HISTORICAL CHANGES IN FLOOD POWER AND RIPARIAN VEGETATION IN LOWER HARRIS WASH, ESCALANTE RIVER BASIN, UTAH

Ginger Hinchman Birkeland
Department of Earth Sciences
Montana State University
Bozeman, Montana 59771
ghbirkeland@imt.net

Abstract: This study quantifies historical changes in flood power (measured by boundary shear stress and unit stream power) and riparian vegetation in a narrow stream canyon. Analyses of historical air and ground photographs since 1922 in lower Harris Wash indicate the occurrence of active channel widening, floodplain narrowing, and an 86 percent increase in riparian vegetation growth on the canyon bottom. To quantify temporal changes in flood power at a cross-section, the WinXSPRO channel cross-section analyzer calculated stage and flood power at various return interval flood discharges for 1922 (using a ground photo) and 1998 (using field measurements). Inputs to the program included estimates of Manning's roughness coefficients and channel and floodplain width measurements for both years. Between 1922 and 1998, active-channel flood power values increased 11 to 53 percent, and floodplain flood power values decreased 44 to 97 percent. Of the floodplain power decrease, 20 to 45 percent (at a minimum) is directly attributable to increased hydraulic roughness caused by woody riparian vegetation establishment. This research suggests (1) that historical ground photos may be useful for quantifying temporal changes in flood power in relationship to vegetation, and (2) that riparian vegetation change has dramatically reduced floodplain flood power values in semiarid stream canyons during this century. [Key words: fluvial geomorphology, flood power, riparian vegetation, channel change, Utah.]

INTRODUCTION

Geomorphic channel change in fluvial systems is closely related to riparian vegetation development, especially in semiarid systems that may be prone to large-scale flooding (Burkham, 1972; Graf, 1983a; Friedman et al., 1996b; Everitt, 1998). Therefore, understanding recent trends in the biogeomorphic evolution of a stream system is important for investigating fluvial behavior. A number of studies tracking historical channel and vegetation change during the 20th century in the western United States show that woody riparian vegetation was almost nonexistent along river and stream channels from the late 1800s, following a period of large and frequent floods, until about the 1930s (Graf, 1983a; Webb et al., 1991). After this period, flood frequency and magnitude decreased, allowing vegetation to establish on floodplains and channel bars, subsequently stabilizing these in-channel areas (Schumm and Lichty, 1963; Graf, 1978; Hereford, 1984). The result of this sequence of events, which apparently was widespread throughout the American

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Southwest and Great Plains, is that recently established riparian vegetation communities now exist in the alluvial valleys, arroyos, and bedrock canyons of this region.

The nature of fluvial and riparian systems is dependent on biophysical interactions along channels and floodplains. From an ecological perspective, flooding is significant because high discharges cause vegetation mortality and enhance vegetation establishment (Bendix, 1998). The distribution and composition of riparian vegetation therefore are closely related to the flood regime, a connection that is pronounced in semiarid regions where flooding is essential for riparian species recruitment and for recharging the groundwater table upon which many riparian plants depend (Bendix, 1994b; Birkeland, 1996; Patten, 1998). In fact, flood frequency, intensity, and duration all play a major role in both the germination and survivorship of riparian species (Stromberg et al., 1993; Huckleberry, 1994; Stromberg, 1997).

From a geomorphic perspective, flooding is associated with the ability to move sediment and perform geomorphic work. Flood power—as represented by boundary shear stress and unit stream power (Baker and Costa, 1987)—is a measure of a flow's ability to transport sediment, and represents the force required for geomorphic change. Vegetation, on the other hand, represents a form of resistance. The hydraulic roughness associated with channel and floodplain vegetation is one of several resisting forces that must be exceeded by a critical flood power for erosion to occur (Bull, 1979, 1988). Thus, the threshold of critical flood power in streams over long time scales may be affected by vegetation change (Graf, 1979).

Despite the emphasis on the connections between hydrogeomorphic processes and riparian vegetation in the literature, only a few studies have investigated the interactions between riparian vegetation and flood power (Bendix, 1994a, 1994b; Birkeland, 1999). Furthermore, historical studies of channel and vegetation change in the American southwest have not specifically quantified changes in flood power, or attempted to link flood power changes to riparian vegetation expansion. In narrow bedrock canyons where flood power is higher, the nature of these biogeomorphic relationships is especially poorly understood (Birkeland, 1996, 1999).

The purpose of this research is to assess quantitatively the temporal changes in channel morphology and flood power in an unregulated, bedrock canyon, and relate them to woody vegetation change. The study area is the lower canyon of Harris Wash, the largest western tributary of the Escalante River in south-central Utah (Fig. 1). This work addresses three research questions. (1) What is the nature of channel and vegetation change in Harris Wash during the latter half of the 20th century? (2) What is the nature of flood power change along active channels and floodplains? (3) How do temporal changes in flood power relate to riparian vegetation change? Like many other streams of the Colorado Plateau, Harris Wash appears to have undergone floodplain aggradation and channel narrowing in the latter half of this century owing to climatic, hydrologic, and vegetation change. It is probable that flood power in this canyon has (1) decreased on floodplains in relationship to increases in hydraulic roughness associated with extensive riparian vegetation establishment, and (2) increased in active channels resulting from channel narrowing and vegetation establishment.

