WETLANDS, Vol. 18, No. 4, December 1998, pp. 591–607

EFFECTS OF FLOW AUGMENTATION ON STREAM CHANNEL MORPHOLOGY AND RIPARIAN VEGETATION: UPPER ARKANSAS RIVER BASIN, COLORADO

DeWitt S. Dominick[1] and Michael P. O'Neill[2]
[1] *Inter-Fluve, Inc.*
25 N. Willson Ave.
Bozeman, Montana, USA 59715

[2] *Department of Geography & Earth Resources*
Watershed Science Unit
Utah State University
Logan, Utah, USA 84322-5240

Abstract: We characterized changes in stream morphology and riparian vegetation cover at eight field sites in tributary basins of the upper Arkansas River, Colorado, USA. Three of these sites have experienced flow augmentation, while five others are responding to natural flow conditions. Data analyzed for the eight field sites included hydrologic data from U.S. Geological Survey gaging stations, extensive field surveys of riparian vegetation and channel and floodplain morphology, and land-cover maps compiled from historic aerial photographs of field sites. Hydrologic analyses indicated that augmented peak annual floods in the Lake Creek basin are more than double those of Clear Creek or Cottonwood Creek, similar tributaries where flow augmentation does not occur. Likewise, augmented peak floods on Lake Fork are roughly double those of a similar tributary basin with a natural flow regime. Flow duration curves from these basins also indicated that flows of a given magnitude are sustained over longer periods of time in the Lake Creek and Lake Fork basins than in comparable basins lacking flow augmentation. Historic changes in the channel pattern at augmented sites indicated a shift from highly sinuous meandering channels to less sinuous or braided channels. Data from field sites also indicated that along augmented reaches, bankfull channel width and width-depth ratios are greater than in comparable sections that lack flow augmentation. Similarly, substrate size on depositional bars at augmented sites is substantially coarser than on streams without flow augmentation. Median particle size for the three sites along augmented reaches ranges from 38 to 56 mm. By contrast, sites where natural flows occur have median particle sizes between 15 and 26 mm. Historic aerial photograph analysis indicated that over the last 56 years, loss of riparian vegetation cover at sites where flow augmentation occurs was greater than that at sites where natural flows occur. Bottomland areas immediately adjacent to the active channel have experienced up to a 10% decrease in riparian vegetation cover at sites affected by augmented flows. These losses primarily occur along channel margins, with commensurate increases in exposed depositional bars and active channel features. By contrast, along reaches where natural flows occur, riparian vegetation cover generally shows a net increase or decrease of less than 2% of the bottomland area. Substantial change in channel and floodplain morphology suggests that augmented streams in the upper Arkansas River basin are continuing to adjust their shape and channel dimensions to achieve a new equilibrium. The complex response of mountain streams to flow augmentation over a relatively short geologic time period makes the prediction of future long-term conditions difficult. Restoration planners working in this or similar watersheds must recognize the historic and potential future impacts of flow augmentation when evaluating sites for restoration efforts.

Key Words: flow augmentation, riparian vegetation, stream geomorphology

INTRODUCTION

Throughout the semi-arid West, healthy and productive natural environments require riparian ecosystems that form an important interface between upland and aquatic ecosystems. A riparian corridor most often forms a conspicuous, narrow ribbon that is characterized by distinctive vegetation, soil, and frequency of flooding (Cowardin et al. 1979).

Within the riparian corridor, dynamic interactions among geomorphic processes, landforms, and vegetation occur on many spatial and temporal scales (Gregory et al. 1991). Until recently, the relationship between spatial and temporal patterns of riparian vegetation, floodplain topography, and stream channel forms received only limited consideration. Hupp and Osterkamp (1985) suggested that patterns of woody riparian vegetation may be associated with observable fluvial landforms. These fluvial landforms include depositional bars, floodplains, and terraces and are usually distinguished by distinct topographic levels above the stream channel. Frequency and duration of flooding, timing of inundation, and aggradation and degradation shape fluvial landforms (Hupp 1988) and thereby determine the plant communities capable of establishment and survival on these alluvial surfaces.

The magnitude of flood impact on channel form and the time necessary for recovery often depend on the character of streamside vegetation (Gupta and Fox 1974, Baker 1977, Wolman and Gerson 1978). Much of the variability in plant communities comes from disturbance caused by flood events and the erosion and deposition of material that results from high flows (Resh et al. 1988, Friedman et al. 1996). Fluvial processes that form floodplains, point bars, and lateral accretion bars create fresh surfaces for the establishment of new plant communities (Swanson 1980, McBride and Strahan 1981). Once established, vegetation becomes an integral part of the fluvial system (Hupp and Osterkamp 1985) and may regulate the movement and temporary storage of sediment from upstream sources.

A substantial body of literature exists describing the response of riparian vegetation and channel patterns to stream diversions and dam closures in western North America (Williams and Wolman 1984, Andrews 1986, Harris et al. 1987, Schmidt and Graf 1990, Stromberg and Patten 1990, Smith et al. 1991, Johnson 1992, 1994, 1998, Ryan 1994, Friedman et al. 1998). These studies show that reduced flows often cause a shift in plant community composition and/or distribution.

Far less is understood about long-term effects of flow augmentation, a less common but increasingly important practice of stream modification (Abbott 1976, Kellerhals et al. 1979, Bray and Kellerhals 1979, Bradley and Smith 1984, Henszey et al. 1991, Stromberg and Patten 1992, Church 1995). Flow augmentation can increase the magnitude, duration, and frequency of large flows, inhibiting vegetation establishment and recruitment by excessive erosion, inundation, and loss of topographic surfaces to colonize adjacent to the active channel.

Stromberg and Patten (1992) found that diverted water from the Mono Basin through the Mono Tunnel tripled the flow volume in the augmented-flow reach along the upper Owens River. Similarly, Bradley and Smith (1984) calculated pre- and post-diversion mean monthly flows on the Milk River and also found a threefold increase in flows due to the St. Mary River diversion. Both and Bradley and Smith (1984) and Stromberg and Patten (1992) found that transbasin diversion practices did not substantially change seasonal flow patterns, they simply increased the magnitude of peak flows.

Schumm (1969) presented a conceptual framework for channel change based on responses of alluvial rivers in the United States Great Plains and Riverine Plain of New South Wales, Australia. This framework depicts changes in channel morphology that occur as a result of a change in quantity of water and/or quantity and type of sediment load. For increases in discharge (Q_w^{+}), Schumm (1969) relates:

$$Qw^{+} \cong \frac{w^{+}d^{+}\lambda^{+}}{S}$$

where a direct relationship exists between Q_w^{+} and channel width (w^{+}), depth (d^{+}), and meander wavelength (λ^{+}), and an inverse relationship with decrease in channel slope. This relationship represents the long-term response of river channels to obtain equilibrium in a specific physiographic region and climatic regime, and it may apply to many fluvial systems.

Kellerhals et al. (1979) provided a qualitative description of morphological effects on 11 Canadian interbasin river diversions. They found that the response of drainage networks to flow augmentation depends largely on the specific case history and local geologic controls. However, some basic trends in riverine systems affected by flow augmentation included channel entrenchment, widening, decreased sinuosity, increased sediment loads, increased substrate size, increased frequency of bankfull discharge, and loss of adjacent vegetation by bank erosion and scour. Bray and Kellerhals (1979) showed that channel response to augmented flow depends on the particular character of the system and described three geomorphic classes of diversion routes: bedrock-controlled; steep, unconsolidated materials; and alluvial. Augmented flows on the steep diversion route of the Little Jackfish River changed mean flow from approximately 5 m^3/sec to 110 m^3/sec. This new flow regime triggered a dramatic increase in suspended sediment load, with an initial rate of 4 × 106 m^3/yr in 1943 decreasing over time to 0.3 × 10^6 m^3/yr in 1977 (Bray and Kellerhals 1979).

Likewise, augmented flows on the Lower Kemano River caused initial channel over-widening by eroding its banks between 1954 and 1975 (Kellerhals et al. 1979). This 20-year transient state was followed by a period of channel degradation once flows breached the armored bed layer and established a new period of floodplain development and channel narrowing (Church 1995). Church (1995) concluded that the timescale for primary morphological adjustment is shorter (decades) on regulated rivers that experience an upward adjustment in channel-forming flows rather than a downward adjustment. The timescale necessary for riparian communities to adjust through autogenic processes and obtain a new equilibrium may be on the order of centuries (Church 1995, Johnson 1998).

The transient response of riparian vegetation to flow regulation varies widely on rivers, depending on different geomorphologies, climate, vegetation composition, and water-use patterns (Johnson 1998). For example, the Platte River is braided, with a large portion of its flow diverted for cropland irrigation, whereas the Missouri is a meandering river with substantial hydroelectric use and relatively little irrigation use. Initial response of the Platte River to flow regulation is channel narrowing and woodland expansion through allogenic processes, but on the Missouri River, pioneer tree recruitment ceases and autogenic or successional processes dominate (Johnson 1998).

Loss or mortality of riparian vegetation adjacent to the active channel is one common response to transbasin diversion practices. Stromberg and Patten's (1992) work compared the density, distribution, and radial growth rates of juvenile and mature willows (*Salix lasiolepis*, Benth.) along a control reach and flow-augmented reach on the upper Owens River, California. Flow augmentation dramatically degraded riparian environments; areal cover, density, and the ratio of live to dead willow trees were significantly lower in the augmented-flow reach than in the control reach (Stromberg and Patten 1992). Stromberg and Patten (1992) observed that willow trees on average occurred about 2 m farther from the streamedge within the augmented-flow reach than in the control reach on the upper Owens River. Densities of juvenile *S. lasiolepis* within streamside recruitment zones were significantly lower in the augmented-flow reach than in the control reach. Likewise, the ratio of juvenile to mature individuals was threefold higher in the augmented-flow reach than in the control reach (Stromberg and Patten 1992).

