elevation; the moderate flows of 1983 and 1984 deposited up to 0.3 m of sediment on surfaces aged 5 through 18 years. In the absence of future large floods the rise in elevation should eventually slow because inundation duration decreases with elevation, and because the roughness of vegetation will decrease as dense willows are shaded out by widely spaced cottonwoods (Nanson and Beach, 1977). Ground-level photographs and cross-sections used to measure discharge both indicate that Plum Creek had banks over a meter above the channel bed before the flood (Fig. 7) (U.S. Geological Survey, unpubl. results). This geometry is consistent with the observation of Kilpatrick and Barnes (1964) that inundation of the flood plain is relatively infrequent on streams with a steep gradient. However, it may be incorrect to assume that the post-flood geometry is tending toward the pre-flood condition.

The Plum Creek channel is wider, straighter, and steeper than it was before the 1965 flood (Table 2). A wide, straight, braided channel is characteristic of streams carrying high bedload (Schumm, 1969). Therefore, the pre-flood geometry is not likely to be regained until bedload is reduced. This may occur slowly as bottomland vegetation stabilizes existing sources of coarse material with the aid of fines introduced from the watershed. The apparent recent damping in fluctuations of bed-level (Fig. 5) suggests that this process is underway.

6. Conclusions

Bed-level fluctuations have played an important role in the process of channel narrowing at Plum Creek from 1973 into 1986. Surfaces formed during this period began as relict portions of the channel bed stranded at high positions following the peak bed-levels of 1973 and 1984. On the other hand, surfaces dating from 1987 through 1991 were formed when vegetation became established in the present channel bed at a time of relatively stable bed-level and low flow. In conclusion, channel narrowing along this sandbed stream has resulted both from fluctuations in bed-level and by establishment of vegetation on the channel bed.

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References

Baker, V.R., 1977. Stream-channel response to floods with examples from central Texas. Geol. Soc. Am. Bull., 88: 1057–1071.

Burkham, D.E., 1972. Channel changes of the Gila River in Safford Valley, Arizona 1846–1970. U.S. Geol. Surv. Prof. Pap., 655-G: 24 pp.

Colorado Climate Center, no date. Temperature summary for Castle Rock, Substation number 51401, Division 4, 40 years ending in

1987. Summary of monthly climatic data for Sedalia, Colorado, Substation number 57510, Division 4, 1955–1990.

Fenneman, N.M., 1931. Physiography of Western United States. McGraw-Hill, New York, 534 pp.

Follansbee, R. and Sawyer, L.R., 1948. Floods in Colorado. U.S. Geol. Surv. Water-Supply Pap., 997: 151 pp.

Friedman, J.M., 1993. Vegetation establishment and channel narrowing along a Great-Plains stream following a catastrophic flood. Ph.D. Dissertation, University of Colorado, Boulder, Colorado, 156 pp.

Gottesfeld, A.S. and Johnson Gottesfeld, L.M.J., 1990. Floodplain dynamics of a wandering river; dendrochronology of the Morice River, British Columbia, Canada. Geomorphology, 3: 159–179.

Graf, W.L., 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geol. Soc. Am. Bull., 89: 1491–1501.

Hadley, R.F., 1961. Influence of riparian vegetation on channel shape, northeastern Arizona: U.S. Geol. Surv. Prof. Pap., 424-C: 30–31.

Hansen, W.R., Chronic, J. and Matelock, J., 1978. Climatography of the Front Range urban corridor and vicinity, Colorado. U.S. Geol. Surv. Prof. Pap., 1019: 59 pp.

Hickin, E.J., 1984. Vegetation and river channel dynamics. Can. Geogr., 28: 111–127.

Hupp, C.R., 1988. Plant ecological aspects of flood geomorphology and paleoflood history. In: V. Baker, R. Kochel and P. Patton (Editors), Flood Geomorphology. Wiley, New York, pp. 335–356.

Hupp, C.R., 1992. Riparian vegetation recovery patterns following stream channelization: a geomorphic perspective. Ecology, 73: 1209–1226.

Johnson, W.C., 1994. Woodland expansion in the Platte River, Nebraska: patterns and causes. Ecol. Monogr., 64: 45–84.

Johnson, W.C., Burgess, R.L. and Keammerer, W.R., 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. Ecol. Monogr., 46: 59–84.

Kilpatrick, F.A. and Barnes, H.H., Jr., 1964. Channel geometry of piedmont streams as related to frequency of floods. U.S. Geol. Surv. Prof. Pap., 422-E: 10 pp.