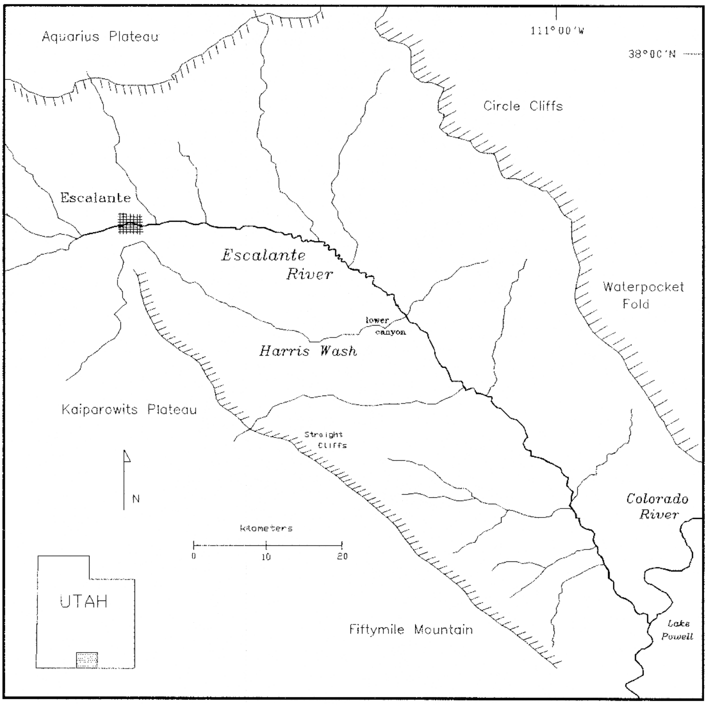

Fig. 1. Map of the Escalante River basin, including Harris Wash, Utah.

BACKGROUND

Historical Channel and Vegetation Change

The study of historical environmental change along rivers of the western United States using repeat photography has been widely applied in geomorphological and ecological research, and has yielded extensive information regarding changes in channel morphology during the 20th century (e.g., Graf, 1987; Everitt, 1998). This research indicates that, beginning in the late 1800s, a period of large and frequent floods initiated channel erosion and arroyo development (Graf, 1983a; Webb, 1985). A depositional period began in the 1940s, causing floodplain formation and narrowing of alluvial channels throughout the region (Hereford, 1984). The primary cause of this sequence of geomorphic activity is thought to be climate related (Balling and Wells, 1990; Webb et al., 1991), although other hypotheses exist for the formation of arroyos (Graf, 1983b).

The connections between these geomorphic changes and widespread riparian vegetation expansion are still not well understood. Research on Great Plains rivers suggests that vegetation establishes on channel surfaces during periods of greater-than-average precipitation but lower-than-average peak flow, and subsequently causes channel stabilization (Schumm and Lichty, 1963; Martin and Johnson, 1987;

Friedman et al., 1996a). Vegetation then contributes to channel narrowing by increasing sediment deposition and enhancing bank stability (Smith, 1976; Friedman et al., 1996b). Historical studies in Arizona suggest similar channel changes associated with vegetation growth (e.g., Leopold and Wolman, 1957), but several investigators hesitate to attribute channel narrowing solely to vegetation encroachment given the larger influences of climatic and hydrologic fluctuations (Burkham, 1972; Turner, 1974). Finally, while several studies associate channel change with both native and non-native riparian forests (Schumm and Lichty, 1963; Howe and Knopf, 1991; Allred and Schmidt, 1999), other work focuses on the recent establishment of non-native tamarisk (*Tamarix* sp.) as a primary force for channel change. This research suggests that in-channel tamarisk growth causes a decline in channel width (Hadley, 1961; Graf, 1978), and then promotes channel incision, increased overbank flooding, or both, during high discharge events (Burkham, 1972, 1976; Turner, 1974; Blackburn et al., 1982). Although the geomorphic significance of tamarisk is established mainly for unconstrained river floodplains with dense stands of vegetation, the influence of this species may be different in confined river canyons where tree density is less and flood power is high (Birkeland, 1996).

Flood Power and Riparian Vegetation

The concept of flood power is based on the combined measurements of shear stress and unit stream power (Baker and Costa, 1987). Boundary shear stress is defined as the tangential boundary shear acting on the channel bed (Magilligan, 1992). Unit stream power is defined as the power exerted by a given discharge per unit area of the stream channel's wetted perimeter (this definition and terminology follows Bagnold, 1966; Costa, 1983; Graf, 1983a; Baker and Costa, 1987). These variables are calculated as:

$$\tau = \gamma RS \tag{1}$$

$$\omega = \gamma RSv \tag{2}$$

where τ = shear stress exerted by the flow in N/m^2, γ = the specific weight of water (9800 N/m^3), R = hydraulic radius in meters, S = the energy slope, represented by the dimensionless gradient of the channel bed, ω= unit stream power in W/m^2, and v = flow velocity in m/s (Baker and Costa, 1987). Shear stress represents stream competence, or the ability of the flow to entrain particles of different sizes and densities. Unit stream power represents stream capacity, or the quantity of material that the flow is able to transport through a given cross-section of the channel. Competence and capacity together measure the ability of the flow to transport sediment, and therefore create an unstable channel condition.

According to Baker and Costa (1987), the geomorphic effectiveness of floods is directly linked to flood power, as it is measured by shear stress and unit stream power. Stress and power provide a better measure of flood power than do magnitude (discharge) and frequency (return interval), which have been used previously to refer indirectly to the power of floods (Wolman and Miller, 1960). Although flood magnitude appears to be a simpler representation of flood power, the latter includes channel gradient and hydraulic radius in its calculation, making it a better indicator of flood force than discharge. For example, discharge, or flood magnitude, might remain constant throughout a given stream segment in which flood power varies dramatically with local changes in channel slope or width. Flood duration is also a major factor in the geomorphic effectiveness of high discharges since more total power is expended over a long-duration flood, causing more geomorphic work to occur (Huckleberry, 1994).

