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CONSTRAINTS ON ESTABLISHMENT OF PLAINS COTTONWOOD IN AN URBAN RIPARIAN PRESERVE

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Abstract: Plot sampling and hydraulic modeling were combined to investigate establishment and survival of plains cottonwood along Boulder Creek, an urban stream on the Colorado Plains. We tested the hypothesis that establishment is limited to bare, moist surfaces produced by spring flooding in the current year. No cottonwood germination was observed in 1989 when peak flow was low. A moderate peak of 11.9 m^3/s in 1990 resulted in cottonwood establishment on surfaces inundated by discharges less than 15 m^3/s. Surviving sapling cottonwoods established before 1989 occurred on surfaces inundated by discharges of 15–31 m^3/s and dated to years with peak flows over 15 m^3/s. Since 1969, establishment of cottonwood has been limited to a floodplain 21 m wide. Flow regulation and channel stabilization upstream and downstream of the study area have reduced the channel movement and overbank flooding that otherwise would have created bare, moist sites suitable for cottonwood establishment across a wider area. GIS analysis of aerial photographs shows that between 1937 and 1992 the channel has not moved and forest has encroached upon formerly open areas near the channel. A terrace, 317 m wide, is now dominated by trees that can reproduce in the absence of disturbance, especially the exotic crack willow.

Key Words: channel change, channel stabilization, cottonwood, dam, disturbance, flood, flow regulation, riparian, urban floodplain

INTRODUCTION

Protection and enhancement of riverine wetland and riparian areas are important components of urban river corridor management. Preservation of undeveloped area in the floodplain limits the risk of flood damages while providing benefits associated with fish and wildlife habitat, water quality improvement, and recreation (Kusler 1989). However, multiple objective management involves tradeoffs. In an urban setting, there is little tolerance for a dynamic river channel. Limitations on the way in which a river creates disturbance patches by flooding and altering course can significantly alter the natural vegetation dynamics of the associated riparian corridor (Klimas 1989, Johnson 1992).

Western riparian systems dominated by cottonwood (*Populus* spp.) are especially sensitive to decreases in natural disturbance because the establishment of cottonwood seedlings is largely restricted to the bare, moist, unshaded sites created by channel movement and flood deposition (Scott et al. 1996, Friedman et al. 1997, Scott et al. 1997). Urban streams are subject to channel clearing, straightening, stabilization, and enlargement, all of which decrease the likelihood of channel movement and overbank flooding. In addition, upstream reservoirs typically decrease peak flow and sediment load, further reducing flood deposition and the rate of channel movement. Such restrictions on channel change and flow variability can greatly decrease the rate of establishment of cottonwood seedlings (Bradley and Smith 1986, Rood and Mahoney 1990, Johnson 1992), although dam construction can initially cause a pulse of cottonwood establishment as trees become established on the bed of a formerly wide, shallow channel (Williams and Wolman 1984, Johnson 1994, Friedman et al. 1997). Therefore, urban riparian cottonwood populations can be expected to decline over the long term even when they are protected from on-site industrial or residential development.

We examined a riparian nature preserve along Boulder Creek in Boulder, Colorado to determine how the vegetation of this patch of riparian forest was being influenced by its position on a partially regulated and constrained stream flowing through an urban area. We used analysis of aerial photographs to document long-term changes in channel alignment and forest cover and carried out repeat plot sampling to investigate establishment and survival of woody plants. Several studies have related establishment of woody plants to