However, Stromberg (1993) also showed the opposite effect where an increase in seasonal flow volume led to an increase in riparian stand width and basal area on streams in the semi-arid southwest, Verde River basin, Arizona. Stromberg's (1993) study supports the idea that change in discharge volume and riparian water availability produces measurable changes in the distribution of riparian vegetation, but the positive correlation between riparian width and mean discharge applies to a undisturbed flow regime in an otherwise arid climate.

Channel and riparian plant community response to a new flow regime depends on many factors, including the nature of disturbance, water-use patterns, sediment supply, and the geomorphic character of the particular river system (Bray and Kellerhals 1979, Friedman 1997, Johnson 1998). Few studies of geomorphology and/or plant community ecology have examined the downstream effects of flow augmentation on montane river systems. This study attempts to document effects of flow augmentation on channel morphology and riparian plant communities on tributaries of the Arkansas River, Colorado by comparing present channel and hydraulic characteristics on non-augmented and augmented streams and mapping historic change of the stream channel morphology and the distribution of riparian plant communities.

STUDY AREA

The project area encompasses the uppermost portion of the Arkansas River watershed, an area that includes approximately 3,155 km^2 from the headwaters just north of Leadville to Salida, Colorado, USA (Figure 1). The Arkansas Valley is the northern end of the Rio Grande Rift (Karnuta 1995) and is characterized by a long, structural down-faulted trough. The main topographic features bordering the valley are two mountain ranges that are parallel in a north-south direction, the Sawatch Range on the west and the Mosquito Range on the east.

The main tributaries of the Arkansas River include Lake Creek, Lake Fork, Clear Creek, Cottonwood Creek, and Chalk Creek. These streams drain east from the continental divide through glacial U-shaped valleys filled with coarse alluvium that originate in the Sawatch Range at elevations over 4,300 m above sea level (ASL). A detailed description of plant community types in these tributaries is presented in Dominick (1997).

Over the past century, the Arkansas River valley has been transformed into an intricate plumbing system controlled by an extensive network of aqueducts, tunnels, canals, and reservoirs. Beginning in 1910, transmountain diversions have moved water from the Colorado River basin across the continental divide to the Arkansas River basin (USFWS 1993). Expansion of hydrologic projects over the last several decades was implemented to provide supplemental water for irrigation and to serve growing demands of urban centers in the lower Arkansas River basin or Front Range, primarily the cities of Pueblo, Colorado Springs, and Aurora, Colorado. Further east in Kansas, the Arkansas River has experienced depleted flow volumes caused by river impoundment and irrigation (Cross and Moss 1987). The opposite effect has occurred in some of the tributaries to the upper Arkansas River examined in this study.

Transmountain diversions and reservoirs are used to transport and store spring and early summer runoff to serve the water demands of downstream users later in

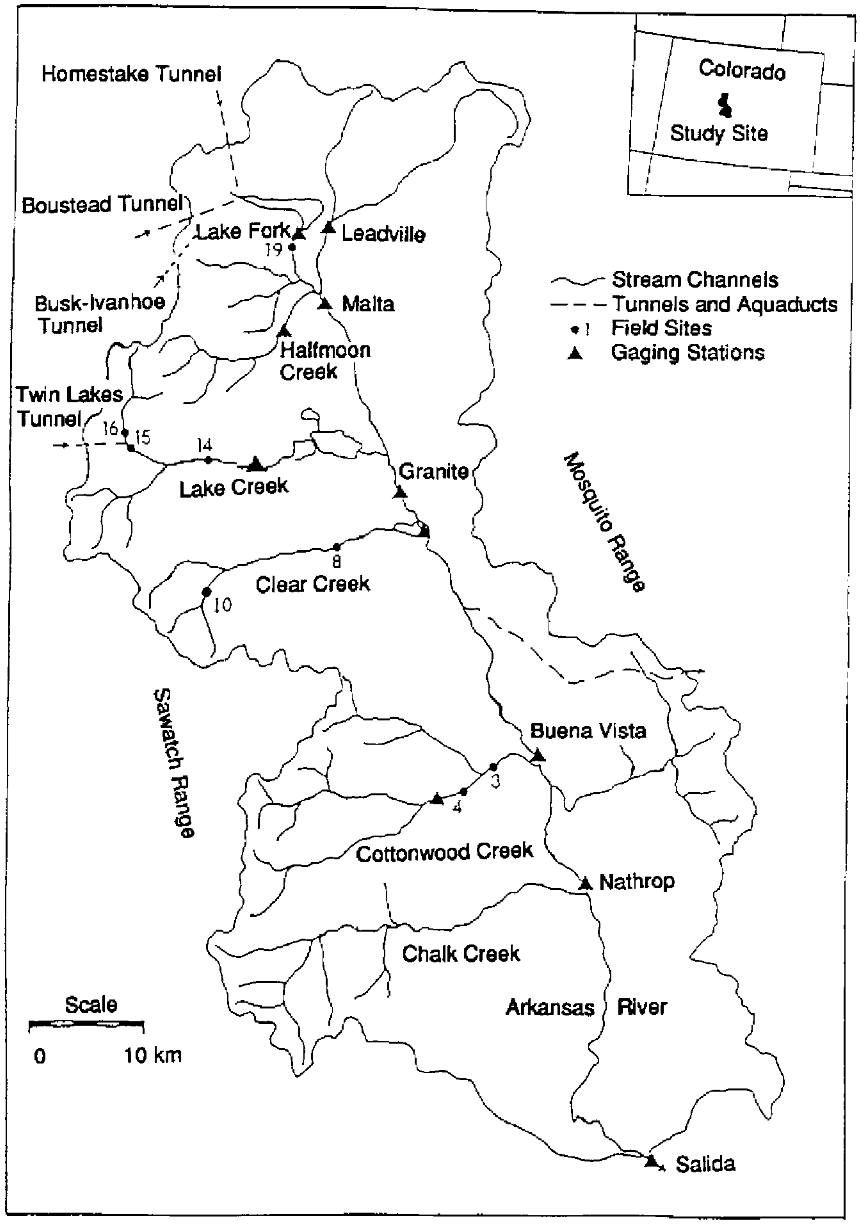

Figure 1. Study area, upper Arkansas River basin, Colorado. Field sites are located on tributaries of the Arkansas River: Lake Fork (site 19), Lake Creek (sites 14, 15, 16), Clear Creek (sites 8, 10), and Cottonwood Creek (sites 3, 4).

the year (Crouch et al. 1984). Completed in 1935, the Twin Lakes Tunnel enters the North Fork of Lake Creek approximately 18 km upstream from Twin Lakes Reservoir (Figure 1). Maximum daily discharge from the tunnel may exceed 18 $m^3 sec^{-1}$, over half the mean annual discharge of Lake Creek recorded near the head of reservoir. Likewise, the addition of transbasin flows in Lake Fork below Turquoise Reservoir has tripled the magnitude and duration of peak flows (Abbott 1976). Maximum flow volumes are most often diverted in June and early July during the annual peak floods when water is most plentiful. Generally, over the last two decades, the total volume of transbasin water has increased as development along the Colorado Front Range expands and the demand for water increases.

METHODS

Twenty-two field sites within the upper Arkansas River basin were examined as part of a project to identify potential restoration sites for riparian wetlands (O'Neill et al. 1997). Here, we report data from eight of these sites (see Figure 1) selected from four tributary basins: Lake Creek (drainage area = 194 km^2), Clear Creek (174 km^2), Cottonwood Creek (168 km^2), and Lake Fork (87 km^2). Study reaches were chosen using the following criteria:

1. availability of high quality historic aerial photograph coverage;
2. access through public or in some cases private lands;
3. consistency of contributing basin area, elevation, natural hydrology, and channel morphology;
4. absence of on-site anthropogenic activity such as the construction of roads, railroads, or other structures; and
5. availability of long-term discharge data.

Independent watershed and channel controls at each field site are described in Table 1.

We characterized changes in stream morphology and riparian vegetation cover at the eight field sites shown on Figure 1. Three of these sites (14, 15, 19) have experienced flow augmentation, while five others (3, 4, 8, 10, 16) are responding to natural flow conditions. The present channel on augmented streams has destroyed most remnants of pre-augmented channel conditions; therefore, non-augmented streams were used to compare channel dimensions and shape. Lake Creek (16), Clear Creek (8, 10), and Cottonwood Creek (3, 4) were used as control sites to illustrate the condition of drainages with no upstream flow augmentation. Lake Creek (14, 15) and Lake Fork (19) have augmented flow regimes and represent two drainages with altered hydrology. Our hydrologic analyses use mean daily discharge data recorded at U.S.G.S. gaging stations located on Lake Creek, Clear Creek, Cottonwood Creek, Lake Fork, and Halfmoon Creek. Unless otherwise noted, we report unit discharges (Q/A) in our hydrologic analyses. Data from aerial photos, U.S.G.S. gaging stations, and extensive field surveys of channel and floodplain cross-sections were compiled to document historic changes in the stream system and adjacent riparian corridor.