Previous research has shown that the highest values of flood power occur in bedrock canyons that produce large flood discharges (O'Connor et al., 1986; Baker and Pickup, 1987; Wohl, 1992), and that even low flows in bedrock systems have higher flood power than equivalent flows in alluvial reaches (Tinkler and Wohl, 1998). Furthermore, the distribution of flood power in fluvial systems appears to be related to regional geologic controls on channel and valley width, with flood power highest in width-constrained areas (Graf, 1990; Lecce, 1997). Flood power is affected by the resistance of the channel to erosion, which includes the resisting force of vegetation in stabilizing channel and floodplain sediment. The composition and density of vegetation affect the hydraulic roughness encountered by the flood flow—increased roughness lowers the velocity of the flow, and thus impairs the ability of the flow to move sediment. In primarily bedrock canyons with sparse riparian vegetation, and where flood flows are constrained by narrow channel width, the erosive power of floods is high and little resistance is offered by vegetation. However, flood power values in wider alluvial/bedrock canyons with dense floodplain vegetation, such as those found in the Colorado Plateau region of the southwestern United States, have rarely been investigated.

ENVIRONMENTAL SETTING

Harris Wash rises on the Kaiparowits Plateau (maximum basin elevation of 2750 m), and flows eastward to its confluence with the Escalante River (at 1418 m elevation; Fig. 1). Precipitation in the Escalante River basin is highly variable. Summer is the wettest season, with the most precipitation occurring in August and the least usually occurring in June (National Climatic Data Center, 1998). Cloudburst floods caused by localized thunderstorms commonly occur during July and August (Woolley, 1946), resulting in flood peaks in drainages throughout the region.

Intermittent streamflow is characteristic of the Harris Wash basin. The 14-km long lower canyon, formed in Mesozoic Navajo sandstone, is characterized by perennial flow from springs and extends to the Escalante River confluence. This canyon is an ideal study area because it has good photographic records from which to examine historical change. In addition, vegetation has been disturbed only by seasonal grazing since 1978, and has been completely ungrazed since lower Harris Wash became part of the Glen Canyon National Recreation Area in 1984. The stream channel flows through an alluvial/bedrock canyon that ranges from bedrock sections with active channels and narrow floodplains composed of silt, sand, and small gravels to wider alluvial sections with discontinuous alluvial terraces that vary in age, areal extent, and height above the channel.

Riparian vegetation established in lower Harris Wash after the 1940s as vegetation expansion occurred throughout the Escalante River basin (Woolsey, 1964; Webb, 1985). Historical photographs and written accounts suggest that non-native species such as tamarisk (*Tamarix ramosissima*) and Russian olive (*Elaeagnus angustifolia*) were not present along the channel of the Escalante River prior to about 1930, but were densely established by the 1980s (Lambrechtse, 1985; Webb, 1985). At present, tamarisk has spread throughout the Escalante basin (Irvine and West, 1979), while Russian olive occurs only in the upper elevations, and mostly along the largest tributaries such as Harris Wash. Native woody riparian species in the lower canyon include Fremont cottonwood (*Populus fremontii*), coyote willow (*Salix exigua*), baccharis (*Baccharis salicina*), Gooddings willow (*Salix gooddingii*), and box elder (*Acer negundo*). The native shrubs rabbitbrush (*Chrysothamnus nauseosus*) and big sagebrush (*Artemesia tridentata*) occupy floodplains and terraces.

HISTORICAL VEGETATION AND CHANNEL CHANGE

Method

Analyses of aerial photographs from April 1958 and September 1993 (scale 1:48,000 and 1:40,000, respectively) measured vegetation change in Harris Wash along the 8-km reach above the Escalante confluence. Enlarged 7.5-minute topographic maps of the study canyon (scale 1:12,000) were magnified to outline the canyon bottom (floodplain and terrace areas) and all areas of vegetation within the canyon bottom (1958 and 1993) on a map overlay. After measuring the canyon bottom (assumed the same area for both photos) and vegetated areas with an electronic digitizing polar planimeter, I compared the calculated percentages of vegetated area in 1958 to 1993. Historical ground photos (1922 and 1953) were then compared to 1998 photo relocations. Finally, the examination of cores from a representative sample of 48 cottonwoods on floodplains of the lower canyon assessed tree establishment dates using standard tree-ring age analyses (the sample included several of the largest, and presumably oldest, trees in the lower canyon). Mounting and sanding of tree cores followed standard procedures (Fritts, 1976), and rings were counted with a dissecting microscope to assess tree age.

Riparian Vegetation Change

Results of the aerial photo analysis show that the vegetated area of the Harris Wash canyon bottom increased from 36 m^2 to 492 m^2 (7 to 93 percent) in the 35-year period from 1958 to 1993. Field observations suggest that all of this change occurred within the high flow channel area, since the small amount of vegetation present in the 1958 photo is likely the sparse cottonwood, scrub oak (*Quercus*), and box elder that still exist on the high terraces throughout the study canyon. Vegetation sampling in 1998 in the riparian area indicates that native species are more frequent than non-natives, with coyote willow (found in 62% of plots), cottonwood (found in 48% of plots), and rabbitbrush (found in 41% of plots) all having relatively