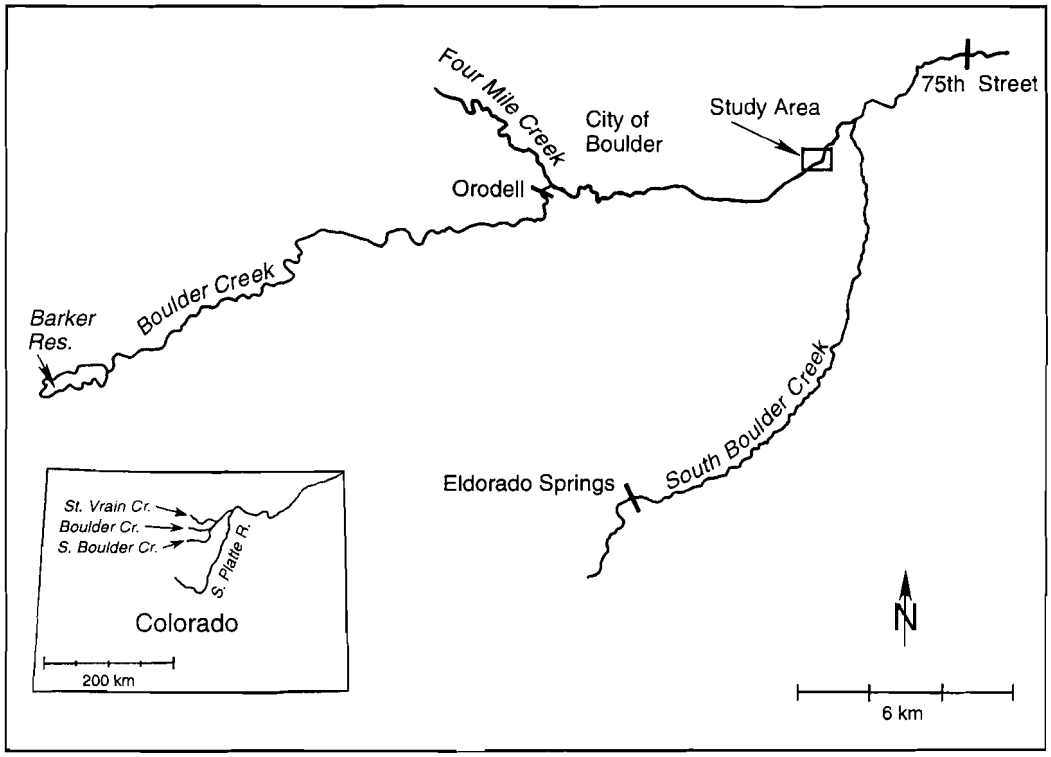

Figure 1. Location of study area along Boulder Creek in Boulder, Colorado, USA.

height above a stream and attributed this relation to the effects of moisture availability and frequency and intensity of riverine disturbance (Stromberg 1993, Johnson 1994, Friedman et al. 1996, Scott et al. 1997). In order to measure this gradient more directly, we used a hydraulic model to determine the discharge necessary to inundate each plot. This allowed us to relate establishment and mortality to specific events in the flow record. We investigated two related hypotheses:

1) cottonwood seedling establishment in any year should be limited to surfaces inundated by a flow lower than the peak instantaneous annual discharge, but higher than the discharge at the end of the seed viability period on August 1;

2) reductions in flow variability and rate of channel movement have decreased the area colonized by cottonwood along Boulder Creek in this century.

STUDY AREA

Boulder Creek arises in the Indian Peaks of the Colorado Rocky Mountains and flows east across the Colorado Piedmont (Madole 1991) to Saint Vrain Creek, a tributary of the South Platte River (Figure 1). The city of Boulder is located at the mouth of a canyon where Boulder Creek reaches the Plains. Relict channels visible on the ground and in aerial photographs of the Boulder area indicate that prior to settlement, this portion of Boulder Creek wandered across a valley more than 1 km wide (Figure 2).

The 12-ha Cottonwood Grove study area is located within the city of Boulder, about 11 km east of the mountain front at an elevation of 1650 m (Figure 1). The area was obtained by the City of Boulder as part of the Boulder Creek Corridor Project and since 1983 has been managed as a nature preserve with no public access or grazing (Windell et al. 1988). The bottomland at the Cottonwood Grove comprises three distinct fluvial surfaces (Figure 3). The channel bed extends up to a pronounced decrease in slope that corresponds to the lower limit of perennial vegetation. The floodplain slopes irregularly up from the channel bed and is inundated with a return frequency of 1–20 yr. This broadly defined floodplain includes the active channel shelf of Osterkamp and Hupp (1984). The terrace, 2 m above the channel bed, is a relatively smooth, flat surface that was probably last inundated in 1969. An average cross section contains 6 m of channel, 21 m of floodplain, and 320 m of terrace. Woody plants larger than 10 cm in diameter are essentially restricted to the terrace. The local channel gradient is 0.0071. The drainage area of Boulder Creek at the study area is about 376 km^2 (Kimbrough 1995). Barker Reservoir, located 19 km upstream from Boulder, was constructed in 1910. Flow in Boulder Creek is regulated by this reservoir and numerous diversions.

