

AERIAL PHOTOGRAPHIC ANALYSIS OF CHANNEL NARROWING AND VEGETATION EXPANSION IN CANYON DE CHELLY NATIONAL MONUMENT, ARIZONA, USA, 1935–2004

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ABSTRACT

Aerial photographs from the past 70 years show narrowing of channels in Canyon de Chelly National Monument, which coincided with the establishment and expansion of woody riparian vegetation, primarily non-native tamarisk (*Tamarix ssp.*) and Russian olive (*Elaeagnus angustifolia*) and native cottonwood (*Populus spp.*). Rectified air photo sets were used to map the extent of woody riparian vegetation cover in the canyon bottom as well as the channel planform geometry for 6 years: 1935, 1964, 1975, 1981, 1989 and 2004. In 1935, vegetation covered less than 1 per cent of the canyon bottom and the channel was braided and 91 m wide on average. By 2004, the channel in the upper 75% of the canyon had narrowed to a single thread an average of 6.5 m wide and was lined by riparian vegetation, with vegetation covering up to 45% of the canyon bottom in some reaches. A relative timing index was developed that incorporates information from both channel and vegetation area expansion or contraction into a single variable. Vegetation establishment lagged channel narrowing in the upper reaches of the canyons, but narrowing and vegetation establishment occurred simultaneously in the middle and lower reaches. Narrowing progressed downstream through time, and the lowermost reaches remained braided and unincised in 2006. We interpret these patterns to suggest that riparian vegetation is responding to and interacting with changes in the channel morphology of Canyon de Chelly rather than driving channel change. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: channel narrowing; invasive vegetation; arroyo formation; remote sensing; Colorado Plateau

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INTRODUCTION

The complex interactions between vegetation, climate and channel morphology complicate the study and management of semi-arid streams and riparian areas such as those of the Colorado Plateau region (e.g. Graf, 1982; Hereford, 1984; Gellis *et al.*, 1991; Swetnam and Betancourt, 1998; Birken and Cooper, 2006). In the case of arroyo incision, for example, it is difficult to determine if channel changes are caused by anthropogenic influences, climate change, both or neither (Antevs, 1952; Leopold, 1976; Schumm, 1979). Yet because semi-arid streams vary widely in channel geometry (Graf, 1983) and vegetation cover (Webb *et al.*, 2007) on decadal time scales, human use of the floodplain is often impacted and the desire to mitigate change may be strong if the changes in the rivers and their floodplain are considered negative by residents or visitors. Vegetation and climate may affect channel morphology in complex ways, and interactions with human-induced landscape change may also occur (Williams and Wolman, 1984; Phippen and Wohl,

2003) (Figure 1). Effective management of semi-arid streams and floodplains is aided by an increased understanding of the potential influences of these interacting processes.

Vegetation may alter channel morphology by providing cohesion, either locally on the river banks or diffusely across the landscape. Landscape-scale vegetation change alters sediment delivery and runoff production (Kondolf *et al.*, 2002; Liébault and Piégay, 2002). Local riparian vegetation change alters bank resistance and floodplain roughness (Turner, 1974; Smith, 1976; Tal *et al.*, 2003; Pollen and Simon, 2005; Pollen-Bankhead *et al.*, 2009). Vegetation establishment and vegetation removal can equally trigger channel changes. Antevs (1952) concluded that historic arroyo cutting in the southwestern USA was caused by landscape-scale vegetation change brought about by climate change and human land use. Subsequent researchers have emphasized climate change and de-emphasized land use as triggers of the 1860–1909 regional episode of arroyo incision in the southwestern USA (Leopold 1976; Hereford, 1984; Graf 1986). Nonetheless, both climate and human activity impact vegetation, and thereby the channel. Droughts and wet periods can alter vegetation ‘naturally’,

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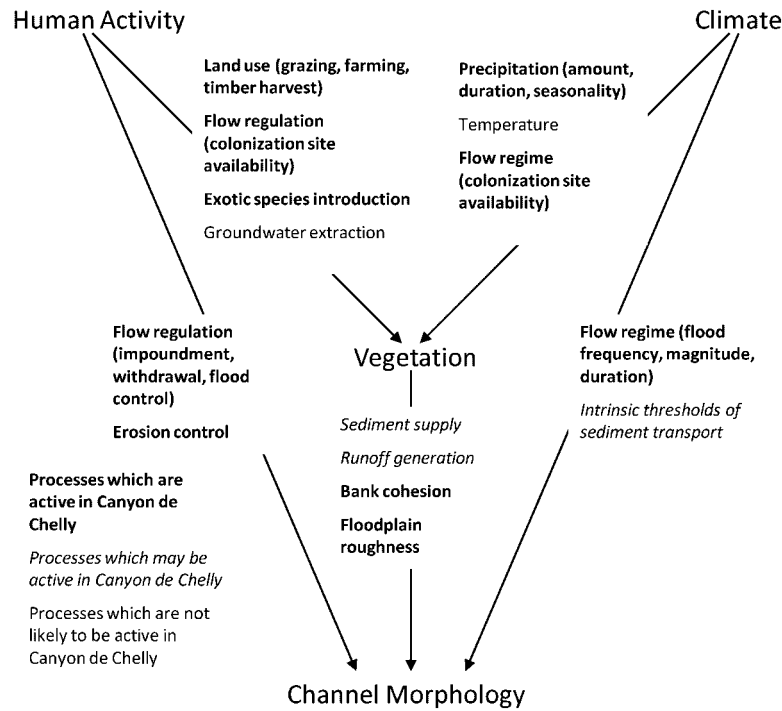


Figure 1. Flow chart summarizing some of the processes that link climate, vegetation, channel morphology and human activity

while overgrazing or exotic species introduction can alter vegetation ‘unnaturally’. In semi-arid regions such as the Colorado Plateau, the harsh environment can act as a limiting factor on vegetation. Slight changes in climate (i.e. decadal cycles of wet and dry periods) can lead to changes in vegetation cover and sediment production (Tucker and Slingerland, 1997; McAuliffe *et al.*, 2006). Finally, flow regime, which is set by climatic patterns, is an important control on riparian vegetation establishment and distribution (Poff *et al.*, 1997; Stromberg, 1998). Human alteration of flow regime through river regulation can likewise alter riparian ecosystems (Friedman *et al.*, 1998; Merritt and Cooper, 2000; Nilsson and Berggren, 2000; Shafroth *et al.*, 2002).

The invasion of Colorado Plateau waterways by the exotic woody riparian species tamarisk (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*) is both a vegetative and anthropogenic influence on channels. The range of tamarisk expanded rapidly once the plants escaped cultivation late in the 19th century and became naturalized in most watersheds by the 1930s (Robinson, 1965; Harris, 1966; Graf, 1978). Nonetheless, the timing of reach-scale establishment of tamarisk is controlled in many ways by flow regime (Allred and Schmidt, 1999; Cooper *et al.*, 2003; Birken and Cooper, 2006). Flood timing, magnitude and frequency control the availability of suitable establishment sites. Tamarisk colonizing floodplains and channel bars trap sediment, and their establishment coincided with channel narrowing in

many cases (Turner, 1974; Graf, 1978; Allred and Schmidt, 1999). Although tamarisk adds an ‘unnatural’ element to the climate–vegetation–channel interaction, it is not unique in its ability to establish near channels and provide bank strength. Native cottonwood (*Populus* spp.) are also effective at stabilizing sediment, but have a shorter time period when their seeds are viable (Stromberg, 1998; Glenn and Nagler, 2005) and may be more sensitive to alterations in flood timing for establishment.

Climate variation and anthropogenic influence can directly alter channel morphology as well, without acting through changes in vegetation, for example by altering flood magnitude or frequency. Larger and more frequent floods have been linked to incision in the Little Colorado River (Hereford, 1984), Paria River (Hereford, 1986; Graf *et al.*, 1991) and Virgin River (Hereford *et al.*, 1996). More frequent El Niño events have been linked to episodes of prehistoric arroyo incision in southern Arizona (Waters and Haynes, 2001). Reduced flow caused by irrigation and impoundment has triggered channel narrowing in the Platte River and other braided Great Plains Rivers (Williams and Wolman, 1984; Johnson, 1994; Friedman *et al.*, 1998). Following regulation of the Green River in northern Utah, channel narrowing was observed, followed by widening and island formation (Lyons and Pucherelli, 1992; Merritt and Cooper, 2000), although Grams and Schmidt (2005) argue that the observed widening was offset by lower elevation post-regulation floodplain development, and that the net

effect was continued narrowing. Even without changes in precipitation patterns, the semi-arid climate may lead to inherent instability in channel form (Schumm, 1979). Schumm and others have suggested that the high sediment production and infrequent flows of the Colorado Plateau lead to sediment accumulation in channels until an intrinsic threshold for bed incision is crossed, resulting in episodic sediment transport and erosion (Schumm and Hadley, 1957; Patton and Schumm, 1981).