Field Survey Methods

Floodplain and channel cross-sections were surveyed with a geodetic total station in late summer months at low flow when wading the streams was possible. At each site, three to five cross-sections were surveyed, spaced along the channel at approximately 50 m increments. Descriptions of dominant vegetation types were made at 1- to 2-m intervals along each cross-section. Major plant community types identified from aerial photographs were used as mapping units to show historic change in land cover. Channel profiles were measured across stream segments characterized by a relatively straight channel and riffle/run complex. Meander bends and areas presently colonized by beaver generally were avoided.

During a flood on 22 June 1995, mean daily discharge was 67 m^3sec^{-1} at the Lake Creek gaging station, and on 25 June 1995 the mean daily discharge was 21.6 m^3sec^{-1} at the Clear Creek gaging station. Our estimate of the 10-year flood event at the Lake Creek gage is 55 m^3sec^{-1} and that at the Clear Creek gage is 22 m^3sec^{-1}. The 1995 peak flows approached or exceeded the 10-year flood event on both Lake Creek and Clear Creek. During these peak flows, the water-surface elevation was measured and drawn on each channel cross-section at these field sites.

The size of bed material on active mid-channel and lateral bars at each field site was estimated using Wolman's (1954) pebble count method. The median particle size (D_{50}) was calculated and used to characterize differences in bed material size between streams with natural and augmented flows.

Aerial Photograph Analysis and Geographic Information Systems

Maps of riparian plant communities and channel morphology along eight segments of Lake Creek, Lake Fork, Clear Creek, and Cottonwood Creek were prepared at a scale of 1:8000 (Dominick 1997). The maps were constructed from 1988 color infrared aerial photographs (1:40,000) and 1939 and 1956–57 black-and-white (1:20,000) aerial photographs (Dominick 1997). For each year of coverage, the same bottomland area was mapped, and appropriate mapping units were converged to three land-cover types to help identify general patterns in river metamorphosis and subsequent change in riparian vegetation cover. Mapping units are expressed in terms of area (ha) occupied by each land-cover type. For each year of photo map coverage, the total area of the land-cover type divided by the total bottomland area (%) is presented. Land-cover types are defined as follows.

1. Total unvegetated channel area (BF) corresponds with approximate bankfull conditions and equals the sum of exposed depositional bars and the active channel area, excluding beaver ponds.
2. Total riparian vegetation area equals the sum of all riparian community types and includes riparian forest, riparian shrub, and sedge meadow mapping units.
3. Total depositional bar area equals the sum of exposed mid-channel bars and lateral bar surfaces at base flow conditions.

Average channel width on historic photographs was measured as total channel area divided by total channel length. Channel pattern was analyzed by calculating sinuosity obtained from map coverages at the 1:8000 scale. Finally, channel characteristics, including channel area, bankfull width, mean depth, maximum depth,

Table 1. Watershed and channel features at selected study sites: upper Arkansas River basin, Colorado

Study Site	Flow Regime Stream Pattern Valley Floor Type	Elevation (m) Basin Area (km^2)	Channel Slope Bed Topography Sinuosity	Bed Material D_{50} (mm)	Estimated Q_{10} (m^3sec^{-1}) Energy Slope at Bankfull (BF)	Avg. W/D Ratio Avg. BF Width (m) Avg. BF Area (m^2)	Riparian Vegetation Type
Lake Fork (site 19)	augmented meandering unconstrained	2926 87	0.006 pool-riffle 1.6	gravel, cobbles (38)	19.0 0.010	45.6 27.2 16.6	willow shrub/shrub cinquefoil grass/sedge meadow
Lake Creek (site 15)	augmented braided unconstrained	3170 52	0.012 riffle 1.1	large cobbles (54)	25.6 0.010	134.3 49.3 18.7	willow/bog birch shrub; conifer; sedge/rush, and grass meadow
Lake Creek (site 14)	augmented straight constrained	2950 180	0.016 pool-riffle-run 1.2	large cobbles, boulders (56)	36.5 0.007	54.6 50.2 48.0	alder/willow shrub; mixed forest (aspen/conifer); sedge meadow
Lake Creek (site 16)	natural meandering constrained	3230 34	0.010 pool-riffle 1.6	sands, gravel (15)	5.6 0.003	21.6 13.3 8.5	willow/bog birch shrub/shrub cinquefoil; sedge meadow
Clear Creek (site 10)	natural meandering unconstrained	3206 32	0.014 pool-riffle 1.6	sands, gravels (18)	5.4 0.005	28.9 19.6 13.6	willow/bog birch shrub/shrub cinquefoil; sedge meadow
Clear Creek (site 8)	natural straight constrained	2780 154	0.033 pool-riffle-run 1.2	gravel, cobbles (21)	16.7 NA	NA	mixed forest (cottonwood/aspen/conifer); alder/willow shrub
Cottonwood Creek (site 4)	natural meandering unconstrained	3011 50	0.023 pool-riffle 1.3	sands, gravel (16)	7.4 0.008	39.4 25.8 17.1	willow/alder/bog birch shrub; mixed forest (cottonwood/conifer)
Cottonwood Creek (site 3)	natural straight constrained	2530 101	0.033 boulder pool-riffle 1.1	gravel, cobbles (26)	12.3 0.027	13.6 9.8 7.4	forest (cottonwood/aspen/maple); willow/alder shrub

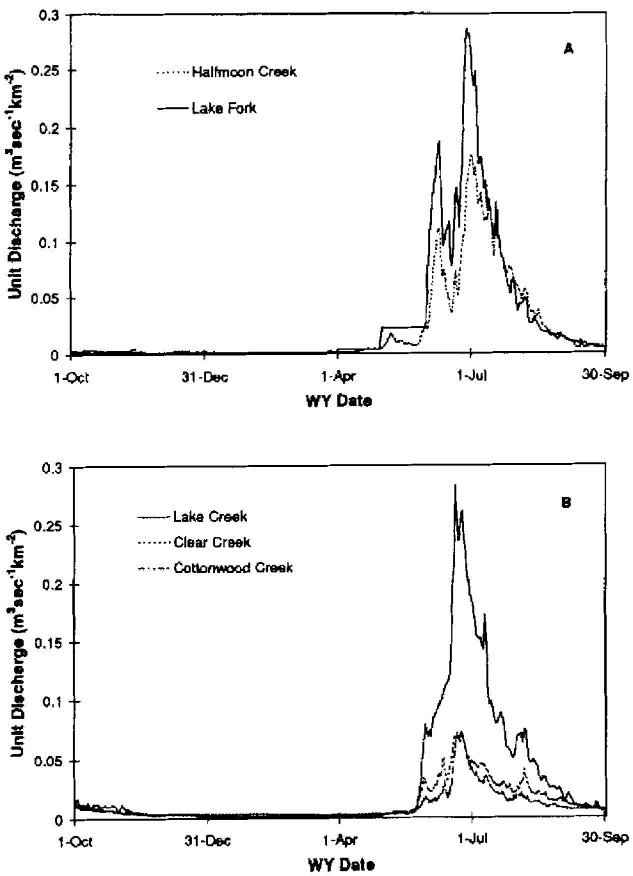

Figure 2. Annual hydrographs for selected gaging stations in the upper Arkansas River basin for 1957 and 1983 comparing augmented and non-augmented streams. A. 1957 water year B. 1983 water year.

and the width-depth ratio were measured for each surveyed cross-section.

RESULTS

Hydrology

Examples of annual unit discharge hydrographs for the five tributaries appear in Figure 2. Augmented flows released from Sugarloaf Dam to Lake Fork dramatically increased the magnitude of peak mean daily unit discharge (Figure 2A). Similarly, flow augmentation on Lake Creek has resulted in the peak mean daily unit discharge three to four times greater than contemporaneous peaks on Clear Creek and Cottonwood Creek (Figure 2B).

Flow duration curves for the five gaging stations appear in Figure 3. These flow duration curves clearly indicate that for relatively infrequent events (1 or 2% Exceedence Probability), augmented streams have much greater unit discharge than non-augmented streams. Similarly, relatively large unit discharges (0.15 $m^3sec^{-1}km^{-2}$) are much more frequent on augmented streams when compared to non-augmented streams. However, no substantial difference exists in the magnitude and duration of low flows on augmented and non-augmented streams (Figure 3).

Length of available flow records varies for each gaging station. Most tributaries have flow data from 1947 to present, but the Cottonwood Creek gaging station was discontinued after 1986. We estimated the 10-year flood event at 9 gaging stations located throughout the upper Arkansas River basin using Log-Pearson Type III flood frequency curves (Viessman et al. 1977). An area-discharge rating curve for the 10-year flood is shown in Figure 4. The empirical relationship for the 9 gage locations, excluding the two augmented tributaries is

$$Q_{10} = 0.44A^{.72}$$

where Q_{10} is the estimated discharge of the 10-year flood for an ungaged study site with drainage basin area, A. Contributing drainage area at field sites was estimated from digital elevation models (O'Neill et al. 1997). This method was used because gaging stations are generally located at the bottom of the valley, near the confluence with the mainstem Arkansas River, while many of our field sites are located much farther upstream in the drainage basin. Thus, the 10-year flood at the gaging station would not represent stage-discharge conditions at field sites. On Lake Creek, the maximum discharge (18 m^3sec^{-1}) from the Twin Lakes Tunnel was added to the estimated Q_{10} at sites 14 and 15 (augmented). Flow records indicate that the maximum Twin Lakes Tunnel discharge coincides with peak floods because the majority of transbasin water is diverted during late spring and early summer runoff conditions when water is most abundant. Similarly, we added the difference in Q_{10} for the Lake Fork and Halfmoon Creek gaging stations (8 m^3sec^{-1}) to the estimated Q_{10} at the Lake Fork site 19 (augmented). The estimated 10-year flood event for each field site is listed in Table 1.