Madole, R.F., 1991. Quaternary geology of the northern Great Plains, Colorado Piedmont Section. In: R.B. Morrison (Editor), Quaternary Nonglacial Geology; Conterminous United States. Boulder, Colorado, Geological Society of America, The Geology of North America, Vol. K-2, pp. 456–462.

Matthai, H.F., 1969. Floods of June 1965 in South Platte River basin, Colorado. U.S. Geol. Surv. Water-Supply Pap., 1850-B: 64 pp.

Nadler, C.T. and Schumm, S.A., 1981. Metamorphosis of South Platte and Arkansas rivers, eastern Colorado. Phys. Geogr., 2: 95–115.

Nanson, G.C., 1986. Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium flood-plain development. Geol. Soc. Am. Bull., 97: 1467–1475.

Nanson, G.C. and Beach, H.F., 1977. Forest succession and sedimentation on a meandering-river floodplain, northeast British Columbia, Canada. J. Biogeogr., 4: 229–251.

Nevins, T.H.F., 1969. River training — the single-thread channel. 1969. N. Z. Eng., pp. 367–373.

Osterkamp, W.R. and Costa, J.E., 1987. Changes accompanying an extraordinary flood on a sandbed stream. In: L. Mayer and D. Nash (Editors), Catastrophic Flooding. Allen and Unwin, Boston, pp. 201–224.

Patton, P.C. and Schumm, S.A., 1981. Ephemeral-stream processes: implications for studies of Quaternary valley fills. Quat. Res., 15: 24–43.

Phipps, R.L., 1985. Collecting, preparing, crossdating, and measuring tree increment cores. U.S. Geol. Surv. Water-Resour. Invest. Rep., 85-4148: 48 pp.

Schick, A.P., 1974. Formation and obliteration of desert stream terraces — a conceptual analysis. Z. Geomorphol., 21: 88–105.

Schumm, S.A., 1969. River metamorphosis. J. Hydraul. Div. Am. Soc. Civ. Eng., 95: 255–273.

Schumm, S.A. and Lichty, R.W., 1963. Channel widening and floodplain construction along Cimarron River in southwestern Kansas. U.S. Geol. Surv. Prof. Pap., 352-D: 88 pp.

Scott, G.R., 1963. Quaternary geology and geomorphic history of the Kassler Quadrangle, Colorado. U.S. Geol. Surv. Prof. Pap., 421-A: 70 pp.

Scott, M.L., Friedman, J.M. and Auble, G.T., 1996. Fluvial process and the establishment of bottomland trees. Geomorphology, 14: 327–339, this issue.

Scott, M.L., Wondzell, M.A. and Auble, G.T., 1993. Hydrograph characteristics relevant to the establishment and growth of western riparian vegetation. In: H.J. Morel-Seytoux (Editor), Proc. Thirteenth Annual American Geophysical Union Hydrology Days. Hydrology Days Publications, Atherton, Cal., pp. 237–246.

Sigafoos, R.S., 1964. Botanical evidence of floods and flood-plain deposition. U.S. Geol. Surv. Prof. Pap., 485A: 35 pp.

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

Turner, R.M., 1974. Quantitative and historical evidence of vegetation changes along the upper Gila River, Arizona. U.S. Geol. Surv. Prof. Pap., 655-H: 20 pp.

Ugland, R.C., Cochran, B.J., Hiner, M.M. and Steger, R.D., 1991. Water resources data, Colorado, water year 1990: U.S. Geological Survey Water-data Report CO-90-1, 489 pp.

Van Haverbeke, D.F., 1990. *Populus deltoides* var. *occidentalis* Rydb., plains cottonwood. In: R.M. Burns and B.H. Honkala (Technical Coordinators), Silvics of North America, Volume 2, Hardwoods. Agriculture Handbook 654, U.S. Department of Agriculture, Forest Service, pp. 536–543.

Ware, G.H. and Penfound, W.T., 1949. The vegetation of the lower levels of the floodplain of the South Canadian River in central Oklahoma. Ecology, 30: 478–484.

Williams, G.P., 1978. The case of the shrinking channels—the North Platte and Platte rivers in Nebraska. U.S. Geol. Surv. Circ., 781: 48 pp.

Williams, G.P. and Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U.S. Geol. Surv. Prof. Pap., 1286: 84 pp.

Wolman, M.G. and Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Process., 3: 189–208.