The changes in morphology of several Colorado Plateau channels have been analysed by researchers who have found a link between channel form and flow regime. In the Little Colorado River, Arizona, and the Paria River basin, Utah and Arizona, channels incised and widened during times of high flood magnitude and frequency, and narrowed by floodplain accretion during times of low peak-floods (Hereford, 1984; Hereford, 1986; Graf *et al.*, 1991). Arroyo entrenchment occurred in the Zuni River, New Mexico, as a result of the transition from drought conditions to a period of frequent flooding (Balling and Wells, 1990). At Chaco Canyon, New Mexico, the braided inner channel narrowed by floodplain accretion during a time of increased precipitation but reduced peak flows (Gellis, 2002). Narrowing of the Green River, near the town of Green River, Utah, by means of floodplain accretion was associated with periods of low flood magnitude (Allred and Schmidt, 1999).

Canyon de Chelly National Monument in northeastern Arizona, USA, has experienced channel narrowing and incision and invasion by tamarisk and Russian olive which have negatively affected the resident Navajo Indian community, and provides a setting in which to analyse the interaction between these two types of change. If managers are to control channel narrowing, incision and exotic plant establishment, it is important to understand whether and how the incision and exotic plant invasion are linked. Increased riparian vegetation cover may drive channel change by altering bank and floodplain characteristics, or the vegetation increase may result from channel modification initiated by precipitation or land used changes.

In Canyon de Chelly, and throughout the Colorado Plateau, the difficulty in identifying the mechanisms and processes driving channel change lies in differentiating between the influence of invasive vegetation and that of climate or human alterations. Analysis of a series of aerial photographs is one method by which differentiation can be attempted and is commonly used in scientific investigations of channel change through time (Graf, 1978; Hereford, 1984; Tal *et al.*, 2003; Birken and Cooper, 2006). Aerial photograph series have high spatial resolution but typically low temporal resolution, and improved interpretation is possible when they are supplemented with field surveys, tree-ring analyses and sedimentological analyses and

mapping. This paper focuses on the aerial photographic component of one such multifaceted project at Canyon de Chelly National Monument, the goal of which was to determine the feasibility of restoring the channel to its state prior to exotic plant invasion and channel incision.

To interpret the history of change in Canyon de Chelly we examined the spatial variation and relative timing of channel narrowing and vegetation establishment, with supplemental data from local precipitation records, tree cores (Reynolds, 2009), and field surveys (Jaeger, 2009). In order for restoration via plant removal to have a likelihood of success, vegetation establishment would need to be the primary driver of change. We analysed air photos for evidence that vegetation colonized channel areas such as bars and islands, stabilizing the channel and forcing channel narrowing. Subsequent flows in the confined and vegetation-stabilized channel would induce bed incision. The loss of channel area would be proportional to the gain in vegetation cover in each stream segment. This model is consistent with narrowing observed on the Green River in Canyonlands National Park, Utah (Graf, 1978), and Plum Creek, Colorado (Osterkamp and Costa, 1987; Friedman *et al.*, 1996), although floodplain aggradation rather than channel incision occurred at these sites.

Another pattern of change observed in the Colorado Plateau is for vegetation to establish on former channel areas during periods between large floods. Later large floods deepen the narrow channel and deposit sediment in vegetated areas. This sequence, attributed to climate variation, has been observed on the Little Colorado River, Arizona (Hereford, 1984). Finally, channel narrowing may pre-date vegetation establishment if there is still the potential for a flood to deposit substrate that provides germination sites for tamarisk and cottonwood, although Russian olive is not dependent on floods for establishment (Reynolds and Cooper, 2010). Narrowing that is not driven by local vegetation could be caused by factors elsewhere in the basin, such as upstream migration of arroyos that initiated downstream (Schumm and Parker, 1973) or changes in sediment production upstream (Kondolf *et al.*, 2002; Liébault and Piégay, 2002) or crossing of an intrinsic threshold of stability (Schumm and Hadley, 1957; Patton and Schumm, 1981). An observation of time transgressive changes such as knickpoint migration would favour this alternate interpretation.

STUDY SITE

Canyon de Chelly National Monument is located in Apache County in northeastern Arizona, on the Navajo Reservation. The monument contains two main steep-sided bedrock canyons, Canyon del Muerto in the north and Canyon de

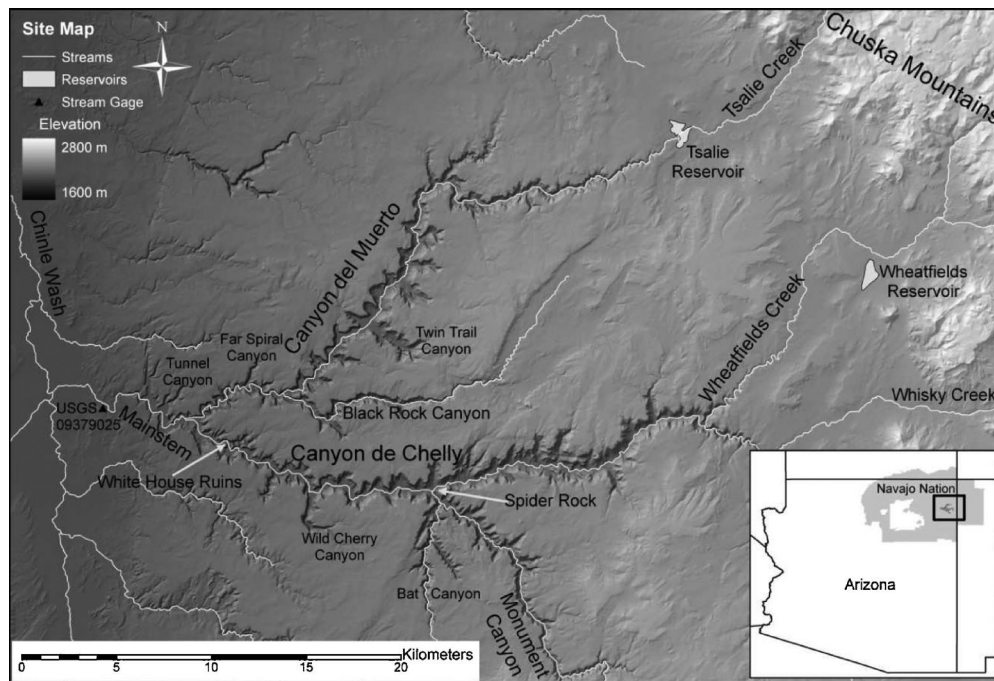


Figure 2. Location map of Canyon de Chelly, Arizona, and its tributaries

Chelly in the south, and numerous tributary canyons (Figure 2). These canyons drain the Chuska Mountains to the east and a portion of the Defiance Uplift, into which the canyons have incised (Gregory, 1917). The main canyons have wide (typically 300–500 m) alluvial bottoms that preserve several terraces along with the recently abandoned historic floodplain and the modern channel. Canyon del Muerto drains approximately 430 km² and Canyon de Chelly drains approximately 1250 km². Downstream from the junction of Canyon del Muerto and Canyon de Chelly, the mainstem of Canyon de Chelly emerges in the Chinle Valley and the stream becomes Chinle Wash, which flows north to the San Juan River in Utah. Small reservoirs exist upstream of both canyon branches. Tsalie Dam, located on Tsalie Wash upstream of Canyon del Muerto, was built in 1964, and has a capacity of 9 991 203 m³. Wheatfields Dam is an off-channel structure located near Wheatfields Creek upstream of Canyon de Chelly and was built in 1963. It has a capacity of 7 030 847 m³ and is operated to capture flow during the winter months and release it for agricultural use in the summer. There are no long-term records of discharge or reservoir stage for either dam (Navajo Nation Safety of Dams, Personal Communication), but we were able to obtain discharge records on Wheatfields Creek downstream of the dam for water years (WY, October–September) 1997–2000 and on Tsalie Wash for WY 1991, 1998, 2001 and 2004–2006. Annual peak flows all occurred in April or May, with a maximum recorded flow in Wheatfields Creek of 4.1 m³ s⁻¹

and in Tsalie Wash of 3.3 m³ s⁻¹, both on 2 May 1998. There were two examples of what appear to be August agricultural flow releases of 1.1 m³ s⁻¹ from Wheatfields Dam, but which could also have been flash flood events.