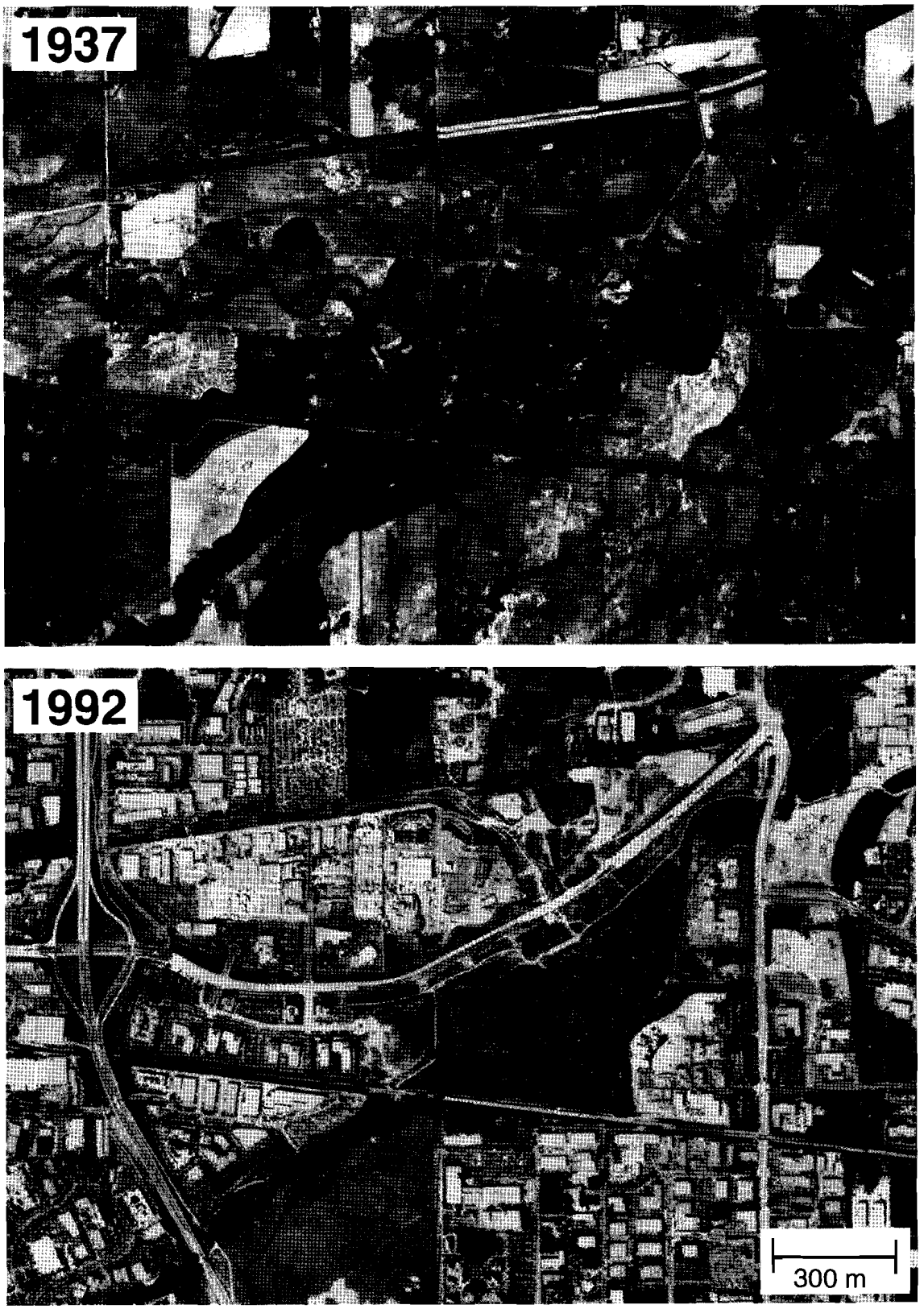

Figure 2. Aerial photographs of the Cottonwood Grove along Boulder Creek in Boulder, Colorado, USA on (A) July 23, 1937 and (B) September 10, 1992.

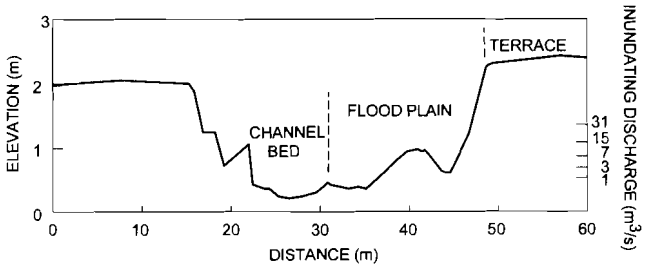

Figure 3. Elevation and inundating discharge *vs.* distance along a sample cross section at Boulder Creek, Boulder, Colorado, USA. The three fluvial surfaces are indicated on the right bank (view is downstream).

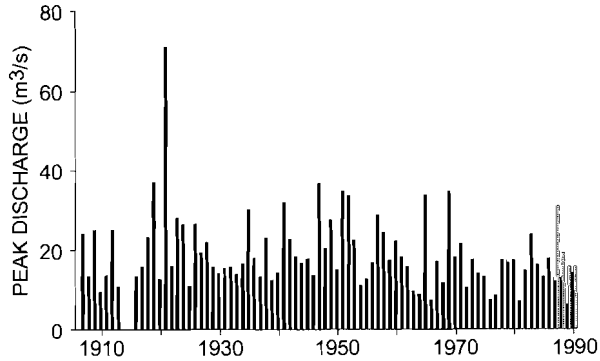

Figure 4. Peak instantaneous annual discharge along Boulder Creek, Colorado, USA, 1907–1990. Solid bars are from the Orodell Gage; stippled bars are from the Seventy-Fifth Street Gage. The Orodell gage was not operating during the greatest flood of this period, approximately 140 m^3/s in Boulder in 1914. The peak discharge at Orodell during the flood of 1969, 35 m^3/s, was much less than the 85 m^3/s experienced in Boulder (U.S. Army Corps of Engineers 1977).

Accounts of explorers between 1820 and 1845 (James 1820, Frémont 1988) indicate that streams like Boulder Creek along the mountain front in Colorado supported discontinuous groves of plains cottonwood (*Populus deltoides* Marsh subsp. *monilifera* (Ait.) Eckenw.). Irrigation for agriculture and landscaping, elimination of bison and fire, tree planting, flow regulation, and channel maintenance have increased Boulder's forest area (Schoolland 1967) and altered the species mix. The dominant trees in the study area are now crack willow (*Salix* × *rubens* Schrank, *S. fragilis* L. × *S. alba* L., Shafroth et al. 1994), green ash (*Fraxinus pennsylvanica* Marsh.), plains cottonwood, Russian-olive (*Elaeagnus angustifolia* L.), box elder (*Acer negundo* L.), and honey locust (*Gleditsia triacanthos* L., Bock 1972). The dominant shrub is sandbar willow (*Salix exigua* Nutt.).

