LATE HOLOCENE FLOODING ON THE ESCALANTE RIVER, SOUTH-CENTRAL UTAH

by

Robert Howard Webb

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As members of the Final Examination Committee, we certify that we have read the dissertation prepared by ROBERT HOWARD WEBB

entitled LATE HOLOCENE FLOODING ON THE ESCALANTE RIVER, SOUTH-CENTRAL UTAH

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of DOCTOR OF PHILOSOPHY.

Victor R Baker	12 April 1985
	Date
Allan J Melvin	4/12/85
	Date
Charles W. [illegible]	April 12, 1985
	Date
Raymond M Turner	April 12, 1985
	Date
Margaret S. Peterson	April 12, 1985
	Date
[illegible]	April 12, 1985
Paul S. Martin	April 12, 1985

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Victor R Baker	12 April 1985
Dissertation Director	Date

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SIGNED: Robert H. Webb

DEDICATION

This dissertation is dedicated to a pair of exceptional individuals who greatly aided in the field work required for the completion of my Ph.D.

KATRINA VON YOCUM, CD
aka "Katie, Waterdog of the Escalante"

and

KLAUS VON YOCUM, CD
aka "Klaus, the Wonderdog"

May we have many more field seasons together.

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TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

TABLE OF CONTENTS--Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS--Continued

LIST OF ILLUSTRATIONS--Continued

LIST OF TABLES

ABSTRACT

The late Holocene flood history and associated channel changes were reconstructed for the Escalante River in south-central Utah. Analyses of flood deposits at 8 sites in the bedrock canyon indicate that the frequency of large floods was at a maximum 1100 to 900 yrs BP and in historic times in a 2000 year record. The largest flood occurred approximately 900 to 1000 yrs BP and was 7 times the largest flood recorded at a gaging station. The paleoflood discharges were close to the "maximum expected flood" derived from a regional flood envelope curve, and the 100-yr flood was increased 220% to 800 cubic meters per second (cms) with the addition of four historic flood discharges. Possible nonstationarity in the distribution due to channel changes and climatic shifts reduced the reliability of statistical flood-frequency analyses. The additional parameters of the "largest recorded flood" in 2000 years of paleoflood record -- 720 cms -- and the "maximum expected flood" -- 1180 cms -- were added to the flood-frequency summary.

Channel changes in the upstream alluvial channel were related to flood-frequency changes. Valley-margin stratigraphy representing 1600 years of deposition indicated

that after 1100 yrs BP, a time of increased frequency of large floods, a marshy floodplain was converted to a dry, fire-swept meadow and an arroyo 24-m wide and 2.5-m deep formed. This arroyo quickly filled with sediments between 500 and 400 yrs BP and a smaller channel then formed and persisted until settlement of the basin. Floods between 1909 and 1940 transformed the small channel into an arroyo up to 100-m wide and 17-m deep.

The cause for flood-frequency and consequent channel changes on the Escalante River is complicated. Land-use practices caused pronounced changes in watershed and floodplain conditions. A subtle shift in climate increased the amount of summer precipitation and intensity of storms. The inability to test either the land-use practices or climatic shift hypotheses independently precludes the determination of a regional cause for arroyos.

CHAPTER 1

INTRODUCTION

River channel change has been a major economic and environmental problem in the southwestern United States. After settlement of the region in the mid- to late-1800's, most ephemeral and small perennial rivers incised their floodplains during floods, creating vertical-walled channels known locally as arroyos (Bryan, 1925). This geomorphic change created severe economic and social problems, ranging from destruction of agricultural and range lands and water supply systems to loss of ecologically valuable riparian habitat (Leopold, 1921). Many townsites were eventually abandoned (Carr, 1972), and the remaining towns had to adjust to the conditions imposed by the new channels (Chidester and Bruhn, 1949; Carroll, 1960; Larson, 1957).

The Escalante River in south-central Utah (fig. 1) provides an example of the influence of large floods on channel change and the initiation of arroyos. This river flows in bedrock-controlled channels for most of its length, but is an alluvial channel for its first 35 kilometers upstream of Escalante, Utah. Large flood events are associated with the formation of an arroyo in the early 1900's and can be traced to specific storm events. The

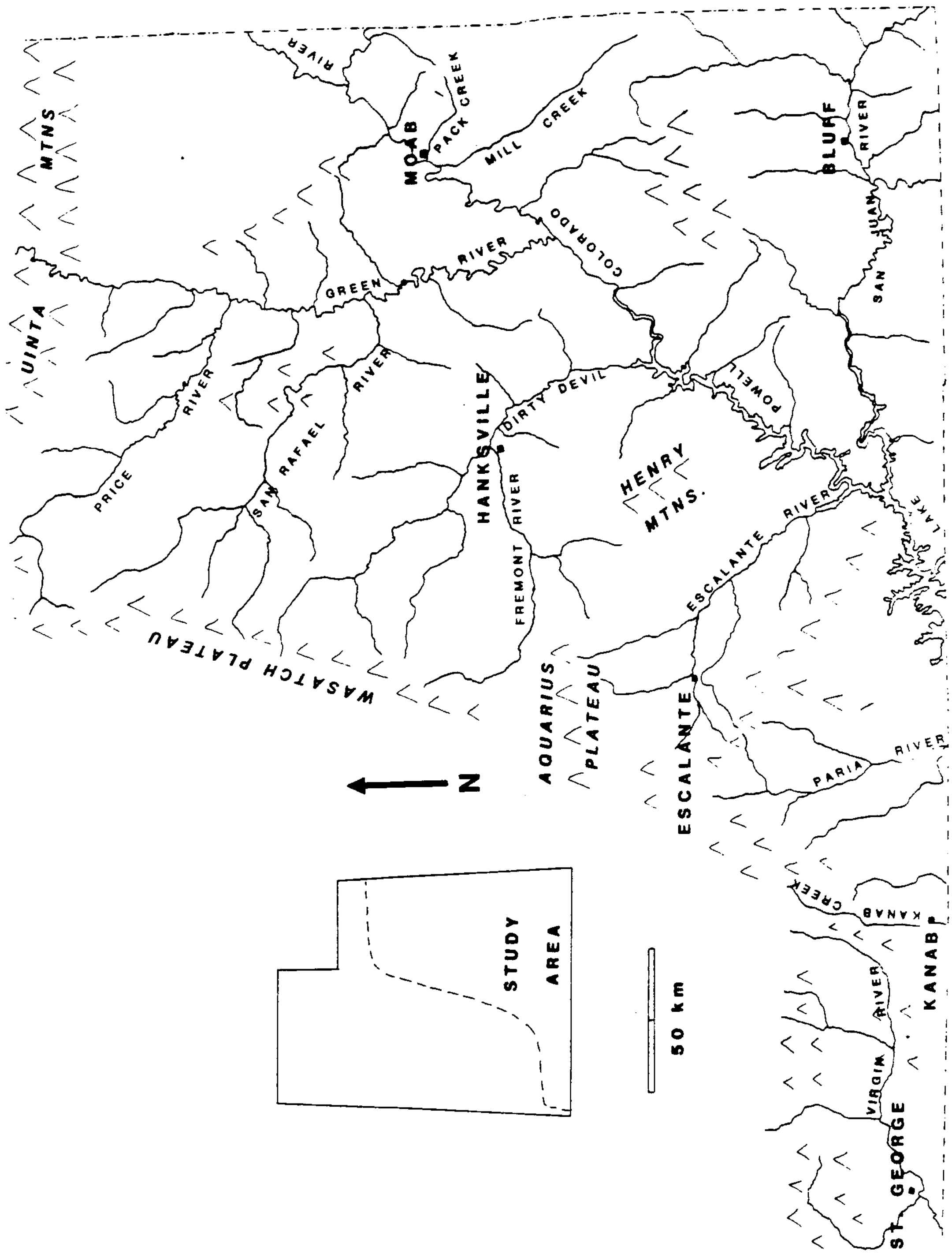


FIGURE 1. Map of southern Utah showing the principal drainage basins.

purpose of this study is to determine changes in prehistoric and historic flood frequency on the Escalante River, and to relate these changes with the formation of paleochannels and the modern arroyo. Flooding on a regional scale will be examined to determine possible regional climatic explanations for floods. The results will be used to address the problem of a regional cause for arroyos in southern Utah.

Historic Floods and Channel Change in Southern Utah

Floods are intimately linked with the initiation of arroyos on every river in southern Utah. This region is particularly suited for reconstruction of historic flood events and their effects because historical records date from settlement in 1857 (e.g. Larson, 1957) and most towns were built on floodplains. Each river system appears to have an independent chronology of flood events and channel changes, but descriptions of the events indicate that in every case the flood was of exceptional size. In discussions of these floods, environmental changes brought about by land-use practices are usually blamed for causing the floods (e.g. Stewart, 1924). A list of historical floods in southern Utah appears in Appendix 1.

The Virgin River

Three winter floods of approximately the same magnitude have caused extensive channel change on the Virgin

River in the last 120 years. The Virgin River in 1852 had low banks, a narrow channel lined with willows and cottonwoods, and a broad floodplain suitable for agriculture. The valley was settled between 1854 and 1857, and construction of irrigation works and floodplain agriculture began immediately (Gregory, 1945).

During late December and January, 1861-2, rain fell for 43 days in southwestern Utah. The Virgin River crested on January 8, destroying the settlement at Grafton (Reid, 1964). The flood on Mill Creek near Washington destroyed a large lumber and grist mill and transported parts 8 km downstream on January 18 (Larson, 1957). The Santa Clara River crested on January 17-18 and February 3-4, destroying Fort Harmony (Reid, 1964). The recently settled towns of Tonaquint, Adventure, and Harrisville were destroyed, and Price City and Heberville, below the confluence of the Virgin and Santa Clara Rivers, were covered by more than a meter of gravel, sand, and silt (Reid, 1964; Carr, 1972). The Virgin River degraded 4 m and widened for many kilometers above its junction with the Santa Clara (Reid, 1964), and the Santa Clara River was transformed into an arroyo 150 m wide and 10 m deep (Bailey, 1961). Channel incision initiated during the 1862 flood progressed headward until 1870, when headwater channels were reportedly incised (Bailey, 1935).

Pioneers were continuously rebuilding irrigation dams and canals along the Virgin River, only to have them destroyed as many as several times a summer. Large floods occurred in July, 1883, and July 4, 1884, the latter causing extensive erosion of agricultural lands as the river widened (Larson, 1957). A pile dam was designed and built to withstand the summer floods and provide irrigation water in 1885-9. However, large floods completely destroyed the newly finished dam on December 7 and 15, 1889. These floods reportedly crested approximately 0.7 m higher than the 1862 flood (Larson, 1957), and caused extensive bank erosion.

An intense, regional storm caused a basin-wide flood on the Virgin River on December 6, 1966 (Butler and Mundorff, 1970). The storm also caused flooding in California, Nevada, and Arizona (Cooley and others, 1977), but not in other Utah drainages. Precipitation for the period of December 3-7 exceeded 280 mm in the mountainous headwaters, but was only 37 mm at St. George. The Virgin River at Virgin crested at 646 cms on December 6, or 1.7 times the second largest flood in the 64-year record (Butler and Mundorff, 1970). The channels of the Virgin and Santa Clara Rivers shifted laterally, causing extensive erosion of channel banks and destruction of roads and buildings.

Kanab Creek

Kanab Creek underwent the most spectacular channel change of any river in southern Utah during the 1880's. The town of Kanab, meaning "willows" in Paiute, was settled next to an essentially flat, marshy drainage in 1870 (Davis, 1903; Gregory, 1950), "so small that one could easily step across it" (Carroll, 1960). Dellenbaugh (1962) noted a headcut 13 km downstream in 1872. Irrigation ditches were built in the floodplain starting in 1870 (Carroll, 1960), and native vegetation was removed for agriculture by 1874 (Gregory, 1950). A cloudburst broke a short drought of several years in 1882 and transformed an irrigation ditch into a 3-m deep arroyo near Fredonia, Arizona (Carroll, 1960). On July 29, 1883, a thunderstorm caused a large flood on Kanab Creek, leaving an arroyo 17 m deep and nearly 30 m wide (Davis, 1903; Woolley, 1946; Carroll, 1960). This event, known locally as "the Great Washout" (Carroll, 1960), eroded a large amount of agricultural land and destroyed irrigation and domestic water supply dams. Additional floods resulting from snowmelt on March 12, 1884, and April 12, 1886, and a storm prior to September 10, 1885 (Woolley, 1946), eroded the channel further.

Paria River

A large snowmelt flood initiated an arroyo on the Paria River in the spring of 1884. The Paria River valley was permanently settled in 1871, and the towns of Cannonville, Paria, Rockhouse, and Adairville were built along the river in the following decade. Rockhouse and Adairville were largely abandoned by 1878 due to flooding

(Gregory, 1945), although a few individuals apparently remained. The winter of 1883-4 was unusually severe, and runoff from a rapidly melting snowpack, probably accelerated by spring rainfall, caused extensive flooding in March, 1884. A headcut present at Rockhouse from 1867-1870 rapidly eroded upstream, causing abandonment of Adairville and Rockhouse (Chidester and Bruhn, 1949). The townsite of Paria was damaged to the extent that half of its population left (Gregory and Moore, 1931), and was mostly abandoned by 1885 (Gregory, 1945). The Paria River was transformed into a wide, braided stream with few alluvial terraces (Gregory and Moore, 1931). Erosion brought the headcut upstream to Cannonville by 1886, where one third of the agricultural land was lost by 1890 (Gregory, 1945; Chidester and Bruhn, 1949). Paria was finally abandoned after 1912 due to continued flooding (Carr, 1972).

Fremont River

Flooding in 1896 caused extensive channel change on the Fremont River (Graf, 1983a). Settlers first arrived in the Fremont River valley in 1875 (Snow, 1977), and built towns along the lower Fremont after 1883. Irrigation ditches were built starting in 1876, with extensive water development in the 1880's and early 1890's (Snow, 1977).

During the late summer of 1893, a "huge" flood occurred on Bullberry Creek west of Teasdale, leading to extensive erosion on that drainage. However, the main channel of the Fremont, a shallow, perennial stream in 1893, remained unincised until 1896 (Hunt and others, 1953; Graf, 1983a), when a large flood on September 22 widened and deepened the lower reaches. The storm causing the flood was regional and orographic in nature; all the towns in the area received 25-50 mm of rainfall or less on September 22. However, Moab in eastern Utah received 127 mm in 24 hours and stations in Colorado reported 68 mm in 24 hours on September 22-23. The towns of Caineville, Giles, and Hanksville were severely damaged when shifting channels destroyed bridges, eroded agricultural lands, and cut into the channel floodplain. Giles and Caineville were abandoned after a flood in 1909.

Bull Creek, a small tributary to the Fremont River at Hanksville, also became incised due to flooding (Everitt, 1979). Two large floods occurred between 1932 and 1935 and changed a "shallow channel" into a 5-m deep arroyo for a 2.4 km distance, with a headcut at the upstream end. However, Everitt (1979) found dendrochronological evidence for discontinuous arroyo incision along Bull Creek starting about 1850.

San Juan River and Tributaries

Floods along the San Juan Rivers and tributaries have created hardships for the inhabitants of Bluff, Utah, since 1883 (Gregory, 1945). Bluff was settled in 1880 after the famous Hole-in-the-Rock Trail immigration (Perkins and others, 1957). Almost immediately, floods damaged houses and irrigation works. The San Juan crested on March 16, 1884, due to "excessive rains", and destroyed fields and shifted its channel. A second flood on Cottonwood Wash buried fields and destroyed houses on June 8, 1884 (Perkins and others, 1957). Gregory (1938) blamed agricultural clearing and grazing for much of the damage. Many of the recently arrived settlers moved to other, more stable communities after the 1884 flood and ensuing floods of 1885-6.

The 1884 flood was succeeded by major floods in 1909 and 1911 (the former to be discussed in the next section). On October 4-5, 1911, more than 200 mm of rainfall fell in 24 hours on the San Juan Mountains. The San Juan River at Bluff crested at 2410 cms on the 7the, and channel changes occurred along the entire length of the river (Brandenburg, 1911). Miser (1924) reports evidence of flood stages as high as 16 m above normal in the narrowest part of the San Juan canyon, presumably resulting from this flood.

An intense cloudburst on August 1, 1968, caused extensive flooding on two tributaries to the San Juan at Bluff. On the morning of August 12, a severe thunderstorm struck the headwaters of Comb and Cottonwood Washes, causing a large volume of runoff from already saturated drainages. Over 165 mm of rain fell in 24 hours in the Abajo Mountains, with record 5-minute intensities of 150 mm/hr (Butler and Marsell, 1972). Cottonwood Wash crested at 1200 cms at Bluff, destroying bridges and flooding the town. This flood caused extensive erosion and channel changes along Comb and Cottonwood Washes.

Pack and Mill Creeks

Pack and Mill Creeks near Moab, Utah, underwent considerable channel change in the 1890's. Moab was settled in 1879, and, like other southern Utah settlements, irrigation ditches were built and livestock grazing began immediately (Tanner, 1976). The floodplain of Mill and Pack Creeks was covered with large sagebrush and grass "belly-high to a horse." The channels of the creeks were deep and narrow enough that "one could step or lay fence planks across them" (Tanner, 1976).

A large flood on September 22, 1896, completely changed the channels of both Mill and Pack Creeks (Tanner, 1976). Moab received a record 127 mm of rainfall in 24 hours after a wet summer, and the creeks crested 3 m above their former channel beds. Both creeks deepened and widened reportedly to three times their former widths (Tanner, 1976).

Channel knickpoints developed during flooding in the late 1800's apparently did not reach the headwaters until the early 1900's. The first flood causing damage to the headwaters of Pack Creek occurred between 1902 and 1905

(Tanner, 1976). However, flooding between 1918 and 1920 caused tremendous erosion and prompted the La Sal National Forest to close the area to grazing in 1920. At Moab, a large flood on Mill Creek crested on August 2, 1919, destroying an electric power plant and damaging bridges, houses, and agricultural land (Tanner, 1976). Although floods have occurred periodically on Mill and Pack Creeks since 1920, the floods of 1896 and 1919 caused the largest amount of channel change in the vicinity of Moab.

Regional Flooding in 1909

In late August and early September, 1909, a mid-latitude low-pressure system moved west to east across southern Utah causing regional flooding. The storm stalled over south-central Utah on August 31 and September 1, causing extensive flooding on Kanab Creek and the Virgin, Paria, Escalante, Fremont, San Rafael, and Price Rivers. Roads were reportedly eroded in places into ravines 1-6 m in depth (Thiessen, 1909). The flood was "the greatest flood in the history of the county" for the Virgin River (Woolley, 1946), although it probably did not exceed the 1862 or 1889 floods. The 1909 flood on Kanab Creek, reportedly more damaging than the 1883 flood (Gregory, 1945), destroyed a 17-year-old flood control and water supply dam (Carroll, 1960). The Escalante River entrenched 1 m and changed its channel, necessitating relocation of a gaging station

(U.S.Geological Survey, 1910). Flooding along the Fremont River destroyed the towns of Caineville and Giles (Carr, 1972) and further eroded the arroyo which formed in 1896. The Price River had the largest flood in its gaging record, and towns adjacent to tributaries of the San Rafael reported severe damage (Woolley, 1946). By September 2, the storm moved eastward to the San Juan River drainage, causing extensive channel changes and destruction of bridges (Freeman, 1909). This is the only known regional flooding which can be attributed to a single storm in southern Utah.

Causes of Channel Change in the Southwest

The regional causes proposed for the formation of arroyos can be grouped into six general categories (table 1). The combination of livestock grazing and climatic fluctuations in the period of 1880 to 1900 is the most widely accepted cause (Butzer, 1976; Dunne and Leopold, 1978). However, the chronology of proposed causes (table 1) reveals that a consensus has not been achieved on a regional cause (Graf, 1983b), and a review of the literature reveals problems with all the proposed causes.

Human Land-Use Practices

Human land-use practices and its hypothesized influence on initiating arroyos are widely cited as the cause for arroyos. The introduction of livestock grazing and utilization of floodplains for agriculture caused, in

TABLE 1. Chronology of research publications on the cause of arroyos in the southwestern United States (partially after Graf, 1983b).

Year	Human Impacts and Livestock Grazing	Climatic Change or Fluctuations	Livestock Grazing and Climatic Change	Large Floods	Intrinsic Geo-morphic Processes	Uncertain Cause
§1900		Dutton (1882)				
1900		Johnson				
1901						
1902	Dodge					
1903				Davis		
1904						
1905						
1906	Hough					
1907						
1908		Barrell				
1909						
1910	Thornber					
1911	Rich					
1912				Dellenbaugh	Dellenbaugh	
1913		Visher				
1914		Huntington	Huntington			
1915						
1916						
1917			Gregory	Gregory	Gregory	
1918	Duce					
1919						
1920		Visher				
1921	Leopold					
1922		Bryan				
1923	Ross					
1924	Miser		Miser	Reagan(2), Stewart		
1925		Bryan				
1926	Swift, Winn					
1927						
1928		Bryan	Bryan			
1929	Hoover	Bryan				
1930	Hoover					
1931			Gregory and Moore	Gregory and Moore		
1932						
1933						
1934	Bailey and others					
1935	Bailey					
1936	Brady, Leighly			Brady		
1937	Cooperrider and Hendricks, Colton			Senter		
1938	Gregory, Knechtel			Woolley and Alter		
1939		Hack	Albritton and Bryan			

TABLE 1. Chronology of research publications on the cause of arroyos in the southwestern United States (partially after Graf, 1983b) (continued).

Year	Human Impacts and Livestock Grazing	Climatic Change or Fluctuations	Livestock Grazing and Climatic Change	Large Floods	Intrinsic Geo-morphic Processes	Uncertain Cause
1940	Cottam and Stewart		Bryan			
1941	Calkins, Thornthwaite and others, Bailey		Bryan	Thornthwaite and others		
1942	Thornthwaite and others	Hack		Thornthwaite and others	Thornthwaite and others	
1943						
1944						
1945		Richardson	Richardson			
1946				Woolley		
1947						
1948						
1949						
1950	Peterson			Gregory		
1951		Leopold, Leopold and Snyder	Leopold	Gregory		
1952	Antevs, Marston	Judson	Antevs, Judson			
1953				Hunt and others		
1954		Leopold and Miller	Bryan			
1955						
1956		Hunt, Leopold and Miller				
1957		Quinn			Schumm and Hadley	
1958		Miller and Wendorf				
1959				Hastings		
1960						
1961						
1962		Cooley				
1963		Martin, Smith and others				
1964		Bull, Schoenwetter and Eddy				
1965	Melton			Hastings and Turner		
1966		Leopold and others		Tuan	LaMarche	Tuan
1967			Denevan			
1968		Haynes				
1969						
1970		Campbell			Born and Ritter	
1971						
1972				Mosley, Burkham		
1973					Schumm and Parker, Schumm	Cooke and Warren
1974		Cooke, Emmett	Emmett			
1975					Patton and Schumm	

TABLE 1. Chronology of research publications on the cause of arroyos in the southwestern United States (partially after Graf, 1983b) (continued).

Year	Human Impacts and Livestock Grazing	Climatic Change or Fluctuations	Livestock Grazing and Climatic Change	Large Floods	Intrinsic Geo-morphic Processes	Uncertain Cause
1976		Leopold	Butzer		Schumm	Cooke and Reeves
1977	Womack and Schumm	Hall		Malde and Scott, Cooley and others	Womack and Schumm, Parker	Malde and Scott
1978		Leopold	Dunne and Leopold			
1979	Graf, Cooley	Leopold and Bull, Euler and others	Mabbutt	Love	Schumm	
1980	Masannat	Reider, Love		Love		
1981	Dobyns				Patton and Schumm	Burkham
1982	Alford					
1983		Hereford		Graf(2)	Bullard, Boison	Wells and others, Love
1984			Hereford		Schumm and others	
1985					Boison and Patton	

Publications are listed by author according to the date of publication. Categorization of authors' conclusions is subjective for several publications.

many cases, rapid changes in watershed and floodplain conditions. Livestock grazing caused severe changes in vegetation, notably reduction in grasses (Dutton, 1882). Floodplains were cleared of vegetation, and irrigation canals and roads were constructed parallel with the existing channels. Channels deepened and coalesced in most localities after settlement, indicating a strong association between human-induced changes and arroyos (Graf, 1979; Cooke and Reeves, 1976).

The introduction of large-scale livestock grazing in the late 1800's has been the most invoked cause for the initiation of arroyos (Cooke and Reeves, 1976; Graf, 1983a; see table 1). Livestock compact soils and reduce the cover of watershed vegetation, thereby inducing increased flood discharges, increased sediment yields from hillslopes, and consequent channel changes. However, livestock were introduced into many areas as early as the 1700's, and large herds were present in New Mexico by 1820 with no associated channel changes (Denevan, 1967). The influence of livestock in increasing runoff is clearly dependent upon the amount of grazing, yet arroyos have apparently formed independent of grazing pressure. Also, the amount of vegetation change caused by grazing is probably exaggerated for many areas (Leopold, 1951a; Hastings, 1959).

Irrigation canals and construction of roads in floodplains are important factors causing channel initiation

(Bailey, 1935; Tuan, 1966; Cooke and Reeves, 1976). Removal of floodplain vegetation and the creation of roads perpendicular to floodplain contours lead to decreased hydraulic roughness (Melton, 1966), concentration of discharges (Cooke and Reeves, 1976), increased peakedness of flood hydrographs, and increased tractive forces (Graf, 1979). The effectiveness of floodplain changes in initiating arroyos is dependent upon the occurrence and size of floods in the watershed, and thus is not independent of climatic effects.

Climatic Fluctuations

Climatic fluctuations in the 1880's and 1890's have been hypothesized as the regional cause for arroyos in Arizona and New Mexico. A late 1800's drought has been associated with the initiation of modern arroyos in New Mexico (Bryan, 1940) and Arizona (Hack, 1942), and drought has been proposed as the cause for paleoarroyos (e.g. Leopold and Miller, 1954). The proposed climatic effects include shifts to wetter conditions (Huntington, 1914); shifts to drier conditions (Bryan, 1928); global warming and cooling (Leopold, 1976); and changes in summer rainfall intensities (Leopold, 1951b; Cooke, 1974). The model usually applied for any climatic hypothesis involves the role of precipitation in regulating vegetation cover and its ability to retard runoff and erosion.

Most of the climatic models can be refuted through a rigorous examination of precipitation and/or tree-ring records. Wet and dry cycles occur in precipitation records (Cooke and Reeves, 1976) and tree-ring records (Rose and others, 1982) prior to and after the initiation of arroyos, indicating that the period of 1880-1900, wherein most modern arroyos formed, was not unusual in terms of annual conditions. Changes in the intensity of summer rainfall is a possible cause if the changes can be demonstrated quantitatively. As Cooke and Reeves (1976) note, point rainfall records, the only available data, are not necessarily representative of rainfall over the entire watershed or regional patterns. However, the lack of seasonality in regional channel change would suggest that analysis of seasonal rainfall intensities is not necessarily applicable.

Climatic Change and Grazing

Livestock grazing and climatic change combined are a possible regional cause for arroyos although neither hypothesis alone is compelling. In this combination, grazing was the "trigger-pull" which initiated changes that would have eventually resulted from climate change alone (Bryan, 1940; Leopold, 1951b). However, this combination does not eliminate problems with each separate hypothesis, and its basis appears to be the association of both a late

1800's drought and the introduction of grazing with the initiation of arroyos.

Large Flood Events

The association of floods with arroyos has been a long-observed yet neglected explanation. Large flood events are often linked with initial downcutting (Graf, 1983a) and channel changes (Burkham, 1972, 1981; Graf, 1983c). The size of the flood is often "the largest in the history of the county." Floods as a cause for arroyos are inextricably linked with climatic-based causes, because factors responsible for generating floods are fluctuations in frequency and intensity of seasonal precipitation (Leopold, 1951b; Cooke, 1974). However, floods in Utah appear to be random in time and space (Woolley, 1946). The frequency and intensity of storms may not have changed (Thornthwaite and others, 1942), supporting the argument that land-use practices are responsible for increased peak discharges and channel change (Stewart, 1924). The question of the relationship between floods and climate is debatable because no quantitative study has been made linking flooding to regional climatic factors or climate change.

Intrinsic Geomorphic Factors

The dynamics of sediment transport within drainage basins has been used to explain the initiation of arroyos independent of climate or land use. Sedimentary processes associated with ephemeral rivers, not climatic changes, are responsible for deposition and erosion of alluvium in semiarid climates (Thornthwaite and others, 1942). Headcuts begin at "critically oversteepened" valley sections (Hadley and Schumm, 1957), where tributary additions have increased the local stream gradient past a "critical threshold" (Patton and Schumm, 1975). Discontinuous channels form and may behave independently of other sections of the same stream (Patton and Schumm, 1981). Local perturbations, such as land-use practices, can hasten coalescence. Intrinsic geomorphic processes alone or in combination with land-use practices or climatic fluctuations can lead to channel incision (Schumm and others, 1984).