At its deepest, the bottom of Canyon de Chelly is 300 m below the surrounding cap rock. This upland is capped by the resistant conglomerate of the Shinarump Member (Thaden, 1989). The canyon walls expose the De Chelly Sandstone immediately below the Shinarump. The canyon has cut below the De Chelly into the Supai Formation (Thaden, 1989) in a few locations, such as in the vicinity of Spider Rock (Figure 2). This shale unit creates more gentle slopes at the base of the canyon walls where it is exposed.

Regional climate is semi-arid, with local average annual precipitation of 231 mm. In late summer, convective thunderstorms driven by monsoonal flow initiate major precipitation events at Canyon de Chelly. Winters are generally dry with periodic snow. Summer temperatures often reach above 35°C and may drop to near freezing at night. Winter temperatures are generally cold, reaching to -20°C in most years.

Precipitation records have been kept in Chinle since 1908. In 1970, the recording station was moved from the town of Chinle to the headquarters of Canyon de Chelly National Monument. The largest single day rainfall recorded to date occurred in January of 1983 when 13 cm of precipitation fell. However, most large rainfall events occur in the late summer monsoon season. Only 46 events have been

recorded with more than 2.5 cm of rain in 1 day, and 34 of these occurred between July and October.

USGS stream gage 09379025 was established on Chinle Wash at the mouth of Canyon de Chelly (Figure 2) in November of 1999 and discontinued in August of 2006. The watershed area above the gage site is 1684 km² and the stream is ephemeral. Flow in Canyon de Chelly has two main sources. Snowmelt runoff from the Chuska Mountains is the primary source of flow in the winter and spring. Following spring runoff, the stream is typically dry during mid-summer. Precipitation from convective thunderstorms may produce stream flow in late summer. Flash floods in late summer and early autumn are common, creating highly variable daily flows. The larger source of flow in total volume is snowmelt, but late summer convective storms produce higher peak discharges, and five of the six recorded yearly peaks occurred in late summer or early autumn. The highest recorded instantaneous discharge was 137 m³ s⁻¹ in July 2006. The second highest peak was 83.3 m³ s⁻¹ on 8 September 2005, but mean discharge for this date was 1.6 m³ s⁻¹, demonstrating that peak flows can be brief. Flash floods are much more turbid than the snowmelt flows, and the highest sediment discharge likely occurs during these events. There is poor correlation between flow at the canyon outlet and flow entering the canyons for the periods that overlap with records from Wheatfields Dam ($R^2 = 0.37$) and Tsalie Dam ($R^2 = 0.37$).

During the years with discharge records there was a strong correlation between total water year (October–September) precipitation and total discharge ($R^2 = 0.89$), as well as between winter precipitation (November–March) and discharge the following spring (March–May) ($R^2 = 0.93$). However, precipitation recorded at Chinle during the monsoon season (July–September) did not correlate with total flow during the same period ($R^2 < 0.01$), likely because of the limited spatial extent of storm cells and the

importance of antecedent moisture conditions in producing flow in ephemeral streams.

METHODS

Aerial photographic mapping

Aerial photographs of the canyons were acquired for the years 1935, 1964, 1975, 1981, 1989 and 2004 (Table I). The study area was divided into 50 1-km-long reaches, seven of which are located below the junction of Canyon del Muerto and Canyon de Chelly (reach #1–7), 19 in Canyon de Chelly (reach #8–26) and 24 in Canyon del Muerto (reach #27–50). Measurements taken from air photos include: (1) area of the canyon bottom (A_B), (2) valley length (L_V), (3) area of riparian vegetation (A_V), (4) channel area (A_C) and (5) channel length (L_C). Three parameters were calculated from these measurements: (6) channel sinuosity (P), (7) reach-averaged channel width (w) and (8) per cent of canyon bottom covered with riparian vegetation. Data gaps exist because three of the six air photo sets do not cover the entire study area. Additional air photos of lower Canyon de Chelly from 1992 and 1997 were observed, but not digitized, in order to clarify recent changes in this vicinity.

Each photo was scanned at a resolution that captured all visible features, ranging from 300 to 450 DPI (dots per inch). The 1935 and 1981 photo sets were composite enlargements and the other four sets were contact prints. The photos were registered to a 2003 Digital Orthophotographic Quadrangle (DOQ) commissioned by Canyon de Chelly National Monument using ERDAS Imagine software. Registration was achieved by identifying ground control points (GCPs) within the canyon bottom and linking the GCPs between the scanned photo and the DOQ. Control points were only selected in the canyon bottom, therefore the rectification applies to the land surface within the canyon and not the

Table I. Year, date, print and film type, scale, resolution, average number of ground control points (GCP) per photo, average root mean square error (RMSE) of the transformation used to rectify the photos and original purpose of the six air photo sets analysed in this study

Year	Dates	Film Type	Print type	Approx. Scale	Estimated Resolution	Average GCPs	Average RMSE	Original Purpose of Aerial Survey
1935	Unknown	Black and white	Composite enlargement	1:20 000	4 m	27	0.049 m	Soil conservation and management
1964	16/9 and 8/10	Black and white	Contact print	1:6700	1 m	12	0.040 m	Road construction
1975	12/5	Black and white	Contact print	1:20 000	2 m	26	0.012 m	Archaeological survey
1981	10/6	Colour Infrared	Composite enlargement	1:10 000	4 m	34	0.026 m	Reservation land management
1989	6/7/89, 10/10/89 and 15/10/90	Colour	Contact print	1:15 840	2 m	25	0.010 m	Agricultural assessment
2004	24/6 and 02/7	Black and white	Contact print	1:12 000	1 m	21	0.010 m	Nat'l Monument management

surrounding uplands. This focused correction reduced rectification errors related to the dramatic topography. Most GCPs identified were rock outcrops, buildings or persistent cottonwood trees. First- and second-order polynomial transformations were performed on the scanned photos based on the GCPs. In most cases the second-order transformation was selected because of the lower resultant root mean square errors (RMSE) (Table I) as well as the recommendations of Hughes *et al.* (2006). With the exception of the 1964 photos, which were very large scale (1:6700) and offered few GCP choices, all photos were rectified with at least eighteen GCPs (Table I). The minimum for the 1964 set was nine GCPs.

The registered and georectified photos were imported into ArcMap GIS software. Polygons or polylines were created for each measured parameter. The canyon bottom was delineated using all photos available because the differing locations of the airplane for each photo gave slightly different viewing angles, some of which were better for delineating the base of one canyon wall, and others of which were better for viewing the opposing canyon wall. Steep talus slopes and sloping bedrock outcrops were not included in the canyon bottom, limiting the delineation to the active channel and all visible terraces and fluvial surfaces. The centreline of the canyon bottom was digitized, and valley length (L_V) calculated. The valley centre line was used to demarcate the 50 1-km-long reaches. Creating a series of distinct channel reaches facilitated both statistical and graphical analysis of the data.

Woody riparian vegetation was outlined where visible on the air photos (Figures 3 and 4). In many cases, individual

trees were mapped with a unique polygon, but when vegetation was dense, a single polygon might encompass hundreds of individuals. No distinction was made between exotic species and native species of cottonwood and willow (*Salix* spp.) in the GIS analysis, although an effort was made to exclude non-riparian woody vegetation such as pinyon pine (*Pinus monophylla*). All riparian vegetation was lumped into one category because channel morphology could be affected by any riparian vegetation, and in some cases we could not reliably identify the different species from the air photos, especially for young plants, making an attempt to digitize species distribution untenable. In some important cases, such as for the first vegetation established in an area, we identified plant species in the air photos by the colour, tone, shape and texture of the vegetation, then tracked individual plants through subsequent photos and field-checked and corrected our designations during 2005 and 2006. This qualitative information was used to enhance the interpretation of the results.