Morphology of Present Channels and Floodplains

Representative cross-sections at four field sites are shown in Figures 5 and 6. These cross-sections characterize floodplain and channel morphology of non-augmented and augmented field sites in both constrained and unconstrained segments of the valley bottom. The cross-section at Clear Creek site 10, a non-augmented, unconstrained site, is characterized by a deep channel with a well-developed thalweg (Figure 5A). The active floodplain extends approximately 70 m across the valley bottom and is vegetated by dense *Salix* spp. Slight topographic irregularities and depressions in the floodplain surface are remnant channels

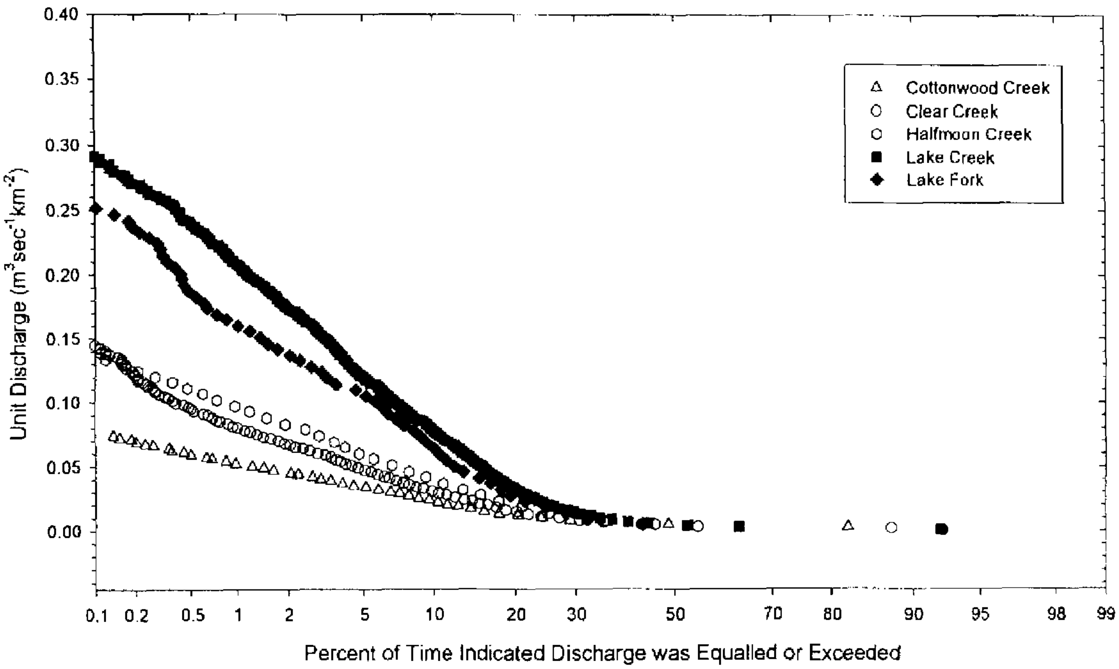

Figure 3. Flow-duration curves for tributaries of the upper Arkansas River. Solid symbols represent data from augmented streams; open symbols represent data from non-augmented streams.

and beaver ponds. The cross-section at Clear Creek site 8 is constrained by steep valley walls that limit channel migration (Figure 6A). A greater proportion of the active floodplain is unvegetated and consists of exposed gravels and cobbles. The cross-section at Lake Creek site 15, an augmented, unconstrained reach, is characterized by a wide, shallow, active channel with numerous large, coarse, mid-channel bar deposits that cause extensive braiding (Figure 5B). It appears that the channel at site 15 experienced approximately 1 m of incision; 1-m vertical channel banks are unvegetated and highly erodible. The period of incision is not known, but the presence of an abandoned floodplain surface 1 m above the active channel suggests that the stream responded to the new flow regime by initial over-widening and degradation. Mass wasting and bank failure seem to be the common mechanisms of erosion; large woody debris and chunks of bank material are found on mid-channel bars at base flow throughout the site. The cross-section at site 14,

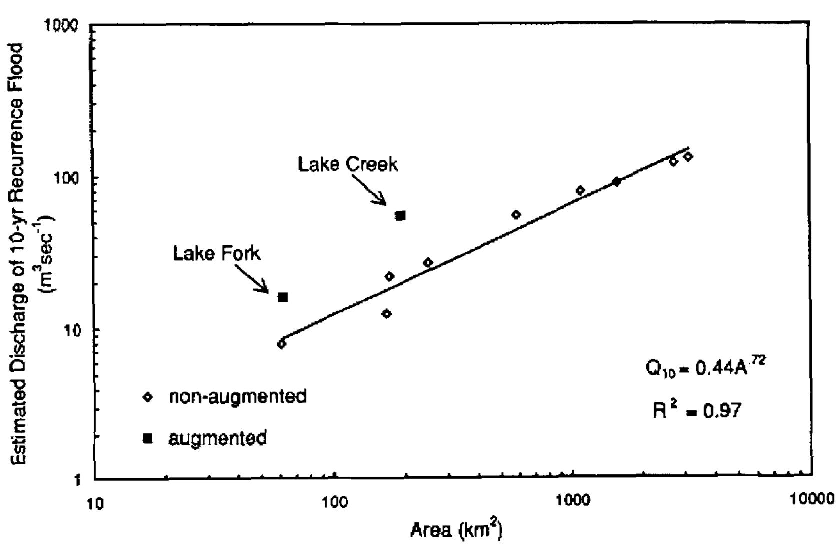

Figure 4. Relationship between estimated 10-year flood and contributing drainage basin area at 11 gaging stations within the upper Arkansas River basin. Line depicts least-squares fit to non-augmented gage data.

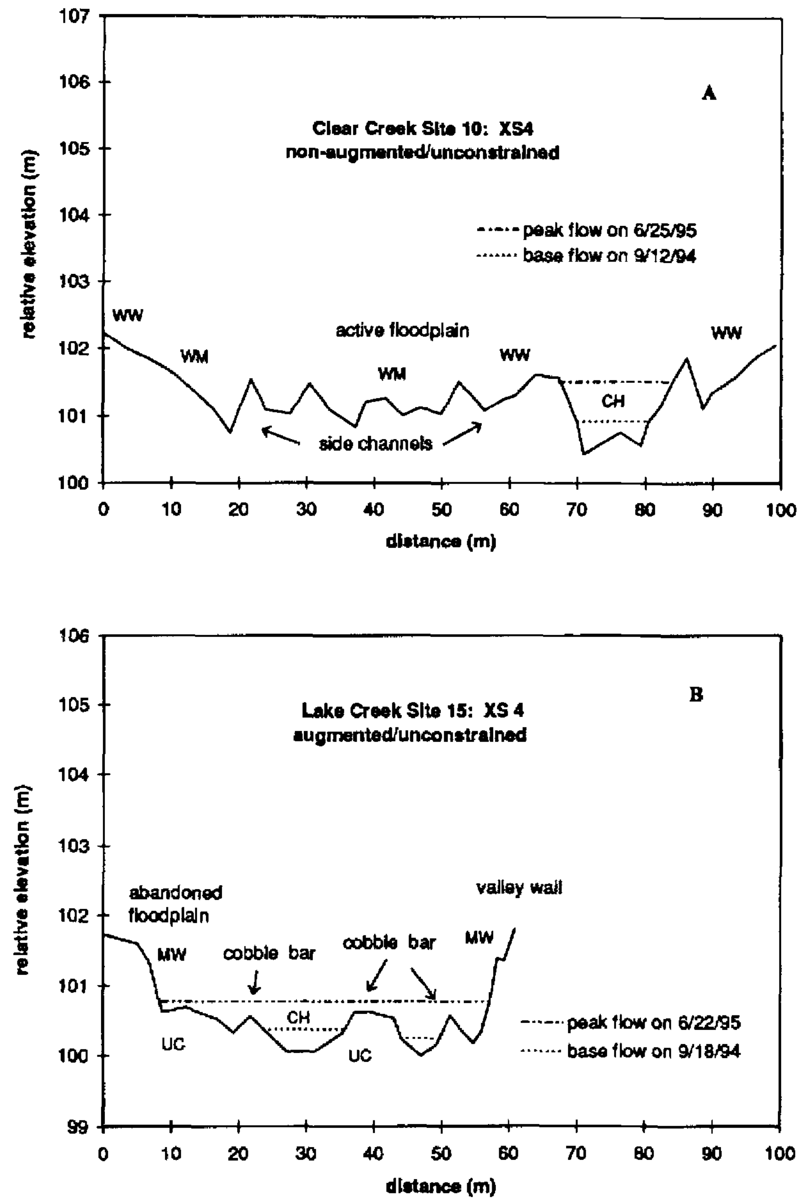

Figure 5. Representative cross-sections from two unconstrained field sites. Dashed lines represent measured water-surface elevation at base flow, and observed water-surface elevation for the 10-year flood stage. Abbreviations for landforms and their associated plant communities include: channel (CH), unvegetated channel (UC), wet willow (WW), moist willow (MW), and wet meadow (WM).

a constrained reach on Lake Creek is characterized by a deep active channel next to the left bank (Figure 6B). During base flow, water is confined to the main channel. The addition of augmented flows during spring runoff probably causes scour in the main channel and inundation of the historic active floodplain, an unvegetated cobble and gravel bar that extends approximately 50 m toward the valley wall.