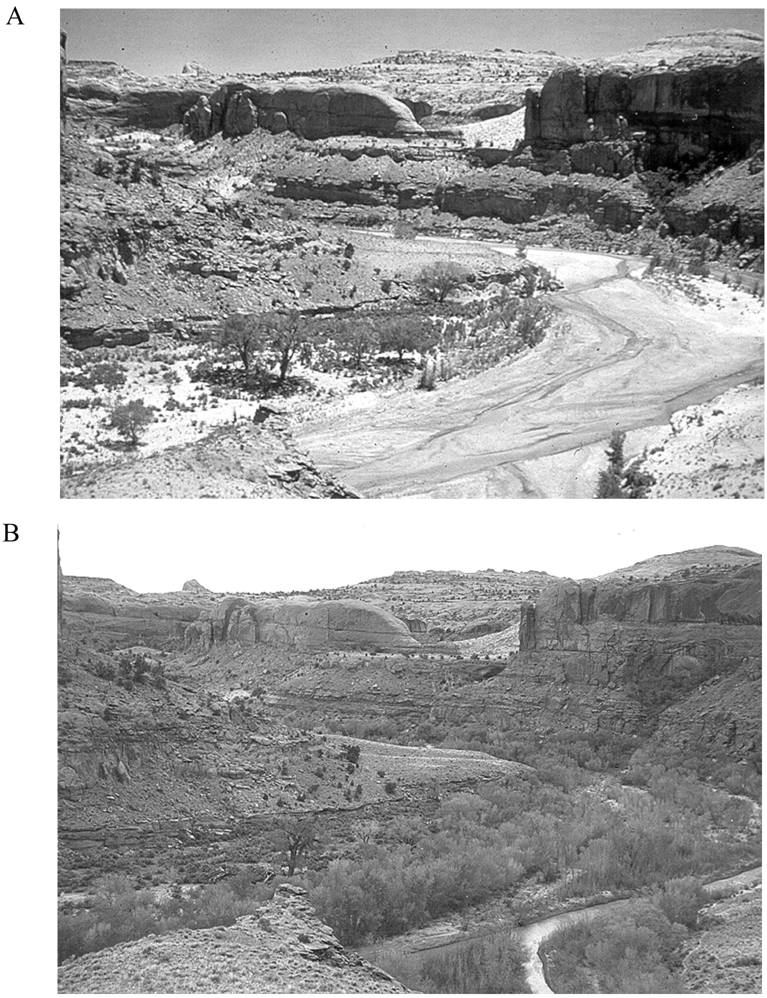

Fig. 2. Looking downstream on the Escalante River at the Harris Wash confluence (Harris Wash enters from bottom of photo). (A) 1953, photo from Brownlee collection (#NAU PH 93.37.1170, courtesy of Cline Library Special Collections and Archives, Northern Arizona University). (B) April 1998, photo by Karl Birkeland.

high frequencies in 116 vegetation plots (Birkeland, 1999). Frequencies for nonnative tamarisk and Russian olive are 16 and 28 percent, respectively.

Examination of ground photos from Harris Wash and the Escalante River confluence reveal little to no vegetation on fluvial deposits before the 1950s, in contrast to dense vegetation along the present day channel (Figs. 2 and 3). Finally, the cottonwood core analysis supports the photographic data—the establishment date of the oldest tree cored is 1952, the mean tree age is 21 years, and the tree ages are fairly evenly distributed. One of the 1922 photo relocations suggests that vegetation has still not established in the narrowest canyon areas where flood power is high

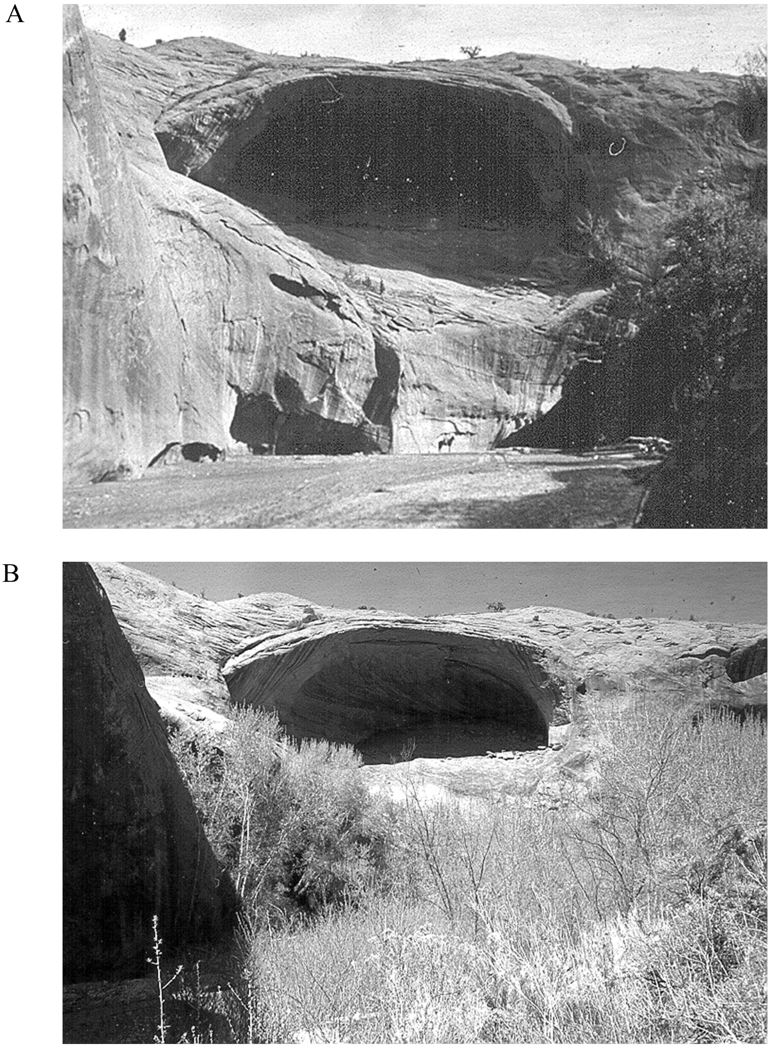

Fig. 3. Looking downstream near the alcove site, Harris Wash. (A) 1922, photo by R. C. Moore (#105, courtesy of the U.S. Geological Survey Photo Library, Denver, Colorado). (B) April 1998, photo by Karl Birkeland. Vegetation in the 1998 photo is mainly coyote willow and Fremont cottonwood.