Resolution varied between photo sets and limited the accuracy of vegetation mapping. To estimate photo resolution, the diameters of small isolated objects that were distinctly visible were measured using the GIS in each photo set. The 1935 photo set resolution was ~ 4 m (Table I). Individuals or clusters of plants at least this size and with colours contrasting the sandy background were visible. The only woody vegetation mapped in the 1935 photos were isolated cottonwood trees with crowns at least 4 m in diameter and patches of lower growing vegetation which contrasted with the sand of the canyon bottom. Shadows were helpful in locating small trees and shrubs because air

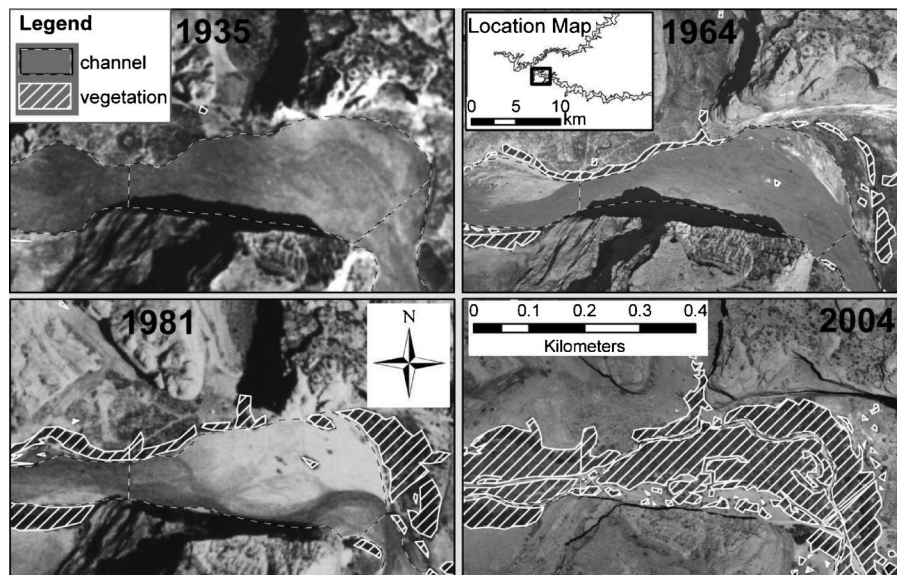


Figure 3. Mapped channel and vegetation in reach #10, near White House Ruins. Narrowing occurred relatively late in this reach, after 1981 but before 2004. The vegetation area increase approximately matched channel area loss in each interval between photos

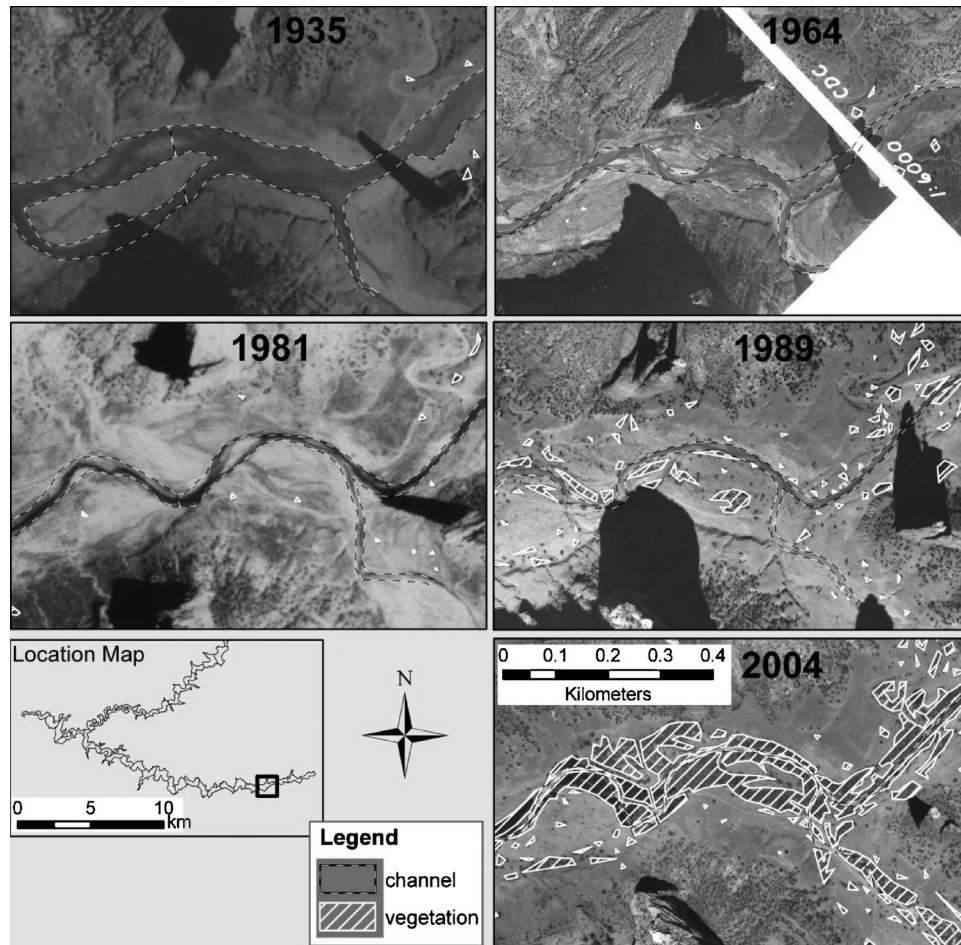


Figure 4. Mapped channel and vegetation in reach #23, near Spider Rock. Narrowing occurred relatively early, primarily 1935–1964, in this reach, with vegetation establishment occurring relatively late, primarily 1989–2004

photos were rarely taken with the sun directly overhead. However, small tamarisk or Russian olive trees could have been present but not visible. By examining the visible diameter of trees of known age (Reynolds, 2009), we conclude that most tamarisk individuals will be visible in 4 m resolution photos (1935 and 1981 sets, Table I) within 20 years after germination, and some individuals may be visible in 10 years. If tamarisk established in patches, as it commonly does, they would be visible at a younger age. Younger trees are visible in the photo sets with finer resolution. The resolution of both the 1975 and 1989 photo sets is 2 m, and the 1964 and 2004 photo sets are 1 m (Table I).

The channel was mapped by digitizing polygons, and the area covered by the channel (A_C) was calculated (Figures 3 and 4). The channel was identified as the unvegetated area on the lowest fluvial surface, following the methodology of Friedman and Lee (2002). In areas where woody vegetation did not coincide with the channel boundary, the bank was

visible as either a step in elevation or as a transition from sand to herbaceous vegetation. We included exposed bars as channel because discharge at the time of the photos varied, so that in some years water was visible in the full area of the channel, whereas in others only a portion of the channel contained water. None of the photos exhibited a completely dry channel. The centre line of the channel was also digitized and used to measure channel length (L_C). Average channel width (w) was found from channel area divided by channel length ($w = A_C/L_C$). We used the channel centre line in conjunction with the canyon bottom centreline to calculate sinuosity ($P = L_C/L_V$).

Relative timing index

To analyse the relative timing of channel narrowing and vegetation establishment, a relative timing index for each reach was calculated by fitting a power function to a plot of vegetation area versus channel area, where the number of

data points equals the number of photo sets that cover the reach. The channel area values were normalized to a 0–1 scale within each reach by subtracting the minimum in that reach from all channel area values and dividing them by the difference between the maximum and minimum values. Vegetation area values were normalized to a 0–1 scale within each reach in the same way. A function of the form $A_{Cn} = 1 - A_{Vn}^i$ was fit to each study reach plot by selecting the value of i that minimized the error sum of squares, where A_{Cn} is the normalized channel area, A_{Vn} is the normalized vegetation area and i is the relative timing index (see Figure 5 for a visual representation and comparison of measured and fitted curves). In this way a single index variable was created that contains information about the relative timing of both channel narrowing and vegetation establishment in each reach. This index allowed simple evaluation of the degree to which channel narrowing preceded vegetation establishment in each reach and also

facilitated identification of longitudinal trends in the relative timing of changes.