Manipulation of the riparian corridor and the adjacent floodplain began in the mid 1800s. Between 1937 and 1993, the Cottonwood Grove was surrounded by urban development (Figure 2). The creek has been subjected to diversion, straightening, stabilization, and clearing upstream and downstream of the Cottonwood Grove. Nearly 83% of Boulder Creek between the mountain front and the eastern city limit had been channelized by 1984 (Windell et al. 1988). The only reaches that had not been straightened or dredged were a 1100-m reach extending below the canyon mouth and the 500-m reach that flows through the Cottonwood Grove. However, even the reach flowing through the Cottonwood Grove shows evidence of some past channel realignment, and this reach is subject to clearing by heavy equipment to maintain high conveyance. During the last hundred years, this reach may have experienced degradation caused by downstream channel straightening as well as aggradation resulting from upstream channel work (Hupp 1992).

The Orodell Gage is 11 km upstream from the study area, above the confluence with Four Mile Creek but below Barker Reservoir (Figure 1). The 75th Street Gage is 5 km downstream from the study area, just below the confluence with South Boulder Creek. The Eldorado Springs Gage on South Boulder Creek is 8 km upstream of the confluence with Boulder Creek. Peak flow in Boulder Creek (Figure 4) usually occurs in May or June as a result of snowmelt. This flow is reduced by filling of Barker Reservoir (Kimbrough 1995). However, the greatest floods in Boulder result largely from intense rainfall in tributaries that enter Boulder Creek downstream of Barker Reservoir and Orodell (Follansbee and Sawyer 1948, Jarrett 1990). Agricultural diversions between Orodell and the study area reduce flow during the snowmelt runoff season by 42% (Kimbrough 1995) but have only a minor effect on peak flows. Dates and approximate peak discharges of floods in Boulder along Boulder Creek are 1894, 255–385 m^3/s; 1914, 140 m^3/s; and 1969, 85 m^3/s (Follansbee and Sawyer 1948, U.S. Army Corps of Engineers 1977). Floods of unknown peak discharge caused damage in Boulder in 1864, 1876, and 1923. Thus, although the greatest flows along Boulder Creek in Boulder have been little affected by water management, flooding has been relatively minor in the last 70 years, apparently because the frequency and magnitude of intense rainfall events have been relatively low in this basin.

METHODS

Vegetation

To characterize woody vegetation on the terrace, sixteen plots 20 m × 20 m were established. Trees and shrubs were tallied in three size classes: seedlings, ≤ 1 m tall; saplings, >1 m tall but ≤ 2.5 cm in diameter

(measured 1.2 m above ground); and trees, > 2.5 cm in diameter. Seedling and sapling numbers were counted in 5 m × 5 m subplots located in the four corners of the larger plots. Plots were sampled once in July or August, 1989.

No individuals of tree size occurred on the floodplain. To characterize the smaller woody vegetation on this surface, 73 plots 1 m × 2 m or 0.5 m × 1 m were randomly spaced along 15 randomly located cross sections. On seven occasions from June through October 1989 and four occasions from June through October 1990, all woody plants in each plot were identified by their coordinates on a grid and tallied. When a cottonwood individual first appeared, it was coded as a seedling if cotyledons were present. New individuals without cotyledons and all individuals older than 1 year were coded as saplings. Vegetative cover was determined in each plot using a plot frame on July 18–19, 1990. Plots of the two sizes were weighted equally in calculations of mean vegetative cover and mean density of each species. After the final sampling date, transverse sections were cut at the excavated root flare of 7 sapling cottonwoods on the floodplain (Scott et al. 1997), and cores were taken with an increment bore 30 cm above the ground from eight cottonwood trees on the terrace. Sections and cores were sanded (600 grit; median particle size, 15 μm) and rings were counted using a microscope (Scott et al. 1997).

Hydrology

Flow data for Boulder Creek at Orodell, Boulder Creek at 75th Street, and South Boulder Creek near Eldorado Springs (Figure 1) were obtained from the U.S. Geological Survey District Office in Denver, Colorado. A temporary gage operated by the U.S. Geological Survey at the Cottonwood Grove in Water Years 1990 and 1991 (Kimbrough 1995) was used to relate flow at Orodell to flow at the study area during the growing season—April 15–October 15.

A hydraulic model was used to calculate the discharge necessary to inundate each vegetation plot on the floodplain. Surveys conducted in 1989 and 1990 determined elevations along 26 cross sections: the fifteen randomly located vegetation cross sections and an additional 11 cross sections located at hydraulic control points. A hydraulic simulation model (Milhous et al. 1989) was calibrated to flows at the study site and used to develop a relation between stage and discharge at these cross sections. Elevations of vegetation plots were compared to these stage-discharge relations to determine the discharge necessary to inundate each plot. Six classes of inundating discharge were defined: 0–1, 1–3, 3–7, 7–15, 15–31, and greater than 31 m^3/s.

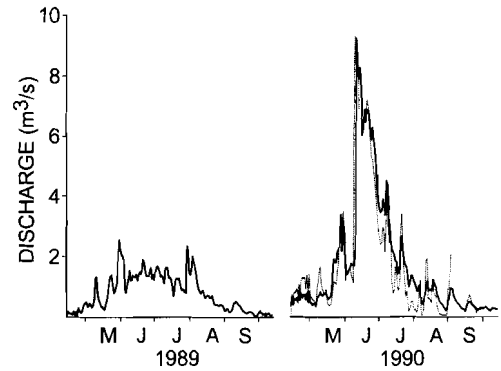

Figure 5. Mean daily discharge at the Cottonwood Grove during the growing season (April 15–October 15) 1989 and 1990. The dotted line indicates measured values from Kimbrough (1995). The solid line indicates modeled values.