Median particle size (D_{50}) describing the character of bed material on active depositional bars at each field site is listed in Table 1. In general, the three augmented sites are characterized by much larger bed material than that at the five non-augmented sites. Median particle size for the three sites along augmented reaches ranges from 38 to 56 mm. By contrast, sites where natural flows occur have median particle sizes between 15 and 26 mm.

Channel Geometry

Floodplain and channel cross-sections were used to calculate several stream parameters, including bankfull channel width and width-depth ratio (Figures 7 and 8). Flow-augmented stream channels are most often char-

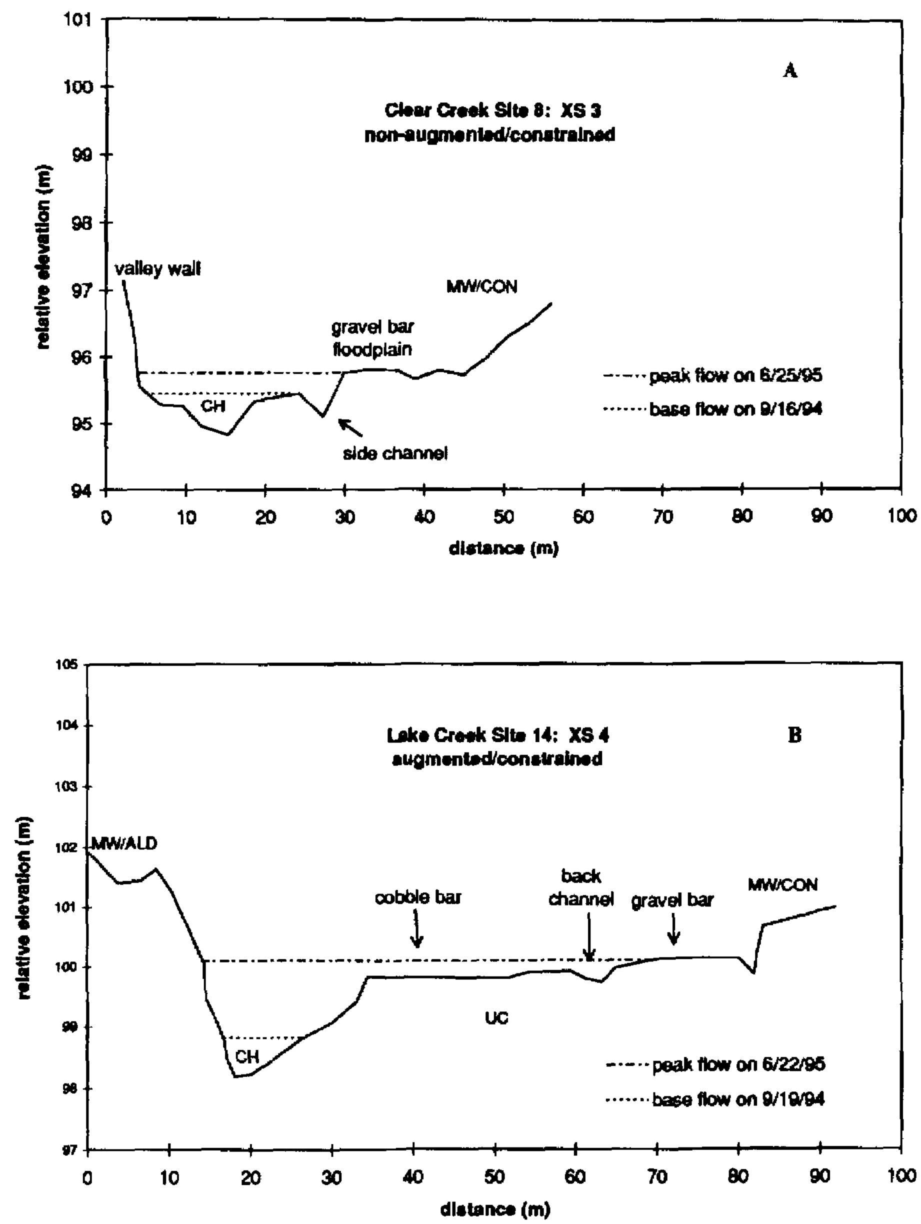

Figure 6. Representative cross-sections from two constrained field sites. Dashed lines represent measured water-surface elevation at base flow, and observed water-surface elevation for the 10-year flood stage. Abbreviations for landforms and their associated plant communities include: channel (CH), unvegetated channel (UC), moist willow (MW), conifer (CON), and alder (ALD).

acterized by bankfull channel width greater than those of streams with similar natural flows. Typical widening of a stream channel as drainage basin area and discharge increase in the upper Arkansas River basin is apparent (Figure 7). The average bankfull channel width at non-augmented field sites ranges from 9.8 to 25.8 m. By contrast, augmented sites have an average bankfull channel width between 27.2 and 50.2 m (see Table 1). Width-depth ratios (W/D) for streams with augmented flows also are greater than those on non-augmented sites (Figure 8). Average W/D for the five sites along non-augmented reaches ranges from 13.6 to 39.4. At the three augmented sites, average W/D ranges from 45.6 to 134.3.

Vegetation and Channel Mapping

Clear Creek (sites 8 and 10), Cottonwood Creek (site 4), and Lake Creek (site 16) represent natural stream reaches with meandering channel sections and well-vegetated floodplains immediately adjacent to the active channel. By contrast, the present condition of

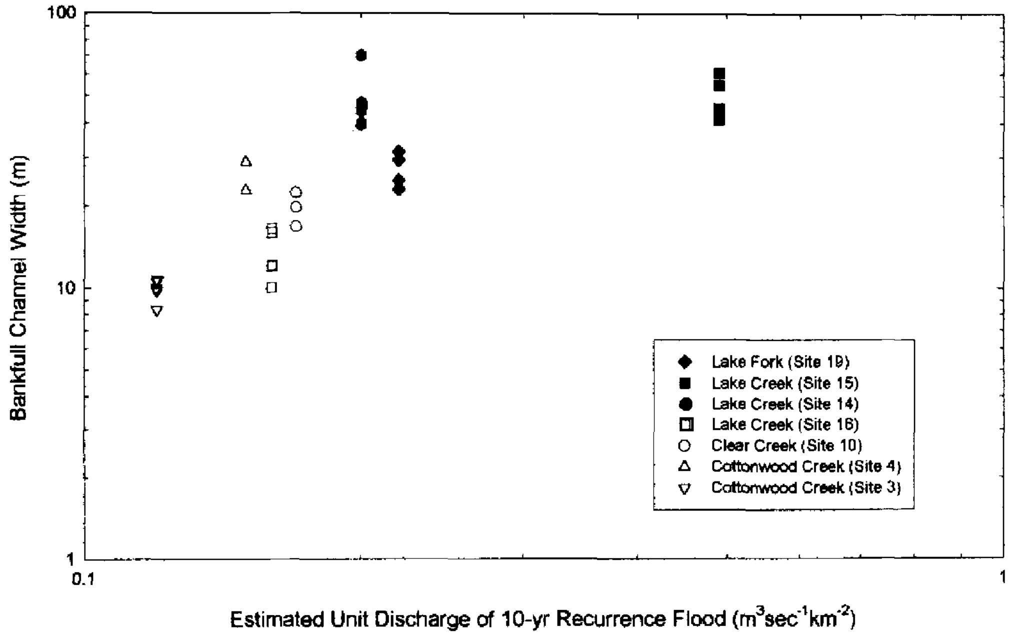

Figure 7. Relationship between bankfull channel width and unit discharge. Data points depicting identical discharge represent measurements from unique cross-sections at the same field site. Solid symbols represent data from augmented streams; open symbols represent data from non-augmented streams.

augmented stream reaches (sites 14 and 15) along Lake Creek and Lake Fork (site 19) are characterized by relatively wide and straight or braided channels with adjacent floodplain surfaces composed of unvegetated, coarse gravel and cobble bars.

Land-cover classification maps prepared from historic aerial photographs at eight field sites showed substantial differences in the character of non-augmented and augmented stream systems. Figures 9 and 10 represent a sequence of historic maps that show changes

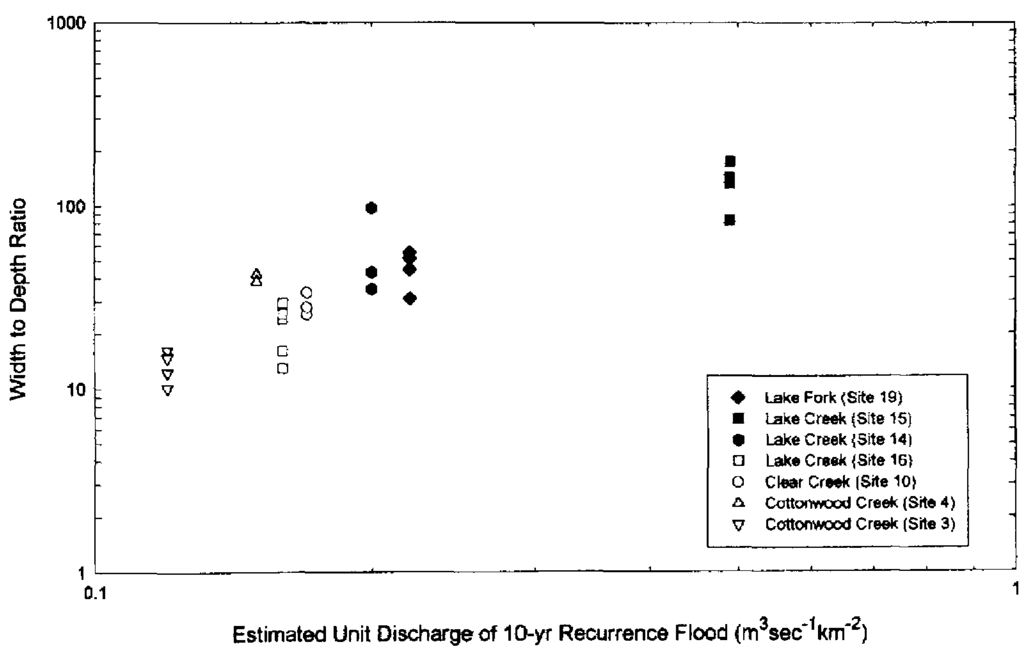

Figure 8. Relationship between width-depth ratio and unit discharge. Data points depicting identical discharge represent measurements from unique cross-sections at the same field site. Solid symbols represent data from augmented streams; open symbols represent data from non-augmented streams.