Sensitivity analysis

A sensitivity analysis was conducted to test the effect of the selected 1-km-long reach length on the results. The full data set was re-analysed using 2-km-long study reach divisions. Also, an 8-km reach in central Canyon de Chelly was re-analysed using 500-m-long study reach divisions. Some spatial statistical analyses produced more significant results with the 2-km study reach length data, whereas others produced more significant results with the 500-m study reach length data. However, the data trends remained similar in each analysis, and we base our interpretations on the 1-km study reach length.

RESULTS

Relative timing of channel narrowing and vegetation establishment

The relative timing of channel and vegetation change varied through the study area. Reaches in the White House Ruins area (lower Canyon de Chelly, reach #8–11) experienced channel area (A_C) loss that was nearly equal to vegetation area (A_V) gain in every time interval in this analysis (Figures 3, 5, 6). In contrast, reaches in the Spider Rock area (upper Canyon de Chelly, reach 22–26) experienced nearly full channel narrowing, apparently due to incision, when vegetation cover was still low, and only later did extensive riparian vegetation cover develop (Figures 4–6). The middle portion of Canyon de Chelly (reach #12–21) was transitional. Between 1935 and 1981 the channel in these middle reaches narrowed from an average of 104 m to 31 m wide and vegetation cover increased from 0.1 to 7.9% of the canyon bottom. From 1981 to 2004 the channel here narrowed from an average of 31 m to 7 m wide while vegetation cover increased from 7.9 to 24.7% (Figure 6). The highest rates of narrowing and vegetation expansion did not coincide, but the processes did overlap in time.

The relative timing indices calculated from the best-fit power functions (Figure 5) show a decrease in trend moving upstream in both canyons (Figure 7). Most of the indices for the lower 14 km of the canyons vary from 0.5 to 1.5, indicating approximately simultaneous channel narrowing and vegetation cover increase. For the two lowermost reaches $i > 1.5$, which would occur if channel narrowing began only after vegetation had already established on the floodplain or terraces. In contrast to the lower reaches, upper reaches had highly concave curves (Figure 5), with $i < 0.5$ (Figure 7). The pattern of change in the upstream reaches

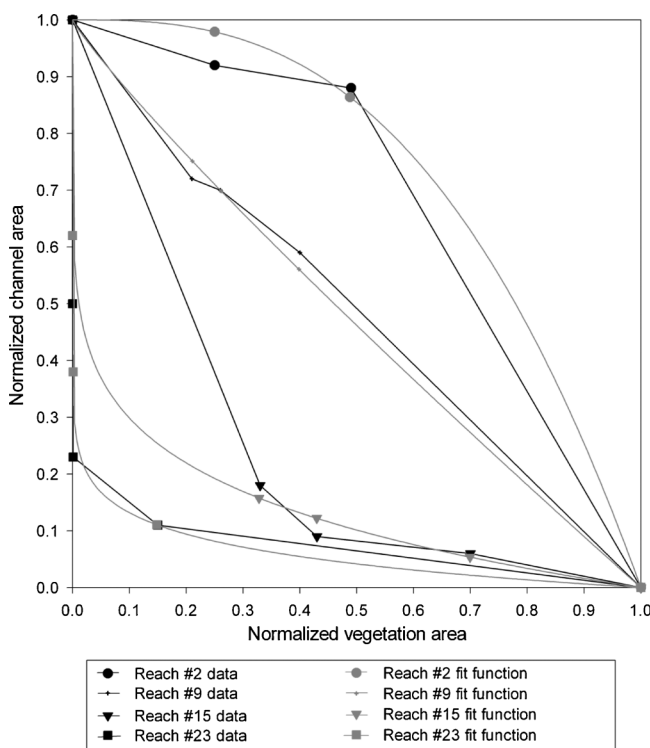


Figure 5. The best-fit relative timing lines plotted with the normalized data for four sample reaches. Reach #2, near Cottonwood Canyon, had a mean square error (MSE) of the fit of 0.97. Reach #9, White House Ruins, MSE = 0.32. Reach #15, Wild Cherry Canyon, MSE = 0.26. Reach #23, Spider Rock, MSE = 8.61. The relative timing indices, which are the exponent i in the equation $A_{Cn} = 1 - A_{Vn}^i$, are 2.82, 0.89, 0.15 and 0.05, respectively. The mean MSE of the fitted curve for all 50 reaches was 7.30, and the median was 2.70, with values ranging from 0.0001 to 87.93. In each plot, the upper left end of the line represented the 1935 data, the lower right end represented the 2004 data and intervening points along the line occurred in chronological order

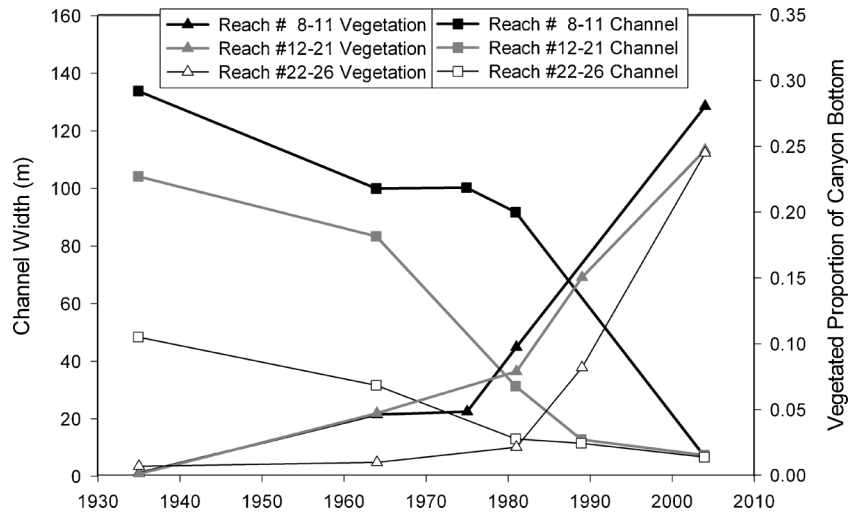


Figure 6. Average channel width and vegetation cover in three sections of Canyon de Chelly. In the lower reaches (#8–11) channel narrowing and vegetation establishment occurred simultaneously, mostly after 1975. In the middle reaches (#12–21) the highest rate of channel narrowing occurred before the highest rate of vegetation establishment, although the processes did overlap in time. In the higher reaches (#22–26) channel narrowing was nearly complete prior to major vegetation establishment. In 2004, channel width and vegetation cover were similar throughout the canyon in spite of the different timing of changes

was characterized by channel narrowing in the absence of vegetation growth during the earlier intervals, particularly in the uppermost reaches, followed by vegetation increase in the absence of channel narrowing during the later intervals.

Spatial and temporal trends of channel narrowing and vegetation establishment

Channel width decreased over every time interval for 90% of the study reaches. Every reach narrowed over the full time interval 1935–2004, by an average of 74 m. At the time of every photo set, the upper reaches of both canyons had narrower channels than the lower reaches (Figure 8). The

channel was a wide sandy wash through 80% of the study reaches in the 1935 photos, with the narrow reaches limited to the uppermost portion of Canyon del Muerto (upstream of the confluence with Twin Trail Canyon) and upper Canyon de Chelly (upstream of the confluence with Monument Canyon at Spider Rock). In contrast, the 2004 photo set showed a narrow meandering channel through 75% of the study area. Canyon de Chelly upstream of the junction with Canyon del Muerto had a single threaded channel that was 6.5 m wide on average, as did Canyon del Muerto upstream of Far Spiral Canyon (Figure 2). Narrowing occurred earliest in the uppermost reaches of the study site, and progressed farther downstream in each subsequent photo set. Narrowed

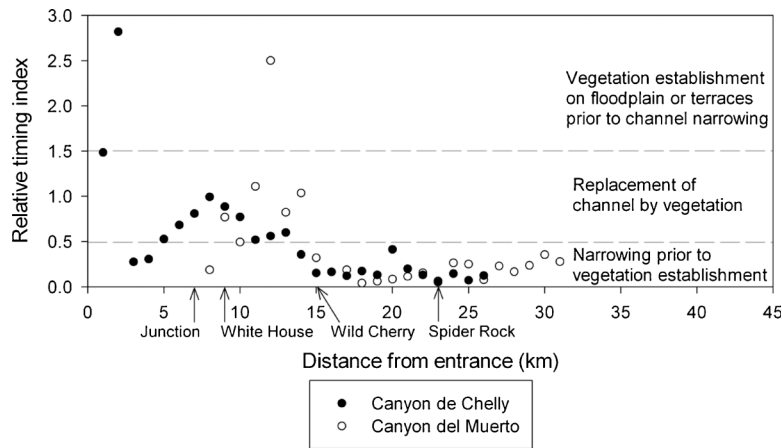


Figure 7. Longitudinal variation in the relative timing indices (*i*) calculated from the relative timing plots (Figure 5). The upper portion of the graph indicates reaches where channel area loss began after vegetation had already established on adjacent floodplains or terraces. The middle portion, with values close to 1, represents proportional replacement of channel area by vegetation area. The lower portion indicates reaches where channel narrowing occurred prior to widespread vegetation establishment, suggesting a cause of narrowing independent of vegetation. Named locations are in Canyon de Chelly