Aerial Photographs

A time series of aerial photographs and a geographical information system (GIS) were used to measure encroachment by trees toward the channel. Contact prints or 2× enlargements were prepared at scales between 1:20,600 and 1:22,700 for photographs taken between July 23 and September 10 in 1937, 1955, 1963, and 1992. The midline of the channel and the outline of forest canopy were traced on mylar overlays. Overlays were combined using a Bausch and Lomb zoom transfer scope on a 1:10,500 scale map. Coverages were digitized using ARC/INFO version 6.1 GIS software and a Calcomp 9100 digitizer, and then rectified to a 7.5-minute topographic map. Forested and unforested areas were calculated within a belt 60 m wide centered along the channel midline.

RESULTS

Hydrology

Quadratic regression of mean daily discharge at the study area (S) against mean daily discharge at the Orodell Gage (R) for the period April 15–October 15 in Water Years 1990 and 1991 produced the relation: $S = R*0.33 + R^2*0.00086$; $n = 332$, $r^2 = 0.72$. We used this relation to model mean daily discharge at the study area in 1989 and 1990 (Figure 5). The year 1989 was dry (Figures 4, 5). The peak instantaneous flow at Orodell, 5.9 m^3/s, was the lowest in the 82-year period of record (Figure 4), and the peak mean daily flow at the study area was modeled as 2.5 m^3/s on May 31 (Figure 5). A secondary peak, modeled as 2.3 m^3/s, occurred on July 30. In 1990, a more typical flow year, the peak instantaneous flow at Orodell, 13.8 m^3/s, was greater than that of 33% of the other years in the record (Figure 4); the peak mean daily flow at the study area was 9.3 m^3/s on June 11 (Figure 5), and the peak

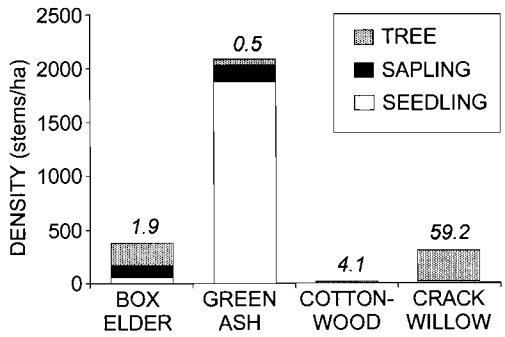

Figure 6. Stem density by size class for four species on the terrace along Boulder Creek, Colorado, USA. Total basal area (m^2/ha) for each species is indicated in italics above the bar.

instantaneous flow at the study area was 11.9 m^3/s (Kimbrough 1995).

Vegetation

Although a few old plains cottonwood were found on the terrace (Figure 6), the surface was dominated by tree-sized individuals of crack willow, an introduced species from Eurasia. The species with the most abundant saplings were green ash, a native of Kansas and Nebraska that has become naturalized in Colorado since settlement, and the native box elder (Figure 6). The species with the most abundant seedlings was green ash. Cottonwood seedlings and saplings were not observed on the terrace. The eight cored cottonwood trees from the terrace dated to 1906–1924. Because these cores were taken above the establishment surface and did not all include the biological center of the tree, the actual establishment dates may be earlier.

The floodplain was dominated by the native species plains cottonwood and sandbar willow, with lower densities of green ash, crack willow, and Russian-olive, another Eurasian introduction (Table 1). Woody species on the floodplain varied in their distribution with respect to time and inundation. Sandbar willow, crack willow, and green ash were common on plots inundated by discharges below 15 m^3/s on all 11 sampling dates (Table 1). These species experienced little mortality of existing individuals or establishment of new individuals during the two-year study. Russian-olive and honey locust were common in low positions in 1989, especially on plots inundated by discharges below 1 m^3/s; however, few individuals of these species survived into the 1990 growing season, and numbers remained low throughout 1990.

In contrast, cottonwood seedlings were absent in 1989 but numerous in 1990 (Table 1, Figure 7). Cottonwood seedlings occurred in plots inundated by discharges below 15 m^3/s, while older individuals were most abundant in plots inundated by discharges between 15 and 31 m^3/s (Table 1, Figure 7). Ring counts in seven of these older cottonwoods indicated that two were established in 1983, two in 1984, and three in 1987. Peak instantaneous discharge in 1987 at 75th Street was 30.6 m^3/s. The low peak annual instantaneous discharge for South Boulder Creek at Eldorado Springs (9.9 m^3/s) indicates that most of the flow measured at 75th Street in 1987 came from Boulder Creek. No data are available for Boulder Creek at 75th Street for 1983 and 1984; however, peak instantaneous discharge at Orodell exceeded 15 m^3/s in both these years (Figure 4).

The relation between vegetative cover and cottonwood establishment varied with the discharge necessary to inundate a surface (Table 2). On surfaces inundated by discharges less than 1 m^3/s, seedling presence was associated with relatively high cover, but on surfaces inundated by discharges of 3–15 m^3/s, seedlings were associated with relatively low cover.