(Fig. 4). Thus, although vegetation change in Harris Wash is similar to regional trends, ground photos suggest that the vegetation change in the study canyon is spatially variable, and may be related to flood power.

Floodplain Formation and Channel Narrowing

Several of the aerial and ground photographs examined for vegetation change also reveal changes in channel morphology. Photos of the confluence of the Escal-

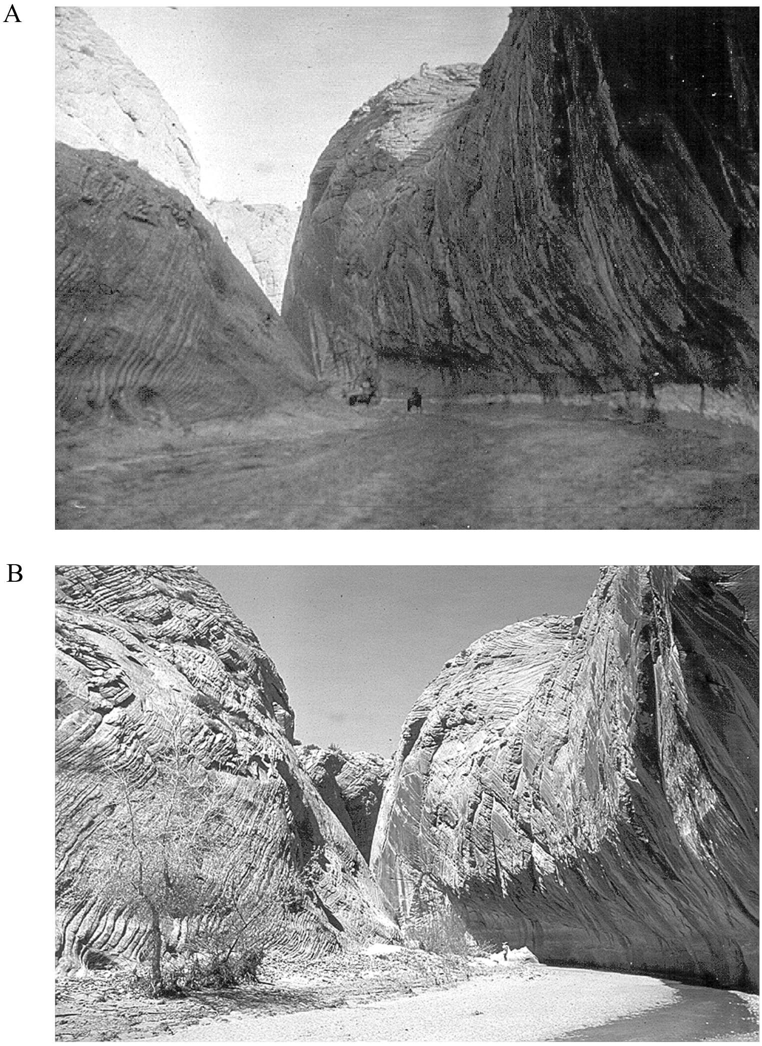

Fig. 4. Looking upstream in Harris Wash, 6 km upstream from the lower canyon. (A) 1922, photo by R. C. Moore (#129, courtesy of the U.S. Geological Survey Photo Library, Denver, Colorado). (B) April 1998, photo by Karl Birkeland. Note that only a few cottonwoods occupy the 1998 channel.

ante River and Harris Wash (Fig. 2) indicate that the wide, braided channel of the 1950s has been replaced along both drainages by a single, narrow active channel with a distinct, vegetated floodplain. Ground photos from the Harris Wash study canyon (Fig. 3) suggest the absence of a floodplain in the early part of this century. By 1998, a new floodplain exists at 0.5 to 2 m in height above the active channel, indicating the onset of a period of aggradation sometime since 1950. Field observations further suggest that the magnitude of channel aggradation is spatially variable throughout the lower Harris Wash study segment, probably in response to flood power variations in this canyon system.

FLOOD POWER CHANGES AT THE ALCOVE SITE, 1922 TO 1998

Method

The alcove shown in Figure 3, taken in 1922 in the lower canyon of Harris Wash (~5 km upstream from the Escalante River confluence), is particularly suitable for quantitative assessments of temporal changes in channel hydraulics. In 1998, a rod-and-level survey of a channel cross-section within the 1922 photo area was completed using standard techniques (Benson and Dalrymple, 1967). A cross-sectional profile for the 1922 channel was then estimated at the same location. The 1922 and 1998 cross-section data were input into the WinXSPRO channel cross-section analyzer program (Grant et al., 1992; U.S. Forest Service, 1997), along with values for roughness and gradient. Manning's roughness coefficients were estimated from the 1922 photo and the 1998 field survey using methods from Arcement and Schneider (1989). For the purpose of this comparison, I assumed a constant channel gradient of .0042 (the gradient of the lower canyon measured from 7.5 minute topographic maps) for the two photos. Using the WinXSPRO program, values were generated for 1922 and 1998 flood stage and power (shear stress and unit stream power) for the 2-, 5-, 10-, 25-, 50-, and 100-year return interval discharges. These discharges were calculated using methods from Thomas and Lindskov (1983) for computing peak discharges in ungaged streams in Utah (calculations incorporated drainage basin area and mean basin elevation, which were measured from topographic maps at a scale of 1:70,500). The return intervals are for the present hydrologic regime in Harris Wash, and may not accurately represent flood flow intervals in the early part of this century. However, they are used only for comparative purposes here, and not for flood prediction. The analysis included comparisons of flood power values for both active channels and floodplains, and calculations of the percent change in shear stress and unit stream power on each surface for each return interval flood. Historical and present stage-discharge relationships were also compared using the selected flood discharges.