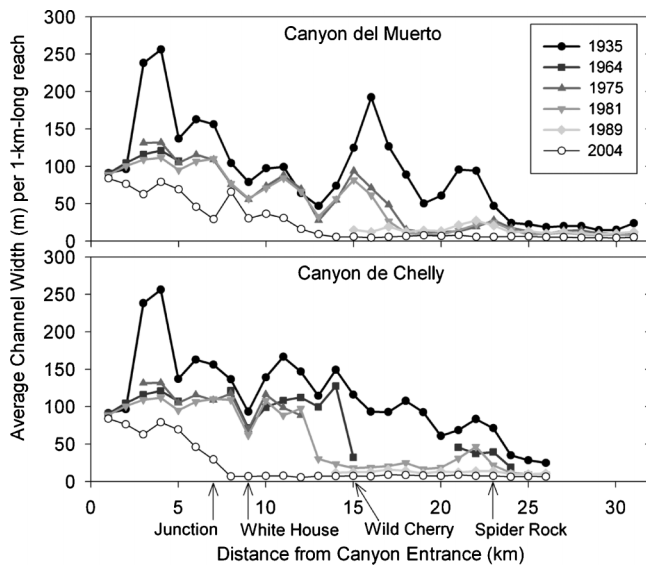


Figure 8. Longitudinal variation in channel width (m) in Canyon del Muerto and Canyon de Chelly. Each line represents data from a single year of air photos. The first 7 km of the two canyons are identical because the junction of Canyon de Chelly and Canyon del Muerto is located 7 km from the canyon entrance

reaches have incised as much as 4 m below the 1935 channel surface, with surveys at 29 random cross sections in Canyon de Chelly finding average depths of 2.3 m in reach #8–14, and 0.9 m in reach #15–26, and a minimum depth of 0.7 m (Jaeger, 2009). Incision is inhibited in reach #22–26 by coarse bed material. Lower Canyon del Muerto and the channel downstream of the junction remain braided and 55 m wide on average. This continuation of braiding 5 km into Canyon del Muerto is the most visible difference between the two main canyons.

The canopy area of woody riparian vegetation (A_V) increased through time in all reaches (Figure 9). Between 1935 and 2004, A_V increased from 0.3% of the total canyon bottom to 20.6%. Canyon de Chelly has significantly greater A_V than Canyon del Muerto ($p < 0.0001$; Wilcoxon Rank Sum test), and A_V was typically higher in more downstream portions of the canyon (Figure 9). The increase in vegetation cover was temporally and spatially discontinuous. Temporally, A_V was initially low and typically remained low until the 1980s, then increased rapidly. Spatially, A_V increased more rapidly near the confluence with several side canyons. At confluences the canyon tends to be wider, with more extensive fluvial surfaces. Two localized areas of early vegetation establishment were noted in the 1964 photo set (Figure 9), one located 3 km upstream of the canyon mouth immediately downstream of Tunnel Canyon, and the other 14 km upstream of the canyon mouth at the confluence with Wild Cherry Canyon (Figure 2), which was the point of transition from meandering to braided morphology in 1964.

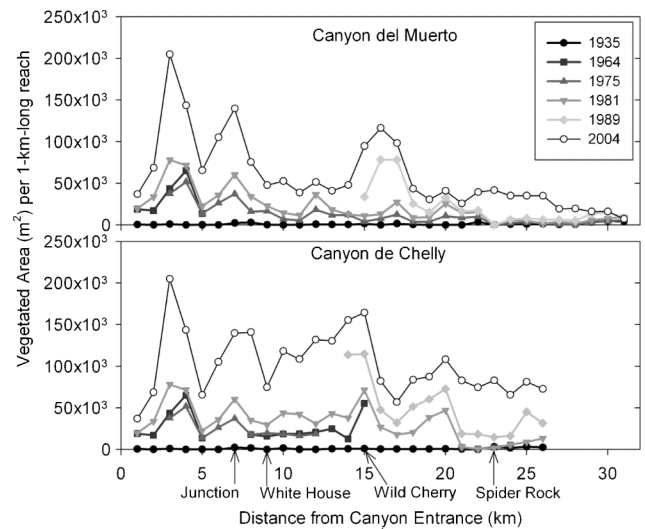


Figure 9. Longitudinal variation in vegetated area (m^2) per 1-km-long study reach in Canyon del Muerto and Canyon de Chelly. Each line represents data from a single year of air photos. The first 7 km of the two canyons are identical because the junction of Canyon de Chelly and Canyon del Muerto is located 7 km from the canyon entrance

Historic ground photos are available at these two locations prior to vegetation establishment, and repeat photos show how the two sites have responded differently to vegetation establishment, with narrowing to 7 m width and incision at Wild Cherry Canyon, but narrowing to 80 m width and no incision at Tunnel Canyon (Figure 10). The relationship between tributary canyon confluences and vegetation establishment is unclear. Although vegetation cover is greater at some confluences than surrounding reaches along the main canyon, such as the junction of Canyon de Chelly and Canyon del Muerto, 7 km into the canyon, and the confluence of Canyon del Muerto with Black Rock Canyon, about 15 km from the canyon entrance (Figure 2), some other large tributary canyons, such as Monument Canyon and Twin Trail Canyon (Figure 2), did not have higher vegetation cover at their junctions with the main canyons. Furthermore, some reaches not associated with side canyons do exhibit locally high vegetation cover.

Between the sites of broad pre-1964 cottonwood establishment at Wild Cherry Canyon and Tunnel Canyon, longitudinal bands of cottonwood established on the channel margins by 1964 and forced some narrowing, but the channel remained about 100 m wide. Subsequently, channel narrowing and vegetation establishment progressed in a downstream direction from Wild Cherry Canyon to the junction of Canyon de Chelly and Canyon del Muerto. In 1964, vegetation had widely established on the channel bed in reach #15. It is reasonable to suggest that in-channel vegetation extended an additional 6 km upstream, based on the similar appearance of vegetation in this area in later photo sets to the area near the Wild Cherry Canyon