Aerial Photographs

Between 1937 and 1992, forest gradually encroached upon open areas near the channel (Figure 8). In a 60-m-wide belt centered on the channel, the fraction of area covered by forest canopy increased from 0.34 to 0.66 (Figures 8, 9). Some, but not all, of this change resulted from crown growth of stems established before 1937. In the 1937 photographs, recently deposited sediment was visible on the inside of channel bends. By 1992, such deposits were no longer visible. There was little movement of the channel within the Cottonwood Grove between 1937 and 1992 (Figure 8).

DISCUSSION

The establishment requirements of cottonwood can be combined with hydrologic and hydraulic information to explain the spatial and temporal distribution of this species along Boulder Creek. Cottonwood seedling establishment is generally limited to moist, bare sites relatively safe from future disturbance (Everitt 1968, Hupp 1992, Johnson 1994, Friedman et al. 1996). In the Boulder area, cottonwood seeds are released in late May and early June (Friedman et al. 1995). Seeds are immediately germinable but remain viable for only a few weeks (Scott et al. 1993). If seedlings are dependent upon moisture and disturbance from inundation, then cottonwood seedling establishment should be limited to surfaces inundated by discharges less than the peak instantaneous annual discharge but greater than the discharge at the end of the seed viability period–approximately August 1. Sec-

Table 1. Density of woody plants (stems/100 m²) in plots on the floodplain and channel bed of Boulder Creek, Colorado.

	Inundating Discharge (m³/s)	1989							1990			
		6/15	7/6	7/19	7/25	8/9	8/22	10/12	6/4	7/12	8/17	10/11
Elaeagnus angustifolia	0–1	18	18	36	55	55	36	14	5	0	0	0
	1–3	8	8	13	13	13	13	8	0	0	0	0
	3–7	0	0	12	12	12	12	9	0	0	0	0
	7–15	0	0	0	0	0	0	0	0	0	0	0
	15–31	0	0	0	0	0	0	0	0	0	0	0
	>31	0	0	0	0	0	0	0	0	0	0	0
Gleditsia triacanthos	0–1	23	23	32	32	32	32	27	5	5	0	0
	1–3	4	4	4	4	4	4	4	0	0	0	0
	3–7	9	9	9	9	6	6	6	6	3	3	3
	7–15	0	0	0	0	0	0	0	0	0	0	0
	15–31	3	3	3	3	3	3	3	3	3	3	0
	>31	0	0	0	0	0	0	0	0	0	0	0
Populus deltoides seedlings	0–1	0	0	0	0	0	0	0	0	332	55	5
	1–3	0	0	0	0	0	0	0	0	175	146	0
	3–7	0	0	0	0	0	0	0	0	294	76	12
	7–15	0	0	0	0	0	0	0	0	400	161	83
	15–31	0	0	0	0	0	0	0	0	0	0	0
	>31	0	0	0	0	0	0	0	0	0	0	0
Populus deltoides saplings	0–1	18	18	18	18	14	14	14	9	9	14	9
	1–3	4	4	4	4	4	4	4	4	4	4	4
	3–7	21	18	21	21	21	21	18	6	0	0	0
	7–15	44	50	50	50	44	44	50	44	39	39	39
	15–31	145	147	145	145	145	145	142	134	134	132	129
	>31	0	0	0	0	0	0	0	0	0	0	0
Salix exigua	0–1	132	132	141	141	145	145	127	109	100	91	86
	1–3	79	83	88	108	104	104	100	63	63	58	38
	3–7	94	97	109	109	109	109	103	97	68	82	68
	7–15	217	222	233	233	250	261	244	239	244	244	233
	15–31	53	55	55	55	55	55	55	55	53	50	53
	>31	0	0	0	0	0	0	0	0	0	0	0
Salix × rubens	0–1	32	36	45	50	50	50	41	50	36	32	32
	1–3	33	38	38	38	38	38	29	8	17	13	13
	3–7	29	35	35	35	41	41	35	68	59	53	38
	7–15	33	33	39	39	33	33	33	33	39	33	33
	15–31	0	0	0	0	0	0	0	0	5	0	0
	>31	0	0	0	0	0	0	0	0	0	0	0
Fraxinus pennsylvanica	0–1	0	0	0	0	0	0	0	0	0	0	0
	1–3	17	21	21	21	17	17	13	17	17	17	17
	3–7	71	71	71	71	71	71	71	68	65	62	62
	7–15	11	11	11	11	11	11	11	11	11	11	11
	15–31	13	11	18	18	18	18	18	18	18	18	18
	>31	0	0	0	0	0	0	0	0	0	0	0

ondary high flows following seed germination should reduce survival within this zone.