Results

Comparisons of channel cross-sectional shape at the Harris Wash alcove site in 1922 and 1998 show a shift in position of the low flow channel and the presence of a 2-m high floodplain in the recent photo (Fig. 5). Stage-discharge rating curves for 1922 and 1998 (Fig. 6) indicate 0.2 to 0.3 m increases in 1998 stages for the selected flood flows. These stage changes reflect the aggradation that has occurred in the channel since 1922, which raised the height of the floodplain. Since the 1998 channel contains more sediment, stage must be higher to accommodate the flow. Depending on when the vegetation established on the floodplain, it may have enhanced floodplain aggradation by increasing roughness and slowing velocity.

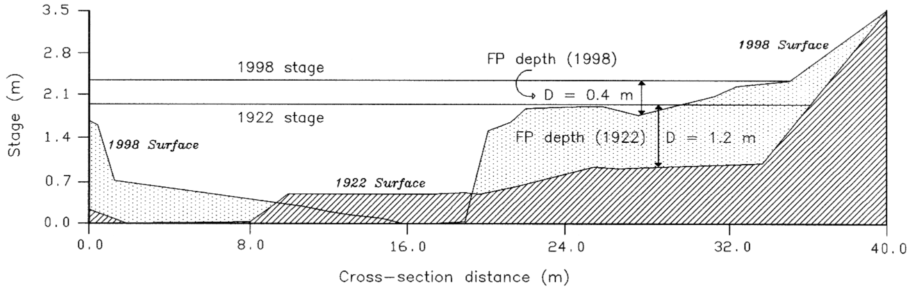

Fig. 5. Channel shape, 25-year flood stage, and 25-year floodplain depth in 1922 and 1998 at the Harris Wash alcove site.

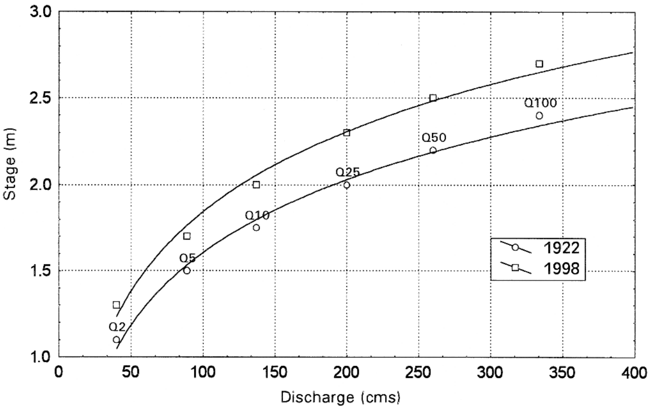

Fig. 6. Stage-discharge rating curve based on selected return-interval flood discharges for 1922 and 1998 at the Harris Wash alcove site.

Flood power values for 1922 and 1998 at this cross-section show different temporal variation according to channel location—an increase of up to 53 percent along the active channel (Table 1), and a decrease as high as 97 percent on the floodplain (Table 2). Both shear stress and unit stream power for the active channel show an increase in 1998, with shear stress change varying between 11 and 20 percent, and unit stream power change varying between 38 and 53 percent. Both shear stress and unit stream power for the floodplain show decreases, with power again showing a greater degree of change (90 to 100 percent) than shear (44 to 100 percent).

These results suggest different processes of change occurring on different channel surfaces, with both processes influenced by an overall change in channel geometry. In the 1998 active channel, flood flows are confined to the active channel by a higher floodplain, and only inundate the floodplain (the overbank area) at discharges approximating the 25-year return interval flood. Thus higher velocity, and

Table 1. Active Channel Flood Power Changes for Various Flood Discharges from 1922 to 1998 at the Harris Wash Alcove Site[a]

	Active channel shear stress			Active channel unit stream power		
	1922	1998	Percent change	1922	1998	Percent change
Q2 (40 m^3/s)	30	36	+20%	57	82	+44%
Q5 (89 m^3/s)	45	50	+11%	120	166	+38%
Q10 (137 m^3/s)	53	62	+17%	178	259	+46%
Q25 (200 m^3/s)	62	73	+18%	248	379	+53%
Q50 (260 m^3/s)	69	80	+16%	316	482	+53%
Q100 (334 m^3/s)	75	88	+17%	400	607	+52%

[a] Calculations used Manning's *n* values of 0.036 (1922) and 0.034 (1998).

Table 2. Floodplain Flood Power[a] Changes for Various Flood Discharges from 1922 to 1998 at the Harris Wash Alcove Site[b]

	Floodplain shear stress			Floodplain unit stream power		
	1922	1998	Percent change	1922	1998	Percent change
Q2 (40 m^3/s)	9.6	0[c]	–100%	7	0[c]	–100%
Q5 (89 m^3/s)	24	6	–76%	36	1	–97%
Q10 (137 m^3/s)	32	8	–76%	64	2	–96%
Q25 (200 m^3/s)	40	15	–62%	100	8	–92%
Q50 (260 m^3/s)	45	22	–52%	136	13	–90%
Q100 (334 m^3/s)	51	28	–44%	178	20	–89%

[a] Calculations used Manning's *n* values of 0.038 (1922) and 0.074 (1998).