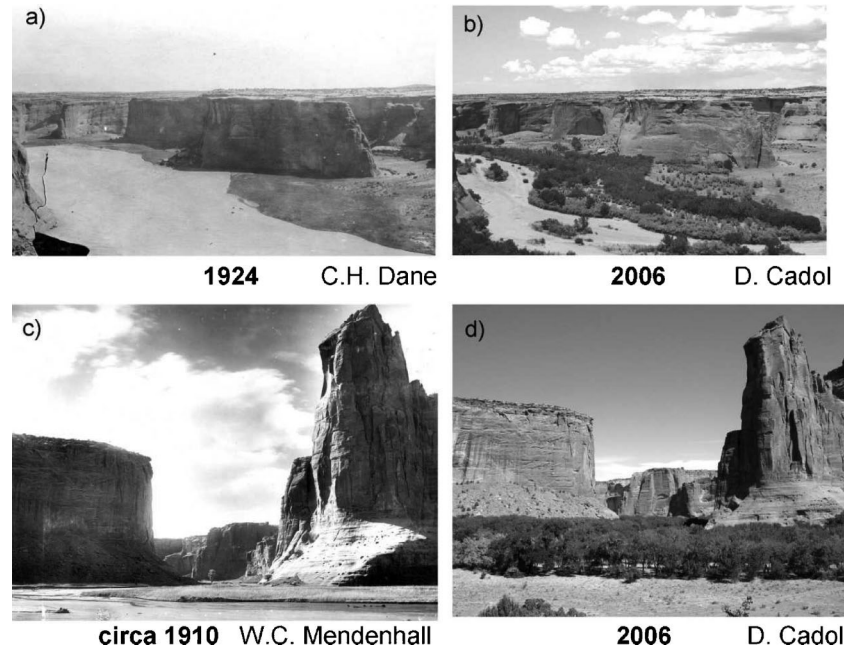


Figure 10. (a) and (b) Repeat photography of view looking downstream toward the confluence of the Mainstem of Canyon de Chelly and Tunnel Canyon (entering from the right in the distance). Most vegetation establishment has occurred on the former wash bed and includes tamarisk, cottonwood, Russian olive and willow. Incision has not occurred at this location, although the channel width narrowed from 255 m to 80 m. (c) and (d) Repeat photography of view looking downstream toward the confluence of Canyon de Chelly and Wild Cherry Canyon (entering from the left). Most vegetation is cottonwood, which established by 1964, with some Russian olive which established much later (lighter foliage on left edge of d). The channel has narrowed from 115 m to 7 m width, changed from a braided to a meandering planform, and incised approximately 2 m into sandy alluvium. The 2006 photo, (d), is taken from a location higher up on a talus slope behind the original photo location, (c), because the view from the original location is now obscured by vegetation. The historic photos by C.H. Dane, and W.C. Mendenhall are used courtesy of the USGS photographic library, online at <http://libraryphoto.cr.usgs.gov/>

confluence, but the 1964 photo set does not cover this area. By 1981 vegetation is visible in the channel bed down to reach #13. The 1989 photo set does not cover the area of interest, but a lower resolution photo from 1992 appears to show vegetation in the channel to reach #10, just upstream of White House Ruins, with open sandy channel downstream. Another lower resolution photo from 1997 appears to show vegetation established in the channel to reach #8, almost to the junction with Canyon del Muerto. Finally, by 2004 thick vegetation covers the former channel bed in the full length of Canyon de Chelly down to the junction. Most vegetation that established in this downstream progressing episode was tamarisk. The area around and upstream of Spider Rock (reach #21–26) was the last to experience widespread establishment of riparian vegetation. Russian olive is the predominant species in this area.

We were unable to identify any knickpoints on the air photos. Either knickpoints were not present at the times aerial photographs were taken, or their form was not visible in planview. Modern knickpoints exist in the channel at several locations, but only where cross-channel erosion control gabions have been maintained, in reach #13–15, and these are all in locations that have already incised at least 1.5 m.

Canyon del Muerto had broadly similar longitudinal trends, although narrowing processes in the lower reaches appear to be delayed relative to Canyon de Chelly. Interpretation is inhibited by the longer gap (1935–1975) between the first two photo sets that cover Canyon del Muerto, as well as the lack of corroborating survey and trenching data.

Precipitation and flow variation through time

The early 1940s and early 1980s were the two wettest 5-year periods in the record (Figure 11). The months with highest total rainfall also occurred in these periods. The late 1930s and early 1950s were the driest 5-year periods. Deviation of the 5-year average precipitation above record average was greater in magnitude, but less frequent, than deviation below average. Extremely dry individual years occurred in the late 1980s and 1990s, but were interspersed with wet years, resulting in 5-year averages similar to the average for the full data set.

Variation in the frequency of rainfall events that delivered at least 2.5 cm in one day is similar to variation in total monthly precipitation. The highest frequency of large events occurred in the 1940s and 1980s. The frequency of large

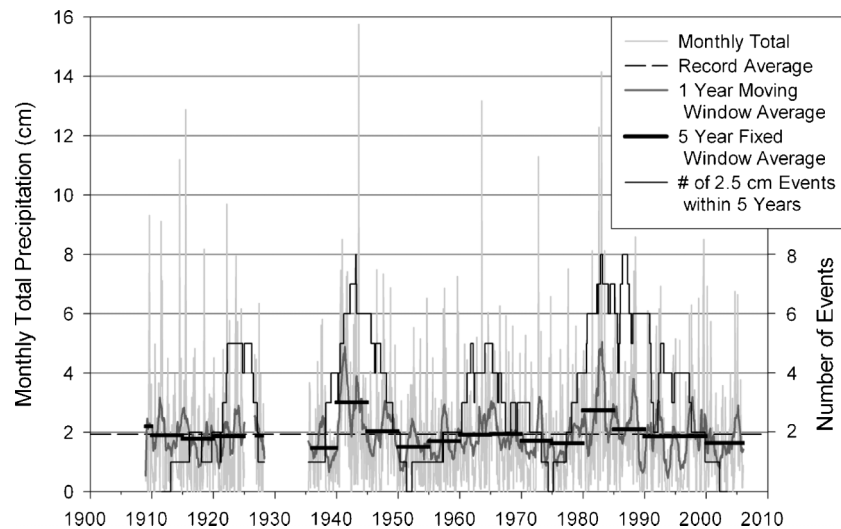


Figure 11. Precipitation data from Chinle, Arizona. Light grey line is the monthly total rainfall in cm. The medium grey line is a 12-month moving average of monthly total precipitation. The thick black horizontal lines are the average monthly rainfall for each 5-year period in the record. The dashed black horizontal line is the average monthly total for the period of record. The stepped black line records the number of large (greater than 2.5 cm in one day) rainfall events in a moving 5-year window

events was moderate in the 1920s, 1960s and 1990s and low in the 1910s, 1950s, 1970s and early 2000s. The climate variation observed for Canyon de Chelly is consistent with the findings of other researchers in the Colorado Plateau (Leopold 1976; Hereford, 1984, 1986; Graf 1986; Graf *et al.*, 1991).

Individual large rain events in Chinle do not necessarily correspond to flow events in the canyons. Unlike total annual flow and spring runoff flow recorded at USGS stream gage 09379025 from 1999 to 2006, which correlate well with local precipitation, summer rain storms were a poor predictor of summer flow (see Study Site). Nonetheless, storm frequencies at Chinle averaged over several years are more likely to reflect storm frequency conditions across the basin than individual events. From our limited information about Tsalie and Wheatfield dams it is uncertain how and if they affect flow in the canyons, but most likely they have reduced the magnitude of snowmelt floods since their construction.

DISCUSSION

In the wash below the junction of Canyon de Chelly and Canyon del Muerto (reach #1–7) and into Canyon del Muerto (reach #27–31), where narrowing was documented but the braided planform was retained, vegetation established on islands and bars. This type of narrowing has also been observed on some larger river systems in the Colorado Plateau (Graf, 1978; Allred and Schmidt, 1999) and appears to be vegetation driven. Thus vegetation removal may

promote widening in these reaches, although the vegetation is mixed native and exotic. However, this portion of the study area has not incised, which is a major focus of management efforts. The reaches that have incised fall into two groups: those that narrowed prior to vegetation establishment ($i < 0.5$, reach #14–26 in Canyon de Chelly and reach #34–50 in Canyon del Muerto), and those that narrowed simultaneously with vegetation establishment ($0.5 < i < 1.5$, reach #8–13 in canyon de Chelly and reach #32–33 in Canyon del Muerto). The use of 0.5 as a division between these two classes is approximate, as the values fall on a continuum with 1 representing perfect replacement of channel by vegetation and 0 representing all channel narrowing occurring prior to all vegetation establishment. Values of i greater than 1 indicate channel narrowing only after vegetation had established on the floodplain or terraces.

While low values of i suggest that vegetation did not contribute to narrowing processes, i values of 1 are more ambiguous, with two end member explanations. First, in a system where narrowing is caused by something other than vegetation, the vegetation could colonize bed area as it is being abandoned, rather than after a time interval. Seedlings would colonize wetted areas which had previously been reworked every year with any plants being uprooted, but which now remain stable as that channel elevation is abandoned, permitting the vegetation to mature. Alternately, i values of 1 would also be generated if vegetation colonized the channel areas immediately prior to an extended period without flooding that was long enough to permit the vegetation to grow to the point that future floods could not

dislodge them, as described by Hereford (1984) and Friedman *et al.* (1996). In the first explanation vegetation does not drive narrowing, while in the second it does. In both cases the possibility of a time lag between the establishment of vegetation and its visibility on aerial photographs would affect photo interpretation and thus the value of i . But because the maximum lag between plant germination and visibility that we calculated was 20 years, and because vegetation which establishes in patches, which is generally the case, would be visible much sooner, we believe our i estimates are satisfactory. In any case, we found many reaches with $i = 1$, and if the visibility lag were affecting our analysis we should not have seen any.