In 1989, the zone available for establishment was narrow because of the unusually low snowmelt peak; the secondary peak on July 30 was probably also detrimental to establishment (Figure 5). This hydrologic information is consistent with the absence of seedlings in vegetation plots in 1989. In 1990, the zone available for cottonwood establishment extended from 0.4 to 9.3 m³/s (Figure 5). The presence of seedlings within this zone, but not above (Table 1), is consistent with the hypothesis that seedling establishment is dependent upon bare, moist, safe sites prepared by scouring flows. The association between cottonwood establish-

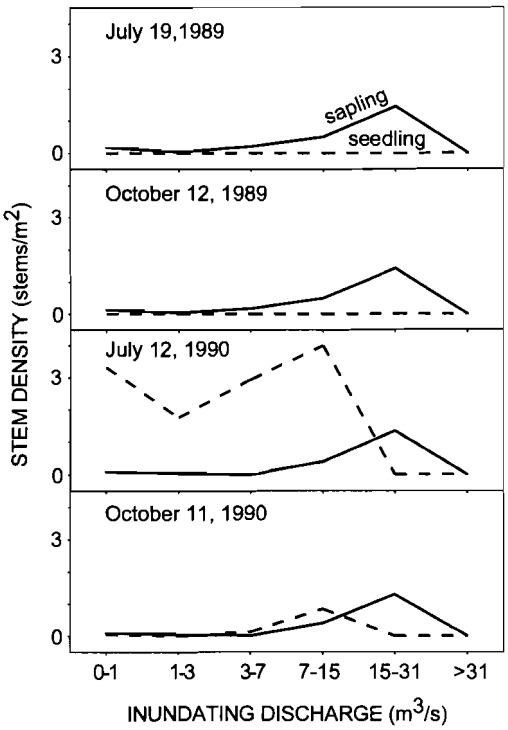

Figure 7. Stem density of cottonwood seedlings and saplings on four different dates *vs.* inundating discharge in plots on the channel bed and floodplain of Boulder Creek, Colorado, USA.

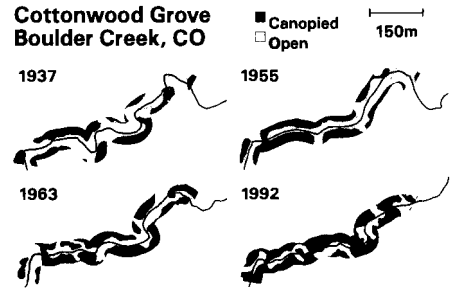

Figure 8. Canopied and open areas in a zone 60 m wide centered along Boulder Creek, Colorado on July 23, 1937; September 4, 1955; August 10, 1963; and September 10, 1992.

ment and low vegetative cover at inundating discharges between 3 and 15 m³/s (Table 2) further supports the importance of bare sites for establishment. This association is reversed on surfaces inundated by discharges below 1 m³/s (Table 2) because repeated flooding in low, exposed plots produces microsites that are low in cover but too frequently disturbed for survival.

Cottonwood seedlings and saplings showed different distributions with respect to the discharge necessary to inundate a plot. The moderate peak discharge in 1990 created bare surfaces suitable for seedling establishment only on sites inundated by discharges less than 15 m³/s (Table 1). Low densities of sapling cottonwoods in this zone (Table 1) suggest that occasional high flows or ice scour remove seedlings from all but the most protected micro-sites. Long-term survival is more likely when higher flows clear and moisten surfaces with inundating discharges above 15 m³/s (Table 1, Figure 7). Harvested saplings dated to 1983, 1984, and 1987—years in which peak instantaneous discharge did exceed 15 m³/s. The absence of cottonwood saplings in plots with inundating discharges over 31 m³/s reflects the absence of floods of this magnitude since 1969. The bimodal distribution of cottonwood observed on the Boulder Creek floodplain (Figure 7) is consistent with the conclusion of Asplund and Gooch (1988) and Scott et al. (1997) that sites where cottonwood seedlings become established in most years are too low for long-term survival.

The dependence of cottonwood upon flood disturbance contrasts with reproductive strategies of other woody species on the Boulder Creek floodplain. Russian-olive and honey locust occurred only on low, moist sites. Most individuals were removed by the spring flow of 1990, and there was no subsequent establishment on bare, moist sites (Table 1). Compared to cottonwood, these species may be more susceptible to mortality from inundation and physical disturbance, and their large seeds may slow colonization of newly formed establishment sites. As a result, these exotic

Table 2. Mean percent vegetative cover ± standard error by inundating discharge in plots with and without cottonwood seedlings. Numbers of plots are indicated in parentheses. Cover was measured July 18–19, 1990. The designation "seedlings absent" indicates that seedlings were not observed in the plot on any of the 4 sampling dates in 1990.

	Inundating Discharge (m³/s)						
Plot characteristic	0–1	1–3	3–7	7–15	15–31	>31	All
Seedlings absent	9 ± 5 (4)	47 ± 13 (7)	77 ± 13 (7)	94 ± 4 (6)	62 ± 8 (19)	65 ± 13 (5)	62 ± 5 (48)
Seedlings present	59 ± 11 (7)	55 ± 8 (5)	46 ± 9 (10)	26 ± 8 (3)	(0)	(0)	49 ± 5 (25)
All plots	41 ± 10 (11)	50 ± 8 (12)	59 ± 8 (17)	72 ± 12 (9)	62 ± 8 (19)	65 ± 13 (5)	57 ± 4 (73)

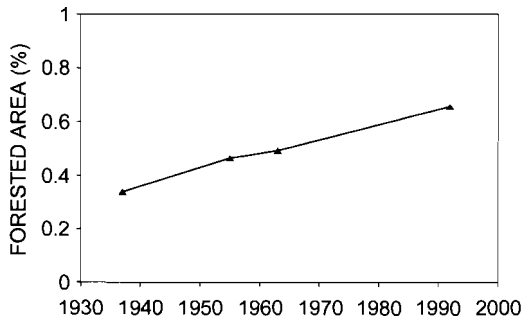

Figure 9. Change over time in percent forested area in a zone 60 m wide centered along Boulder Creek, Colorado, USA.

species may be favored by the moist stable environment along some strongly regulated streams (Shafroth et al. 1995).