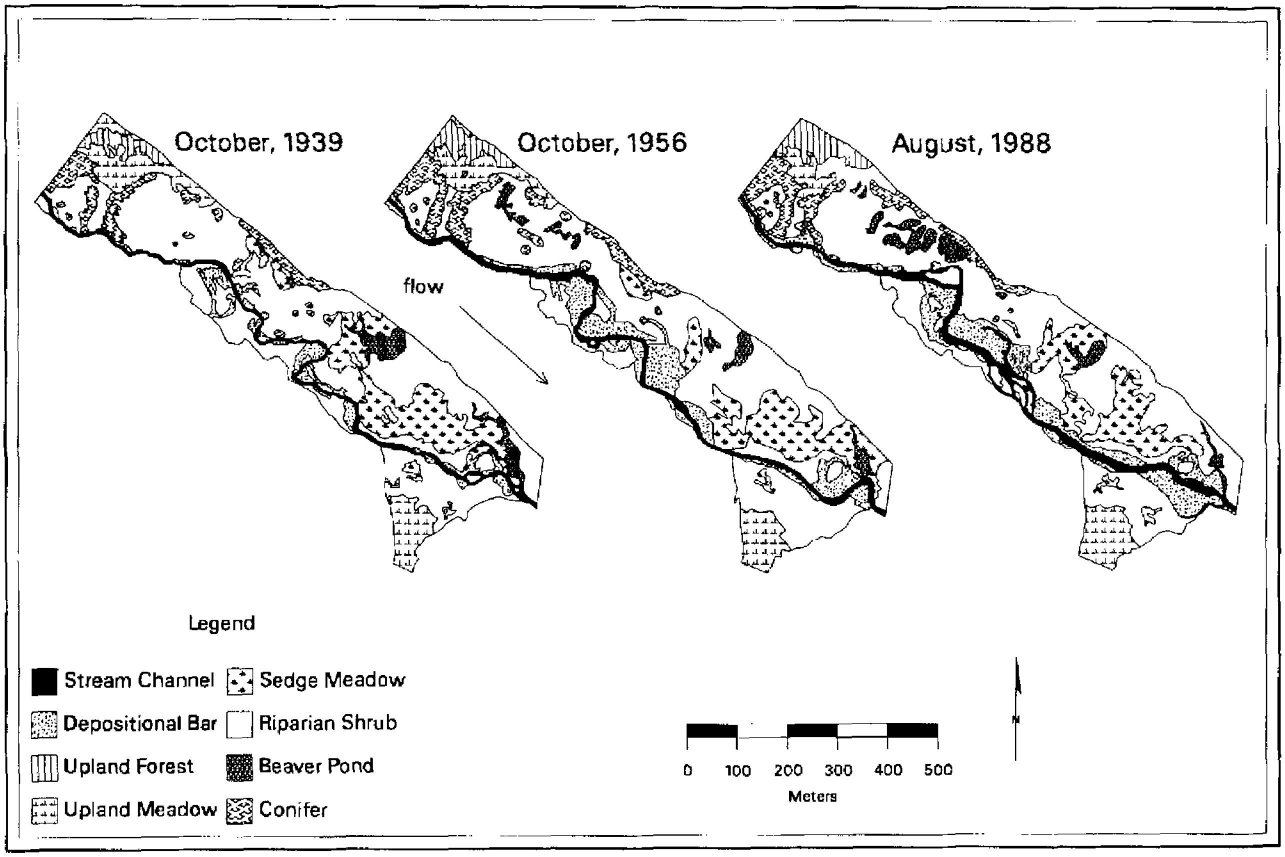

Figure 9. Maps of Lake Creek (site 15), an augmented, unconstrained reach, show changes in channel morphology and vegetation distribution.

in the spatial distribution of vegetation and channel form at Lake Creek augmented field sites 15 and 14, respectively. Table 2 quantifies spatial and temporal change in % area for three land-cover types: total unvegetated channel or bankfull area (BF), total riparian vegetation area, and total exposed bar area. The three field sites where flow augmentation occurs all showed a substantial decrease in total % area of riparian vegetation cover and an increase in the total % area of exposed depositional bars and bankfull channel area. In 1939, total riparian vegetation cover, gravel bar area, and bankfull channel area at Lake Creek (site 15) were 75%, 6%, and 10%, respectively. By 1988, total riparian vegetation cover had decreased to 65%, and gravel bar and bankfull channel area had increased to 14 and 21%, respectively. The two other augmented field sites experienced similar patterns of change that included a loss of riparian vegetation and a subsequent gain of exposed bar surfaces in proximity to the active channel (Table 2).

Loss of riparian vegetation cover on floodplains of augmented streams occurred along surfaces immediately adjacent to the active stream channel. These areas were colonized by riparian vegetation in the past but have been replaced by unvegetated gravel or cobble bars. Historic maps indicate that the distal portions of floodplains on augmented stream reaches are not adding riparian vegetation in response to losses adjacent to the channel. Avulsive channel straightening and the physical removal of vegetation from near-stream recruitment sites during high flood flows has caused a net loss of riparian vegetation cover and a net gain of exposed bars. By contrast, the five non-augmented field sites showed little change in the areal extent of riparian vegetation and channel features over the same period (Table 2).

Historic channel adjustment for the eight sites in the upper Arkansas River basin appears in Table 2. Stream channels at augmented sites experienced a substantial increase of 22 to 25% in average channel width. Most non-augmented sites experienced moderate change in average channel width within the last 50 years. An exception to this trend was found at upper Lake Creek site 16, a non-augmented stream reach. The large flux in channel width at this site may be a result of a backwater effect caused by a beaver dam located on the main channel, visible in 1939 and 1956 aerial photographs. In 1957, Lake Creek experienced a 5-year

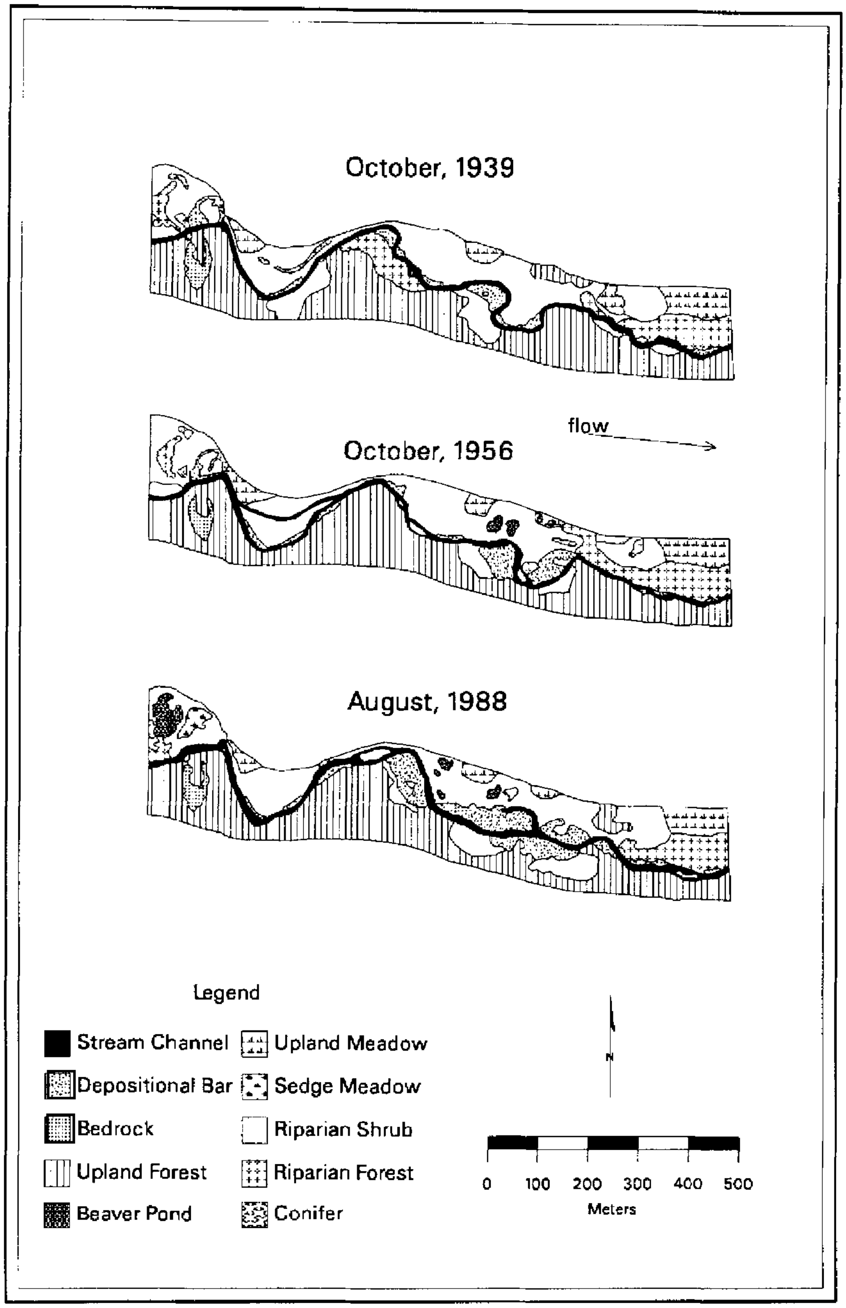

Figure 10. Maps of Lake Creek (site 14), an augmented, constrained reach, show changes in channel morphology and vegetation distribution.