Intrinsic geomorphic factors, termed "complex response" (Schumm, 1973) due to lack of synchroneity of events and "equifinality" (Cooke and Reeves, 1976) of different processes, are caused by the discharge and flood-frequency regimes of semiarid drainages. Thornthwaite and others (1942), for example, stress the importance of sequences of heavy storm events in determining channel morphology. Patton and Schumm (1975) use drainage-basin area as an index of potential discharge. Schumm (1979) expressed his concept of geomorphic thresholds in terms of floods eroding a decreasingly stable valley floor without a channel which eventually would have incised into channels without the flood. Intrinsic geomorphic factors are useful explanations for the mechanics and spatial variation in arroyos, but do not necessarily explain the initiation of arroyos without the extrinsic factor of floods.

Complex or Uncertain Cause

The complexities of semiarid region fluvial systems has led several researchers to conclude that a regional cause for the initiation of arroyos cannot be determined. Burkham (1981) notes that future channel changes cannot be predicted for rivers in arid and semiarid regions because of incomplete knowledge of the sequence of flood events and sediment transport rates. Cooke and Reeves (1976) concluded that each individual arroyo may have been initiated by a unique set of factors. The initiation of arroyos in New Mexico had an uncertain cause because of complex grazing and climatic histories and lack of detailed information (Tuan, 1966). The lack of detailed land-use and climatic data, principally livestock distribution and amounts and storm intensity data, combined with an incomplete knowledge of flow dynamics and sediment transport, may preclude determination of the cause for arroyo initiation.

Previous Research in Southern Utah

Many researchers have examined aspects of the late Holocene alluvial stratigraphy and geomorphology in southern Utah. Research began with Dutton (1882) and Davis (1903), and was concentrated primarily on tectonic geomorphology of southern Utah. Gregory (1917) and Gregory and Moore (1931) were the first researchers to address the cause of regional channel change in southern Utah. Gregory concluded in numerous publications (see table 1) that floods unrelated to climate change to wet or dry conditions were responsible for arroyos (Gregory, 1917). Human-induced changes in watershed conditions were considered a major contributing factor to the channel changes.

Two conflicting hypotheses for the cause of arroyos in southern Utah were presented during the early to mid-1900's. Bryan (1925) listed the dates for entrenchment of several rivers in southern Utah, and cited a climatic shift to drier conditions as the cause. Bailey (1935), studying many of the same rivers, rejected Bryan's climatic argument in favor of overgrazing as the cause. Thornthwaite and others (1942), working in northern Arizona, presented data to reject mean-annual climatic changes as a cause, and concluded that poor land-use practices led to arroyos. Hack (1942), studying the same rivers as Thornthwaite and others, concluded that evidence of arroyos in prehistoric stratigraphy exonerated human influences and supported climatic change to drier conditions as the cause.

Recent studies have added additional causes for arroyos for consideration. Agenbroad (1975) tacitly supported Hack's (1942) conclusions in his direct correlation of stratigraphy in Grand Gulch, a tributary of the San Juan, with stratigraphy in northern Arizona. Euler and others (1979) considered cyclic changes from wet to dry conditions as the controlling factor in alluvial processes on the Colorado Plateau. Hereford (1984) concluded that periodic droughts were the controlling cause for twentieth-century channel changes on the Little Colorado River in Arizona. Boison (1983) concluded that lack of synchroneity in the alluvial stratigraphy of three tributaries of the Escalante River precluded a regional cause for channel change. Boison and Patton (1985) concluded that landslide-generated sediment pulses, with later sediment flushing, was responsible for the formation of terraces in Coyote Gulch, a tributary of the Escalante River.

As the literature review indicates, no consensus has been achieved among researchers studying the cause for arroyos on the Colorado Plateau. Opinions on the controlling factors of channel change are polarized at two, relatively extreme hypotheses. Channel change is either controlled completely by climatic fluctuations, as manifested by annual or decadal changes (e.g. Hereford, 1984), or by intrinsic geomorphic processes of sediment delivery and transport (e.g. Boison and Patton, 1985). These two hypotheses, in addition to others including land-use practices and large flood events, will be tested in the case of late Holocene channel changes on the Escalante River in this investigation.

CHAPTER 2

PALEOHYDROLOGIC RECONSTRUCTION OF FLOOD FREQUENCY ON THE ESCALANTE RIVER

Paleohydrology is a subdiscipline of geomorphology concerned with the reconstruction of fluvial events from characteristic alluvial deposits. This subdiscipline uses principles from both hydrology and geomorphology and has been used to calculate discharges for Pleistocene rivers (Birkeland, 1968; Baker, 1974), flash-flood peaks (Costa, 1983), and large pre-gaging record floods (Baker, 1984; Kochel and Baker, 1982). Flood-frequency reconstructions are based on distinctive, fine-grained sediments called "slackwater deposits" which are deposited in low-velocity or eddy zones adjacent to river channels. This method has been applied to determine flood-frequency on the Pecos River in Texas (Kochel and Baker, 1982; Patton and Dibble, 1983), the Katherine River in Australia (Baker and others, 1983), and Boulder Creek in south-central Utah (O'Connor, 1985).

The Escalante River provides an excellent setting for paleohydrologic reconstruction of flood frequency. The river flows through 135 km of bedrock canyons upstream from Lake Powell (fig. 2) which control channel width and bed elevation at high discharges. Numerous rock shelters and

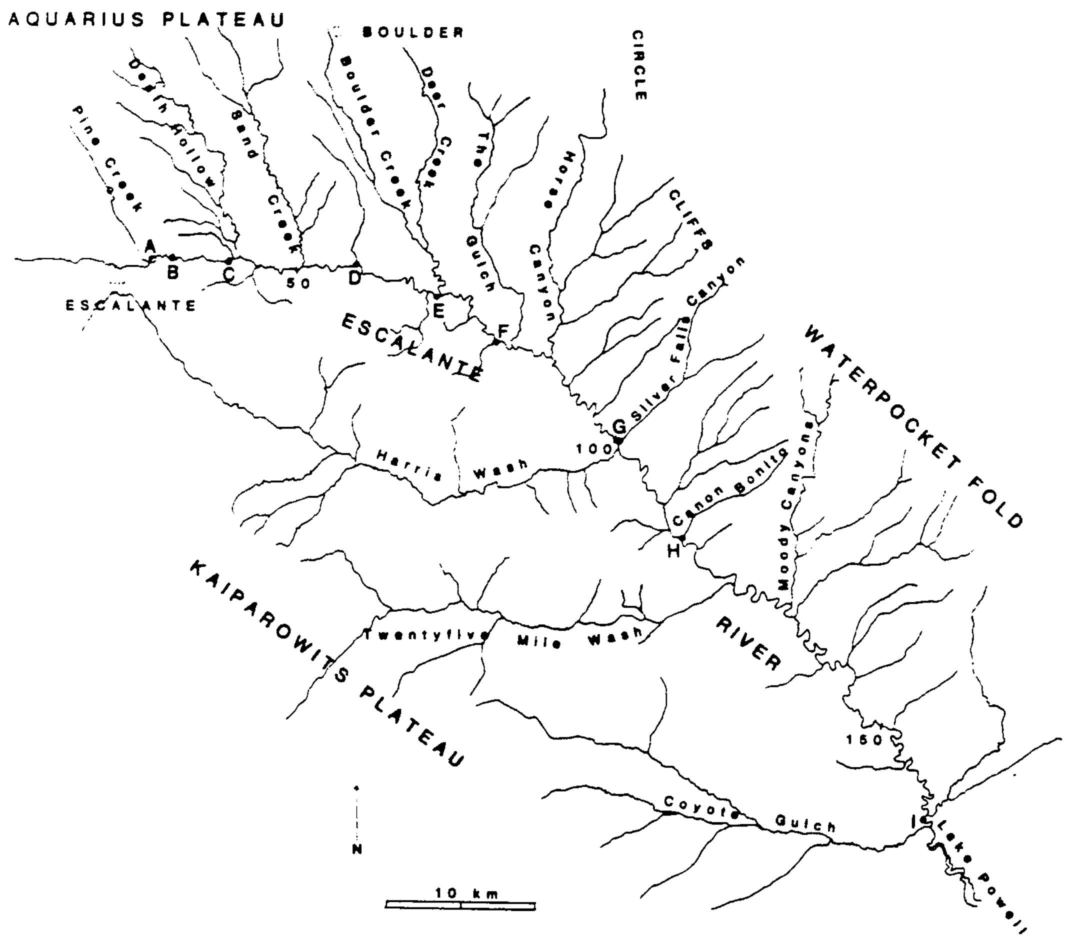


FIGURE 2. Map of the Escalante River, south-central Utah.

Numbers adjacent to the channel are river kilometers measured from the headwaters.

alcoves along the river result in channel irregularities conducive to formation of low-velocity eddy zones and protection of alluvial deposits from weathering. The semiarid climate of the drainage basin is conducive to flash-flood generation, allowing rapid formation of slackwater deposits from high sediment-concentration discharges. Flood-frequency data generated from these slackwater deposits will be used to determine hydroclimatological conditions in the alluvial channel upstream of the bedrock canyon.

The Geological and Environmental Setting

Geology and Physiography

The Escalante River is a major southeast-flowing tributary of the Colorado River in south-central Utah (fig. 2). The drainage basin, 4800 km^2 in total size, displays an incremental increase in drainage area distance downstream (fig. 3), with the largest increases at Boulder Creek, Horse Canyon, Harris Wash, and Twentyfive Mile Wash. Bounded by the Kaiparowits Plateau on the west, the Aquarius Plateau on the north, and the Circle Cliffs and Waterpocket Fold on the east, the basin is developed predominantly on Triassic to Upper Cretaceous sedimentary rocks, with Tertiary volcanic rocks capping the Aquarius Plateau (Hackman and Wyant, 1973).

The Escalante River has two hydraulically distinct channel types which are governed by the ambient geologic

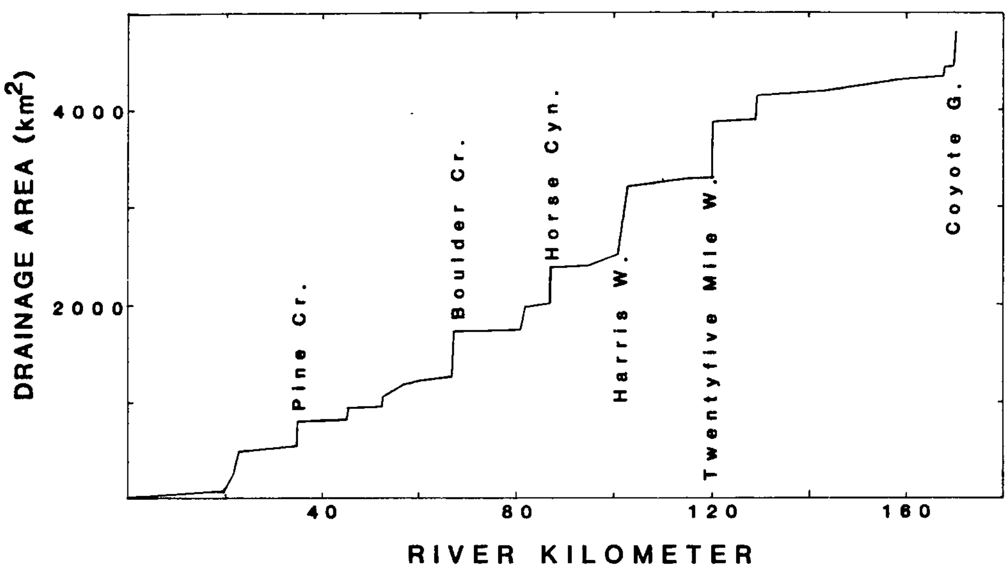


FIGURE 3. Drainage-basin area as a function of river kilometer from the headwaters for the Escalante River.

formations. Upstream of Escalante, the channel is predominantly alluvial with infrequent bedrock controls. The geology of the southern-half of the upper watershed consists mainly of Upper Cretaceous Kaiparowits Formation sandstones; Straight Cliffs sandstones, mudstones, and shales; and locally important Tropic Shale (Hackman and Wyant, 1973). These formations are easily eroded into wide valleys conducive to alluviation.

North and west of Upper Valley Creek (fig. 2), Tertiary latitic and basaltic andesite form resistant caps on the Upper Cretaceous formations. Pleistocene glaciation and periglacial conditions on the Aquarius Plateau (Flint and Denny, 1958) created U-shaped valleys with steep upper slopes controlled by the volcanic rocks. This terrain is highly susceptible to debris avalanches and landslides. Shroder (1978) reported debris avalanches occurring as recently as 1958, and Fuller and others (1981) mapped many landslides of less than 1000 years age on the flanks of the Aquarius Plateau. Debris flows originating from the landslides are a potentially important source of sediment for downstream alluvial deposits, particularly in Coyote and Willow Gulches (Boison, 1983; Williams, 1984; Boison and Patton, 1985).

The Escalante River downstream of Escalante flows through a deep canyon superposed on Triassic and Jurassic sedimentary rocks (Hunt, 1956). At Escalante, the river is incised into the Escalante monocline (Hackman and Wyant, 1973) to transform the river setting from a wide, alluvial valley to a bedrock-controlled channel in a 350-m deep canyon. The Triassic(?)-Jurassic Navajo Sandstone is the predominant bedrock control of the first 40 km of canyon, with the Triassic(?) Kayenta Formation and Triassic Wingate Sandstone appearing at river level between kilometers 45 and 60 (fig. 2). Downstream of km 75, the bedrock at river level is Wingate Sandstone with the underlying Triassic Chinle Formation at river level between kilometers 120 and 160 (Hackman and Wyant, 1973).

Several distinct Quaternary deposits have been preserved along the Escalante River due to the morphology of the canyon walls. Overhangs and alcoves, characteristic of lateral cutting in an incising river (Moore, 1926), occur at many levels on the nearly vertical walls. Alluvial terraces or remnants occur throughout the canyon, but are relatively sparse downstream of Harris Wash (fig. 2). Sand dunes migrating across the nearly level plateau above the river fall into the canyon and are preserved as slides against the canyon walls. Slackwater deposits occur sporadically in caves and alcoves, but are more commonly found perched in small cavities in the bedrock walls or in tributary mouths. Rounded basalt and andesite boulders of glacial outwash origin (Flint and Denny, 1958) form distinctive terraces along walls in the upper 100 km of the canyon. These boulders are transported by floods into the Escalante River at Pine Creek and Boulder Creek (O'Connor, 1985), creating lateral bars which decrease in particle size downstream of the tributary and merge with the finer-grained terraces.

Climate and Vegetation

The Escalante River basin has a warm, semiarid climate characterized by high variability in mean annual precipitation. Strong orographic gradients in temperature and precipitation occur: lower-elevation sites experience 12°C mean annual temperature and 250 mm or less mean annual precipitation, and the Aquarius Plateau experiences 2°C mean annual temperature and 575 mm mean annual precipitation. The mean annual precipitation at Escalante from 1902 to the present is 295 mm, with extremes of 103 mm in 1956 to 551 mm in 1927 (fig. 4).

Vegetation in the basin ranges from desert shrub assemblages to spruce-fir forests. The low desert between 1400 and 1700 m elevation is a mixture of shrublands and grasslands (Tanner, 1940). Pinyon and juniper woodland occurs between 1800 and 2300 m, and a yellow-pine, oak, and manzanita assemblage occurs between 2300 and 2700 m. The southern face and top of the Aquarius Plateau supports a spruce-fir assemblage above 2700 m. The riverine environment of the Escalante River supports dense stands of cottonwoods, willows, salt cedar, and Russian olive (Irvine

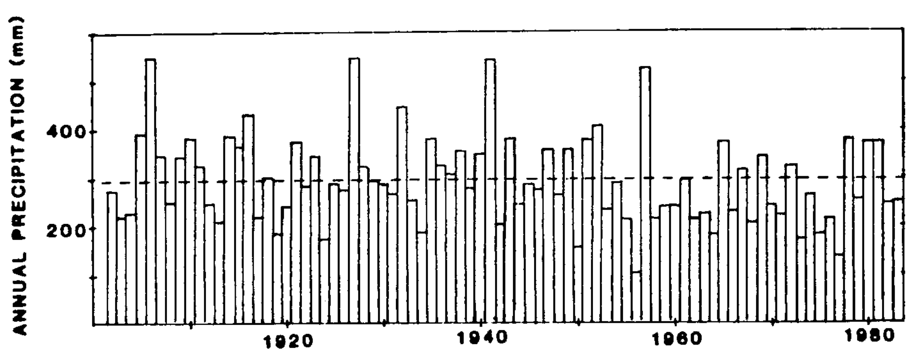


FIGURE 4. Annual precipitation at Escalante, Utah, from 1902 to 1980.

and West, 1979), the latter two species being non-native to the Colorado Plateau (Robinson, 1965) and possibly influencing hydraulics of floods (Burkham, 1976) and recent deposition on floodplains (Graf, 1978).

Prehistory and Settlement

Humans have lived in the Escalante River basin sporadically for the last two thousand years. Although few Archaic or Basketmaker sites (pre-1200 yrs BP) have been excavated in the Glen Canyon area, and none in the Escalante River basin (Jennings, 1966), occupation by these people would be expected. Evidence of later Fremont and Anasazi Indian occupation is widespread, especially near Boulder, Utah, and the Kaiparowits Plateau (fig. 1; Lister, 1964). Fremont peoples, at their most southerly limits, were living in the vicinity of Escalante and in the downstream canyons from about 1100 to 900 yrs BP. Permanent Fremont structures were built at Escalante and Boulder, indicating some stability in the occupation. The date of abandonment of these sites is not known, but probably occurred prior to 800 yrs BP.

Kayenta Anasazi migrated up the Escalante River starting about 900 yrs BP and occupied parts of the basin. The Coombs site at Boulder, where Kayenta Anasazi reoccupied a Fremont-habitation site, is the largest aboriginal village in the basin (Lister, 1964). Evidence of Kayenta visitation in the form of pottery sherds has been found throughout the basin, yet permanent habitation appears limited to the Boulder area and the Kaiparowits Plateau. Abandonment of the area occurred after 850 yrs BP, and perhaps as late as 750 yrs BP (Jennings, 1966).

Nomadic Anasazi continued to visit the basin after abandonment of the permanent structures. Although pot sherds from Hopi Indians dating after 750 yrs BP have been found, no permanent occupation structures were built (Lister, 1964). Southern Paiute Indians apparently occupied parts of the basin from about 450 yrs BP to historic times, and several Paiute families were living at Escalante at the time of Mormon settlement (Gregory and Moore, 1931).

Historic exploration of the Escalante River began in the 1860's with the influx of prospectors and trappers to the region. The first known exploration was a cavalry excursion led by Captain James Andrus in 1866 (Woolsey, 1964). An exploration party led by Jacob Hamblin traversed 80 km of the Escalante River in 1871. However, an expedition of the Powell Survey, led by Almon Harris Thompson in 1872, provided the first written accounts of the basin (Thompson, 1875). Thompson named the Escalante River, the last discovered in the conterminous United States, after Father Silvestre Valez de Escalante, the first European explorer of Utah in 1776. Details of the settlement history are given in Chapter 3.

Stream Gaging Records

The stream gaging record for the Escalante River is sparse and fragmentary (Price, 1978). The U.S. Geological Survey maintains only two stations in the drainage basin at Pine Creek and at Escalante (fig. 2). The Escalante River at Escalante has a mean annual discharge of 0.43 cubic meters per second (cms) from an 810 km^2 watershed, with a maximum recorded peak discharge of 98 cms for the 26 year record (1943-1955; 1972-1984). The log-Pearson type III flood-frequency curve (Water Resources Council, 1981) indicates a 100-year flood for this station of 200 cms (Thomas and Lindskov, 1983). The 100-year flood for the Pine Creek gage, with a record of 32 years for a drainage-basin area of 175 km^2, is only 61 cms. A recording gage on Boulder Creek near its headwaters recorded snowmelt runoff from 1951 to 1972 and is inconsequential.

Records of several discontinued gaging stations and crest-stage recorders are available for the basin. Gaging stations were present from 1951 to 1955 on Birch Creek, North Creek, Boulder Creek, Deer Creek, and the Escalante River below Coyote Gulch (fig. 2). A gaging station on the Escalante River below Coyote Gulch (4590 km^2) recorded a 410 cms flood on August 23, 1953. A gage on Boulder Creek (450 km^2) recorded a 132 cms flood on July 25, 1955. Crest-stage recorders were present from 1959 to 1974 on Deer Creek, Upper Valley Creek, Birch Creek, and Harris Wash (fig. 2).

However, this network of gages, combined with the Escalante River at Escalante, provides only a fragmentary record of flood events after 1943.

Analysis of Slackwater Flood Deposits

Methods

Eight slackwater-deposit sites were studied to quantify flood-frequency relationships along the Escalante River (fig. 2). Sites were selected on the basis of either excellent stratigraphy with multiple flood events and channel stability, or evidence of the last major flood in the canyon. Sites were surveyed with a transit and stadia rod with the exception of the Orthogonal Canyons and Silver Falls Canyon sites, which were surveyed with a tape, level, and stadia rod. Surveys were designed to carefully delineate channel irregularities creating nonuniform flow conditions with respect to emplacement of the slackwater deposits.

Discharge Calculations. Discharges were calculated using step-backwater equations (HEC-2; Feldman, 1981) and slope-area methods (Dalrymple and Benson, 1967). All measured cross sections were used in the step-backwater method, while only the two "best" sections with highwater marks were used for the slope-area method. Deposits adjacent to expected high-velocity flow, such as silt lines or slackwater deposits in certain rock cavities, were considered as representative water-surface elevations. Silt lines were measured to have elevations no higher than 10 cm above the associated slackwater deposit. The elevation of deposits in large caves or tributary mouths were considered as representative of the energy-grade-line elevation (Chow, 1959). Non-effective flow areas were eliminated from the measured cross sections for discharge calculation.

The hydraulic parameters used in the models were based on published values or estimation in the field. Manning n values were estimated using published photographs (Barnes, 1967) or tables (Benson and Dalrymple, 1967). Generally, the Manning n value for the channel of the Escalante River was considered to be 0.035 on the basis of a median particle size of about 0.4 m (Strickler's n; Chow, 1959). The expansion and contraction coefficients used were 0.3 and 0.1 for the step-backwater method (Hydrologic Engineering Center, 1982) and 0.5 and 0.0 for the slope-area method (Dalrymple and Benson, 1967). Since the use of the different coefficients could cause minor discrepancies in the discharge calculations (Motayed and Dawdy, 1979), this factor was evaluated in the study. Initial energy slopes for the step-backwater method were calculated from the elevations of silt lines and slackwater deposits, or determined through trial-and-error. The energy slope for the slope-area method was determined as the slope between the high-water marks along the channel. The discharges at all sites were subcritical, although critical depth occurred at several constrictions.

An approximate error value was assigned to each discharge calculated using the step-backwater method. The error involved in matching the calculated water-surface elevation with the known water-surface elevation (or energy-grade line) was evaluated by bracketing the discharges needed to explain all deposits or silt lines. Usually, the discharge accepted as representative of the flow evidence had a minimum error of ±40 cms, or about 5-10% of most of the calculated discharges. Variation in Manning n values by ±10% and use of different expansion and contraction coefficients did not create as much uncertainty in the calculated discharges, in agreement with the results of Dawdy and Motayed (1979). Therefore, the uncertainties involved in selection of hydraulic parameters were considered less important than the variability in elevation of slackwater deposits and high-water marks.

Radiocarbon Dating. The chronology of flood events needed for flood-frequency analysis was determined using radiocarbon dating. Radiocarbon samples were collected and stored in aluminum foil at each site and pretreated, prior to submission to a radiocarbon facility, with hydrochloric acid and sodium hydroxide to remove soluble contaminants. "Ultramodern" radiocarbon dates (younger than 1950 AD) were determined from curves presented in Linnick (1975) and Nydal and Lovseth (1983)(see Baker and others, 1985).

Radiocarbon samples were rated for association with the time of the flood event from (1) (most reliable) to (6) (least reliable) by the following criteria. (1) Flood transported organic material, primarily consisting of leaves and twigs, which would have a short residence time in the soil. (2) Charcoal from in situ burned horizons or hearths where the wood burned was of local origin. (3) Organic mats in alluvial settings which probably accumulated over many years. (4) Flood transported wood, which may be significantly older than the flood event. (5) Flood transported charcoal, which may be reworked from older sediments. (6) Organic material not in direct association with the flood deposit, but which provides an age constraint for the event. A list of the radiocarbon dates used in this study appears in Appendix 2.

The Alcove, km 38.3

Slackwater sedimentary deposits at "The Alcove" (figs. 2 and 5) provide a history of flooding along the Escalante River. At this site, the largest alcove at river level on the Escalante, flow around a 120° bend impinges on a bedrock wall causing flow separation and reverse-flow deposition under low-velocity conditions. The lowermost layer at this site is perched 2.5 m above the modern low-water surface. Nine radiocarbon dates provide excellent age control on this section, and silt lines have been preserved under the overhanging canyon walls. Pictographs on the back

FIGURE 5. Photograph of The Alcove, km 38.3 (1984).

View is upstream. Water flowing in the Escalante River impinges on the bedrock wall at far right, causing flow separation and a reverse-flow eddy into the alcove.

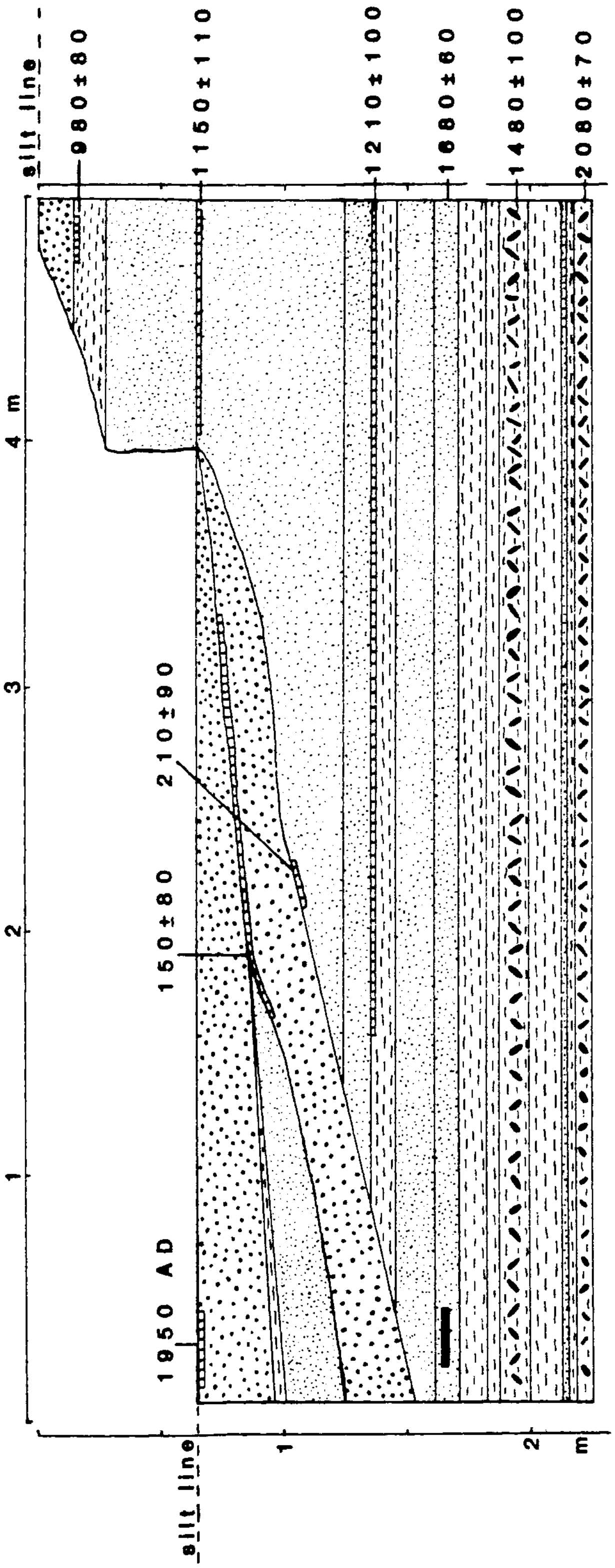
wall of The Alcove indicate visitation and possible occupation of the shelter by Kayenta or Fremont Anasazi. The Alcove is located 3.2 km downstream of the gaging station at Escalante with no intervening tributaries; therefore, any flood-frequency data derived from this site should be applicable to the gage record.