Sandbar willow, crack willow, and green ash were relatively unaffected by the high flow of 1990 (Table 1). Their wider and higher elevational range apparently made them less susceptible to flood damage than Russian-olive and honey locust (Table 1). Unlike cottonwood, these species did not show a burst of recruitment following the high flow of 1990. The absence of male crack willow in the Cottonwood Grove (Shafroth et al. 1994) suggests that this hybrid is reproducing entirely vegetatively. Sandbar willow seedling establishment may have failed because its small seed size results in slower initial growth, and therefore greater low-moisture stress than that experienced by cottonwood (Friedman 1993). In addition, a relatively late period of seed release may uncouple this species in time from the bare moist sites produced by late spring flooding. On the other hand, sandbar willow produces root sprouts more prolifically than cottonwood, allowing it to colonize riparian sites that are unsuitable for seedlings (Friedman 1993). Green ash seedlings are uncommon on recent flood deposits, apparently because the period of seed release is late and because seedlings may require the mesic conditions provided by soils with high organic matter (Johnson et al. 1976).

Since 1937, channel maintenance, water management, and decreased frequency of intense rainstorms have reduced the unforested area adjacent to the channel by about half (Figures 8, 9). The effects of channel maintenance include channel clearing within the study area and straightening and stabilization upstream and downstream. Increased gradient resulting from straightening can lead to downcutting (Hupp 1992). Although no data are available to determine whether downcutting has occurred at the study area, the presence of decades-old concrete weirs in the channel bed indicates that downcutting has at least been a subject of concern. Reductions in flood peaks, channel clearing, and possibly downcutting have all combined to reduce the frequency of flooding on the terrace and floodplain. Channel clearing and reduction in sediment load may have decreased channel movement by decreasing the extent of point bar formation. All of these factors have diminished the area physically disturbed by the stream.

The zone of cottonwood establishment since 1969 (those surfaces inundated by discharges of roughly 15–31 m^3/s) is a band less than 21 m wide, a small fraction of the Boulder Creek bottomland. If occasional high flows were allowed to inundate and scour surfaces on the broad terrace, then the band of establishment could be wider (Scott et al. 1997). If the channel was allowed to move, then multiple bands of cottonwood could be established (Everitt 1968, Bradley and Smith 1986, Friedman et al. 1997). By preventing these processes of bottomland change, channel maintenance and flow regulation have greatly reduced the area available for cottonwood recruitment.

The isolation of the terrace from riverine disturbance has apparently reduced cottonwood establishment and favored other species (mostly exotics) that do not require disturbance for continued reproduction. The abundance of seedlings and saplings of green ash and box elder (Figure 6) reflects the shade tolerance of these species relative to cottonwood. The exotic crack willow, whose seedlings are not shade-tolerant, is apparently reproducing by sprouts from decumbent branches and stumps. The shift toward species that can reproduce in the absence of disturbance is reminiscent of succession on old point bars along meandering streams in the eastern and central Plains (Friedman et al. 1997). At the scale of the entire bottomland, this shift is similar to that produced by dam construction along formerly meandering streams (Johnson 1992).

MANAGEMENT IMPLICATIONS

The decline of cottonwood relative to other woody species at the study area is not a result of severe stream modifications by the city of Boulder. To the contrary, Boulder's approach to flood management has focused on minimizing floodplain development instead of the more traditional construction of dams for flood control and over-sized concrete-lined channels to minimize overbank flooding (Windell et al. 1988). The lack of protection of the city from the effects of flash floods continues to be a major concern (U. S. Army Corps of Engineers 1977). Therefore, limitations on cottonwood recruitment at least as severe as those observed in Boulder are likely in other cities and towns along the front of the Rocky Mountains.

Several choices remain for water resource planners. The first choice is simply accepting loss of most urban

cottonwood forest as a consequence of development. This requires living with a forest dominated by exotic species that do not require physical disturbance for establishment. A second choice is to mimic the effects of flood disturbance to remove exotic plants and induce establishment of cottonwood from natural seedfall. For example, earth-moving equipment and irrigation have been used to establish cottonwood from natural seedfall elsewhere along Boulder Creek (Friedman et al. 1995). Third, cottonwood populations could be maintained by pole planting (Ohmart et al. 1988).

Outside of the urban core, channel stabilization activities should be minimized if maintenance of native ecosystems is an important concern. Many attempts at stream "restoration" have involved use of boulders to prevent erosion of cutbanks and elimination of woody debris to prevent channel movement and ease passage of fish and boats. These activities reduce the channel movement that forms the new bare, moist sites necessary for establishment of cottonwood and other riparian species native to streams of the Colorado Piedmont (Friedman et al. 1996). Similarly, most fish native to Plains streams have characteristics enabling them to thrive in shifting turbid streams subject to wide variations in flow (Cross and Moss 1987); reducing flow variability and channel movement tends to favor exotic fish (Fausch and Bestgen 1997). Managers need to be aware that bank erosion, shifting channels, sediment transport, and overbank flooding are natural processes that promote and maintain native ecosystems in the Great Plains.

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