flood event. In the 1957 aerial photo, taken during base flow conditions, the beaver dam is absent, suggesting that the structure was blown out during peak flows, and therefore, the width of the wetted channel decreased by 32%. In 1988, beaver activity is again present at the site, and the width of the channel subsequently increased by 24%. Channel adjustment through time also was measured by calculating sinuosity for each study reach. Sinuosity decreased at all augmented sites but remained relatively constant at non-augmented stream sites (Table 2).

DISCUSSION

Our investigation identified several key changes in channel morphology and distribution of riparian vegetation that result from flow augmentation on high mountain streams. These changes include an increase

Table 2. Historic channel adjustment: upper Arkansas River basin, Colorado

Study Site	Flow Regime	Date	Average Channel Width (m)	% Channel Width Change from Last Mapped Date	Land Cover Types: % of Total Bottomland Area: Unvegetated Channel Area (BF)	Riparian Vegetation Area	Depositional Bar Area at Baseflow	Sinuosity
Lake Fork (site 19)	augmented	1956	7.2	—	5.0	46.8	0.9	2.0
		1988	9.4	+23	9.0	39.7	2.8	1.6
Lake Creek (site 15)	augmented	1939	7.0	—	10.3	75.5	5.8	1.3
		1956	9.4	+25	17.9	69.6	12.3	1.2
		1988	12.0	+22	21.3	65.4	14.4	1.1
Lake Creek (site 14)	augmented	1939	8.6	—	10.6	40.8	4.4	1.4
		1956	9.0	+4	12.4	38.2	5.7	1.2
		1988	12.0	+25	18.7	33.9	10.7	1.2
Lake Creek (site 16)	natural	1939	8.6	—	12.0	81.2	2.4	1.7
		1957	6.5	−32	10.8	82.8	4.8	1.6
		1988	8.6	+24	11.2	78.8	3.9	1.6
Clear Creek (site 10)	natural	1956	6.6	—	5.7	40.8	2.0	1.6
		1988	6.8	+4	5.9	40.3	2.0	1.6
Clear Creek (site 8)	natural	1939	9.7	—	9.2	28.4	4.2	1.2
		1956	9.0	−7	8.4	28.7	3.9	1.2
		1988	9.5	+5	9.0	27.8	4.4	1.2
Cottonwood Creek (site 4)	natural	1956	7.9	—	9.4	49.9	0.4	1.3
		1988	6.7	−18	5.2	56.1	0.3	1.3
Cottonwood Creek (site 3)	natural	1956	5.5	—	3.3	38.4	0.5	1.1
		1988	5.5	0	3.7	36.3	0.2	1.1

in width-depth ratios of the active stream channel, an increase in the median particle size of bed material on exposed mid-channel and lateral point bars, an increase in total % area of exposed bars, and a decrease in total riparian vegetation cover. These changes occurred in the last 50 + years, and some of these conditions may represent a short-term response to a new flow regime. Nearly all present studies are limited by a relatively short period of observation (25–50 years) that often does not reflect long-term channel equilibrium or vegetation conditions (Church 1995). The temporal dynamics related to riparian vegetation succession and channel adjustment to a new flow regime are complex. Our observations on the Lake Creek drainage indicate that the channel has morphologically adjusted to establish new equilibrium conditions. The ability of pioneer riparian species to re-establish along typical recruitment sites along the channel perimeter in augmented tributaries appears inhibited by the unnatural flow variability. Long-duration high flows prevent establishment, and base flows cannot support new vegetation because the water table is too low.

Similar to the Kemano River in British Columbia (Church 1995), Lake Creek and Lake Fork have not experienced any known changes in sediment delivery from adjacent upland sources. It seems likely that augmented reaches of Lake Creek and Lake Fork have experienced an increase in sediment load caused from accelerated erosion along the floodplain margins. The ability to transport larger material and a greater sediment load would suggest that augmented streams may initially carry more bedload and suspended sediment load than similar streams with a natural flow regime.

Change in channel and floodplain morphology caused by an increase in discharge along augmented tributaries of the upper Arkansas River seems to be controlled by local geologic and morphological parameters and distance downstream of transbasin diversions. These results are consistent with those reported by Kellerhals et al. (1979) for several rivers affected by transbasin diversions in Canada. They found that extensive bank erosion and slumping, increased sediment loads, braiding, and channel entrenchment occurred in moraine and other unconsolidated Pleistocene sediments. Kellerhals et al. (1979) also observed substantial channel widening and alteration of the floodplain on the Cheslatta River, British Columbia.

In the upper Arkansas River basin, flow augmentation does not alter seasonal flow patterns but dramatically increases the magnitude and frequency of disturbances caused by flood events, similar to results described by Bradley and Smith (1984) and Stromberg and Patten (1992). The most substantial changes in flow regime were found on Lake Creek. Peak annual flows on Lake Creek are four times greater than similar non-augmented streams, Clear Creek and Cottonwood Creek. High flows are maintained for a much longer duration and occur with greater frequency on augmented stream reaches.

The implications of these results are a change in channel dimensions and geomorphic characteristics of the affected stream reaches. It should be noted, however, that during years when the largest peak flows occurred (i.e., 1957, 1983), floods on augmented streams were not as large relative to those on non-augmented streams. These results suggest that moderate floods show greater impacts of flow augmentation and may render relatively greater amounts of geomorphic change.

In our study, the Lake Creek drainage basin showed the most dramatic effects of flow augmentation. Channel widening, entrenchment, and armoring of the bed is most prevalent immediately downstream from the diversion tunnel because the valley floor is narrow and the channel is confined by steep valley slopes. Transbasin flow may be called "hungry" water because it lacks a sediment load, which makes the reach directly below the tunnel more susceptible to scour and erosion. Bradley and Smith (1984) also examined the downstream width effects caused by a diversion on two meandering reaches of the Milk River and found that average channel width increased by 5.5 m and the rate of meander migration increased by 0.85 m/year. Along augmented tributaries of the upper Arkansas River, average channel width increased as much as 42% between 1939 and 1988.

Our research indicates that W/D ratios are greater on augmented streams than non-augmented streams, reflecting channel changes similar to those described by Kellerhals et al. (1979). Differences in the bed-material size distribution on tributaries of the Arkansas River also show the effects of flow augmentation. Winnowing of fine material by high magnitude flows leads to a coarsening of substrate on exposed lateral and mid-channel bars along augmented stream reaches.

We found that formation of large mid-channel gravel and cobble bar deposits is common in unconstrained reaches of augmented streams. These bars alter stream pattern by dividing flow into multiple channels. Often, the development of a new bar may redirect flows and initiate erosion of unconsolidated terrace banks (Kellerhals et al. 1979), causing downstream deposition and braiding. Bradley and Smith (1984) determined that accelerated rates of sediment transport caused by flow diversions on the Milk River may be attributed to increased rates of erosion on meander bends that has led to increased rates of lateral channel migration. Unfortunately, no sediment transport data were collected in this study. Successful prediction of long-term channel adjustment requires knowledge of how natural and augmented streams differ in terms of sediment load (Schumm 1969).

In confined, narrow reaches of Lake Creek, loss of riparian vegetation appears to be a result of the channel adjusting to a new equilibrium to accommodate the larger flows. A larger active channel in a narrow valley floor inhibits vegetation establishment by occupying pre-existing recruitment sites. Established seedling habitat appears to be reduced, and an increase in seed mortality probably occurs due to extreme flow fluctuations and excessive water associated with transbasin diversions (Scott et al. 1993). In unconfined reaches of Lake Creek, the loss of riparian vegetation and the subsequent increase in exposed depositional bars may be more complex. In these reaches, the development of a new floodplain may lead to a new phase of channel narrowing and vegetation establishment that is indicative of long-term equilibrium conditions (Church 1995). However, after nearly six decades of augmented flow practice, it appears that the augmented channel has morphologically adjusted, but the establishment of a new riparian plant community on a new floodplain surface has not readily occurred. This transient state may be a result of water-use patterns where augmented flows dramatically increased the duration and magnitude of high flows but did not affect base flow conditions. Thus, long-duration high flows probably kill vegetation near the channel, and low base flows prevent vegetation establishment on floodplain surfaces perched well above the water table. A more thorough examination of riparian community dynamics would help predict if geomorphic adjustment caused by an altered flow regime also causes a shift in riparian vegetation composition (i.e., flood-tolerant riparian species with deep rooting capacity for low flow conditions replace pre-existing riparian species).