Stratigraphy. Slackwater deposits at The Alcove provide evidence for 19 floods over the last 2000 years (fig. 6). The top of the deposit is level, indicating that the sediments were deposited in a low-velocity eddy. The stratigraphy between 1.7 and 2.3 m depth suggests a period of relatively small floods on the basis of the silty, very fine sand grain-size and the thin layers (fig. 6). These layers could represent overbank sedimentation associated with a higher channel bed. Radiocarbon dates of 2080±70 (2) and 1480±100 (2) yrs BP bracket the deposition. Overlying flood layers have coarser grain-sizes and are generally thicker, and the timing of this change in deposition is complicated by a 200-year age reversal in the stratigraphy (fig. 6). The radiocarbon date of 1680±80 (4) yrs BP, on transported wood, probably represents a flood which occurred about 1300 yrs BP on the basis of the bracketing radiocarbon dates of 1480±100 (2) and 1210±100 (1) yrs BP.

Deposits higher in the stratigraphy indicate changes in flood frequency after about 1200 yrs BP. Five flood layers were deposited above the 1210 yrs BP layer (fig. 6),

FIGURE 6. Stratigraphy of slackwater-flood deposits in The Alcove, km 38.3

Coarse stippling indicates sand, fine stippling indicates fine sand, and dashes indicate silty fine sand to very fine sand. Radiocarbon dates are in ^{14}C yrs BP; see text and Appendix 2 for more information on the dates.


silt line
980±80
1150±110
1210±100
1680±60
1480±100
2080±70
4 m
3
2
1
210±90
150±80
1950 AD
silt line
1
2
m

culminating in a flood layer of sand overlying a 980±80 (1) yrs BP The highest flood layer, with an estimated age of 900 to 1000 yrs BP, has an associated silt line preserved on the bedrock wall. The floods in this sequence are generally thicker and coarser-grained than the underlying deposits, and the short radiocarbon span indicates a change in the frequency of large floods.

After a hiatus of at least 700 years, four flood deposits were inset against the older deposit after 210±90 yrs BP. Two of these deposits are massive sands with the top of the lowermost layer, eroded during subsequent floods, at approximately the same height as the highest layer (fig. 3). A silt line associated with the top layer in the inset is preserved on the bedrock wall beneath the 900 to 1000 yrs BP silt line. No resolution is available in the radiocarbon time-scale for the period of 0 to 250 yrs BP (1700-1950 AD; Stuiver, 1982), hence the most recent floods cannot be accurately radiocarbon dated and are considered "modern."

The stratigraphy of a downstream terrace deposit provides evidence for additional floods (fig. 7). A flood deposit dated at 550±90 yrs BP is sandwiched between two colluvial deposits at 90 to 105 cm depth. Two flood layers overlie the colluvium at 78 cm, the uppermost with a radiocarbon date of 430±100 yrs BP at its top. Deposition of colluvium occurred after this time, and three of the modern flood deposits are preserved in the upper 40 cm (fig.

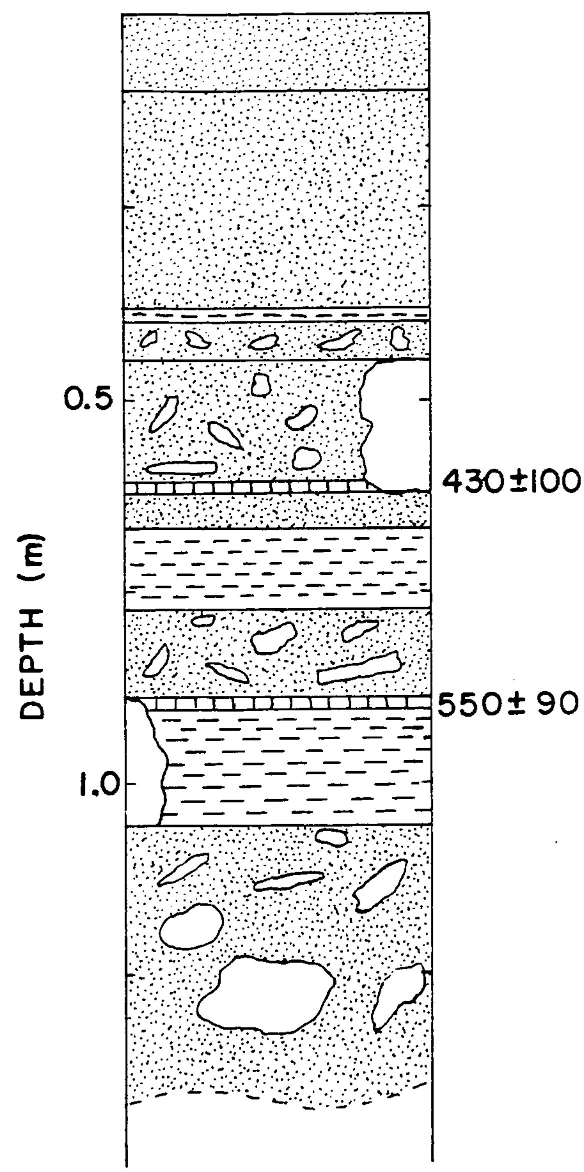


FIGURE 7. Stratigraphy of a terrace deposit 200 m downstream from The Alcove, km 38.3.

Stippling indicates fine sand, dashes indicate silty fine sand to very fine sand, and rock symbols indicate colluvium. Radiocarbon dates are in ^{14}C yrs BP; see text and Appendix 2 for more information on the dates.

7). The height of these deposits indicates the discharges for these floods were smaller than the "modern" floods.

The stratigraphy suggests a history of flooding at The Alcove. Relatively small floods occurred between about 2000 and 1300 yrs BP, with an average of about 1 flood layer per radiocarbon century. Flood frequency and magnitude increased after about 1300 yrs BP until approximately 900 yrs BP, with an average of about 2 flood layers per radiocarbon century and the largest flood in the record. Between 900 and 600 yrs BP, no floods were recorded in the stratigraphy at this site. Between 600 and 400 yrs BP, 3 smaller floods occurred with an average of 1.5 flood layers per radiocarbon century. Another hiatus occurred until "modern" times, after which 4 major floods occurred with an average of perhaps 2 flood layers per radiocarbon century. Three of the modern floods were larger than the floods which occurred between 400 and 600 yrs BP.

Discharge Calculations. Calculation of the discharges associated with the deposition of the slackwater sediments requires information concerning channel stability. Four cottonwood trees (*Populus fremontii*) growing within 1.5 m of the low-water surface were determined to be in excess of 150 years old (S. Clark, written comm., 1985), indicating that the channel morphology has been stable over that time period. No changes in desert varnish were observed on exposed canyon walls down to within 1 m of the low-water surface, suggesting an even longer period of channel stability.

Historical photographs provide additional evidence of channel stability. Jack Hillers, photographer of the Powell Survey (Fowler, 1972), photographed the Escalante River downstream of Pine Creek and the Escalante River gage in 1872 (fig. 8A). A matching photo taken in 1984 (fig. 8B) indicates that although some changes have occurred in the intervening 112 years, the channel morphology has changed very little. Ponderosa pine (Pinus ponderosa) has decreased on the floodplain and has been replaced largely by Populus. Sagebrush (Artemisia sp.) grew on the level, sandy terrace in the foreground in 1872, but was replaced by rabbitbrush (Chrysothamnus sp.) growing on a surface armored with a lag gravel by 1984. The channel has incised a maximum of 1 m, and the meander at the center midground of the photograph in 1872 (fig. 8A) had shifted approximately 3 m left by 1984; these changes may have occurred during the flood of September, 1909 (see Chapter 1). Apparently the channel of the Escalante River shifts slightly in its low-water floodplain, but the overall morphology of the channel between the bedrock walls undergoes little or no change.

The silt lines and associated slack-water deposits at The Alcove were used to calculate the discharges for the two largest flood events. Trash lines on trees and the terrace deposit (fig. 7) provided a control on the water surface 120

FIGURE 8. Photographs of the Escalante River 100 m downstream of the gaging station near Escalante, Utah.

A. Taken in 1872 by Jack Hillers (photo #670; U.S. Geological Survey Photo Library, Denver, CO). River channel is lined with *Pinus ponderosa*, occasional *Populus fremontii*, and willows (*Salix* sp.). The low-water channel is visible in the center of the photograph (A and B). The foreground terrace is sandy and covered with *Artemisia* sp.

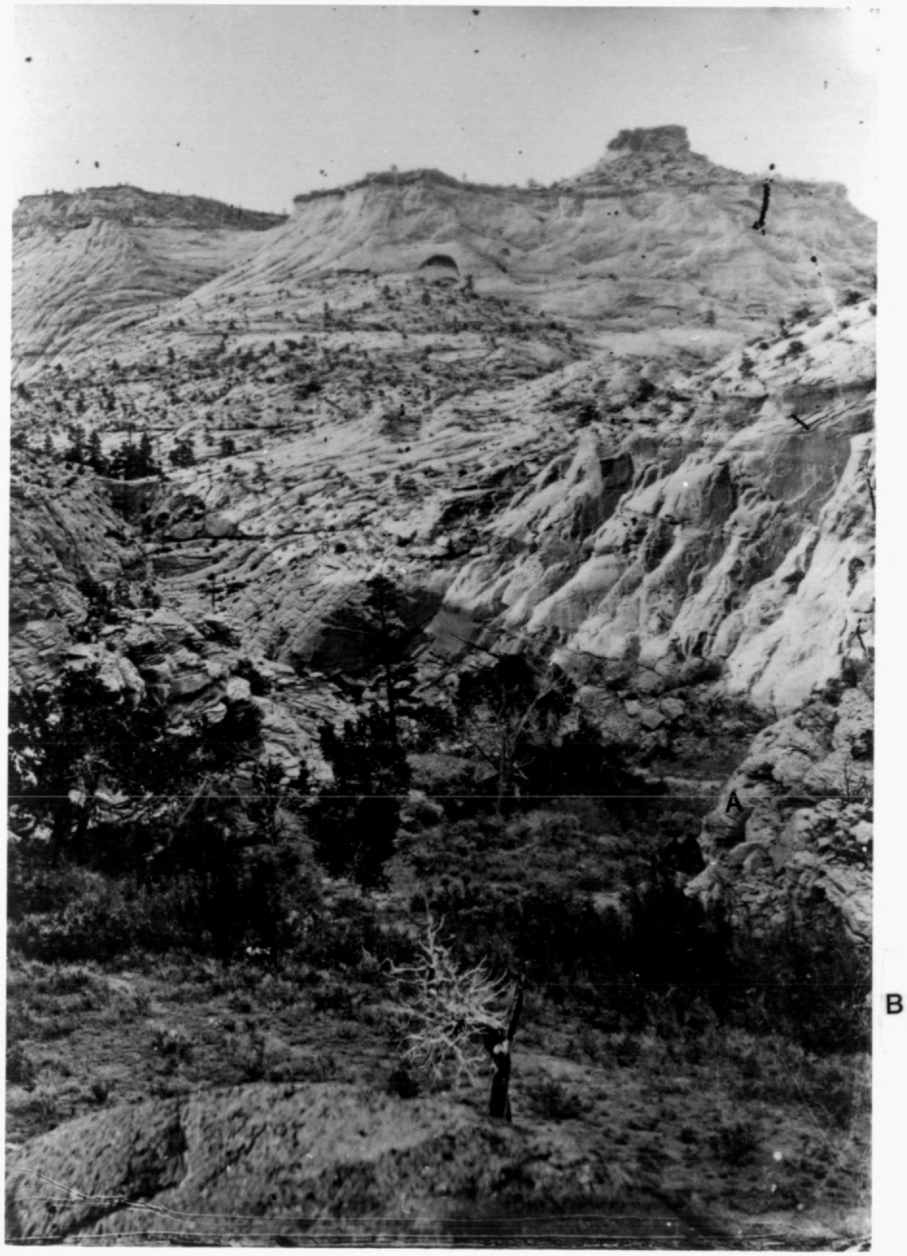
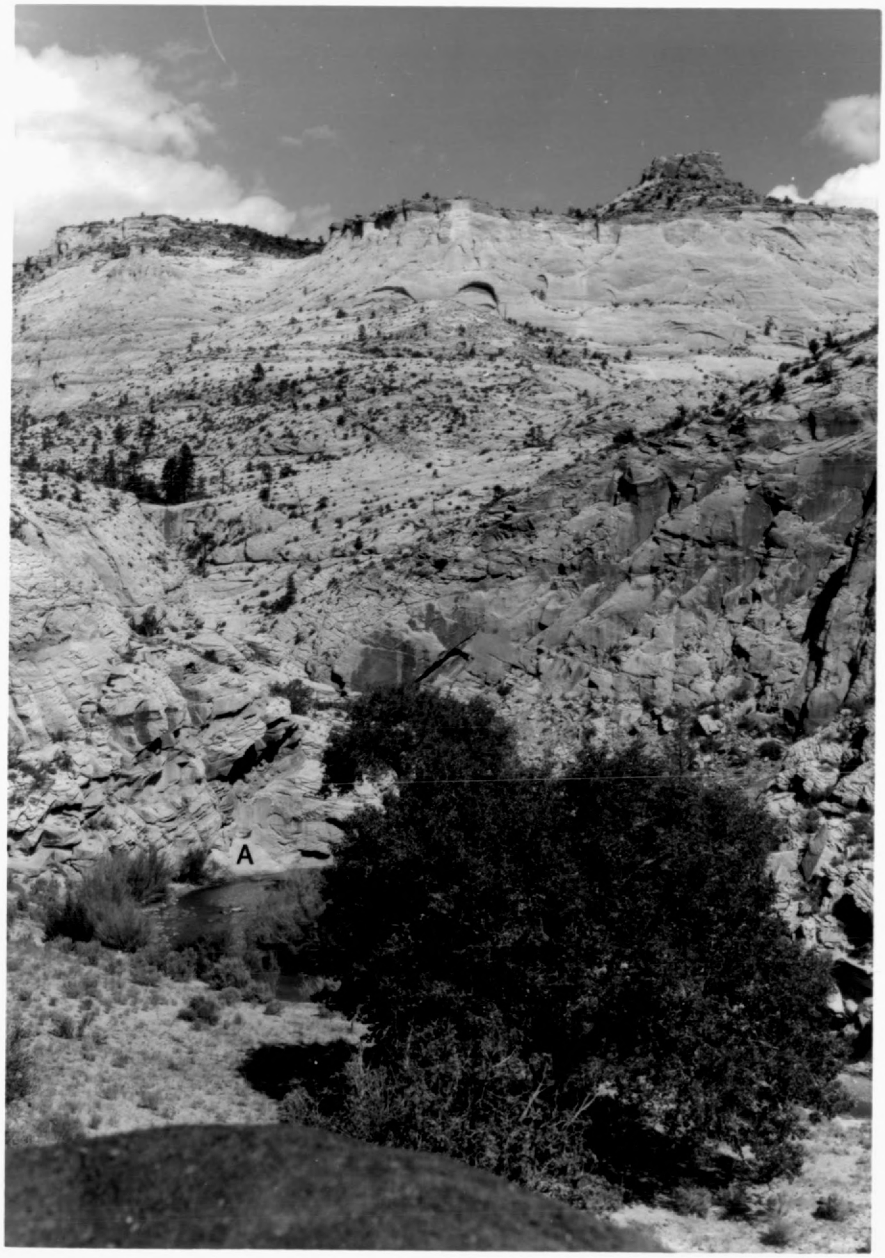

A
B

FIGURE 8. Photographs of the Escalante River 100 m downstream of the gaging station near Escalante, Utah (continued).

B. Taken in 1984 by Robert Webb. The low-water channel has incised about 1 m and has shifted to the left on the bend (A). *Populus* has largely replaced *Pinus* along the channel, and the foreground terrace is partially armored with gravel and supports *Chrysothamnus* sp.


A

m downstream, and two small slackwater deposits perched in cavities provided an upstream control. The slackwater deposit in The Alcove was assumed to represent the height of the energy-grade line. Ten cross sections were surveyed in this reach and spaced to account for channel expansions and contractions.

The step-backwater method, using a Manning-n value of 0.035, related a discharge of 600 cms to the low silt line associated with the largest "modern" flood layer (table 2). This discharge had an estimated error of ±40 cms. A stage-rating relationship was developed to estimate discharges required to deposit several of the other flood layers, assuming ±parallel water-surface profiles. The highest flood layer (900 to 1000 yrs BP; fig. 6) was deposited during an estimated 720 cms flood. The discharges for the other three "modern" flood layers were 550, 550, and 600 cms, respectively, with increasing depth in the inset (fig. 6). The slope-area method was used to calculate a discharge, based on cross sections at The Alcove and the terrace deposit 120 m downstream, of 880 cms for the largest "modern" flood layer.

Anasazi Alcove, km 42.9

A second slackwater deposit was found 5.6 km downstream of The Alcove at a site named "Anasazi Alcove." This site, on the outside of a 30° river bend, is a

TABLE 2. Details of discharge calculations at The Alcove, km 38.3.

SITE CHARACTERISTICS

Drainage Area: 803 km^2

Length of reach: 477 m

Average channel topwidth: 70 m

Average bed slope: 0.012

Number of cross sections: 10

Channel Manning-n value: 0.035

Average overbank Manning-n value: 0.035

LAST "MODERN" FLOOD (1932): Discharge: 600 cms

Number of high-water marks: 5

Assumptions: silt line and downstream terrace are water-surface elevations; slackwater deposit is an energy-grade-line elevation.

Average energy slope: 0.0048 Range: 0.002 - 0.009

Average mean velocity: 3.9 m/s Range: 2.7 - 5.5 m/s

Average Froude number: 0.55 Range: 0.38 - 1.0

Estimated error: ±40 cms

Slope-area discharge: 880 cms

HIGH SILT LINE (900-1000 yrs BP FLOOD): Discharge: 720 cms

Number of high-water marks: 1

Assumptions: ±parallel water-surface and energy-grade profile with the last "modern" flood

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contracting reach with deposition in low-velocity flow under a rock overhang at high discharges (fig 9). The Escalante River flows directly on bedrock at this site, reducing the uncertainty concerning bed elevation and channel geometry. An analysis of flooding at this site complements the results obtained from The Alcove.

Stratigraphy. The stratigraphy at Anasazi Alcove is complicated but correlative with the stratigraphy at The Alcove. The slackwater deposit (fig. 9) is separated into three distinct sections by waterfall-scour holes which are filled with recent sediments (fig. 10). The deposits greater than 1100 yrs BP are much more complicated at this site than at The Alcove because of erosional contacts, cultural disturbances (particularly in the upstream section; fig. 10), and variability in the thickness and grain-size of the deposits. The lower parts of all three sections are bracketed by radiocarbon dates of 1100±150 (6) and 2590±860 (1) yrs BP. Age reversals at the bottoms of the upstream and downstream sections (fig. 10) are caused by erosional insets against the older deposits. The deposits dated between 2600 and 1400 yrs BP are generally thinner and finer-grained than the younger deposits, although thicker, culturally disturbed layers of this age were found in the upstream section.

After 1100 yrs BP, three flood layers of fine sand were deposited in the upstream section, with the lower two containing abundant flaked rock, hearths, and bone. A large

FIGURE 9. Photograph of Anasazi Alcove, km 42.9 (1984).

View is downstream. Flow in the channel forms a backwater behind a channel contraction, leading to deposition in the bedrock underhang at left.

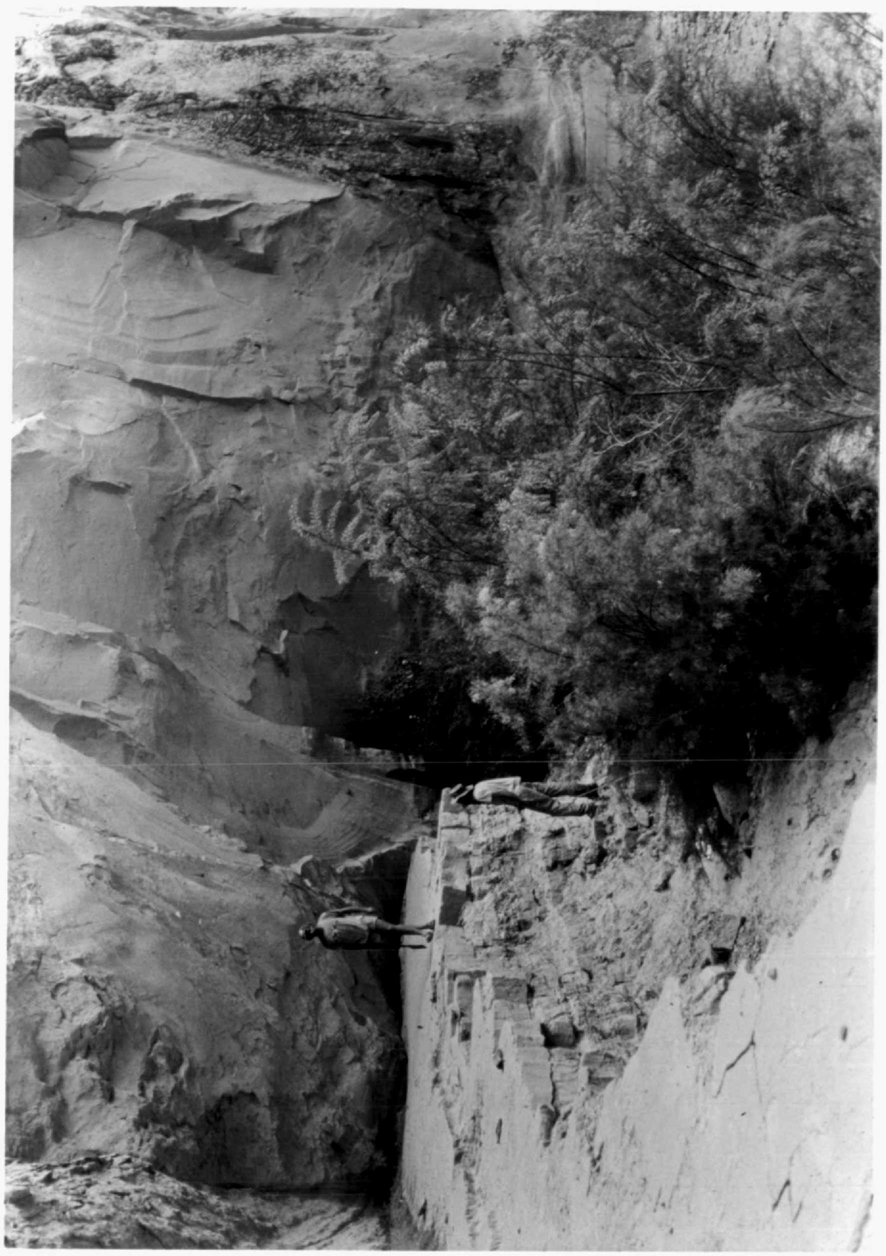
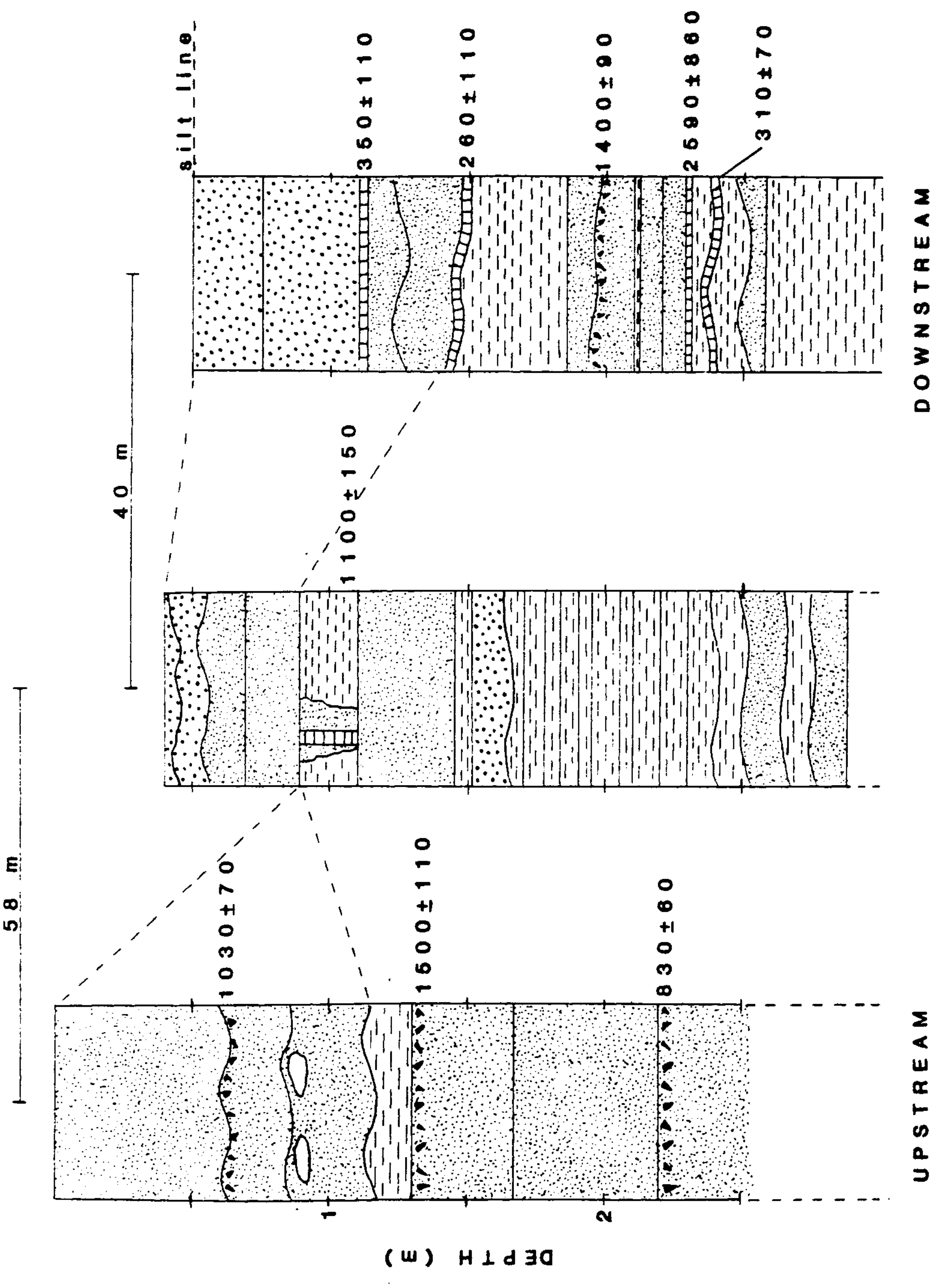


FIGURE 10. Stratigraphy of slackwater-flood deposits at Anasazi Alcove, km 42.9.

Coarse stippling indicates sand, fine stippling indicates fine sand, dashes indicate silty fine to very fine sand, rock symbols indicate aboriginal hearths, and wavy lines indicate erosional contacts. Radiocarbon dates are in ^{14}C yrs BP; see text and Appendix 2 for more information on the dates.


silt line
350±110
260±110
1400±90
2590±860
310±70
DOWNSTREAM
40 m
1100±150
58 m
1030±70
1500±110
830±60
UPSTREAM
1
2
DEPTH (m)

panel of petroglyphs is centered over this deposit. A radiocarbon date of 1030±70 (2) yrs BP indicates that perhaps two floods occurred between 1000 and 1100 yrs BP (fig. 10). The highest flood layer had less cultural material on top, suggesting that occupation was less intense than for the previous layers. This layer was probably deposited between 1000 and 900 yrs BP on the basis of the artifacts found and correlation with the highest flood deposit at The Alcove 5.6 km upstream.

Four modern flood deposits unconformably overlie the greater than 1100 yrs BP deposits in middle and downstream sections (fig. 10). These flood deposits, with a basal date of 260±110 yrs BP (1), correlate directly with the deposits at The Alcove. Cattle dung in direct association with a radiocarbon date of 350±110 (1) yrs BP (fig. 10) indicates that at least 3 of these floods were post-settlement. The fine-sand to sand grain size and morphology of these layers were distinct from the older flood deposits.

The stratigraphy at Anasazi Alcove suggests a history of flooding similar to the history developed for The Alcove. Deposits dated between 2600 and 1100 yrs BP are generally fine-grained and thin, and suggestive of variable but relatively small floods. The tops of many of the deposits contain evidence of aboriginal occupation, most likely by Fremont Indians (Lister, 1964) but possibly by earlier peoples. A flood frequency could not be estimated because numerous flood layers occur which cannot be directly correlated between sections. Between 1100 and approximately 900 yrs BP, 3 flood layers were deposited for an average of 1.5 to 2 flood layers per radiocarbon century. These deposits are culturally disturbed, with the top of the highest deposit, the largest flood event in the sequence, being least disturbed. A hiatus occurred between 900 yrs BP and 260 yrs BP, or "modern" times. Four "modern" flood layers were preserved in two sections, suggesting a flood frequency of 1.5 to 2 flood layers per radiocarbon century.