In our study area, channel narrowing is linked to incision, whereas other researchers have found vegetation establishment and channel narrowing to be linked to floodplain aggradation (Hereford, 1984, 1986; Allred and Schmidt, 1999; Birken and Cooper, 2006). Excavations across four transects of Canyon de Chelly found that sediment thickness above the germination point of the vegetation was 7.7 ± 0.8 cm (mean \pm standard error) in reach #8, 7.7 ± 0.6 cm in reach #10, 6.4 ± 1.3 cm in reach #12 and 30.6 ± 3.7 cm in reach #23 (Reynolds, 2009). This evidence favours the first interpretation of i values near 1, that vegetation took advantage of incision to colonize channel areas as they were being abandoned, because we would expect greater aggradation around the vegetation in the second interpretation. Hereford (1984) observed 2–5 m of floodplain accretion, and Allred and Schmidt (1999) observed 2 m of accretion above tamarisk germination points in the narrowing reaches they studied. In contrast, Friedman *et al.* (1996) observed a maximum of 30 cm of deposition above the germination point on abandoned channel surfaces which had formed during a phase of narrowing and incision which they attributed to flood induced bed level fluctuation, although they did credit the vegetation with stabilizing the surface. If vegetation took advantage of incision to colonize abandoned channel areas in Canyon de Chelly, vegetation removal may destabilize the new surfaces, but will not necessarily result in a return to the previous bed elevation.

We observed a dramatic increase in the rate of vegetation establishment beginning after the 1975 photo set (Figure 6). Vegetation visible prior to 1975 was dominated by cottonwood, but vegetation that established post-1975 was dominated by tamarisk and Russian olive. A tree ring analysis of tamarisk and Russian olive in transects in reach #8, 10, 12 and 23, and of cottonwood throughout both canyons, support our findings (Reynolds, 2009). They found that most tamarisk and Russian olive established neither immediately after introduction in the 1930s, nor immediately after dam construction in 1965, but rather in the 1980s. A search of the canyons for extremely large tamarisks found

7 individuals that established prior to 1965. The cottonwood age distribution, in contrast, has two major peaks, one in the 1940s and one extending from the 1980s to present. We were not able to distinguish the contribution of cottonwood to recent mixed vegetation establishment in the air photos, but this does confirm our observation of widespread pre-1964 cottonwood establishment. The years 1941–1945 and 1983–1989 had relatively high frequencies of large precipitation events (Figure 11) which could have provided the substrate necessary for tamarisk and cottonwood establishment. Even if the channel had already begun to incise, these floods could still have inundated areas that were no longer active braided channel, enabling vegetation establishment in locations that would afterward be isolated from flooding by continued incision. This is one mechanism by which vegetation that requires inundation for germination could establish, yet escape removal by subsequent flows.

A major finding that we did not anticipate was that the channel narrowing occurred earliest in the uppermost reaches of the study site and progressed farther downstream in each subsequent photo set. This could be analogous to the final phase of complex channel response to a base level drop observed in flumes by other researchers (Lewis, 1944; Schumm and Parker, 1973), in which a knickpoint migrated upstream, partially re-aggrading downstream reaches as it rejuvenated the tributary network, followed by downstream migrating entrenchment as the tributaries came into equilibrium with the new base level and ceased to supply heightened sediment loads.

The narrowing in Canyon de Chelly could equally be a channel response to reduced sediment loads, potentially caused by dramatic herd size reductions beginning in 1930s. Sediment delivery to the canyons may have been at elevated levels during the 19th and early 20th centuries as a result of the high intensity grazing practiced on the Navajo Reservation. A range survey of the reservation conducted in 1930 estimated the total number of Navajo sheep at 1.3 million, about twice the capacity of the land, and a soil survey in 1933 estimated that 70% of the land area had been seriously eroded because of over grazing (Parman, 1976: pp. 22, 37–38). Navajo herds have grazed the upper catchment of Canyon de Chelly, especially the Chuska Mountains, since the mid 1700s, with the exception of the years 1864–1868 when the tribe was held at Fort Sumner (Savage, 1991). Herd sizes on the reservation are estimated to have exceeded 1 million sheep in 1880–1900 and 1910–1934 (Savage, 1991). The forced herd reductions of the 1930s traumatically altered Navajo pastoral culture, and the herds have never since exceeded the estimated carrying capacity of the reservation of 500 000 sheep (Savage, 1991; McPherson, 1998).

If narrowing is driven by sediment load reduction, this would explain why reach #1–7 did not incise in spite of some

narrowing. Lower Canyon del Muerto (reach #27–31) is still braided and delivering sediment to the junction, although if the channel is in fact responding to reduced sediment load, the conversion of the braided channel to a meandering channel in Canyon del Muerto will eventually reach the junction and progress into these lowermost reaches.

Although this analysis suggests that vegetation is not driving channel narrowing, vegetation does affect bank strength and thereby channel morphology. Pollen-Bankhead *et al.*, (2009) found that tamarisk roots at study sites in reach #10 and 12 contributed an average of 2.5 kPa of additional cohesion throughout the bank profile, while Russian olive added 3.2 kPa of cohesion on average. Their bank models suggest that this additional cohesion significantly increases bank stability and reduces bank failure frequency. If tamarisk were not present, then reach #8–14, the reaches that are most incised and dominated by tamarisk, would presumably be more like reach #15–23, which are dominated by cottonwood and are less incised (Jaeger, 2009) and slightly wider (7.7 m wide compared to 6.7 m wide on average).

It is unknown how old a plant must be before it effectively stabilizes sediment during high flows typical of Canyon de Chelly rather than being dislodged, although stand age should be a predictor of stability (McKenney *et al.*, 1995). The geomorphic effectiveness of vegetation depends on the balance between the erosive force of a given flood and the resistive force of the root network of the vegetation. One potential weakness of air photo analyses of riparian vegetation is that a time lag may exist between the age when vegetation is geomorphically effective and when it is visible on aerial photographs. Geomorphic effectiveness may occur before, at, or after plant visibility on aerial photographs, and this likely varies between riparian species, and will certainly depend on the magnitude of floods that occur.

Our aerial photographic data set had several shortcomings which we have worked to minimize. First, the time gaps between photographs are long in several instances. If channel narrowing occurred prior to vegetation establishment, and no photograph set was available for the intervening period, we could not differentiate the events. Also, knickpoints may have been initiated and migrated beyond the study area in the time period between photographs. Second, the 1964, 1975 and 1989 photograph sets do not cover parts of the canyon, contributing to the time gaps between photographs in these locations. A full analysis of the 1992 and 1997 aerial photographs would have helped in some locations, but it would not address the important gap between 1935 and 1964 and the lower resolution of the 1992 and 1997 photographs could have reduced digitizing accuracy. The corroboration of our findings by tree core data (Reynolds, 2009) suggests that in spite of these

shortcomings, the data adequately document the major changes in the canyons.

CONCLUSIONS

The portions of the present channel within Canyon de Chelly and Canyon del Muerto that are incised correspond with the areas that have switched from a braided to a meandering planform. This channel conversion has generally progressed in a downstream direction, although narrowing occurred throughout the canyons, even in reaches that remain braided. Narrowing began prior to widespread local vegetation establishment, particularly in the uppermost reaches. This indicates that the channel was unstable prior to the invasion by tamarisk and Russian olive. In the middle reaches, where the channel became single-threaded after 1981, channel area loss was simultaneous with and equal in magnitude to vegetation establishment. We also observe deep incision and minimal sedimentation around the vegetation in these middle reaches, suggesting that it is more likely that vegetation established as channel area was being abandoned, or in floods soon thereafter, rather than establishing on continuously active braided channel areas and forcing narrowing. The drivers of incision and vegetation establishment are likely to be a complex interaction of factors, potentially including reduced sediment supply from land use changes, variation in flood frequency or magnitude, river regulation and delayed response to a prior base level change. Although exotic vegetation does not appear to have initiated narrowing and incision, it does stabilize the abandoned channel surface and maintains steep banks that result in a very narrow channel planform, possibly exacerbating incision. This study demonstrates that an understanding of the historical context of channel change in semi-arid region streams should inform management decisions, and that a relative timing index to compare the timing of vegetation and channel change is a useful way to gain additional insight.

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