Results of our study indicate that encroachment of the stream into the floodplain and the equivalent loss of streamside vegetation and subsequent gain of exposed bars has occurred along augmented flow reaches of Lake Creek and Lake Fork. The loss of recruitment areas for riparian vegetation has not been compensated by an addition of riparian vegetation on the distal portions of the floodplain in the last several decades. Historic maps of flow augmented reaches in the upper Arkansas River basin show that channel meanders have straightened or braided, a response to the new flow regime. The erosion and mass wasting of banks physically removes the lateral accretion point bars associated with meandering channels, typical recruitment sites for riparian vegetation adjacent to the active channel.

CONCLUSION

This research focused primarily on hydrologic and geomorphic processes and the effects of flow augmentation on channel form and the distribution of riparian vegetation. However, many other causal factors such as climate, livestock grazing, historic mining, unnatural barriers (highway/railroad tracks) that restrict channel migration, and natural geomorphic disturbances are all probable mechanisms of spatial and temporal change in stream systems.

Analyses of hydrologic data, geomorphic characteristics, and historic aerial photographs suggest that flow augmentation in the Lake Creek and Lake Fork drainage has resulted in the following conditions downstream: 1) an increase in width-depth ratios of the channel, 2) an increase in median particle size of bed material, 3) an increase in total % area of exposed bars, and 4) a decrease in total riparian vegetation cover. The preceding conditions are attributed to a dramatic increase in stream energy associated with flow augmentation. On a geologic timescale, these conditions may be a short-term response that does not affect the overall direction of channel and floodplain evolution. Our results are based on measurements and observations in the last 50+ years and may represent a transient state of geomorphic and ecological adjustment towards a more long-term equilibrium condition. Clearly, effects of changes in stream-flow regimes on channel morphology and riparian ecosystems on existing or proposed water-transfer projects should be studied more closely. Research that focuses on linkages between geomorphic processes and riparian ecosystems is necessary to facilitate better management of our natural resources for the future.

LITERATURE CITED

Abbott, P. O. 1976. Observed channel changes in a mountain stream due to increased flow from transbasin imports. Proceedings of the Third Federal Inter-agency Sedimentation Conference. Denver, CO, USA.

Andrews, E. D. 1986. Persistence in the size distribution of surficial bed material during an extreme snowmelt flood. Water Resources Research 2:191–197.

Baker, V. R. 1977. Stream channel response to floods with examples from central Texas. Geological Society of America Bulletin 86: 975–978.

Bradley, C. and D. G. Smith. 1984. Meandering channel response to altered flow regime: Milk River, Alberta and Montana. Water Resources Research 20:1913–1920.

Bray, D. I. And R. Kellerhals. 1979. Some Canadian examples of the response of rivers to man-made changes. p. 351–372. *In* D. D. Rhodes. and G. P. Williams (eds.) Adjustments of the Fluvial System. Kendall Hunt Publishing Co. Binghamton, NY, USA.

Church, M. 1995. Geomorphic response to river regulation: case studies and time-scales. Regulated Rivers: Research and Management 11:3–22.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetland and deepwater habitats of the United States. U. S. Fish and Wildlife Service, Washingtion, DC, USA. Biological Report 79(31).

Cross, F. B. and R. E. Moss. 1987. Historic changes in fish communities and aquatic habitats in plains streams of Kansas. p. 155–165. *In* W. J. Matthews and D. C. Heins (eds.) Community and Evolutionary Ecology of North American Stream Fishes. University of Oklahoma Press, Norman, OK. USA.

Crouch, T. M., D. Cain, P. O. Abbott, R. D. Penley, and T. R. Hurr. 1984. Water resources appraisal of the upper Arkansas River basin from Leadville to Pueblo, Colorado. U. S. Geological Survey Water-Resources Investigations Report 82-4114.

Dominick, D. S. 1997. Effects of flow augmentation on stream channel morphology and riparian vegetation: upper Arkansas River basin, Colorado. M.S. Thesis. Utah State University, Logan, UT, USA.

Friedman, J. M., W. R. Osterkamp, and W. M. Lewis. 1996. Channel narrowing and vegetation development following a Great Plains flood. Ecology 77:2167–2181.

Friedman, J. M., M. L. Scott, and G. T. Auble. 1997. Water management and cottonwood forest dynamics along prairie streams. p. 49–71. *In* F. L. Knopf and F. B. Samson (eds.) Ecology and Conservation of Great Plains Vertebrates. Springer-Verlag Inc., New York, NY, USA.

Friedman, J. M., W. R. Osterkamp, M. L. Scott, and G. T. Auble. 1998. Regional pattern in response of riparian forest to water management in the Great Plains. Wetlands 18:619–633.

Gregory, S. V., F. J Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience 4: 540–551.

Gupta, A. and H. Fox. 1974. Effects of high-magnitude floods on channel form: a case study in Maryland piedmont. Water Resources Research 10:499–509.

Harris, R. R., C. A. Fox, and R. Risser. 1987. Impacts of hydroelectric development on riparian vegetation in the Sierra Nevada Region, California, USA. Environmental Management 11:519–527.

Henszey, R. J., Q. D. Skinner, and T. A. Wesche. 1991. Response of montane meadow vegetation after two years of streamflow augmentation. Regulated Rivers: Research and Management 6:29–38.

Hupp, C. R. 1988. Plant ecological aspects of flood geomorphology and paleoflood history. p. 335–356. *In* V. Baker, R. Kochel, and P. Patton (eds.) Flood Geomorphology. John Wiley and Sons, New York, NY, USA.

Hupp, C. R. and W. R. Osterkamp. 1985. Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. Ecology 66:670–681.

Johnson, W. C. 1992. Dams and riparian forests: case study from the upper Missouri River. Rivers 3:229–242.

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

Johnson, W. C. 1998. Adjustment or riparian vegetation to river regulation in the Great Plains U.S.A. Wetlands 18:608–618.

Karnuta, T. 1995. Road and riverside geology of the Upper Arkansas Valley: Arkansas headwaters recreation area. Chaffee Press Inc., Salida, CO, USA.

Kellerhals, R., M. Church, and L. B. Davies. 1979. Morphological effects of interbasin river diversions. Canadian Journal of Civil Engineering 6:18–31.

McBride, J. R. and J. Strahan. 1981. Fluvial processes and woodland succession along Dry Creek, Sonoma County, California. California Riparian Systems Conference, September 17–19. University of California, Davis, CA, USA.

O'Neill, M. P., J. C. Schmidt, J. P. Dobrowolski, C. P. Hawkins, and C. M. U. Neale. 1997. Identifying sites for riparian wetland restoration: application of a model to the upper Arkansas River basin. Restoration Ecology 5:85–102.

Resh, V. H., A. V. Brown, A. P. Covich, M. E. Gurtz, H. W. Li, G. W. Minshall, S. R. Reice, A. L. Sheldon, J. B. Wallace, and R. C.

Wissmer. 1988. The role of disturbance in stream ecology. Journal of North American Benthological Society 7:433–455.

Ryan, S. E. 1994. Effects of transbasin diversion on flow regime, bed load transport, and channel morphology in Colorado mountain streams. Ph.D. Dissertation. University of Colorado, Boulder, CO, USA.

Schmidt, J. C. and J. B. Graf. 1990. Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. U. S. Geological Survey Professional Paper 1493.

Schumm, S. A. 1969. River metamorphosis. American Society of Civil Engineers. Journal of Hydraulics Division. HY1:255–273.

Scott, M. L., M. A. Wondzell, and G. T. Auble. 1993. Hydrograph characteristics relevant to the establishment and growth of western riparian vegetation. p. 237–246. *In* H. J. Morel-Seytoux (ed.) Proceedings of the 13th Annual American Geophysical Union Hydrology Days. Hydrology Days Publications, Atherton, CA, USA.

Smith, S. D., A. B. Wellington, J. L. Nachlinger, and C. A. Fox. 1991. Functional responses of riparian vegetation to streamflow diversion in the eastern Sierra Nevada. Ecological Applications 1: 89 97.

Stromberg, J. C. and D. T. Patten. 1990. Riparian vegetation instream flow requirements: a case study from a diverted stream in the eastern Sierra Nevada, California, USA. Environmental Management 14:185–194.

Stromberg, J. C. and D. T. Patten. 1992. Response of *Salix lasiolepis* to augmented stream flows in the upper Owens River. Madrono 39:224–235.

Stromberg, J. C. 1993. Instream flow models for mixed deciduous riparian vegetation within a semiarid region. Regulated Rivers: Research and Management 8:225–235.

Swanson, F. J. 1980. Geomorphology and ecosystems. p. 159–170. *In* R. W. Waring (ed.) Forests: Fresh Perspectives from Ecosystem Analysis, Proceedings of the 40th Annual Biology Colloquium. Oregon State University Press, Corvallis, OR, USA.

Viessman, W., J. W. Knapp, G. L. Lewis, and T. E. Harbaugh. 1977. Introduction to Hydrology. Harper and Row Publishers, Inc., New York, NY, USA.

Williams, G. P. and M. G. Wolman. 1984. Downstream effects of dams on alluvial rivers. U. S. Geological Survey Professional Paper 1286.

Wolman, M. G. 1954. A method of sampling coarse river-bed materials. Transactions American Geophysical Union 35:951–956.

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

Manuscript received 11 August 1997; revision received 24 July 1998; accepted 7 August 1998.