Discharge Calculations. Slackwater flood deposits at Anasazi Alcove (fig. 10) provide a direct means for calculation of discharges. The top of the deposit has a slope of 0.002, indicating the backwater surface forming behind the downstream constriction (table 3). Silt lines extending directly into the top of the highest "modern" flood layer provided an additional constraint on the water-surface profile. The step-backwater method, using a Manning-n value of 0.035, produced a discharge of 540 cms with an estimated error of ±40 cms for the largest "modern" flood (table 3). The water surface calculated from this discharge closely matched all but the furthest downstream silt line; the discrepancy in stage of +30 cm was possibly caused by changing flow conditions in the unsurveyed downstream direction past the constriction. Use of expansion and contraction coefficients of 0.5 and 0.0, respectively,

TABLE 3. Details of discharge calculations at Anasazi Alcove, km 42.9.

SITE CHARACTERISTICS

Drainage Area: 809 km^2

Length of reach: 128 m

Average channel topwidth: 48 m

Average channel slope: 0.008

Number of cross sections: 6

Channel Manning-n value: 0.035

Average overbank Manning-n value: 0.035

LAST "MODERN" FLOOD (1932): Discharge: 540 cms

Number of high-water marks: 4

Assumptions: All marks are water-surface elevations

Average energy slope: 0.003

Average mean velocity: 4.3 m/s Range: 3.6 - 5.2 m/s

Average Froude number: 0.6 Range: 0.5 - 0.8

Estimated error: ±40 cms

Slope-area discharge: 650 cms

HIGHEST DEPOSIT (900-1000 yrs BP): Discharge: 640 cms

Number of high-water marks: 1

Assumptions: ±parallel water-surface and energy-grade elevations with the 1932 flood.

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resulted in a 2% decrease in the discharge to 530 cms. In contrast, the slope-area method produced a discharge of 650 cms.

Discharges for other flood layers were estimated by the step-backwater method assuming a ±parallel water-surface profile with the largest "modern" flood. The 1000 to 900 yrs BP deposit in the upstream section (fig. 10) is explained by a discharge of 640 cms. The Discharge associated with the second highest "modern" flood layer (fig. 10) was estimated to be 490 cms. Discharges for the other flood events were not determined because the upper surface was generally an erosional contact and not representative of a water-surface elevation.

Calf Creek, km 57.5

Slackwater deposits at Calf Creek (fig. 2) provided evidence for the magnitude of the last large flood on the Escalante River. A bridge on the Escalante-Boulder highway, completed in 1940 (Woolsey, 1964), spans the Escalante River at this site. On August 21, 1947, a flood generated by as much as 100 mm of rainfall destroyed both approaches to this bridge, which was designed to be overtopped during high discharges (*Garfield County News*, August 28, 1947). The floodplain was photographed one year later by Jack Breed (fig. 11*A*; Breed, 1949). Evidently, most of the floodplain vegetation was removed, only to be replaced in ensuing years

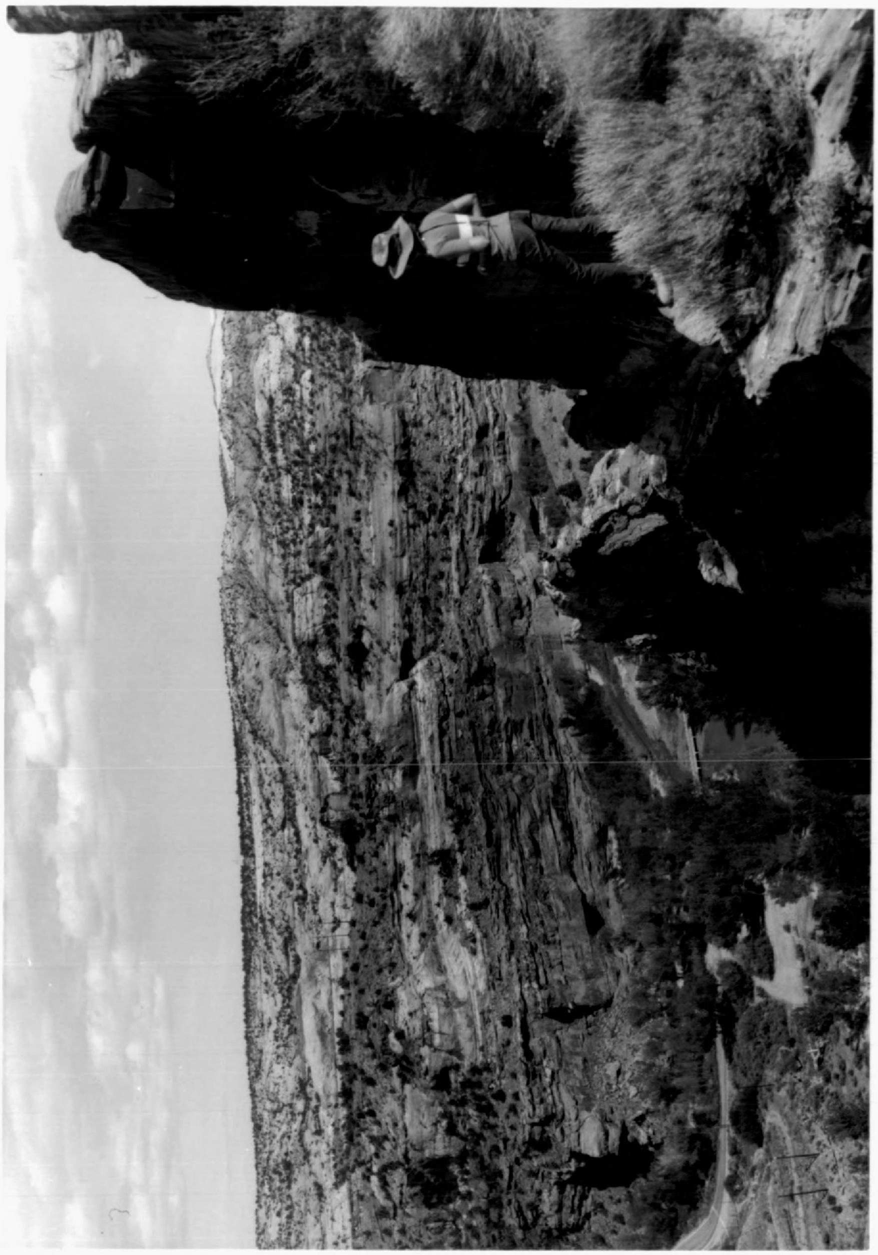
FIGURE 11. Photographs of the confluence of Calf Creek and the Escalante River, km 57.5.

A. Photo by Jack Breed, 1948 (used with the permission of National Geographic Magazine and the photographer's estate). Both approaches to the Escalante-Boulder highway bridge, built in 1940, were destroyed in a flood in August, 1947. Slackwater site is in the bedrock along the channel in midground (A).


A

FIGURE 11. Photographs of the confluence of Calf Creek and the Escalante River, km 57.5 (continued).

B. Photo by Robert Webb, 1984. The growth of floodplain vegetation, primarily *Populus*, *Salix*, and *Tamarix* masks most of the floodplain. The low-water channel has shifted slightly towards the upper left, but no major changes in channel morphology have occurred.



with *Populus*, *Tamarisk*, and *Salix* (fig. 11B). The low-water channel of the Escalante has migrated across the floodplain, but little other physical change has occurred in the 36 years between the photographs.

Small slackwater flood deposits were found along the bedrock wall at the downstream bend. These deposits, which are barely visible in the downstream river bend shown in Figure 11A, are higher in elevation than the sediments deposited on the floodplain in 1947. Evidence for only one event was preserved in the deposit with a short silt line. Two cross sections were surveyed 47 m upstream and 140 m downstream of the bridge for a slope-area calculation of the discharge. The tops of an upstream terrace and downstream slackwater deposit provided an approximate water-surface slope, and the hydraulic influence of the bridge was assumed negligible. The resultant discharge of 650 cms had an uncertainty considered to be at best ±150 cms. This flood apparently occurred before the 1947 flood and probably is correlative with the largest modern flood deposit at the Alcove and Anasazi Alcove upstream.

Arch Bend, km 66.8

High-water marks and a large slackwater deposit provide information on flooding at "Arch Bend" (fig. 2). The Escalante River at this site flows through a 120° bend into a downstream contraction 0.5 km above Boulder Creek. Flood-borne sediments were deposited in a small alcove on the outside of the bend, and additional high-water marks upstream and downstream of this deposit provided water-surface constraints for discharge calculations.

Stratigraphy. A slackwater deposit 6.45 m high located on the outside of the bend provided evidence for flooding over the last thousand years. Sediments were deposited in an unstable alcove which had a rapid rate of roof fall. A 23-cm thick flood layer capping the deposit overlies colluvium dated at 1170$\pm$60 (4) yrs BP. Four additional flood deposits of uncertain older age, separated by colluvium, underlie this colluvial layer. No discharges could be calculated for any of these floods because additional high-water marks could not be found in the reach.

Slackwater sediments from the last large "modern" flood are inset against the deposit 3.55 m below the top, and are directly correlated with other high-water marks (fig. 12). A silt line associated with this inset was at approximately the same elevation as a silt line in a cave 30 m downstream. This cave contained slackwater deposits from this flood and two additional, older floods. Another cave 160 m downstream had a silt line and a plank from a fence or house incorporated in the sediment, indicating a post-settlement age for the flood.

The stratigraphy of a terrace 2.6 m lower than the modern-flood deposit and 40 m upstream was examined for evidence of smaller floods. The deposit consisted of

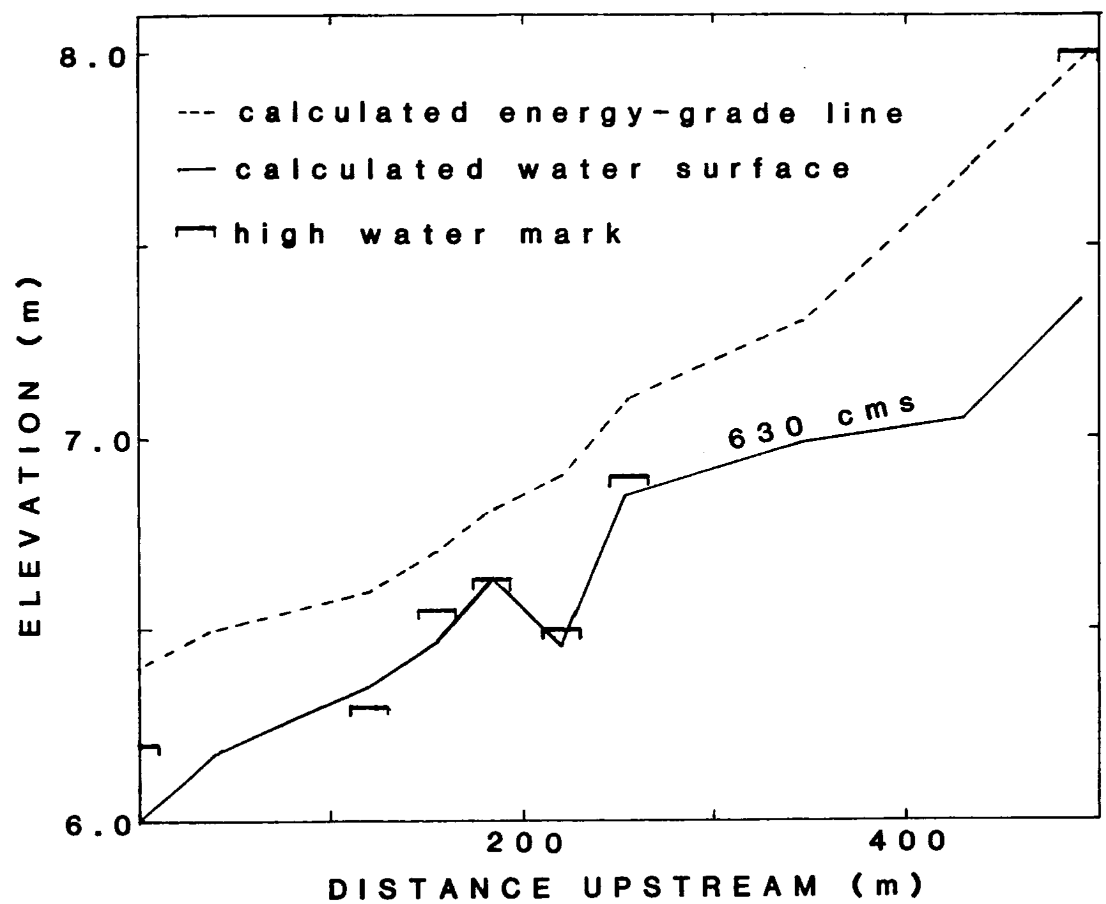


FIGURE 12. Elevations of high-water marks and the calculated water-surface profile for Arch Bend, km 66.8.

interbedded Escalante River sands, alluvial sands from a small tributary, and colluvium. An ultramodern radiocarbon date of 1958 (2) was obtained from a burned horizon at 95 cm depth below one Escalante River deposit, three tributary deposits, and one colluvial deposit. This stratigraphy suggests that more frequent, smaller floods are affecting the canyon morphology on a local scale.

<u>Discharge Calculations.</u> Eleven cross sections and six high-water marks were used in the step-backwater analysis at Arch Bend. The cross sections were subdivided into channel and overbank areas, with Manning-n values of 0.035 and 0.045-0.070 for each, respectively (table 4). A discharge of 630 cms, with an estimated error of $\pm$40 cms, was indicated by the middle three high-water marks (fig. 12). However, the discharge variation was between 610 and 700 cms as indicated by all except the furthest upstream mark. The height of this high-water mark, slackwater sediments perched in a small cavity, suggests deposition during a different flood of unknown age, or a possible energy-grade line elevation (fig. 12).

The slope-area method was used to calculate a discharge associated with the downstream high-water marks. A weighted-average Manning-n value of 0.045 was used with a contraction coefficient of 0.0. Use of marks 1 and 2 and 1 and 3 (fig. 12) in the calculations resulted in discharges of 410 and 590 cms, respectively. Variation in the Manning-

TABLE 4. Details of discharge calculations at Arch Bend, km 66.8.

SITE CHARACTERISTICS

Drainage Area: 1253 km^2

Length of reach: 490 m

Average channel topwidth: 96 m

Average channel slope: 0.004

Number of cross sections: 11

Channel Manning-n value: 0.035

Average overbank Manning-n value: 0.05 Range: 0.045 - 0.070

RECENT FLOOD EVIDENCE (1932): Discharge: 630 cms

Number of high-water marks: 7

Assumptions: All marks assumed to be the water-surface elevation

Average energy slope: 0.0019 Range: 0.006 - 0.0045

Average mean velocity: 3.9 m/s Range: 2.1 - 5.5 m/s

Average Froude number: 0.47 Range: 0.25 - 0.73

Estimated error: $\pm$40 cms

Slope-area discharge: 410 and 590 cms

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n value from 0.040 to 0.050 resulted in a range of 370 to 450 cms in discharge, and use of a contraction coefficient of 0.1 changed the discharge by less than 1%.

Orthogonal Canyons, km 78.9

Slackwater deposits and high-water marks were found around a 180° river bend at a small tributary named "Orthogonal Canyons" (fig. 2). The Escalante River in this reach is entrenched approximately 140 m into Navajo Sandstone, and vertical to overhanging walls combined with bedrock in the channel control the channel width and depth. Slackwater deposits at Orthogonal Canyons illustrate problems with radiocarbon dating of flood events and the magnitude of tributary contributions to peak discharges on the Escalante River.

Stratigraphy. Two slackwater deposits were radiocarbon dated at the Orthogonal Canyons. The first, at an alcove called "Waterfall Hollow," consisted of two Escalante River flood deposits separated by 5- to 10-cm thick tributary deposits. These deposits were emplaced under low-velocity conditions in an eddy. The upper flood layer was a massive sand 110-cm thick containing no datable material. The lower flood layer, 80-cm thick, had a thin band of transported charcoal in its center dated at 1958 AD (5).

The second slackwater deposit, located 340 m downstream, consists of four flood layers from the Escalante

River. A large rock just upstream provided enough channel irregularity to allow deposition and preservation of the deposit. The upper flood layer was a massive fine sand 128-cm thick, with no datable organic material, separated from lower layers by 20 cm of colluvium. A burned horizon at the top of the next flood layer, 10-cm thick, yielded a date of 230±100 (2) yrs BP. Two lower flood layers, 5- to 15-cm thick, were separated by colluvium. Burned horizons on each layer yielded dates of 1962 AD (2) and 1960-62 AD (2) for the upper and lower of these layers, respectively. This age reversal is difficult to explain, because the lower two flood layers did not appear to be inset against older deposits.

The uppermost layer of both of these slackwater deposits appeared to represent the last large flood which occurred on the Escalante River. Evidence for this flood was found at 5 sites around this bend, but no datable material was entrained in the layers. Conflicting radiocarbon dates of 230±100 yrs BP, 1958 AD, 1960-62 AD, and 1962 AD were obtained from underlying flood layers. Therefore, the date of this flood is uncertain and assumed correlated with the youngest flood deposits at the other sites, which were dated as "modern."

Discharge Calculations. Nine cross sections were surveyed at Orthogonal Canyons, with 5 high-water marks of varying degrees of preservation (table 5). Using Manning-n values of 0.035 for the channel and 0.040 to 0.070 for the floodplain, a discharge of 900 cms provided the best explanation for the high-water marks, with a range from 880 to 920 cms. Due to uncertainties about the quality of the survey data (compiled with level and tape), the uncertainty in the discharge calculation was considered to be ±100 cms. The slope-area method was used with a Manning-n value of 0.042 to calculate a discharge of 600 cms for the two slackwater deposits.

The Orthogonal Canyons site is 10.5 km downstream from the mouth of Boulder Creek, a major tributary (fig. 2). O'Connor (1985) found evidence for three modern floods on Boulder Creek in a reach extending 1 km upstream from the confluence. The largest two floods had discharges of 400±50 cms, while the most recent had a discharge of 300±50 cms (O'Connor, 1985). Therefore, the discharge for the last modern flood on the Escalante River at Orthogonal Canyons should be 250 to 450 cms larger than the discharge calculated at Arch Bend, assuming correlative flood events and some coincidence in the timing of peak discharges.

Silver Falls Canyon, km 101.0

Slackwater deposits in the mouth of Silver Falls Canyon (fig. 2) were surveyed and described by Peter C.

TABLE 5. Details of discharge calculations at Orthogonal Canyons, km 79.3.

SITE CHARACTERISTICS

Drainage Area: 1990 km^2

Length of reach: 530 m

Average channel topwidth: 80 m

Average channel slope: 0.003

Number of cross sections: 9

Channel Manning-n value: 0.035

Average overbank Manning-n value: 0.052 Range: 0.04 - 0.07

RECENT FLOOD EVIDENCE (1932?): Discharge: 900 cms

Number of high-water marks: 5

Assumptions: All except one mark assumed as water-surface elevation

Average energy slope: 0.0010 Range: 0.0003 - 0.002

Average mean velocity: 2.9 m/s Range: 1.8 - 4.1 m/s

Average Froude number: 0.035 Range: 0.22 - 0.52

Estimated error: ±100 cms

Slope-area discharge: 600 cms

Patton in 1979 (Patton, written comm., 1984). Patton described a stratigraphic section at this site with interlayered colluvium, tributary deposits, and Escalante River slackwater deposits. A radiocarbon date of 140±150 obtained at about 1.0 m depth indicated that at least four Escalante River flood layers were deposited in "modern" times.

The highest Escalante River flood layer, a silty fine sand, was used to estimate a discharge from a cross section measured by Patton. This unit was assumed to be the last major flood in the canyon, correlating with all the other measured sites. Using a Manning equation with an Manning-n value of 0.050, an area of 481 m^2 from Patton's cross section, and an energy slope equal to the local valley slope of 0.005 measured from a topographic map, a peak discharge of 1400 cms was calculated. Variation in Manning n and uncertainty in the energy slope suggested an error at best of ±150 cms for this discharge.

Cañon Bonito, km 112.5

A slackwater deposit in a tributary mouth and silt lines and cavity deposits downstream provided discharge information at "Cañon Bonito," an unnamed tributary (fig. 2). The channel reach was straight and representative of a gradual expansion. No obvious controls on the bed elevation were present, and the floodplain was covered with a dense growth of _Salix, Tamarisk_, and large _Populus_.

Stratigraphy. The mouth of Cañon Bonito contains a large deposit of interbedded tributary and Escalante River alluvium, capped with a 30 to 70 cm thick fine sand. This sand, of Escalante River origin, contained transported organic material radiocarbon dated at 130±130 (Peter C. Patton, written comm., 1984). A silt line associated with this deposit was preserved under an overhang and extended up Cañon Bonito to a small perched slackwater deposit. The underlying colluvium contained cattle dung, indicating that this flood was post-settlement. Small cavity fillings and a silt line preserved 350 m downstream were directly correlated with the upstream deposit and silt line.

Discharge Calculations. The step-backwater method was used to calculate a discharge based on the silt lines and associated deposits, and four cross sections at equal spacings between Cañon Bonito and the downstream silt line. The high-water marks were considered as energy-grade-line elevations because of their remoteness from the expected high-velocity zone. The calculated discharge was 2000 cms, with an estimated error of ±50 cms (table 6). The slope-area method produced a discharge of 2780 cms using cross sections and silt lines as high-water marks at the ends of the reach. The difference between the two methods was attributed to use of the high-water marks as water-surface elevations in the slope-area method.

TABLE 6. Details of discharge calculations at Cañon Bonito, km 112.5.

SITE CHARACTERISTICS

Drainage Area: 3290 km^2

Length of reach: 350 m

Average channel topwidth: 160 m

Average channel slope: 0.0031

Number of cross sections: 4

Channel Manning-n value: 0.035

Average overbank Manning-n value: 0.046 Range: 0.04-0.07

RECENT FLOOD EVIDENCE (1932?): Discharge: 2000 cms

Number of high-water marks: 3

Assumptions: All high-water marks are energy-grade line elevations

Average energy slope: 0.0055 Range: 0.0044 - 0.0066

Average mean velocity: 6.15 m/s Range: 5.29 - 6.57 m/s

Average Froude number: 0.85 Range: 0.76 - 0.89

Estimated error: ±40 cms

Slope-area discharge: 2780 cms

The discharge of 2000 cms for Cañon Bonito, the highest calculated for the Escalante River, was associated with a distinct change in channel morphology downstream of Harris Wash (fig. 2). At Silver Falls Canyon, the topography of the channel consisted of paired terraces abutting the bedrock walls, and gravel bars and narrow chute channels on the floodplain (fig. 13). Below Harris Wash, terraces were limited to sites protected by bedrock spurs, and the floodplain was wide and sandy with broad chutes. This change, apparent on aerial photography, suggests that Harris Wash contributes a large discharge to the peak discharge of the Escalante River. On the basis of the difference in peak discharge between Silver Falls Canyon and Cañon Bonito, this contribution was approximately 600 cms for the last major flood from Harris Wash.

Stevens Arch Bend, km 168.8

Large slackwater deposits and an associated silt line provided evidence for multiple flood events at "Stevens Arch Bend" (fig. 2). In this slightly curving reach (fig. 14), only 1 km above the Escalante River's terminus in Lake Powell, slackwater sediments were deposited upstream of a contraction under an overhang. A continuous silt line provided a water-surface profile through the reach, and bedrock exposed locally in the channel suggested minimal bed-elevation changes during floods.

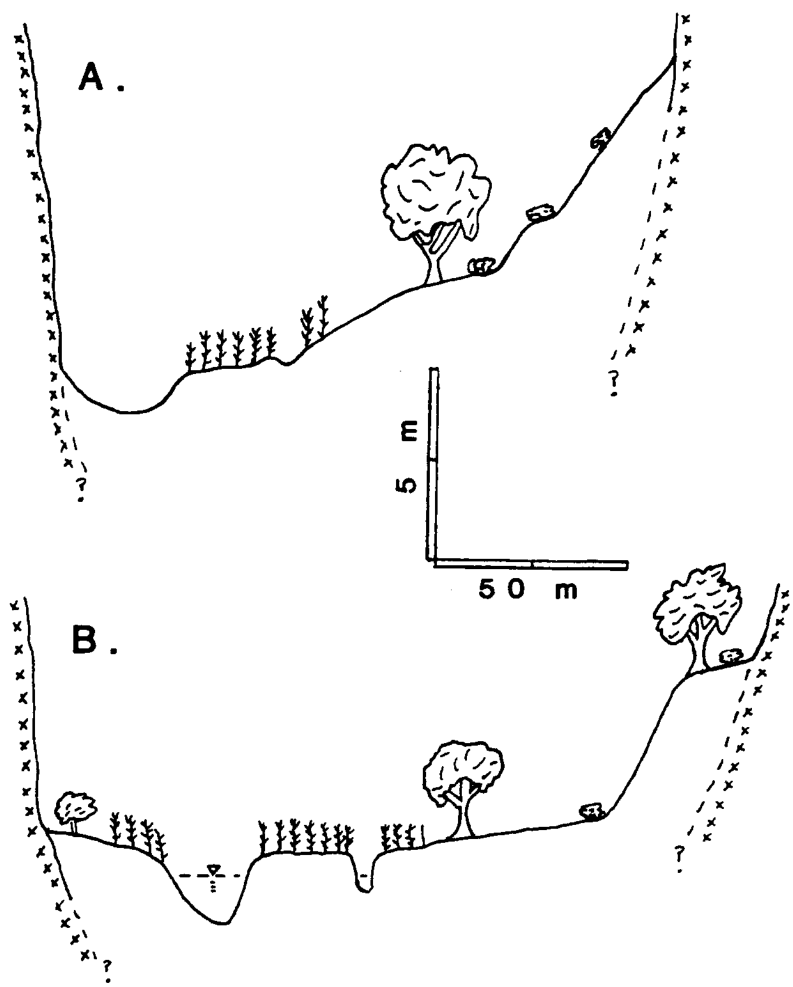


FIGURE 13. Cross sections of the Escalante River canyon.

A. At Silver Falls Canyon, km 101 (P.C. Patton, written comm., 1984).

B. At Cañon Bonito, km 112.5.

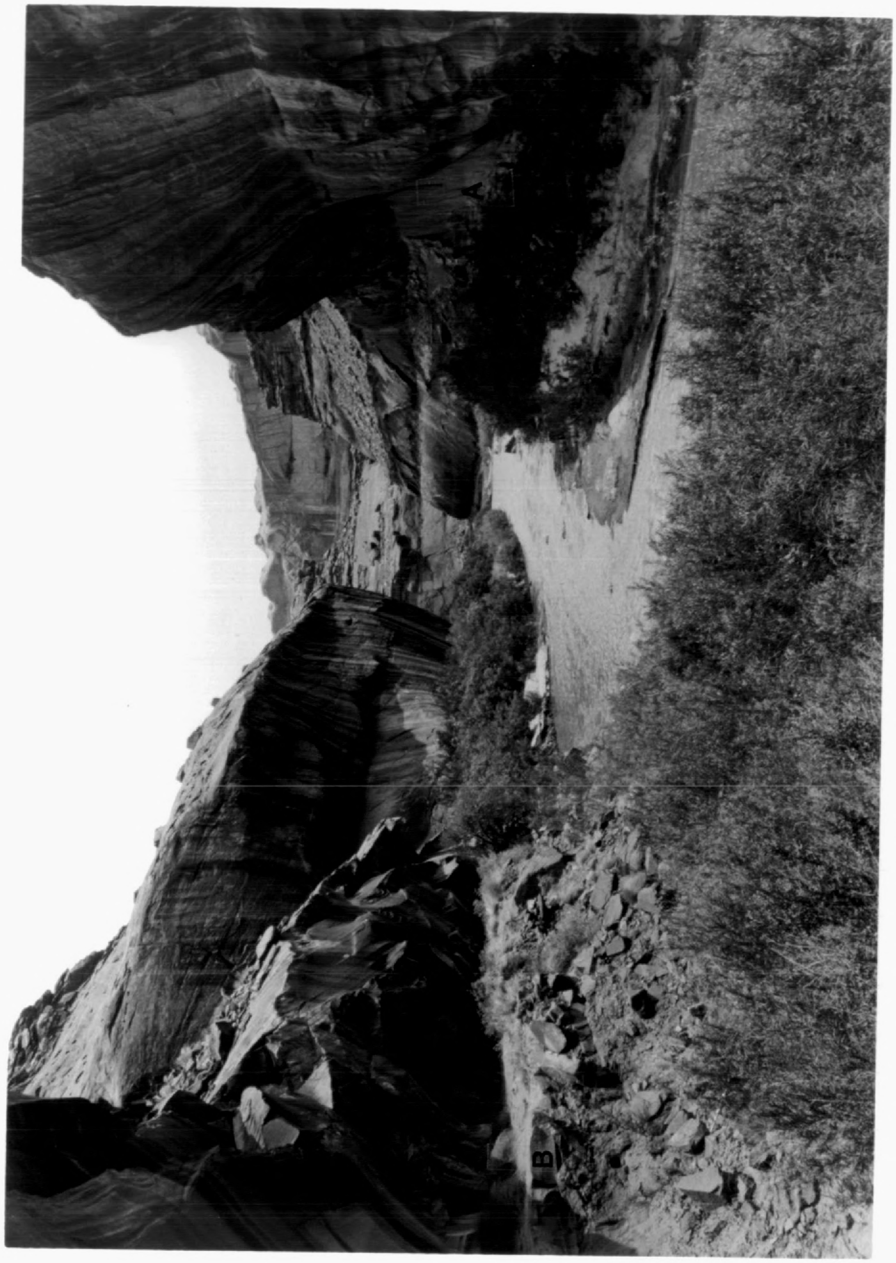

A
B

FIGURE 14. Photograph of Stevens Arch Bend, km 168.8 (1984).