[b] Flood stage changes (in meters) from 1922 to 1998 are as follows: Q2, 1.1 to 1.3; Q5, 1.5 to 1.7; Q10, 1.75 to 2.0; Q25, 2.0 to 2.3; Q50, 2.2 to 2.5; Q100, 2.4 to 2.7.

[c] The floodplain was not inundated at this discharge.

therefore higher flood power, occurs in the deeper 1998 active channel. On the 1998 floodplain, flood flows have shallow depth owing to a higher surface and slower velocity owing to increased roughness, both of which lower overall flood power (Fig. 5). This type of geomorphic change has been observed along a number of rivers in the western United States during this century (e.g., Schumm and Lichty, 1963), although temporal changes in shear stress and unit stream power at a single location have not been quantified before this study.

THE INFLUENCE OF VEGETATION ON FLOOD POWER

The Role of Vegetation in Flood Power Change

Causes of the changes in flood power at the alcove site since 1922 suggest that densely established riparian vegetation may have a strong influence on floodplain flood power. According to the equation for boundary shear stress (Equation 1), temporal changes in shear stress must relate to changes in hydraulic radius since the specific weight of water and the slope are constant for the two analyses. Therefore, changes in floodplain shear stress reflect (1) decreased flood depth on an aggraded floodplain surface, and (2) increased flood depth owing to the presence of riparian vegetation, which slows velocity and deepens flow over the floodplain surface (Petryk and Bosmajian, 1975). These two aspects of depth-related change initially appear to work in opposition to one another—higher surfaces decrease depth, but slower velocity and vegetation increase depth. However, the change in depth resulting from a higher floodplain surface (~0.8 m decrease for the 25-year return interval discharge, as shown in Fig. 5) is greater in magnitude than changes in depth associated with a rougher surface, which have been estimated on the order of 0.3 m or less during peak flows (Burkham, 1976). Floodplain shear stress change thus relates to channel morphology change; since depth and therefore hydraulic radius decrease in the 1998 channel, shear stress decreases as well.

According to the equation for unit stream power (Equation 2), temporal changes in unit stream power directly reflect velocity, which decreases with increasing hydraulic roughness caused by vegetation. The value of Manning's *n* on the floodplain at this cross-section increased from 0.038 in 1922 to 0.074 in 1998 because of the presence of riparian vegetation (which is the channel roughness factor with the strongest influence on the *n* value in Harris Wash). This change in vegetation is directly reflected in the unit stream power values through the velocity variable in the equation. Because velocity decreases as a result of roughness, and hydraulic radius decreases as a result of channel geometry change, unit stream power decreases on floodplains as well. The magnitude of the decrease is greater for unit stream power than for shear stress because of the additional factor of velocity in the stream power calculation. Since velocity is inversely related to roughness, riparian vegetation is a key factor in this unit stream power change.

The difference between the decrease in floodplain shear stress (reflecting channel morphology and thus hydraulic radius change) and the decrease in floodplain unit stream power (reflecting roughness and thus velocity change) is indicative of flood power changes that are directly related to vegetation. The change in hydraulic radius caused by floodplain aggradation may or may not be related to riparian vegetation establishment—if vegetation caused the channel morphology change, then it *indirectly* contributed to the decrease in floodplain shear stress since 1922. However, if vegetation established after the higher floodplain formed, then it is not related to shear stress change. The change in velocity is clearly caused by increased roughness resulting from riparian vegetation change. Therefore, vegetation *directly* contributes to the decrease in floodplain unit stream power since 1922.

Table 3. Percentage Decreases in Temporal Floodplain Flood Power (1922 to 1998) Directly Attributable[a] to Riparian Vegetation Establishment at the Alcove Site

	Q2	Q5	Q10	Q25	Q50	Q100
Percent change	0%	21%	20%	30%	38%	45%

[a] Calculated as the difference between the change in shear stress and the change in unit stream power for each return interval.

At the Harris Wash alcove site, it follows that riparian vegetation has directly contributed to at least a 21 to 45 percent decrease in unit stream power for the selected flood discharges (Table 3). The influence of vegetation becomes more pronounced at higher discharges as the entire floodplain becomes inundated, and less pronounced during lower flows, which remain primarily contained within the active channel. It is important to reiterate that the changes in depth (and hydraulic radius) caused by channel aggradation also may be related *indirectly* to vegetation growth. Since plant establishment increases roughness, slows velocity, and enhances sedimentation, the growth of vegetation may influence the height and/or shape of a floodplain (as well as the depth of flow over the surface). Thus, since riparian vegetation has the potential to change channel morphology by inducing sedimentation, it therefore has the potential to alter shear stress. It is clearly possible then that the establishment of vegetation along the channel of Harris Wash accounts for the entire decrease in floodplain flood power (89 to 100 percent) observed in this analysis.

The increases in active channel flood power are linked to the changes on the floodplain. Because 1998 vegetation stabilizes banks and floodplains during all but the largest floods, flood flows are confined to the active channel, which has deepened and slightly narrowed as a result. Thus changes in the active channel also are related to floodplain vegetation establishment since the 1950s.