View is upstream. Flow forms a backwater behind a constriction at right foreground, leading to preservation of silt lines and deposition of sediments in the overhang at right. Slackwater deposits are upstream at A and downstream at B.

Stratigraphy. Slackwater deposits at the upstream and downstream reaches provided evidence for flooding during the last thousand years. At the upstream section (fig. 15A), a prominent silt line graded directly into the top of a 97-cm thick slackwater deposit of fine sand. Oak leaves (*Quercus gambelii*) entrained in the top of this deposit were radiocarbon dated at 580±230 (1) yrs BP. This layer overlaid dune sand containing flakes of chert of probable aboriginal origin.

Sediments inset against this deposit indicate the occurrence of additional, smaller floods (fig. 15A). Four additional flood deposits lower in elevation are bracketed with radiocarbon dates of 280±120 (1) and 220±150 (1) yrs BP near the top and bottom of the section (fig. 15A). These "modern" floods were directly correlated with deposits upstream and downstream from their sedimentological characteristics and elevation above the channel. The top layer represented the last large "modern" flood at this site.

Deposits 160 m downstream represent a complex arrangement of flood layers and colluvium (fig. 15B). Four flood deposits overlie a hiatus-indicating organic mat, radiocarbon dated at 510±110 (6) and 440±120 (6) yrs BP. The lowermost of the four flood layers had "modern" (1) organic material directly entrained in it, but driftwood incorporated in the second-highest layer was dated at 400±50 (4) yrs BP. This age reversal is probably not significant

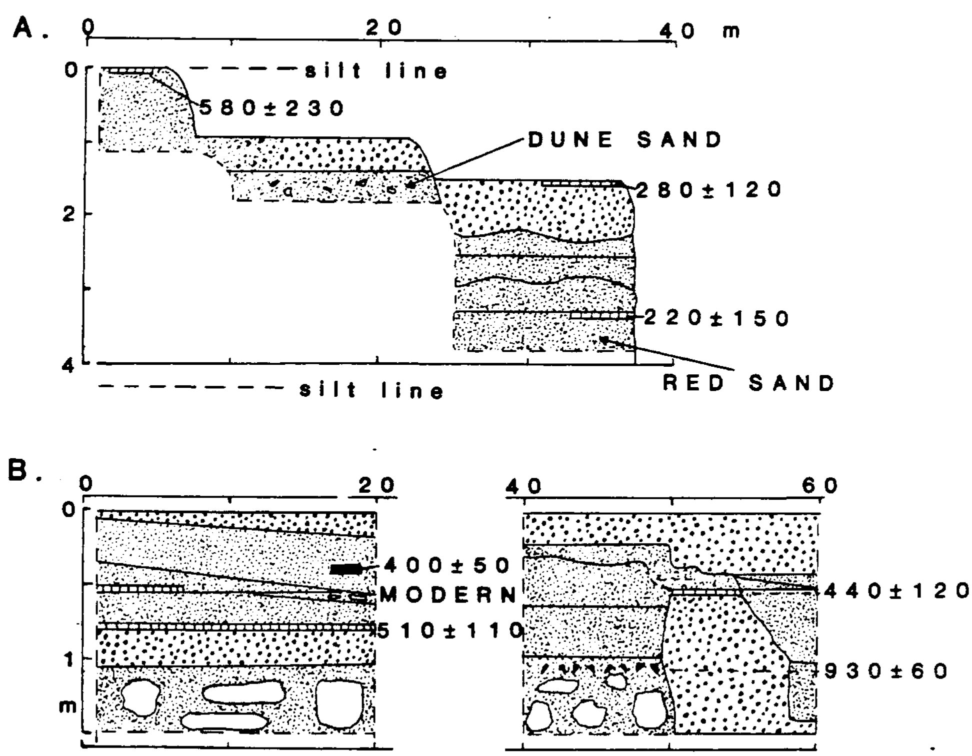


FIGURE 15. Stratigraphy of slackwater-flood deposits at Stevens Arch Bend, km 168.8.

Coarse stippling indicates sand, fine stippling indicates fine sand, rock symbols indicate colluvium, bars indicate organic material for radiocarbon dating. Contacts are dashed where uncertain. Radiocarbon dates are in ^{14}C yrs BP; see text and Appendix 2 for more information on the dates.

because of the probable long residence time of wood in the semi-arid climate of the watershed. A silt line 140 to 190 cm above the deposit was correlated directly with the upstream silt line.

Discharge Calculations. Abundant high-water marks facilitated the calculation of discharges at Stevens Arch Bend. Five of the six cross sections surveyed had an elevation for the high silt line, and four had an elevation for the largest "modern" flood deposit (table 7). Using Manning-n values of 0.035 for the channel and 0.045 to 0.060 for overbank areas, the water-surface profile for a discharge of 900 cms closely matched the high silt line with an estimated error of ±40 cms (table 7). The slope-area method was used to calculate a discharge of 830 cms using the high-water marks at both ends of the reach and a weighted-average Manning-n value of 0.045.

Four high-water marks were used to calculate a discharge associated with the largest "modern" flood deposit. Using the same Manning-n values as for the high silt line calculations, discharges of 670 and 660 cms were calculated using the step-backwater and slope-area methods, respectively (table 7). The close agreement of the methods at this site can be attributed to the lack of channel irregularities, the gradual contraction, and the assumption that silt lines and slackwater deposits represented water-surface instead of energy-grade-line elevations.

TABLE 7. Details of discharge calculations at Stevens Arch Bend, km 168.8.

SITE CHARACTERISTICS

Drainage Area: 4430 km^2

Length of reach: 220 m

Average channel topwidth: 53 m

Average channel slope: 0.0046

Number of cross sections: 6

Channel Manning-n value: 0.035

Average overbank Manning-n value: 0.052 Range: 0.045-0.060

HIGH SILT LINE (580 yrs BP): Discharge: 900 cms

Number of high-water marks: 5

Assumptions: All marks represented water-surface elevations (All were silt lines)

Average energy slope: 0.0013 Range: 0.0010 - 0.0012

Average mean velocity: 3.99 m/s Range: 3.64 - 5.04 m/s

Average Froude number: 0.45 Range: 0.40 - 0.57

Estimated error: ±40 cms

Slope-area discharge: 830 cms

TABLE 7. Details of discharge calculations at Stevens Arch Bend, km 168.8 (continued).

LOW SILT LINE (1932? FLOOD): Discharge: 670 cms

Number of high-water marks: 4

Assumptions: All marks represented water-surface elevations (4 slackwater deposits)

Average energy slope: 0.0014 Range: 0.0011 - 0.002

Average mean velocity: 3.64 m/s Range: 3.25 - 4.48 m/s

Average Froude number: 0.45 Range: 0.40 - 0.55

Estimated error: ±50 cms

Slope-area discharge: 660 cms

The largest recorded flood on the Escalante River, 410 cms, occurred on August 4, 1951, at a gage near the confluence of the Escalante and Colorado Rivers prior to the creation of Lake Powell. Assuming that a similar-magnitude discharge passed through Stevens Arch Bend, the step-backwater method was used to calculate a stage at this site. The calculated stage was 1.2 to 1.6 m lower than the stage associated with the last "modern" flood. This result illustrates the difference in magnitude of recorded flooding after 1950 AD with the floods recorded in slackwater-flood deposits at Stevens Arch Bend.

Correlation and Dates of the "Modern" Floods

Slackwater deposits on the Escalante River indicate that four large floods have occurred during the last 260 radiocarbon years BP. As discussed earlier, no resolution in radiocarbon ages can be obtained for the last 250 yrs BP (Stuiver, 1982), and dates for these floods is desirable for flood-frequency analysis. At several sites, cattle dung and modern artifacts entrained in flood deposits indicated a post-settlement date for several of the floods. Also, with the exception of deposits at Orthogonal Canyons, the date for the floods were pre-1950 AD (table 8).

The large "modern" floods on the Escalante River were assumed correlative, despite variations in radiocarbon dating. The last large flood deposited distinctive sediments

TABLE 8. Direct and indirect dates on the last large floods on the Escalante River.

Site	Date[1]	Flood Layer[2] Represented	Association
The Alcove	MODERN	1932	Organic material directly entrained in the deposit
	150±80	1909	Organic material entrained in the deposit
	210±90	1909	Organic material underlying the deposit
Anasazi Alcove	350±110	1916?	Organic material entrained in the deposit
	PS	1916?	Cattle dung entrained in the deposit
	260±110	1909	Organic material underlying the deposit
Arch Bend	PS	1932	Lumber entrained in deposit
	100±80	1932?	Wood underlying two flood deposits
	110±90	1932?	Last flood on Boulder Creek (O'Connor, 1985)
Orthogonal Canyons	1958 AD	1927?	Transported charcoal
	230±100	1932	Burned horizon under the deposit
	1962 AD	1927?	Burned horizon in deposit
	1960-2 AD	1916?	Burned horizon in deposit
Silver Falls Canyon	140±150	Four	Underlies flood deposits
Cañon Bonito	130±130	1932?	Directly entrained in the deposit
	PS	1932?	Cattle dung underlying deposit
Stevens Arch Bend	280±120	1927?, 1909?	Organic material entrained in the deposit
	220±150	?	Organic material

TABLE 8. Direct and indirect dates on the last large floods on the Escalante River (continued).

Site	Date[1]	Flood Layer[2] Represented	Association
Stevens Arch	400±50	1927?	Transported wood entrained in deposit
	MODERN	1909?	Organic material at top of the deposit

1. PS -- post-settlement; MODERN -- ~100% PMC ^{14}C, near 1950. Radiocarbon dates of <250 yrs BP are considered "modern" (1700-1950 AD; Stuiver, 1982).
2. See text for explanation of the dates for floods.

throughout the canyon. The Munsell color of these sediments, 10 YR 6/4, was consistent and easily distinguished from tributary sediments or eolian sand, generally of 5 YR hue, and older Escalante flood deposits, generally of 7.5 YR hue. The particle-size distribution generally represented a well-sorted sand, although the distribution varied from fine sand to sand as a function of proximity to the channel. The deposits, where thick, were distinctively slightly indurated and massive. A silt line was associated with the deposits in protected locations.

Historical information, newspaper accounts, rainfall records, and growth suppressions in trees indicate the dates for the four "modern" floods. The first "modern" flood, on August 29, 1909, was the first large flood in the history of Escalante (Edson Alvey, written comm., 1985) and caused abandonment of the first gaging station (U.S.G.S., 1910). Flood-induced growth suppressions in *Pinus ponderosa* on Pine Creek (fig. 2) were infrequent prior to 1909, the year of the most pervasive growth suppressions in the 270-year record (fig. 16; Laing and Stockton, 1976). Growth suppressions were also recorded in *Populus fremontii* on Twentyfive Mile Wash (fig. 2) in 1909 (S. Clark, oral comm., 1985). A total of 91 mm of rainfall fell at Escalante during the 4-day storm, which was the only storm to cause regional flooding in southern Utah (see Appendix 1).

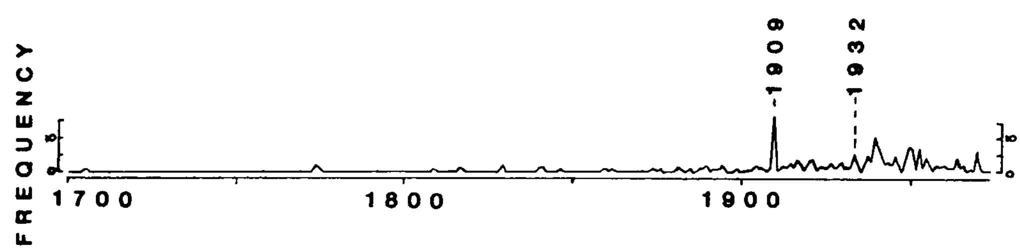


FIGURE 16. Tree-growth suppressions in *Pinus ponderosa* indicative of flooding on Pine Creek (after Laing and Stockton, 1976).

The last large "modern" flood on the Escalante River is well-documented in newspaper accounts and the rainfall record. The summer of 1932 is the wettest of the 80-year rainfall record for Escalante with a total rainfall of 248 mm for July and August. A large flood on August 27, 1932, swept a large bridge 100 m downstream, destroyed the power station at Escalante (washing the roof downstream; Buryl Shurtz, oral comm., 1983), and destroyed a house on the floodplain (Garfield County News, September 2, 1932). No floods of this magnitude occurred after 1932.

The dates of the other two "modern" floods recorded in the slackwater deposits are not as readily determined. Years for other possible floods are 1914, 1916, 1921 and 1927. Rainfall for July, 1914, totalled 134 mm, the second highest July rainfall total (behind 1932) at Escalante. On October 6, 1916, 86 mm of rainfall fell after a relatively wet summer. Rainfall totalling more than 25 mm fell on August 31, 1921, causing widespread flooding throughout southern Utah (Woolley, 1946). Rainfall totalling 81 mm fell during a storm on September 13, 1927, after a wet summer. October, 1916, and September, 1927, are the most likely dates for the large floods because of the large, 24-hr rainfall total following wet summers. No verification for flooding during these years could be obtained.

Flood Frequency on the Escalante River

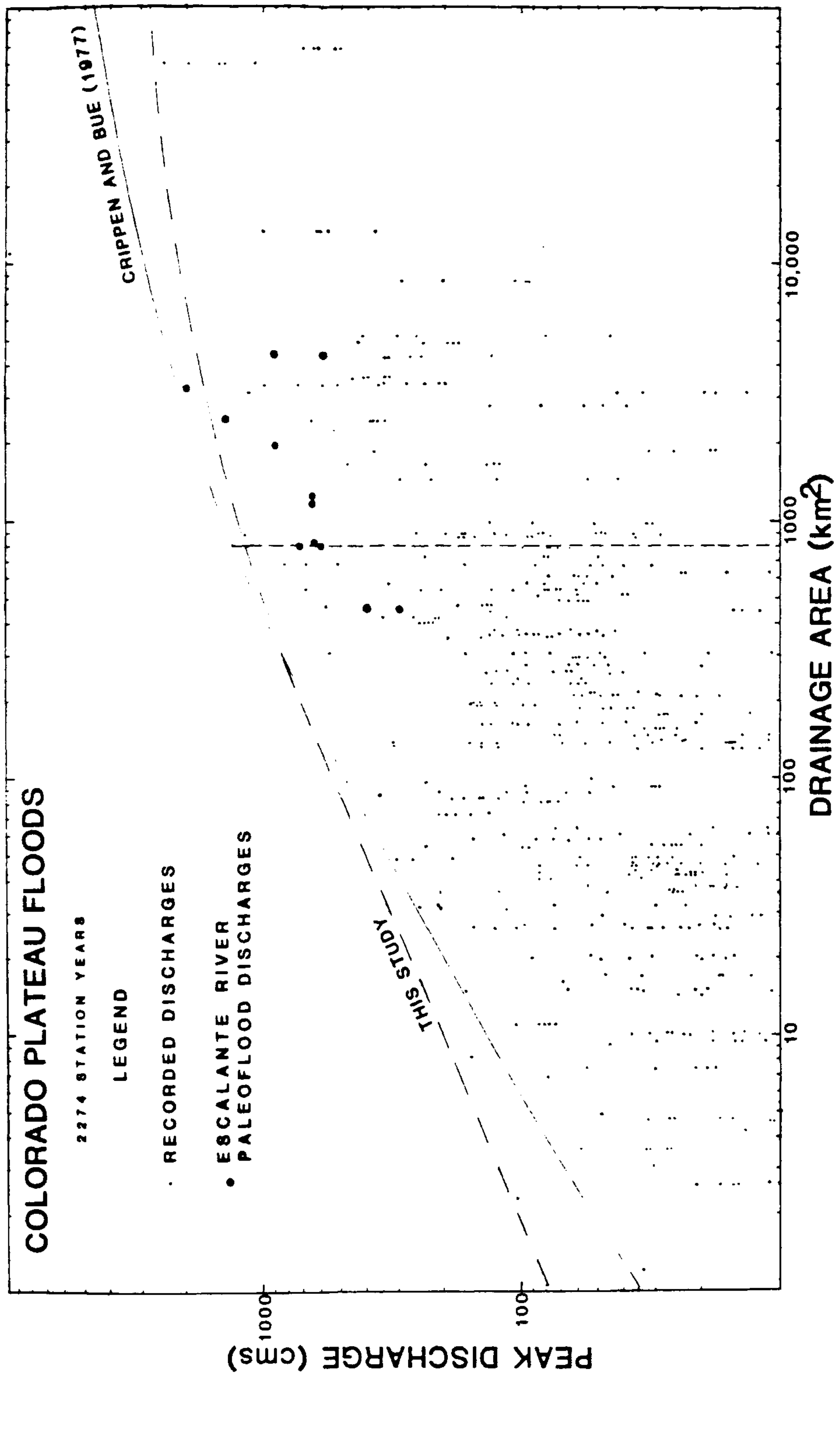
Regional Analysis of Flood Magnitudes

The paleohydrologic analyses of slackwater deposits revealed that large pre-gaging record floods have occurred in distinct periods over the last 2000 years. These floods had discharges 6 to 7 times larger than the largest flood at the Escalante River gage, and 2.2 times larger than the largest flood recorded (410 cms). Therefore, a regional envelope curve was developed to assess the physical possibility of the calculated discharges. Regional envelope curves require the assumption that a maximum possible flood exists for all watersheds dependent only on the drainage-basin area and regional hydrometeorology. The envelope curves are developed either from plotting an upper-bounding envelope on the largest floods experienced (Crippen and Bue, 1977) or by placing an upper-bounding envelope on all floods measured (Malvick, 1980) in a region. Envelope curves have been developed for specific regions of the conterminous United States (Crippen and Bue, 1977) and specifically for Arizona (Malvick, 1980).

An envelope curve was developed from 2274 station-years of floods measured at 147 stations on the Colorado Plateau, plotted by drainage-basin area (fig. 17). The region studied was bounded by the Little Colorado River on the south, the Arizona-New Mexico and Utah-Colorado borders on the east, the Uinta and Wasatch Ranges on the north and

FIGURE 17. Envelope curves for the largest floods on the Colorado Plateau.

Dashed line indicates the drainage-basin area for the Escalante River near Escalante gaging station.


COLORADO PLATEAU FLOODS
2274 STATION YEARS
LEGEND
· RECORDED DISCHARGES
● ESCALANTE RIVER PALEOFLOOD DISCHARGES
CRIPPEN AND BUE (1977)
THIS STUDY
PEAK DISCHARGE (cms)
1000
100
DRAINAGE AREA (km2)
10
100
1000
10,000

northwest, and the Nevada border and drainage divide of the Colorado River tributaries on the west and southwest. A list of the gaging stations, crest-stage stations, and miscellaneous sites used appears in Appendix 3. The five largest peak discharges of record for each gaging record longer than 5 years, and all discharges for all other sites, were obtained from U.S. Geological Survey Water-Supply Papers (e.g. U.S.G.S., 1949), Butler and Marsell (1972), and Crippen and Bue (1977).

The plotted data indicate that Crippen and Bue's (1977) curve for region 14, which was larger than and included the region studied here, overestimates floods for large drainage basins and underestimated floods for small drainage basins (fig. 17). Therefore, another curve was plotted to better represent the plotted data. Floods which essentially define the curve include Dry Canyon near Cedar City, 2.3 km^2 with a flood of 104 cms on August 17, 1965; The Gap near St. George, 8.2 km^2 with a flood of 160 cms on August 12, 1964; Hog Canyon near Kanab, 48 km^2 with a flood of 307 cms on August 12, 1964; Cottonwood Creek near Bluff, 884 km^2 with a flood of 1190 cms on August 1, 1968; and the San Juan River, 59,900 km^2 with a flood of 2410 cms in 1884 and 1911. The envelope curve can be expressed approximately as

$$(1) \quad Q_e = 60 * A^{(0.58 - 0.02 \ln A)}$$

where Q_e is the "maximum expected flood" (Malvick, 1980) in cms and A is the drainage-basin area in km^2.

Examination of the peak discharge records indicated that all discharges were calculated from flood marks using the slope-area method. Some significant deviations were obtained between paleoflood discharges calculated from the same evidence using the slope-area and step-backwater methods (fig. 18). The step-backwater method is assumed to be the more accurate method on the basis of explicit nonuniform-flow evaluation and use of additional (more than 2) cross sections and high-water marks. Differences in the calculated discharges could be caused by use of high-water marks which are probably representative of the energy-grade line for the water-surface elevation, and the lack of allowance for nonuniform flow conditions in the slope-area method. The results suggest that the step-backwater method should be used in highly nonuniform flow reaches, while the slope-area method may be adequate for reaches with gradually varied flow and high-water marks representing water-surface elevations.

The paleoflood discharges calculated using the step-backwater method, including two from O'Connor (1985) for Boulder Creek, were found to plot very close to the envelope curve (fig. 17). The plotting positions for the paleofloods could be conservative because all other floods which define the curve were calculated using the slope-area method. The fact that all paleofloods plot below Crippen and Bue's (1977) curve and all but one (from Cañon Bonito) below the

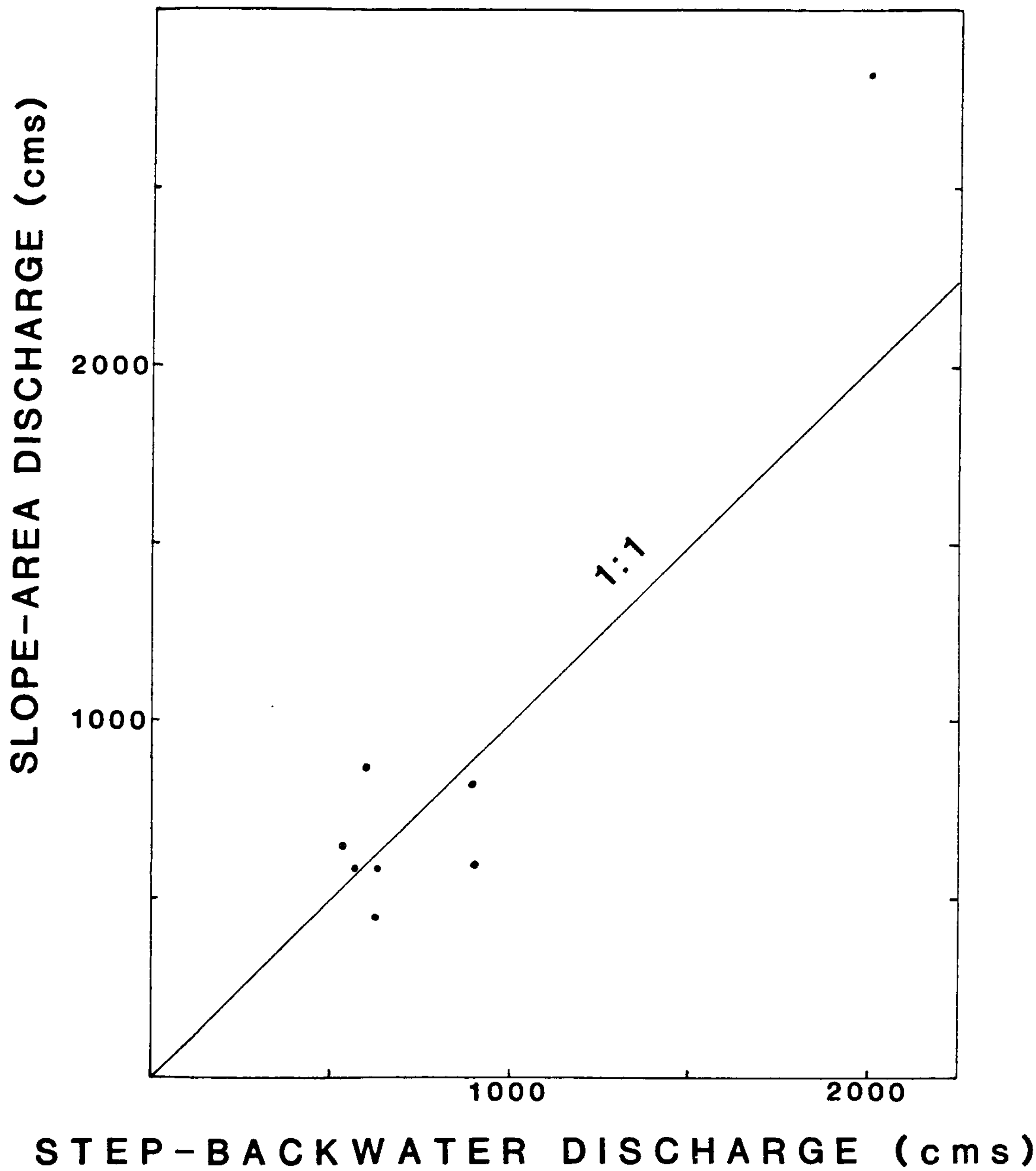


FIGURE 18. Relationship between discharges calculated using the slope-area and step-backwater (HEC-2) methods.

Data include 1 discharge from Boulder Creek (O'Connor, 1985).

revised curve indicates that these floods are physically possible for the Escalante River. The close proximity of the paleofloods and the envelope curve strengthens the concept of "maximum expected flood" (Malvick, 1980).

Flood Routing

The most recent (1932) large flood on the Escalante River left highly visible and characteristic deposits throughout the canyon. The peak discharges associated with the 1932 deposits at the 8 previously described sites are plotted in Figure 19 by river kilometer. Clearly, floods on this river do not behave like floods in regions with more humid climates. Leopold and Maddock (1953) note that discharges tend to increase in the downstream direction for most rivers excluding those in arid areas. Figure 19 suggests that the peak discharge at any given location is more likely controlled by local tributary addition and upstream attenuation than by drainage-basin area on the Escalante River. Therefore, the location of storms in the drainage basin also influences the peak discharge because it controls the discharges from tributaries.

The Alcove and Anasazi Alcove are, respectively, 3.2 and 7.9 km downstream of the gaging station with no intervening tributaries. The only hydrologic factor affecting the combination of the slackwater flood record with the systematic record is channel attenuation of flood

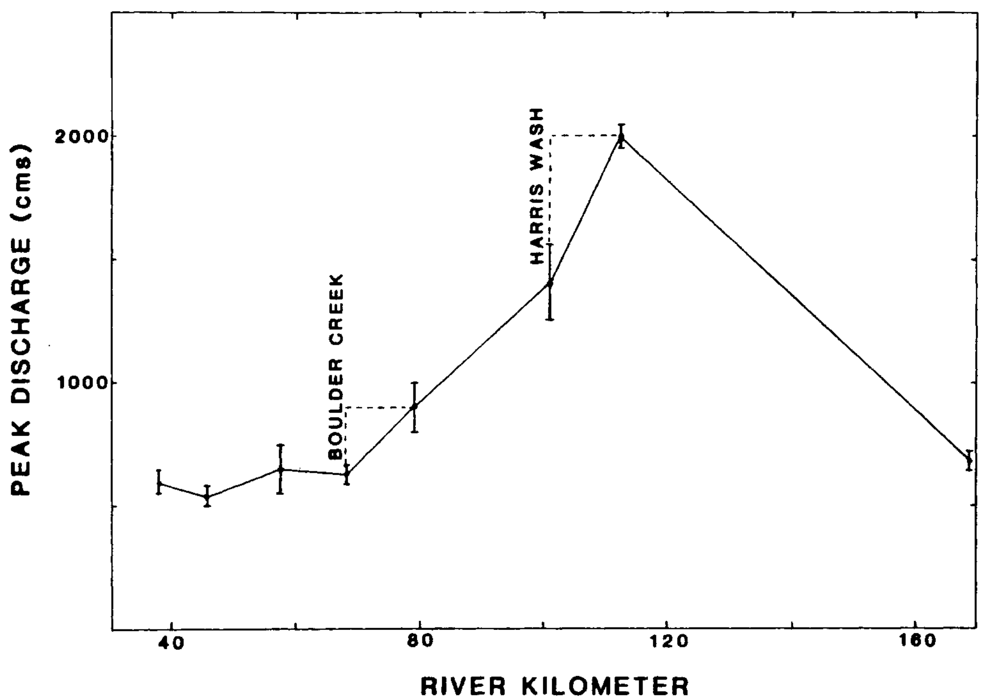


FIGURE 19. Routing of the 1932 peak discharge through the Escalante River canyon.

peaks downstream of the gage. Calculation of discharge for the 1932 flood at The Alcove and Anasazi Alcove yielded 600 and 540 cms, respectively, or an attenuation of roughly 13 cms/km in peak discharge. A similar calculation for the largest flood at these sites (1000 to 900 yrs BP) yielded an attenuation of 17 cms/km. Consideration of the error in the discharge calculations (minimum of $\pm$40 cms) suggests a range of 5 to 25 cms/km for the attenuation. The attenuation between Calf Creek and Arch Bend, calculated from peak discharges of 650 and 630 cms, respectively, for the 1932 flood, is only 2 cms/km, although the error involved in the discharge calculations suggests a possible range of 0 to 15 cms/km.

An attenuation between Cañon Bonito and Stevens Arch Bend was calculated to be 25 cms/km from discharges of 2000 and 590 cms at each respective site. Calculation of this attenuation required the assumption of no addition from Twentyfive Mile Wash (fig. 2), which had a significant discharge on the basis of growth-suppressions in channel-margin cottonwoods (S. Clark, oral communication, 1985). The 25 cms/km attenuation, therefore, is a minimum value for this section. All attenuation of flood peaks on the Escalante River is presumably caused by storage along the channel margins, because losses through infiltration would be minimal in this bedrock-controlled river.

Flood Frequency

The close proximity of slackwater deposits to the gaging station (fig. 2) allows a revision of the flood-frequency relationship for the Escalante River using the log-Pearson type III analysis (Water Resources Council, 1981). Previous researchers have calculated 197 cms for the 100-yr flood and 154 and 168 cms for the 50-yr flood at this gage (Thomas and Lindskov, 1983; Berwick, 1962). The largest recorded flood is 97 cms in 22 years of record.

The log-Pearson type III distribution was fit to the Escalante River gaging record from water years 1943-1955, 1972-1984 with the "modern" slackwater floods included as historic events. A skew coefficient of -0.2 and generalized mean-square error of 0.81 were determined from a regional flood-frequency analysis (see Chapter 4). The calculated 50- and 100-yr floods were 193 and 248 cms, respectively (fig. 20). The increase of these discharges over Thomas and Lindskov's (1983) 50- and 100-yr floods is due to inclusion of 1981-84 floods and rejection of 1910-1912 floods, which were not from a recording gage, in the analysis. Addition of the historic floods, with dates of 1909, 1916(?), 1927(?) and 1932 and discharges of 600, 550, 550, and 600 cms, respectively, increased the 50- and 100-yr floods to 500 and 800 cms, respectively (fig. 20). Incorporation of possible channel attenuation of 13 cms/km for these floods increased the 100-yr flood by 10 cms.

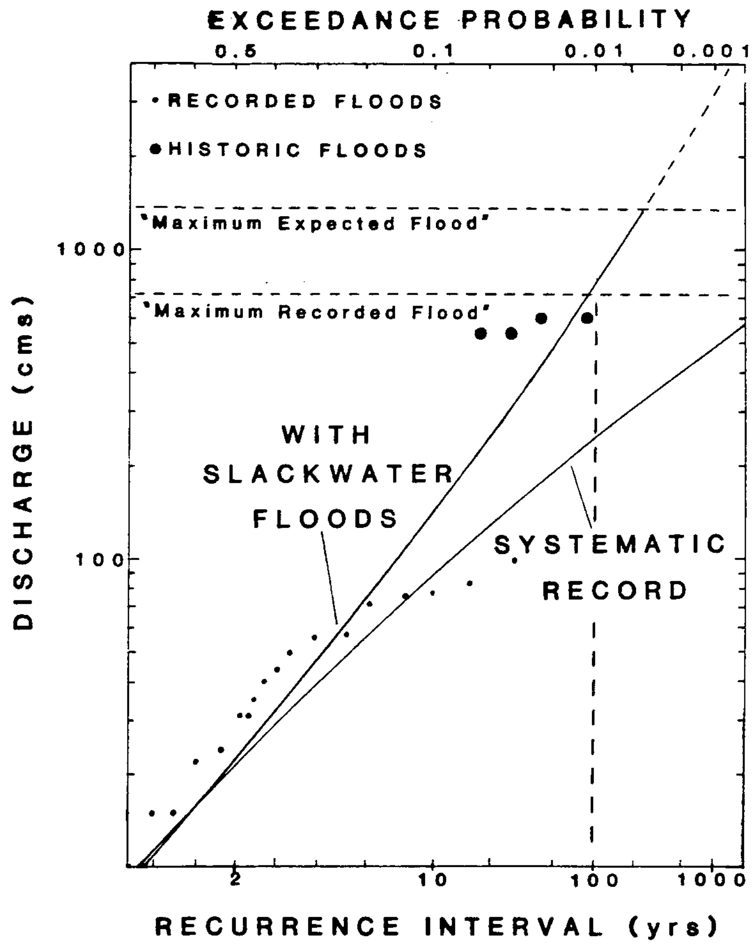


FIGURE 20. Log-Pearson type III flood-frequency analysis for the Escalante River.

The 100-yr flood calculated from the 22-year systematic record is 248 cms. The 100-yr flood calculated with the modern floods entered as historic floods is 800 cms. The "largest flood of record" is 720 cms (900-1000 yrs BP) from table 2. The "maximum expected flood" is 1190 cms from Figure 17.

The slackwater-flood record suggests that flood frequency on the Escalante River is not stationary, a statistical requisite for flood-frequency analysis (Water Resources Council, 1981). The frequency of large flood events, which the log-Pearson type III analysis was developed to predict, has changed significantly over the last 2000 years. Peaks in flooding between 1200 and 900 yrs BP, 600 and 400 yrs BP, and in the historic period indicate the nonstationarity. Uncertainty concerning the 100-yr flood discharge occurs when the largest flood of record, which occurred approximately 900-1000 yrs BP, is added to the analysis. The inclusion results in a 100-yr flood of 280 cms, or 13% larger than that calculated from the systematic record.

A composite flood-frequency relationship can be developed for the Escalante River gage, assuming stationarity only between 1909 and 1984. This assumed stationarity is based on the initiation and coalescence of an incised channel upstream of Escalante after 1909 (Chapter 3), which presumably would have a large influence on peak discharges. The frequency of floods with a recurrence interval <100 years is specified by the curve which included the "modern" floods (fig. 20). The "100-yr flood" from this curve is 800 cms. The "maximum recorded flood" is 720 cms, the largest flood in the slackwater flood record spanning 2000 years. The "maximum expected flood" from the regional envelope curve (fig. 17) is 1190 cms. These values should be reasonable for future work requiring flood-frequency information for this gage.

Implications for Upstream Alluvial Processes

The slackwater-flood record for the Escalante River suggests a nonstationarity in flood frequency which may be important in upstream processes. The increased flood frequency between 1200 and 900 yrs BP, 600 and 400 yrs BP, and in "modern" times suggests either hydrometeorological or geomorphological changes in the upstream hydrologic system. Several possible scenarios can explain the flood frequency changes.

The increase in flood frequency may be due to a periodic increase in the frequency and/or intensity of summer storm events (Leopold, 1951b). In this case, the change would be independent of watershed factors. On the other hand, channel incision in an unstable floodplain may have occurred during a relatively minor flood (in accordance with the concept of "thresholds"; Schumm, 1979), leading to increased hydraulic conveyance, increased peak discharges, and higher flood frequency independent of climate. A random, large storm event not related to climate may have caused a large flood and initiated the arroyo, increasing subsequent peak discharges from lesser storm events. Both Anasazi and historic settlement may have induced watershed changes (Betancourt and Van Devender, 1981) significant enough to cause incision of the floodplain during a relatively large flood, again leading to increased peak discharges (Stewart, 1924). Evidence supporting one or more of these hypotheses will be discussed in the next chapter.

CHAPTER 3

THE GEOMORPHIC HISTORY OF THE UPPER VALLEY ARROYO

Upper Valley Creek (fig. 21) underwent spectacular channel change in the late 1890's and early 1900's. The discontinuous, ephemeral channels viewed by the first explorers and settlers were transformed into a continuous, 50- to 100-m wide and up to 17 m deep arroyo by a series of large, summer floods. This change had a profound negative effect on inhabitants of Escalante, who watched as irrigation works and agricultural land were destroyed. A reconstruction of historical events, in addition to stratigraphic reconstruction of prehistoric conditions, provides some details concerning changes in watershed conditions associated with the channel change.

Settlement and Land Use

Mormon pioneers settled along the Escalante River and founded the town of Escalante in 1875 (Woolsey, 1964). Abundant grazing lands and irrigation water attracted settlers, and the population expanded from 140 in 1876 to 445 in 1878. By 1880, stockmen began using the ranges on the south side of the Aquarius Plateau and the town of Boulder was settled there in 1889. The most important industries in

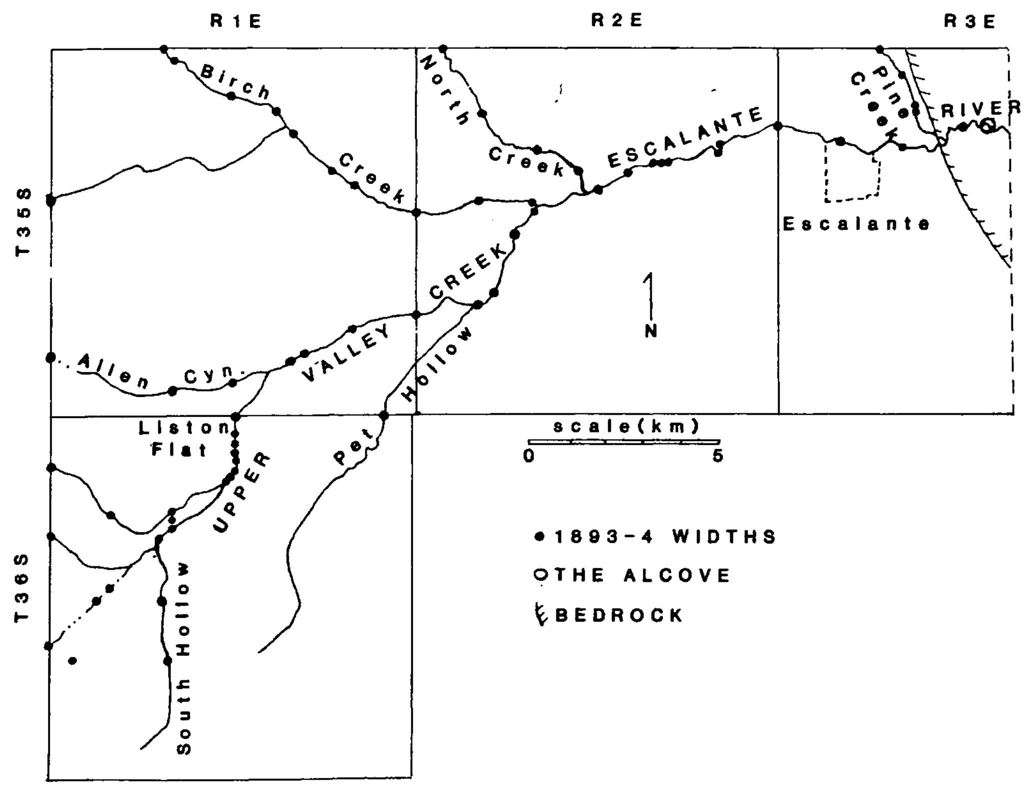


FIGURE 21. Map of the Escalante River and tributaries upstream of Escalante, Utah.

the newly settled area were agriculture, livestock grazing, and logging (Woolsey, 1964).

The Escalante River floodplain was cleared of vegetation, and agriculture began immediately after settlement (table 9). Farmsites were cleared in Upper Valley, but permanent residences were maintained only in Escalante. Irrigation canals were built to utilize perennial surface waterin 1876, and an irrigation district was organized in 1877. Dams were built as part of the irrigation system, but relatively small floods destroyed the dams every two years. A cement dam apparently was constructed in the 1890's to establish a more permanent irrigation system (Woolsey, 1964).

Livestock grazing increased as the population grew (table 9). "Sizeable" herds in excess of 1000 head of cattle were introduced by 1880, and flocks of sheep in excess of 2000 head were introduced by 1886 (Woolsey, 1964). Range conditions deteriorated under the intense grazing pressure, and severe losses of livestock began in 1893. A severe drought beginning in 1896 caused a loss of one half of the livestock by 1900 (Gregory and Moore, 1931; Gregory, 1945). However, herds were restocked, and grazing reached its peak in 1917 (Woolsey, 1964).

Logging was an important early industry in Escalante as the need for housing grew. The first sawmill was built using water power from the Escalante River in 1877 (Woolsey,

TABLE 9. Chronology of settlement, land-use practices, and hydrologic change in the Escalante River basin (compiled from Woolsey, 1964; LeFevre, 1973; and Chidester and Bruhn, 1949).

Date	Population of Escalante	Livestock Numbers[1]	Watershed Conditions	Hydrologic Changes
1876	223	30c	Abundant grass and forage for livestock	Discontinuous channels in the floodplain
1878	445	Sizeable herds (greater than 800c)	Clearing of floodplain vegetation	Dams and canals built
1884	435	Large increases	Logging begins	
1890	692	Large herds (more than 12,000c)	Conversion of flood-plain to sagebrush	Fivefold increase in average discharge
1895	896	One-half depletion	Drought conditions; range deteriorates	
1900	723	75,000s, 12,500c	Lower range deteriorates	
1910	846	55,000s, 11,000c	Mountain ranges deteriorates	Major flood (1909); initiation of arroyo
1915	---	Peak of livestock	Scarce feed on range	Major flood (1916)
1920	1052	60,000s, 11,330c	48,000 ha of forest damaged by insects	Flood occurs (1921)
1925	1033	23,200s, 8,550c		Major flood (1927
1930	1016	21,150s, 5,550c	No range improvement	Last major flood (1932)
1935	---	BLM starts quotas on livestock	Logging; insect damage	
1940	1161	15,600s, 5,350c	Reseeding project in Upper Valley	Arroyo incision complete
1950	916	5,900s, 5,070c	Insect damage to forests; reseeding	Minor floods
1960	702	1,400s, 4,807c	Large sawmill built	

1. c -- cattle numbers, s -- sheep numbers (approximate).

1964). The number of small mills increased as timber cutting increased on the Aquarius Plateau. Clear-cutting of forests and overgrazing were responsible for the establishment of the Powell (later Aquarius) National Forest in 1903.

Pre-Arroyo Channel and Floodplain Conditions

The Thompson Expedition

Upper Valley was first described by an expedition led by Almon Harris Thompson, Chief Topographer of the Powell Survey, in 1872 (Thompson, 1875). Diaries of the expedition kept by Thompson (Gregory, 1939), Jack Hillers (Fowler, 1972), Stephen Vandiver Jones (Gregory, 1948), Walter C. Powell (Kelly, 1949), and Frederick C. Dellenbaugh (1962) provide invaluable descriptions of the pre-arroyo conditions in Upper Valley. Thompson returned to the Escalante River in 1875, and was responsible for naming both the river and the town of Escalante (Gregory, 1939).

The expedition entered Upper Valley from the west on the evening of June 2 and camped 3 km downstream at a spring. Thompson noted the "fine grassy valley" with "the best grass I have seen" and "springs seep out almost at the summit." Hillers, Jones, and Dellenbaugh all note the abundant grass, and Powell wrote that "good crops could be raised without irrigation." On June 3rd, the expedition travelled 17 km downstream to the confluence of Upper Valley and Birch Creeks (fig. 21). Thompson wrote "the valley in the upper part is quite marshy...as soon as a little stream begins to run it dries." Jones noted "numerous springs on each side of the valley, grass splendid, soil good..." At the end of the day, Birch Creek presented a formidable obstacle. Thompson observed "could not ford it, or rather could not find a place where we could get down." Jones described Birch Creek as narrow, deep, and muddy, and wrote that the expedition decided to camp "as we would have to dig down the banks and fill the stream to cross."

On June 5th, the expedition spent an hour crossing the swollen Upper Valley Creek above Birch Creek, and travelled about 14 km to the present site of Escalante. Jones wrote that their route required crossing "deep gulches." This ambiguous notation by Jones could refer either to channels incised into the floodplain or bedrock channels on the south side of the valley, probably the latter. The expedition camped at a place east of the modern town because the Escalante River, according to Thompson, was "15 feet (5 m) wide, swift, and deep, swollen by rains." Thompson also noted "poor grass and a few cedars" at this site.

The Thompson Expedition diaries indicate several important hydrologic and geomorphic features of Upper Valley in 1872. The widespread presence of grassy meadows and excellent rangelands is important in light of later changes.

Upper Valley Creek was not continuously incised but instead was a discontinuous ephemeral stream above its confluence with Birch Creek in 1872. The diaries do not mention any impediment to travel in Upper Valley other than the Upper Valley - Birch Creek confluence, indicating that the currently imposing 10-15 m deep channels were not present. A prominent headcut had become established near the confluence of Upper Valley and Birch Creeks, although this headcut apparently did not extend into Upper Valley, as the decision to cross Upper Valley Creek above the confluence suggests.

Land Survey Notes

William Lewman surveyed Upper Valley and the Escalante River upstream of Escalante for the General Land Office in 1893-4. His descriptions of Upper Valley and the accompanying measurements of stream width (fig. 21, table 10; Lewman, 1893-4) provide a contrast with the observations of the Thompson Expedition. No measurements of channel depth were made. The grassy meadows present along Upper Valley Creek in 1872 had been replaced by sagebrush (Artemisia sp.) and greasewood (Sarcobatus vermiculatus) by 1893. The average width noted for Upper Valley Creek and the Escalante River was 8.2 m (30 measurements; table 10), indicating that a wide, continuous arroyo was not present.

Several notes indicate the spatial condition of the floodplains and the geomorphic nature of the channel. In a

TABLE 10. Widths of the Escalante River, Upper Valley Creek, and selected tributaries in 1893-4.

Between Sections	Width (m)	Notes
		DOWNSTREAM
		T35S, R4E
12-13	12.7	Escalante R.
11-12	12.0	Escalante R.
10-11	9.0	Escalante R.
		T35S, R3E
E of 9	5.2	Escalante R.
8-9	6.7	Escalante R., swamp on south bank
7-8	7.1	Escalante R.
W of 7	6.9	Escalante R.
		T35S, R2E
11-12	7.5	Escalante R.
11-12	6.9	Escalante R.
10-11	10.1	Escalante R., dense brush on floodplain
10-11	10.8	Escalante R., dense brush on floodplain
10-11	7.5	Escalante R., dense brush on floodplain
10-15	8.0	Escalante R.
15-16	8.6	Escalante R.
16-17	6.5	Birch Cr., dense brush on North side
16-17	7.7	Upper Valley Cr.
17-20	6.0	Upper Valley Cr.
20-29	6.0	Upper Valley Cr.
29-30	15.5	Upper Valley Cr.
		T35S, R1E
E of 25	4.3	Upper Valley Cr.
25-26	10.8	Upper Valley Cr.
26-35	17.9	Upper Valley Cr.
34-35	36.1	Upper Valley Cr.
S of 34	6.5	Upper Valley Cr.

TABLE 10. Widths of the Escalante River, Upper Valley Creek, and selected tributaries in 1893-4 (continued).

Between Sections	Width (m)	Notes
		T36S, R1E
3-4	5.4	Upper Valley Cr., "deep washes"
3-4	5.4	Upper Valley Cr., "deep washes"
3-4	5.4	Upper Valley Cr., "deep washes"
4-9	4.7	Upper Valley Cr.
8-9	5.2	Upper Valley Cr.
9-10	4.7	Upper Valley Cr.
9-10	4.5	Upper Valley Cr.
8-17	6.4	Upper Valley Creek, swampy
17-18	4.5	Upper Valley Creek, swampy
18-19	4.5	Upper Valley Creek
19-30	4.5	Upper Valley Creek
W of 18	---	no mention of channel, Upper Valley Creek
W of 19	---	no mention of channel, Upper Valley Creek
W of 30	---	no mention of channel, Upper Valley Creek
		UPSTREAM

Compiled from Lewman (1893-4).

traverse of Liston Flat (T36S, R1E, sections 9-10; table 10, fig. 21), Lewman (1893-4, p. 380) notes that "the land (is) cut up with deep washes; otherwise nearly level." This section of the channel apparently had discontinuous channels with headcuts. Notes on the upstream floodplain indicate marshy conditions with numerous springs, and notes for downstream crossings do not indicate arroyos. No channels were reported in Pet Hollow or Allen Canyon (fig. 21) in 1894 (Lewman, 1893-4, p. 457).

Floods and Channel Change in Upper Valley

A Chronology of Flooding

Human activities in the Escalante River basin increased rapidly from settlement until widespread range deterioration and floodplain erosion occurred. As indicated in Table 9, land-use practices and channel changes appear to be related. Average streamflow increased fivefold after settlement (Gregory and Moore, 1931), and the change was thought to be in response to land-use practices (Woolsey, 1964).

The initiation of the continuous arroyo occurred during a major flood in 1909. The following is an account of this flood by Wallace Roundy, a pioneer of Escalante, recorded in a school journal (Edson Alvey, written comm., 1985).

> Wallace described how the Escalante River looked in those early days. He said that it was a little creek winding down through the valley with lots of

> willows growing along its banks. There was a little footbridge on which to cross the stream. It was a pretty place.
>
> Wallace also told us about the first and biggest flood to ever come down the Escalante Creek. That was on August 29, 1909. Joe Barney had his grain all in shocks out in his field. As Wallace watched from his house the flood water spread out over all the farmland and floated all of the grain crop away. It also took Wallace's father's and Joe Spencer's crops and it dug out a big hole over near the face of the canyon. After that, floods began coming often and cut the hole back farther and farther (emphasis mine).

The bed of the Escalante River at the gaging station 2 km downstream of Escalante was lowered 1 m and the channel shifted laterally during this flood (U.S.G.S., 1910).

The floods causing the extension of the headcut (Wallace's "big hole") probably occurred during 1910, 1911, 1914, 1916, and 1921. The summer of 1910 was wet, and a storm dropped 42 mm of rainfall on September 29, 1911 causing local flooding on the Paria River (Thiessen, 1911). July, 1914, was the second wettest July recorded at Escalante. The summer of 1916 was the third wettest at Escalante, and one of the large historic floods possibly occurred on October 6, 1916 (Chapter 2). Flood that occurred before August 31, 1921, caused extensive erosion and destruction of roads in Upper Valley and destruction of cement flood gates and irrigation works near Escalante (Woolley, 1946).

Headcuts in Upper Valley were undoubtedly extended as a result of the floods between 1909 and the early-1920's.

Gregory (1918, p. 43) wrote that Upper Valley Creek "(is) cutting rapidly and may destroy tillable land" in 1918. Photos by Gregory (figs. 22 and 23) indicate that the arroyo below the Birch-Upper Valley Creek confluence had completely formed by 1918. By 1921, Upper Valley Creek had eroded the floodplain locally up to the canyon bedrock walls (Deseret News, August 31, 1921). By 1922, Pet Hollow had an incised channel 43 m wide and 10 m deep (Rigby, 1922, p. 73).

Flooding and associated channel change continued in the mid-1920's. Large storms caused damage to crops, roads, and irrigation canals along the Paria River in August, 1923. The two largest floods of record for the Paria River occurred on October 5, 1925, and September 13, 1927, and the fourth largest on August 2, 1929. A flood originating on Birch Creek on August 27, 1927, caused damage to bridge approaches near the confluence of Birch and Upper Valley Creeks (Garfield County News, September 13, 1927). This flood or an unreported flood later in September was probably one of the four "modern" floods on the Escalante River (see Chapter 2). The channel of Upper Valley Creek probably shifted laterally during these floods.

Flooding continued to cause channel change in the early 1930's. Storms in August, 1930, caused damage in the Sevier and Paria River basins. A storm in early August, 1931, caused flood damage to roads and irrigation ditches near Escalante (Garfield County News, August 7, 1931).

FIGURE 22. Photographs of Escalante, Utah.

A. Photo by Herbert Gregory, taken in 1918 (Photo #370, U.S. Geological Survey Photo Library, Denver, CO). View is to the east. Arroyo of the Escalante River is at the left side (A) with the bedrock canyon in the background.

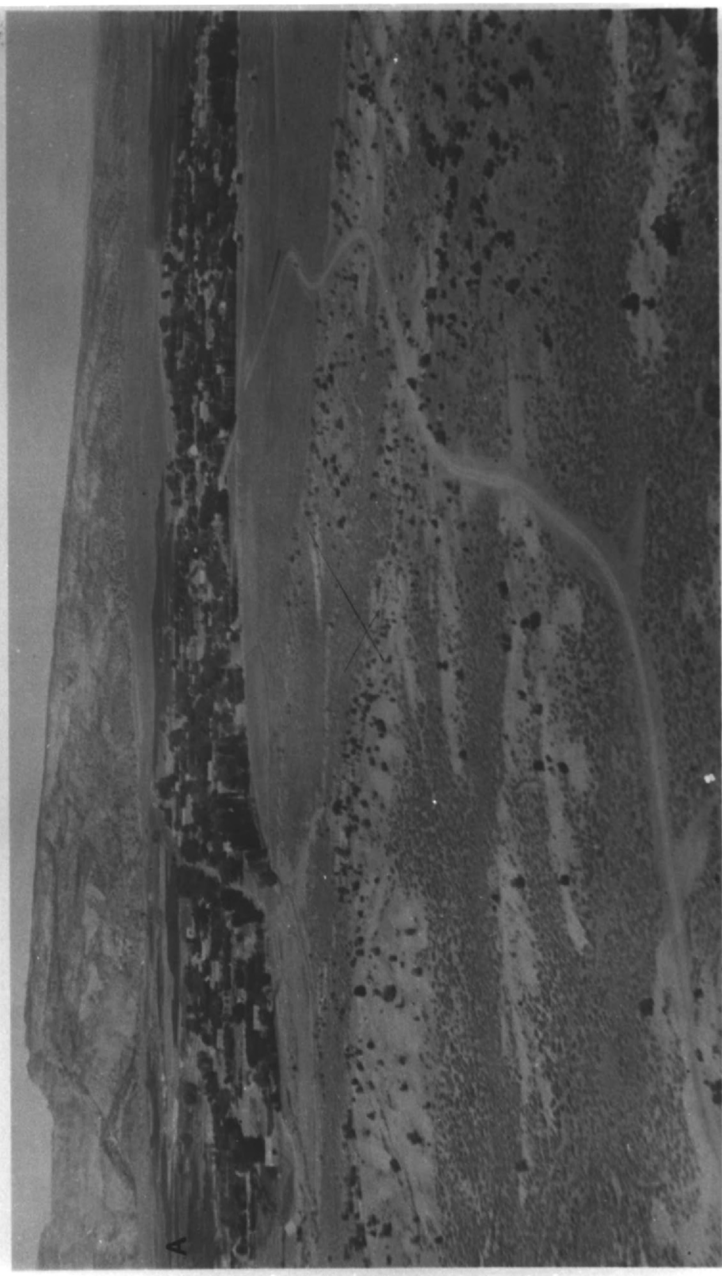

A

FIGURE 22. Photographs of Escalante, Utah (continued).

B. Photo by Robert Webb, taken in 1984. The arroyo has abundant vegetation between the channel walls consisting mainly of *Tamarix* and *Elaeagnus angustifolia* (Russian olive). The number of junipers (probably *Juniperus monosperma*) in the foreground (A) have increased despite construction disturbances.


A

FIGURE 23. Photographs of Wide Hollow near Escalante, Utah.

A. Photo by Herbert Gregory, taken in 1918 (Photo #369, U.S. Geological Survey Photo Library, Denver, CO). View is northwest from the same camera station as Figure 22. Arroyo (A) is shown in right midground.


A

FIGURE 23. Photographs of Wide Hollow near Escalante, Utah (continued).

B. Photograph by Robert Webb, taken in 1984. The arroyo walls (A) are essentially unchanged, but vegetation consisting mainly of *Tamarix* has colonized the channel margins. *Juniperus* sp. have increased in numbers in the left foreground (B).


A
B

Floods occurring on July 12 and August 20, 1932, caused considerable damage to bridge approaches and agricultural lands in Upper Valley (Garfield County News, July 15 and August 26, 1932). The large flood of August 27, 1932, destroyed a power plant, houses, and bridges near Escalante, and caused extensive erosion of agricultural land (Garfield County News, September 2, 1932). This flood was the last of the four historic floods recorded in slackwater deposits on the Escalante River (see Chapter 2). In 1935, Birch Creek was an arroyo locally 85 m wide and 6.5 m deep (Bird and Nelson, 1937).

After 1932, reports of flooding are rare for the Escalante River. A flood on August 28, 1947, destroyed both approaches to the bridge across the river at Calf Creek; however, no large flood was recorded at the gaging station upstream (U.S.G.S., 1949). The records for this date are fragmentary, suggesting that a large flood may have occurred and not been recorded; however, the size of the flood was undoubtedly less than the 1932 flood (see Chapter 2).