Implications for the Fluvial and Riparian System

These temporal changes in flood power have several effects on the overall fluvial and riparian system. It appears that two interrelated positive feedback loops have been initiated in the present-day channel of the lower Harris Wash canyon (Fig. 7)—a cycle of floodplain aggradation, and a cycle of active channel erosion. Since the overall power of a given discharge is less on the 1998 floodplain, the ability of the flow to transport sediment is less, and the probability of increased sedimentation when the surface is inundated is higher. Conversely, the power of flow in the 1998 active channel is greater, making sediment transport and thus erosion more likely, especially during a high flow. The 1998 flood power conditions increase the likelihood that the active channel will erode and the floodplain will aggrade at the selected flood discharges. The present geomorphic conditions and trends of historical change in Harris Wash fit those described by a number of studies of historical

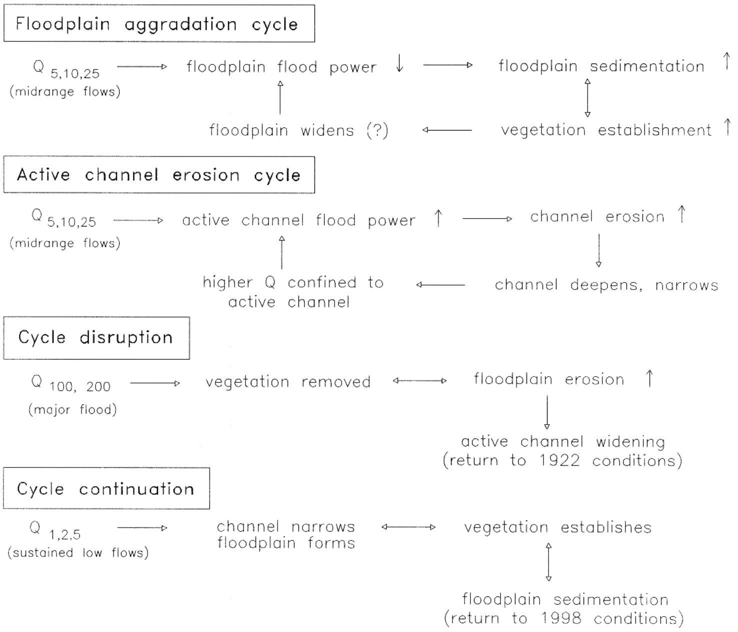

Fig. 7. Conceptual diagram of positive feedback cycles probably occurring in the lower Harris Wash canyon from 1922 to the present.

channel and riparian vegetation change (e.g., Leopold and Wolman, 1957; Hadley, 1961; Schumm and Lichty, 1963; Hereford, 1984), although these studies did not quantify temporal flood power change. In the absence of large and frequent flood events, the present channel and vegetation conditions may continue in a positive feedback cycle where small or midsized floods cause floodplain sedimentation and channel narrowing, thereby enhancing conditions for vegetation growth on the floodplain, increasing roughness, and causing further decreases in floodplain flood power. Frequent, large-scale flooding would disrupt the cycle (Fig. 7), transporting floodplain sediment, removing vegetation, and causing overall channel degradation. Such hydrologic changes would return the channel to a form resembling its 1922 condition. At that point, sustained low flows may narrow the channel and allow vegetation establishment, which would enhance sedimentation, and the cycle of floodplain formation and channel narrowing would begin again. This cycle has been observed on other rivers such as the Cimarron River in Kansas (Schumm and Lichty, 1963), and on the Gila River in Arizona (Burkham, 1972).

The exact timing of vegetation establishment along the Harris Wash channel cannot be determined. However, knowledge of exactly when and at what floodplain height the vegetation established is not necessary to interpret the overall results reported here, which are that 1998 riparian vegetation appears to have a significant influence on floodplain flood power values. Other studies have pointed out that in canyon systems with large drainage basins that produce frequent large floods, riparian vegetation does not establish in high densities, and its influence on channel morphology may be minimal (Birkeland, 1996). But as this analysis shows, the present vegetation in Harris Wash is established in densities high enough to cause substantial increases in channel roughness, and thus have major effects on floodplain flood power. It also is relevant to note that peak floods in Harris Wash occur during the summer and fall monsoon season, when vegetation is in full foliage, and roughness values are equivalent to those reported here. If winter flooding while vegetation is in a dormant state were the norm along the channel of Harris Wash, then the roughness values in this study would overestimate actual roughness during floods. Thus the seasonal timing of floods in this canyon enhances the potential effects of vegetation to reduce flood power.

Sediment accumulation and vegetation density are highly variable throughout the Harris Wash canyon (Birkeland, 1999). In areas along the stream where flood power is concentrated on the outside of bends, floodplain aggradation may occur on the inside of bends and vegetation may be absent or minimal. Therefore, while the direction of change for active channel and floodplain flood power probably remains fairly constant, the magnitude of change may vary throughout the canyon. Rates of change probably vary with the amount of vegetation that has established, as well as with the overall flood power magnitude at that particular cross-section. Further study in an area with abundant historical data is needed in order to expand on the preliminary quantitative analyses presented here.

CONCLUSION

It is clear from both historical evidence and field observations that changes in channel morphology and flood power in the lower canyon of Harris Wash from 1922 to 1998 are characterized by floodplain formation and aggradation, and active channel narrowing. Based on the results from a detailed geomorphic analysis at a cross-section, it appears that 1998 floodplain aggradation is associated with a decrease in floodplain flood power, and that 1998 channel narrowing is associated with an increase in active channel flood power. Changes in hydraulic roughness caused by the establishment of riparian vegetation throughout the canyon appear to be a major factor presently affecting floodplain flood power—as shown by shear stress and unit stream power decreases ranging from 44 to 100 percent since 1922. It is likely that the present positive feedback cycles of floodplain sedimentation and channel erosion associated with vegetation expansion will continue until a flood disrupts the system, removes some or all of the vegetation, and returns the system to its 1922 morphology of a wide active channel with little floodplain development. The nature of vegetation and channel changes in Harris Wash are conducive to this kind of flood power analysis, and the technique used here for quantifying the role of vegetation in flood power change holds promise for more extensive analyses in other fluvial systems with appropriate historical records.

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