Minor floods occurred during the 1950's, although reports of damage and channel changes are scarce. The Escalante River and Harris Wash were reported at "high stage" at the end of July, 1951. The largest flood recorded at the gaging station near Escalante occurred in August, 1953. Floods were apparently widespread in southern Utah in mid-August, 1957, and the "largest flood in history" for

Upper Valley -- 158 cms -- occurred on August 2, 1959 (Butler and Marsell, 1972). This flood was unimportant compared with the floods between 1909 and 1932.

Channel Change at Liston Flat

Upper Valley Creek at Liston Flat (figs. 21 and 24) underwent extensive channel change during flooding between 1909 and 1940. The drainage-basin area above this reach is 77 km^2. The channel bed incised between 5 and 15 m deep and widened from 4.5 to over 75 m on the Flat. This reach of Upper Valley Creek was apparently a discontinuous, ephemeral stream in 1893, according to the land-survey notes (T36S, R1E, between sections 3 and 4; table 10) and the Thompson (1875) observation that "as soon as a little stream begins to run it dries." Therefore, this reach may have been a destabilizing influence in the initiation of headcuts and eventual coalescence of the arroyo.

Upper Valley Creek on Liston Flat coalesced rapidly into a continuous arroyo between 1893 and 1940. In 1893, the average width of Upper Valley Creek in T36S, R1E was only 5.0 m for eleven measurements (table 10). Therefore, despite the notation of "deep washes" at this site, Upper Valley Creek could not have been very deep. Aerial photography taken in 1940, 1958, and 1974 indicates the arroyo on Liston Flat had fully formed by 1940 (fig. 24). Between 1940 and 1974, the main stem of Upper Valley Creek

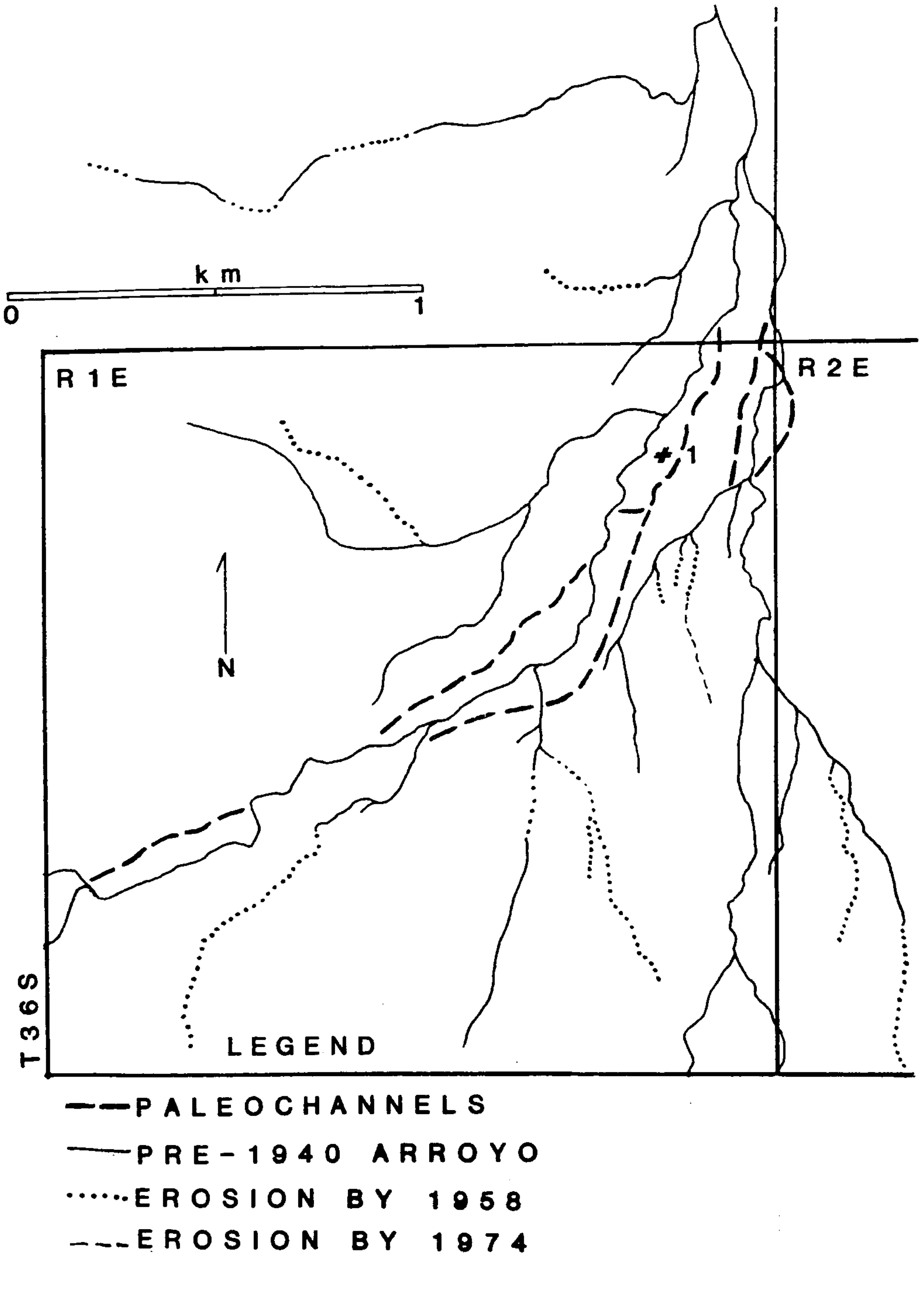


FIGURE 24. Map of Upper Valley Creek on Liston Flat.

changed very little, although some headward erosion occurred on tributary channels (fig. 24).

Aerial photographs taken in 1940 by the U.S. Department of Agriculture were used to identify relicts of the 1893 channel (fig. 24). A 220-m reach of this channel (site #1, fig. 24) was surveyed to provide a contrast in hydraulic parameters with the modern arroyo. The channel reach represented 1 cycle of a gully-fan system typical of discontinuous ephemeral streams (Patton and Schumm, 1975, 1981). Comparisons were made with cross sections of the modern arroyo made on the same section lines as the 1893 survey (table 10).

The 1893 channel ranged in topwidth from 7 to 44 m in this reach, with a range of width/bank-height ratio of 6.6 to 34.7 (table 11). The channel radius appeared to be the most sensitive index of the discontinuity in the arroyo, ranging from <1.0 on fan cross sections (#2 and #3, table 11) to >1.0 on entrenched cross sections (#1, #4, and #5, table 11). The valley slope was steepest at the end of the entrenched section (between cross sections #3 and #4) and the start of the fan section (between cross sections #2 and #3). In contrast, the modern arroyo ranged from 29 to 79 m in topwidth with a range of 3.5 to 5.3 in the width/bank-height ratio (table 11). The channel radii of 3 cross sections of the modern arroyo are 4 to 8 times the radii of 5 cross sections of the 1893 channel (table 11).

TABLE 11. Dimensional comparison of the 1893 channel and the modern arroyo on Liston Flat.

1893 CHANNEL

Cross Section Number	Width (m)	Bank Height (m)	Area (m^2)	Channel Radius (m)	Width/Bank-Height Ratio
			UPSTREAM		
1	44.0	3.4	84.0	1.87	13.1
2	20.8	0.6	4.0	0.19	34.7
3	7.0	0.9	4.6	0.62	7.8
4	12.5	1.9	13.5	1.02	6.6
5	12.2	1.8	15.9	1.20	6.8
			DOWNSTREAM		

Between Cross Sections	Distance (m)	Valley Slope	Channel Slope
1-2	95	0.011	0.042
2-3	24	0.033	0.010
3-4	61	0.031	0.013
4-5	41	0.008	0.011
1-5	216	0.018	0.026

MODERN ARROYO
(T36S, R1E)

Between T36S,R1E Sections	1893 Width (m)	1984 Width (m)	Bank Height (m)	Area (m^2)	Channel Radius (m)	Width/Height Ratio	Valley Slope
4-9	4.7	79.3	15.0	810	9.08	5.3	0.013
8-17	4.5	33.5	9.6	185	4.50	3.5	0.039
17-18	4.5	28.6	7.2	158	4.44	3.97	0.018

The differences measured between the dimensional parameters of the 1893 channel and the modern arroyo serve to underscore the magnitude of the channel change at this site. A hypothetical bankfull discharge for the 1893 channel was calculated to be 40 cms, while the modern-arroyo bankfull discharge was calculated to be greater than 11,000 cms, assuming no scour. The channel floodplain prior to 1893 must have sustained periodic sheet floods as the bankfull discharge was exceeded, while no conceivable modern flood could possibly overtop the modern arroyo banks (see Chapter 2).

The Birch - Upper Valley Creek Confluence

Historical information and stratigraphic analyses were used to reconstruct the last 1500 years of geomorphic history at the confluence of Birch and Upper Valley Creeks (fig. 25). This confluence is an extremely important focal point for channel change because the contributing drainage area feeding the downstream channel (269 km^2) is nearly twice as large as the areas feeding the upstream channels. Critical valley oversteepening (Hadley and Schumm, 1957) and the potential for doubling flood discharges downstream are important factors controlling the erosion and aggradation of channels at this site.

Historic Channel Change. The confluence of Birch and Upper Valley Creeks was apparently a headcut in 1872 as described in the Thompson Expedition diaries. However, in

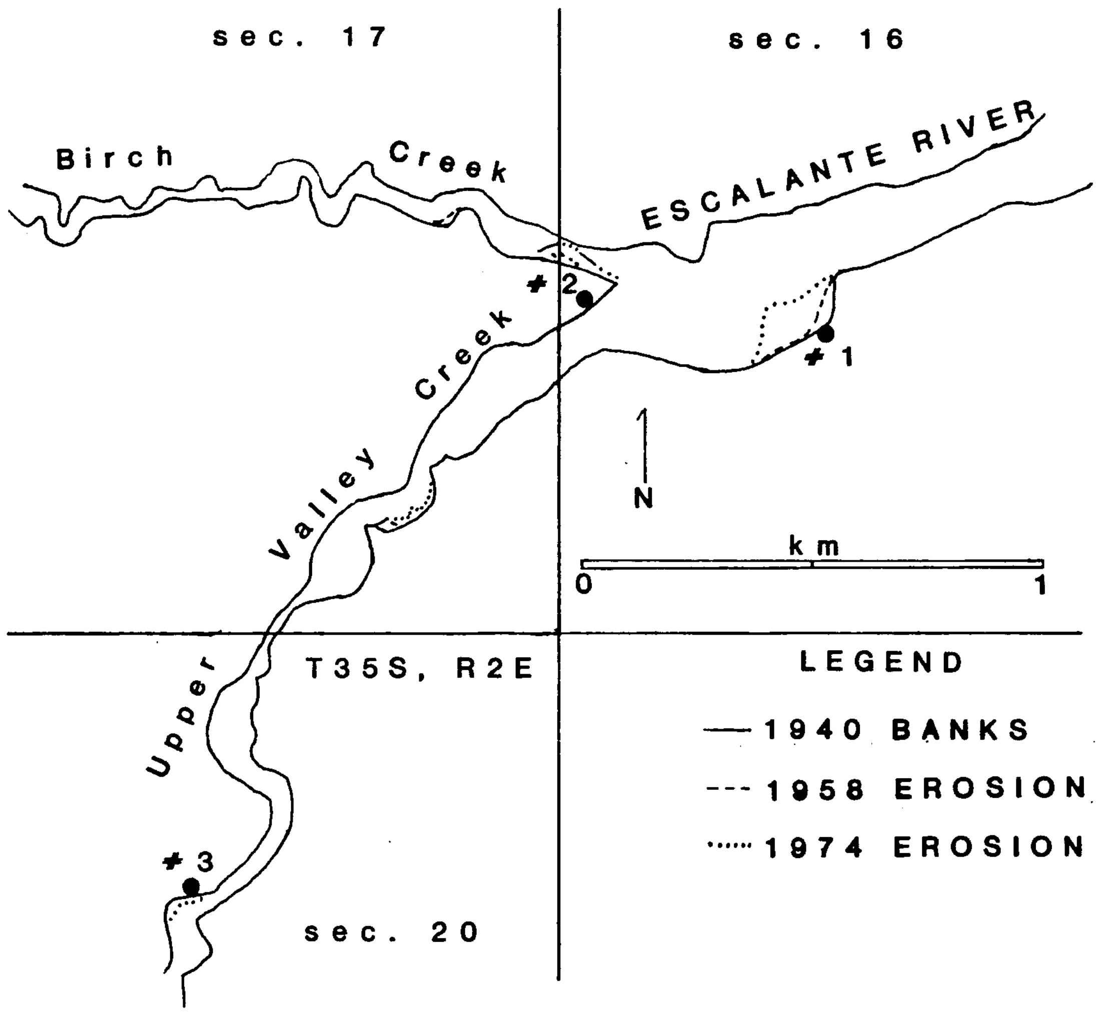


FIGURE 25. Map of the confluence of Upper Valley and Birch Creeks.

#1 indicates the site where valley margin stratigraphy was described; #2 indicates the site where modern channels were described; #3 indicates the site where a paleochannel was described.

1892-3, the widths of Upper Valley and Birch Creeks a short distance upstream from the confluence were 6.4 and 7.8 m, respectively, and the Escalante River downstream was only 8.6 m wide. Therefore, any headcut present at this site, while undoubtedly a destabilizing influence on the floodplain, was only of localized extent.

Main Canyon, in which Birch Creek flows, was the only route out of the Escalante River basin until about 1935. A road crossed the Escalante River on a bridge 200 m downstream of the confluence, and the history of this bridge provides some information on modern channel changes. Bridges were probably unnecessary prior to the 1909 flood, but subsequent floods and channel changes created the need for a large, permanent structure. In 1921, the bridge and its approaches were destroyed during repeated, relatively small floods, suggesting a period of channel widening (Deseret News, August 31, 1921). In 1927 and 1931, floods caused damage to the bridge approaches and undermined the road, indicating channel widening. Three floods in 1932 -- on July 15, August 20, and August 27 -- damaged the bridge, the latter transporting the entire structure 100 m downstream. These floods widened and deepened this reach, as reports on the destruction of irrigation works only 300 m downstream suggest (Garfield County News, September 2, 1932).

After the 1932 floods, the floodplain downstream of the Birch-Upper Valley Creek confluence to the confluence with North Creek (fig. 21) was permanently stabilized to prevent further damage. A causeway was built spanning the 150-m wide channel, and the Escalante River was diverted to a man-made bedrock channel on the south side with a 6.4-m drop over a 10-m distance. As a result of this artificial base-level rise, the channel aggraded upstream, partially filling the arroyo.

Maps drawn from aerial photographs of the site, taken in 1940, 1958, and 1974 indicate little change in the arroyo walls during the last 44 years (fig. 25). Floods emanating from Birch Creek scoured the south wall of the arroyo, leading to a crescent-shaped pocket which has increased in size since 1940 (fig. 25). The channel downstream of the confluence changed from an essentially undefined, braided channel in 1940, to a well-defined channel by 1958, to apparently stable, anastomosing channels by 1974. Extensive vegetation establishment and growth, especially of non-native species including Tamarix sp., accompanied the channel changes.

Stratigraphy of the Channel Margin. The stratigraphy of sediments on the valley margin (site #1, fig. 25) indicates hydrologic changes during the last 1600 years (fig. 26). Below 2.5 m depth, the sediments are slightly gleyed (2.5 Y 6/4 color), very poorly sorted silts

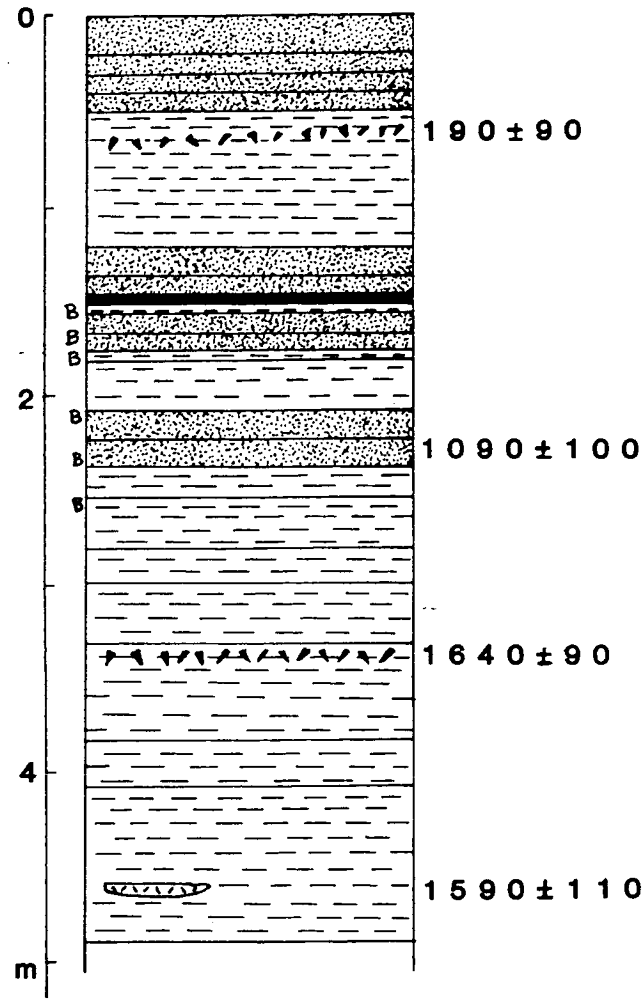


FIGURE 26. Stratigraphy of valley margin sediments at the confluence of Birch and Upper Valley Creeks.

Fine stippling indicates fine sand, dashes indicate poorly sorted gravelly, silty, very fine sand, solid black indicates clay, B indicates a burned horizon, crescent shape indicates a hearth, and black triangles indicate charcoal. Radiocarbon dates are given in yrs BP; see Appendix 2 for more information.

to fine sands mottled with iron and manganese oxides. The particles range in size from gravel to clay with indistinct boundaries. A date of 1590±110 (2) yrs BP provides a age control at 4.5 m depth; charcoal collected from 3.3 m depth, dated at 1640±90 (5) yrs BP, was probably redeposited from older sediments. The color and poor sorting suggest a marshy floodplain environment with extensive bioturbation and high groundwater levels.

Sediments above 2.5 m depth suggest a different floodplain environment. Colors are of 10 YR hue for better-sorted silty very-fine to fine sands. Sharp contacts suggest little bioturbation, and 6 burned horizons, as indicated by red, oxidized layers containing charcoal (fig. 26), suggest a dry meadow environment. Bracketing radiocarbon dates of 1090±100 (2) and 190±90 (5) yrs BP suggest the change occurred after 1500 yrs BP but prior to and probably near 1100 yrs BP (fig. 26).

A Paleochannel of Birch Creek. A paleochannel about 5 m wide and 2.5 m deep was described near the confluence (site #2, fig. 25). The channel was probably the 1892 channel of Birch Creek, which measured 6.4 m in width a short distance upstream in 1893 (table 10). Ultramodern radiocarbon dates of 1957 (2) and 1958 (5) AD on charcoal (see Appendix 2) indicate that the filling of this paleochannel with silty fine sand occurred rapidly during the 1950's. The size of this channel, compared with the current 46-m wide and 8-m deep arroyo, indicates the enormous channel change associated with the formation of the arroyo.

Stratigraphy of Paleochannels. Paleochannels found in an arroyo wall 2 km above the confluence (site #3, fig. 25) indicate that arroyos had formed prehistorically in Upper Valley. A 24-m wide paleoarroyo (fig. 27) is inset into slightly gleyed (2.5 Y) sediments which are directly correlated with sediments below 2.5 m depth on the channel margin (fig. 26). This relationship suggests a pre-1100 year but post-1500 year date for the incision. A radiocarbon date of "modern" (2) on charcoal from a burned horizon near the top of the gleyed sediments was rejected on the basis of the stratigraphic correlation and other radiocarbon dates from overlying sediments.

The stratigraphy of this paleoarroyo indicates sediment transport and morphologic changes associated with the filling of an arroyo. After incision, Upper Valley Creek created a bar-and-swale channel-bed topography (fig. 27) of coarse sand and gravel similar to the bed of the modern channel. If the arroyo formed around 1100 yrs BP, as suggested by the sediments on the valley margin (fig. 26), this channel persisted for 500 to 600 years with a width/bank-height ratio of 7.1. The arroyo rapidly filled with fine sand after about 500 yrs BP, as indicated by radiocarbon dates of 470±120 (1), 420±90 (1), and 470±60 (1)

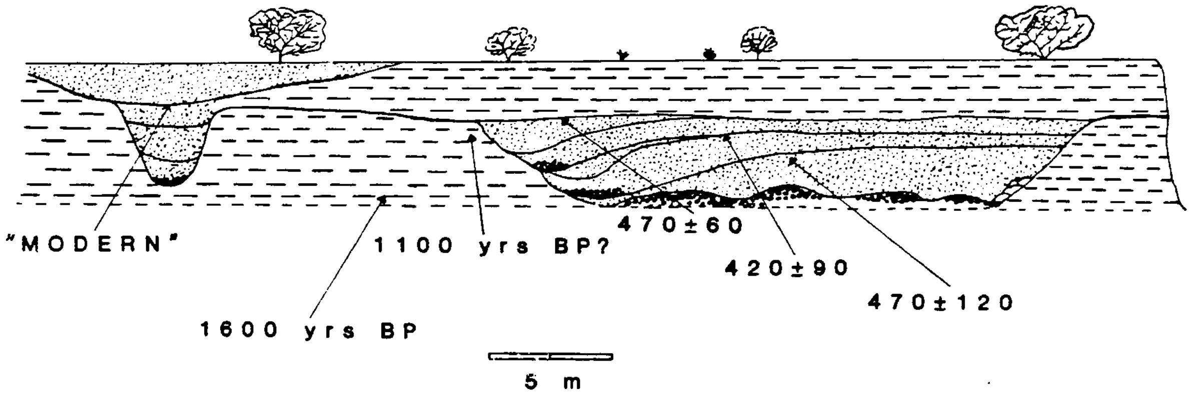


FIGURE 27. Stratigraphy of paleochannels on Upper Valley Creek.

Small circles indicate gravelly sediments, fine stippling indicates sandy sediments, dashes indicate silty sediments. Drawing is to scale. Radiocarbon dates are given as yrs BP; see Appendix 2 for more information.

yrs BP (fig. 27), although the channel still transported some gravel. The width/bank-height ratio decreased from 8.8 to 6.8 as the arroyo filled, and then decreased further to 1.2 as the stream shifted left to cut a new, narrow channel (fig. 27). This channel and floodplain aggraded with fine sand and evolved into the historic, pre-arroyo channel, with a width of 15 m and a width/bank-height ratio of 9.6. The 1892 channel, measured at 16 m width 1 km upstream (table 10), filled with sediments during the 1950's.

The paleoarroyo and the modern arroyo of the Escalante River are not morphologically comparable. The paleoarroyo could not be traced longitudinally through the valley because of erosion of valley-center sediments by the modern arroyo; therefore, channel slopes could not be compared. The modern arroyo, 40 m wide and 5.7 m deep, is 2.9 times larger than the paleoarroyo although the width/ bank-height ratios, 7.0 and 7.1, are nearly identical.

Channel Changes at Pine Creek

The Escalante River above its confluence with Pine Creek (fig. 21) provides a contrast in channel change with the upstream reaches. The Escalante River enters the bedrock canyon about 450 m above Pine Creek, although the channel is not controlled by bedrock until downstream of the confluence. The location of this site -- at the downstream end of a rapidly eroding arroyo -- is an ideal site for "complex response" (Schumm, 1973) wherein sediment mobilized upstream is temporarily stored at downstream sites.

The channel of the Escalante River at Pine Creek was apparently unstable after most of the upstream arroyo had formed. Large cottonwood trees along the channel are only 25 to 50 years in age (Sue Clark, written comm., 1985) in contrast with trees in excess of 150 years in age 2 km downstream at The Alcove (see fig. 8). The Escalante River gaging station, located 70 m downstream from the confluence, was established in August, 1909, only to be destroyed in the large flood on the 31st of that month (U.S.G.S., 1910). Early records at the re-established station showed problems with the shifting channel from 1910 to 1913, when the second gage was discontinued. The third gage, a water-stage recorder, was installed in 1943 and maintained until 1955. The "shifting-control method," used to calculate discharges for unstable channels, was used between 1943 and 1955. The gaging station was re-established in 1972, and the post-1972 record does not indicate problems with a shifting channel.

The Escalante River-Pine Creek confluence was surveyed in 1983 and again in 1984 to assess changes. A flood with a discharge of less that 50 cms on October 2, 1983, scoured the floodplain in places 1 m in depth. A 4.4 m high alluvial wall 50 m upstream of the confluence was eroded back 1-2 m. These changes from a minor flood illustrate further the unstable nature of this channel reach.

Stratigraphy at the site indicates rapid deposition and erosion in historic times (fig. 28). Four "ultramodern" radiocarbon dates indicate the deposition of 2.5 m of sediment, in 9 layers, from 1962 to 1975-6 AD. A channel apparently associated with this deposition filled and was then abandoned at an unknown time. The stratigraphy indicates that this site is a temporary repository for sediments flushed from the headwaters. The timing of the deposition and the location of the site downstream of the arroyo support the "complex response" model of terrace formation following arroyo incision upstream.

Implications: What Caused the Arroyo?

Arroyos have been a geomorphic feature of the Escalante River for half of the last 1000 years. The stratigraphy of a paleochannel near the Birch and Upper Valley Creek confluence indicates that an arroyo incised about 1100 yrs BP into older sediments deposited under marshy conditions. This paleoarroyo, of unknown longitudinal extent, was much smaller than the modern arroyo and persisted until 500 yrs BP. Between 400 and 500 yrs BP, the paleoarroyo rapidly filled with sandy sediments. The life of the paleoarroyo -- an estimated 700 to 1000 yrs -- is longer than Emmett's (1974) estimate of 200 to 700 years for the filling of modern arroyos.

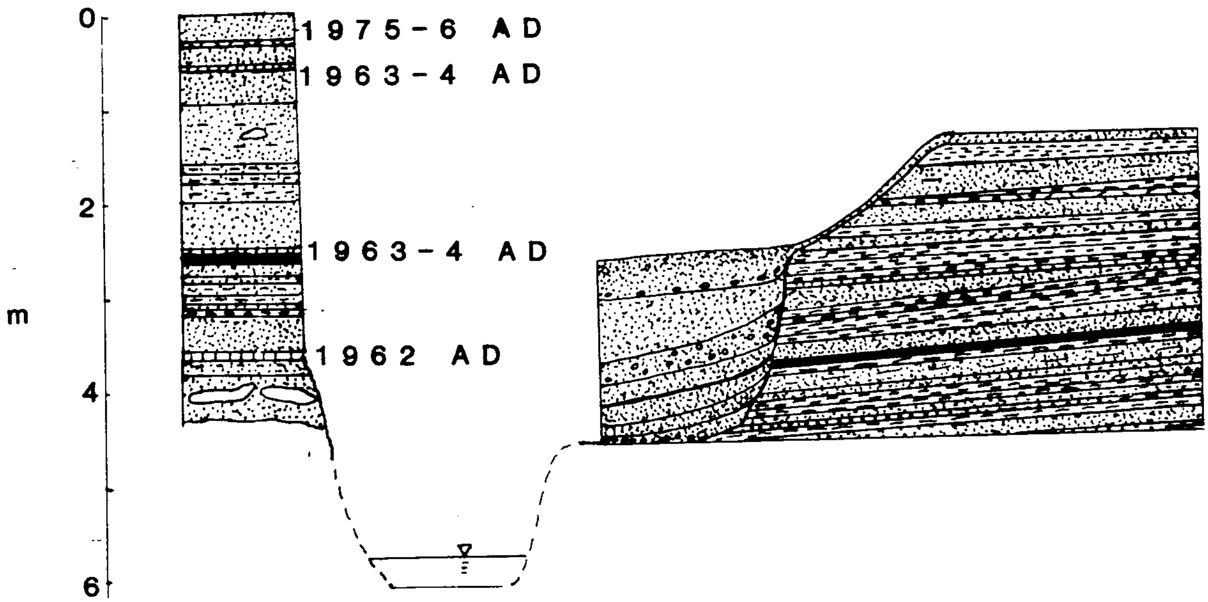


FIGURE 28. Stratigraphy and schematic cross section of the Escalante River 30 m upstream of Pine Creek.

Stippling indicates fine sand, dashes indicate silty fine sand to sandy silt, solid black indicates clay, rock symbols indicate colluvium, B indicates burned horizon. Radiocarbon dates are given as yrs BP; see Appendix 2 for more information.

The channel which replaced the paleoarroyo after 400 yrs BP was narrow and deep. This channel gradually aggraded with sandy sediments and evolved into the relatively wide, shallow channel observed by the first settlers and measured during the General Land Office survey. This channel was a discontinuous, ephemeral stream in Upper Valley, lined with willows and draining marshy areas. The floodplain supported a lush growth of grasses which attracted livestock grazers to the basin.

Channel change occurred rapidly along the Escalante River. A large flood in 1909 mobilized headcuts at Escalante and possibly at the Birch-Upper Valley Creek confluence and on Liston Flat. The headcut at Escalante rapidly eroded headward, and the lower 5 km of arroyo was completely incised by 1918. The major channel changes on the mainstem of Upper Valley Creek were completed by 1940, and only headward extension on tributaries occurred after 1940. Relatively minor deposition and channel changes associated with sediment storage and transport in the 1960's occurred near Pine Creek. The modern arroyo is much larger than either the channel it replaced in 1909, or with any paleochannels preserved in the stratigraphy.

What caused these arroyos to form? The formation of the paleoarroyo on Upper Valley Creek is roughly coincident with a peak in the frequency of large flood events recorded at The Alcove and Anasazi Alcove (see Chapter 2). The formation of the modern arroyo is directly linked to large, historic floods on the Escalante River which occurred during a discrete, quarter-century timespan. Because large floods are known to have initiated arroyos on every river in southern Utah (see Chapter 1), the association between paleofloods and the formation of a paleoarroyo can be inferred as causal. Lack of a more precise dating method than radiocarbon analysis precludes a more precise correlation of the timing of floods and the initiation of the arroyo.

The cause for large floods on the Colorado Plateau, then, is the important issue if a regional cause for arroyos is to be addressed. Human settlement and land-use practices are associated with both the paleoarroyo and the modern arroyo. Watershed changes induced by grazing and irrigation practices increased in severity until the modern arroyo formed on the Escalante River (table 9), with only minor changes occurring after grazing was curtailed. Anasazi- and Mormon settler-induced changes in watershed and floodplain conditions could have destabilized the hydrologic system and induced higher peak discharges.

The effect of land-use practices on inducing floods and initiating arroyos is not separable from climatic influences. The climate of Escalante and southern Utah could have changed, perhaps leading to more frequent large floods. An analysis of climate, presented in Chapter 4, will provide new information concerning the cause of floods and arroyos on the Escalante River and in southern Utah.

CHAPTER 4

CLIMATE AND FLOODS ON THE COLORADO PLATEAU

Arroyos in southern Utah were initiated during large flood events during the late 1800's and early 1900's (Chapter 1). Coalescence and channel widening on many rivers, including the Escalante River, can be attributed to a series of floods, some exceptionally large (Chapter 3). Floods are not necessarily a unique, independent factor in the initiation of arroyos, however. Flood magnitudes may have increased due to poor land-use practices. Flood frequency may be controlled by some manifestation of climate which may fluctuate with time. Numerous researchers have linked channel change with changes in mean annual precipitation, suggesting that fluctuations in annual or decadal conditions is a controlling factor in the frequency of large storm events.

Synchroneity in regional flooding is an important consideration if a regional climatic change is the cause for arroyo. Because of imprecision in radiocarbon dating, as manifested in standard deviations of greater than 50 years, some researchers have correlated events spanning perhaps thousands of years in the mid-Holocene as "synchronous" (see

Haynes, 1968). Because an arroyo can be initiated during a one- to two-day storm, regional synchroneity of flood events is of great importance. Synchroneity of flood events, the relationship of flood events to annual and decadal conditions, and the frequency of storm events at Escalante will be analyzed in this chapter.

Regional Climate and Floods

The climate of southern Utah is characterized by an ambiguous seasonality and by strong orographic gradients of precipitation. Statistically, precipitation falls equally during all four seasons, yet pragmatically winter and summer are the dominant rainy seasons. Cold air masses from the north Pacific are the dominant circulation features controlling winter precipitation (Mitchell, 1976), while several interacting features control summer precipitation. The "summer monsoon" airmass boundary bisects southern Utah, leading to a combination of continental interior and/or tropical Pacific sources of summer moisture (fig. 29; Mitchell, 1976)

Storm Types Causing Floods in Southern Utah

Several storm types are capable of producing large floods in southern Utah. Probable-maximum precipitation in the Southwest is based on either a local convective thunderstorm or a general storm originating from many sources (Hansen and Shwarz, 1981). Probable-maximum

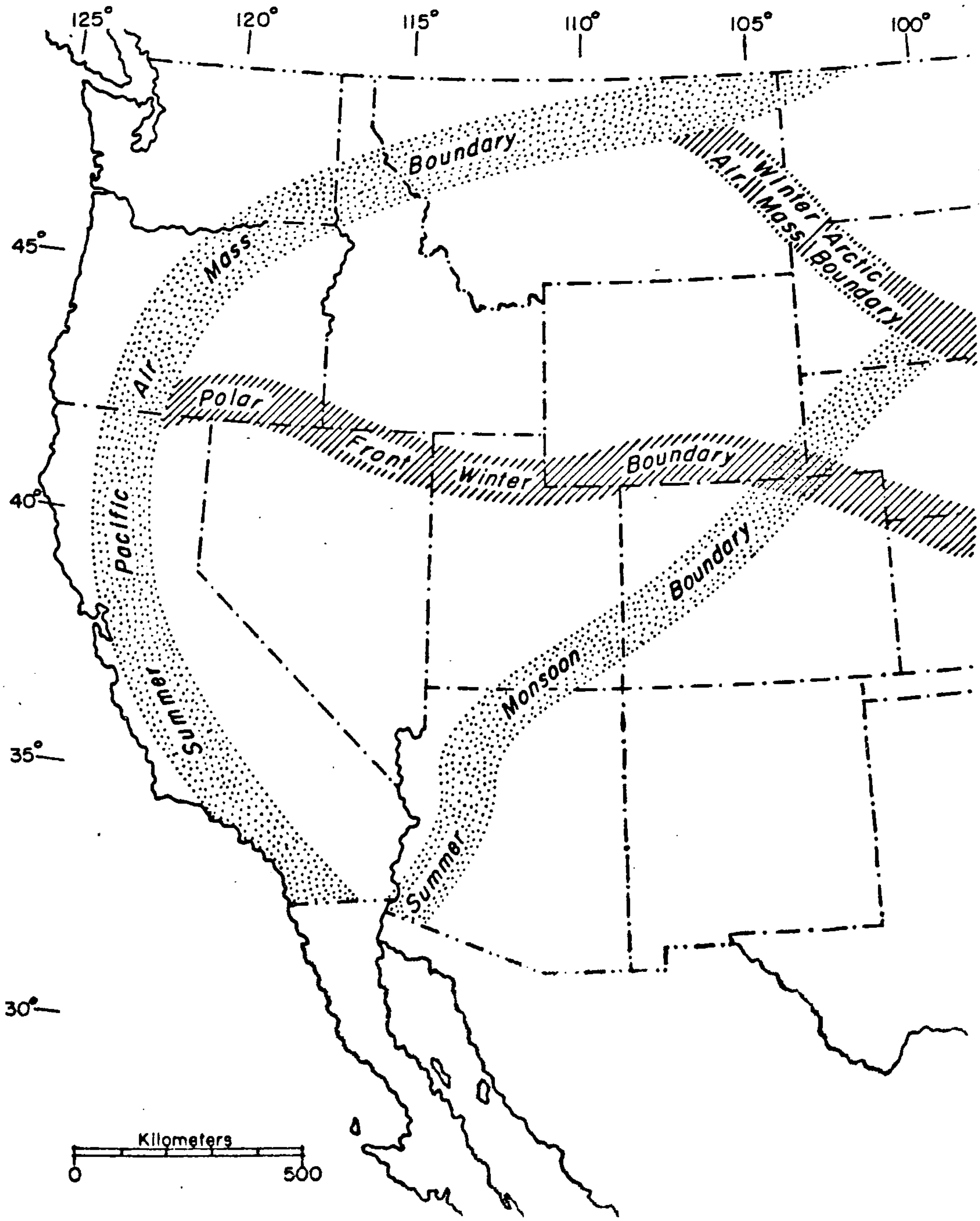


FIGURE 29. Airmass boundaries of the western United States (after Mitchell, 1976).

Boundaries were derived from calculation of "equivalent potential temperature," a synthesis of temperature, humidity, and surface pressure, for primary weather stations in the western United States from 1931 to 1960.

precipitation estimates for the Escalante River basin indicate a possibility for 250 mm of rainfall in 6 hours over a 2.4 km^2 area during a local storm (up to 600 mm/hr intensity), or 377 mm in 72 hours over the entire basin during a general storm in September or October (from Hansen and others, 1977). The highest recorded rainfall intensity in southern Utah is 150 mm/hr for 5 minutes and 102 mm/24 hrs, recorded during a thunderstorm at Blanding on August 1, 1968 (Butler and Marsell, 1972).

Thunderstorms may be localized (areal extent less than 1300 km^2) or part of a larger general circulation feature. Maddox and others (1980) describe two types of upper air flow regimes leading to flash floods in southern Utah. In both types, a well-developed meridional-flow pattern with a 500 mb short-wave trough interacts with a long-wave ridge to transport moisture, probably of tropical Pacific origin (Hansen and Shwarz, 1981), deep into the continent. The resulting coordinated thunderstorm system may generate flash floods over a larger area than a mere localized thunderstorm, leading to synchronous flooding on many rivers. The August 1, 1968, storm over Blanding, which caused record flooding on Comb and Cottonwood Washes (Butler and Marsell, 1972), was of one of these types.

Storm precipitation is highly dependent on topography. Large elevational gradients in southern Utah affect the potential rainfall amount and intensity. In areas of pronounced orographic uplift of air masses, such as the Aquarius Plateau, the 100-yr, 24-hr storm may have twice the rainfall of a similar storm on flat ground (Hansen and others, 1977). Storms decrease in intensity on the lee sides of orographic barriers, indicating that the direction of the storm track is extremely important for the generation of high-intensity precipitation and floods in southern Utah.

General storms may be convergent or orographic, tropical or extratropical, with origins in the North Pacific or tropical waters off the west coast of Mexico (Hansen and Shwarz, 1981). The storm types producing large, historic floods in southern Utah illustrate the variety of possible general storms. Descriptions of the 1862 and 1889 Virgin River floods (Larson, 1957) and the 1884 Paria and San Juan River floods (Chidester and Bruhn, 1949; Perkins and others, 1957) suggest multiple winter convergent storms from the North Pacific. The Virgin River flood of 1966 (Butler and Mundorff, 1966) resulted from a North Pacific storm moving nearly west to east, with a large, orographic component to the precipitation (see Cooley and others, 1977). The largest recorded floods on the Paria River -- in 1925, 1926, and 1939 -- resulted from the penetration of moisture related to tropical cyclones off the west coast of Mexico (K. Smith, oral comm., 1985); the storm triggering the 1932 Escalante River flood was also related to a tropical cyclone (see Hurd, 1932). The 1909 regional flooding occurred during a slow-moving, west-to-east tracking storm (Brandenburg, 1909) which had the characteristics of a mid-latitude, cutoff low (Douglas, 1974).

Seasonality and Correlation of Floods

Floods can occur in southern Utah in any season, depending upon the river system (table 12). The Virgin River in southwestern Utah (fig. 1) is susceptible to very large floods from winter (December-January) storms. Large floods on the Escalante River, in south-central Utah, occur primarily during late August. The San Juan River, in southeastern Utah and southwestern Colorado, floods in response to late September - early October storms. Comparison of Figures 1 and 29 and Table 12 reveals that rivers nearest the "summer monsoon" airmass boundary flood principally in July and August, while rivers to the east and west tend to flood more in September - October or November - June.

Flooding is seldom regional in southern Utah in terms of coincidence in the date or timing of annual flood peaks. A comparison of the timing and magnitudes indicates that flood events are rarely regionally synchronous (see fig. 30). For example, the largest recorded floods on the San Juan and Paria Rivers resulted from fall storms, but occurred in 1927 and 1925, respectively. The Virgin River's largest recorded flood occurred during the winter of 1966,

TABLE 12. Seasonality of major, historic floods in southern Utah.

River	Drainage Area (km2)	PERCENTAGE OF TOTAL FLOODS, 1850 - 1980 Nov-Jun	Jul-Aug	Sep-Oct
Virgin River	9920	20	50	30
Kanab Creek	510	6	61	33
Paria River	4070	7	71	21
Escalante River	810	0	92	8
Fremont River	3130	11	53	37
San Rafael River	2410	6	72	22
Price River	3990	0	76	24
Pack and Mill Creeks	150-190	14	57	29
San Juan River and tribs.	59,570	11	15	74

Compiled from Appendix 1.

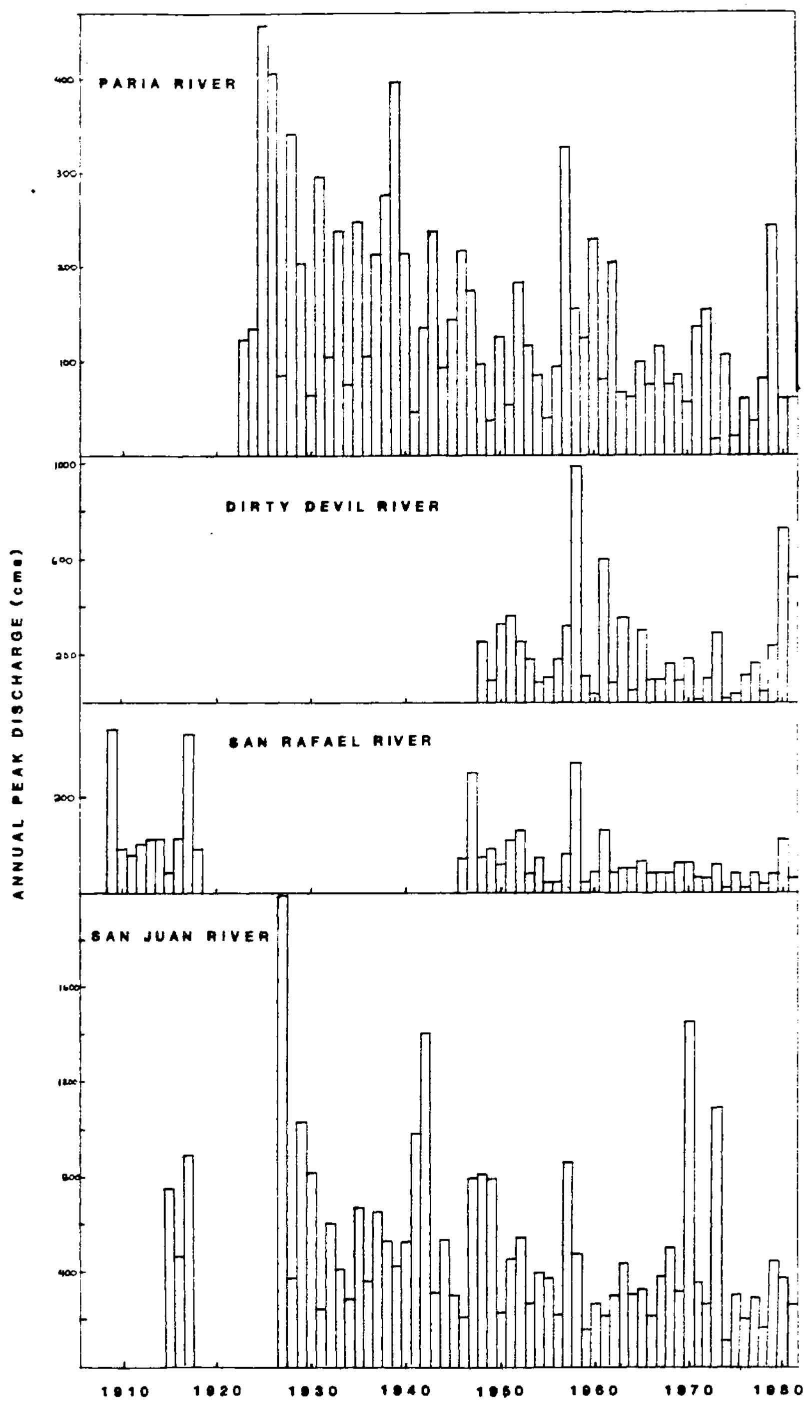


FIGURE 30. Annual peak discharges for four major rivers in southern Utah.

while the Dirty Devil (Fremont) River flooded in the winter of 1958. The 1909 flooding (see Chapter 1) is the only regional flooding which can be attributed to a single storm in southern Utah.

Only 41% of the recorded flood peaks for 28 rivers on the Colorado Plateau (1087 gaging station years) were coincident in date (within 1-2 days) with another flood peak. Of the largest floods of record, only 51% were coincident with one or more flood peaks; 39, 54, and 7% of the floods occurred during the fall, summer, and winter months, respectively. The largest floods of record for the 28 rivers are apparently randomly distributed in time, suggesting no regional controls on flooding between drainage basins. Rivers on the Colorado Plateau appear to flood normally in response to essentially random, local storms, and the size and coordination of the storms are the most important regional climatic factors.

Coincidence of Virgin River Floods

The flood records at three stations along the Virgin River -- near Springdale, at Virgin, and at Littlefield -- were compared for coincidence of annual flood peaks and major floods on the same river between 1930 and 1971 (fig. 31). The dates of the annual flood peaks were distributed with 33-40% during the winter, 36-38% during the summer, and 22-31% during the fall. Only 12 to 29% of the annual flood peaks occurred on the same date, while 38-50% occurred

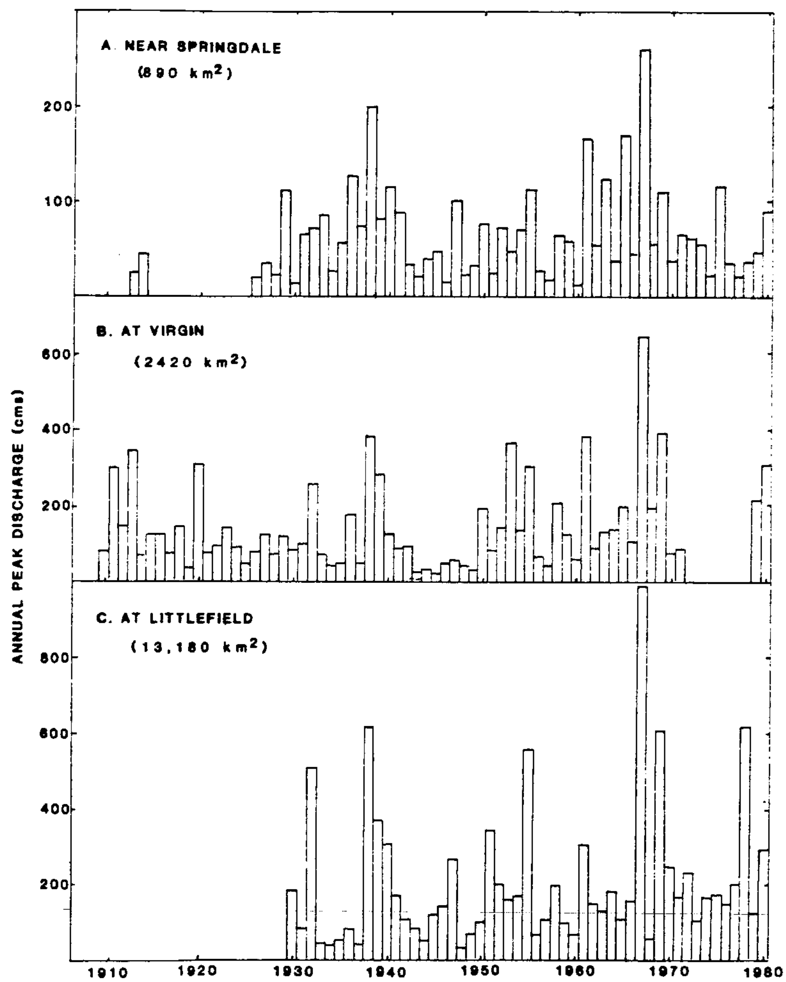


FIGURE 31. Annual peak discharges for three stations on the Virgin River in southwestern Utah.

during the same storm and 71-79% occurred during the same season. Of the 10 largest floods at each station, 30-50% occurred on the same date, 50-60% occurred during the same storm (within 1-2 days), and 60-70% occurred during the same season. Large system-wide floods were recorded on the Virgin River on March 3, 1938, August 25, 1955, December 6, 1966, and January 25, 1969. These results suggest that the timing of annual flood peaks, with the exception of large events, may be nonsynchronous even at different sections of the same river.

Flood-Frequency Analysis

The annual flood-peak records for Colorado Plateau rivers and streams were analyzed for flood frequency using the log-Pearson type III probability distribution (Water Resources Council, 1981). The flood-frequency curves for six major southern Utah rivers indicate that flood-frequency curve shapes are extremely variable (fig. 32). The skew coefficient, the determinant of curve shape and the most important variable for prediction of infrequent events, varies from +0.27 to -0.88 for these rivers.

A histogram of skew coefficients for 100 drainages, each with 10 or more years of record, suggests that the skew coefficient is normally distributed with a mean of -0.23 and variance of 0.81 (fig. 33; see Appendix 3). This generalized mean skew coefficient is close to the -0.1 value

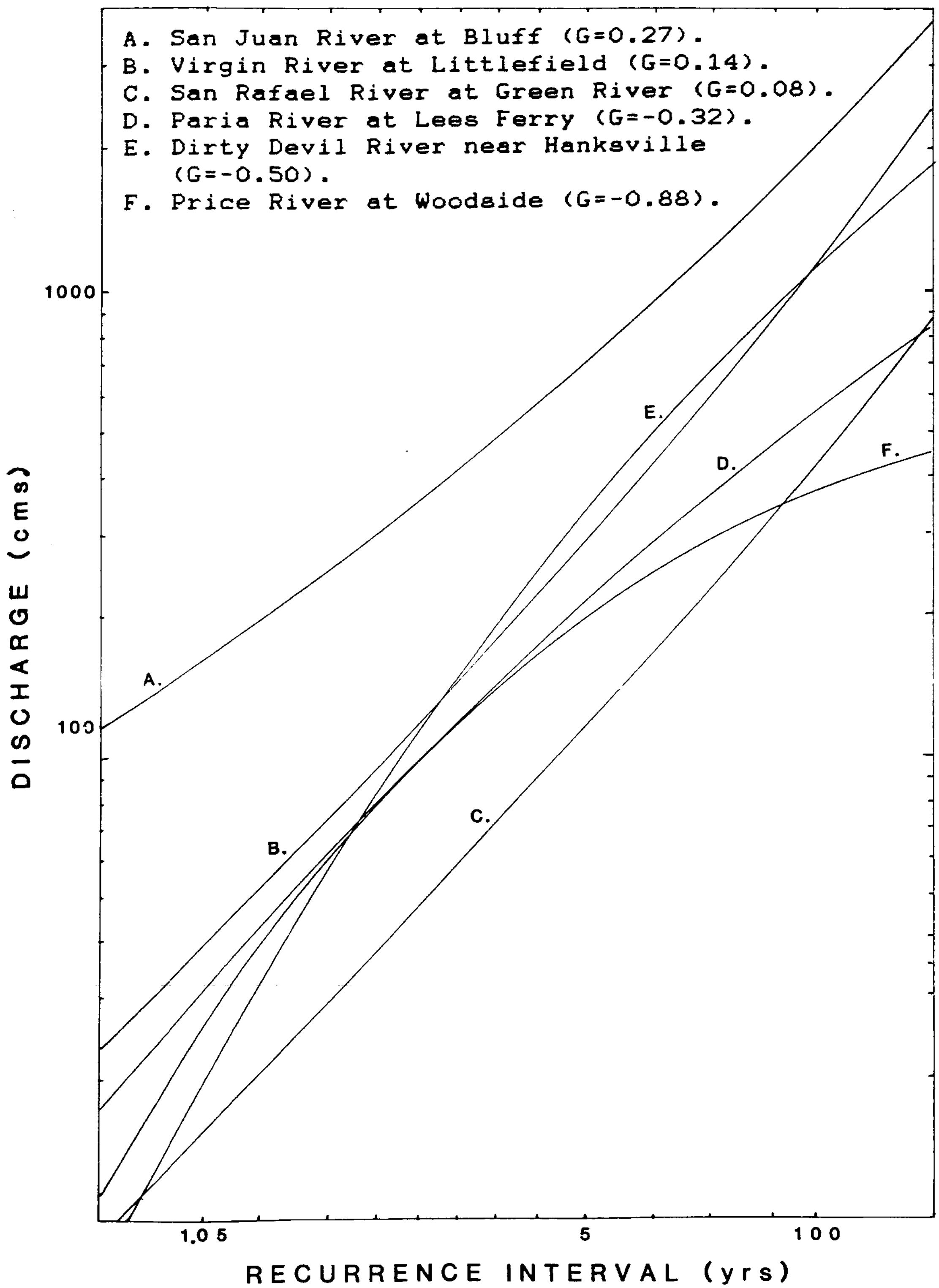


FIGURE 32. Log-Pearson type III flood-frequency curves for six major rivers in southern Utah.

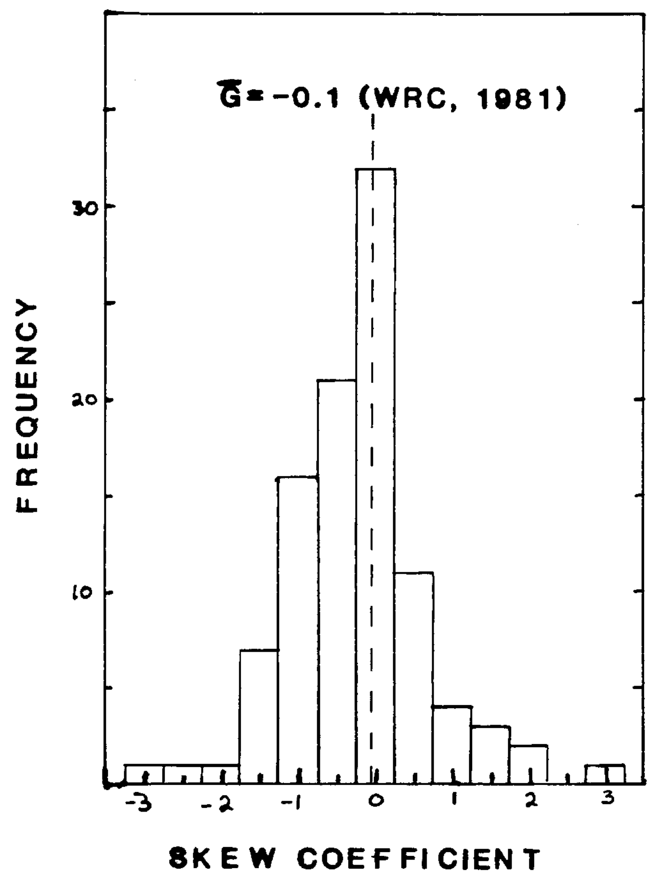


FIGURE 33. Histogram of log-Pearson type III skew coefficients for 100 drainages on the Colorado Plateau.

given by the Water Resources Council (1981). The skew coefficient for 32 stations with greater than 20 years of record ranged from +0.3 to -1.5 with a mean of -0.15. No significant statistical relationship was obtained between the skew coefficient and drainage-basin size or mean elevation.

Prediction of the 100-year flood in southern Utah is uncertain due to problems with the determination of log-Pearson type III, and presumably other, skew coefficients. The histogram of skew coefficients (fig. 33) is suggestive of random sampling from a normal distribution with a mean close to 0.0 and variance close to 1.0. Thomas and Lindskov (1983) developed a prediction equation for 100-year floods using multiple regression of drainage-basin characteristics in an attempt to correct this problem; they obtained standard errors of 65 to 87% for the "Low Plateaus" region of southern Utah. Lack of correlation between basin characteristics and the skew coefficient suggests that individual drainage-basin characteristics, rather than regional factors, are the most important determinants of flood frequency in southern Utah.

Annual Climate and Floods

Changes in annual precipitation and climate have been proposed as the cause for channel change since the first research on arroyos in the Southwest was published (see Huntington, 1914). The current model (Hereford, 1984) depicts channel changes during periods of climatic fluctuation, with incision occurring during periods of higher temperature and precipitation, and floodplains forming during periods of drought. This model can be tested for channel change on the Escalante River and other rivers in southern Utah.

Annual Floods and Annual Climate

The relationship of annual flood peaks and annual runoff volume was investigated to determine if floods are larger during wetter or drier years. The annual runoff volume of a drainage basin reflects the complicated interactions of precipitation, temperature, and drainage-basin characteristics. Absolute values of annual runoff volume may not reflect the absolute regional climate, yet fluctuations in annual runoff volume should serve as an accurate index of climate. Use of tree-ring widths, sensitive to climatic fluctuations, in the prediction of prehistoric runoff volumes (see Stockton and Boggess, 1979) further underscores the relationship.

The gaging record of the Paria River at Lees Ferry, Arizona, graphically shows the relationship between annual runoff volume and peak discharge (fig. 34). The correlation coefficient between the two variables is 0.70 for this river (r^2=0.49). Little temporal trend is apparent in the runoff volume, while the trend in annual peak discharges has been

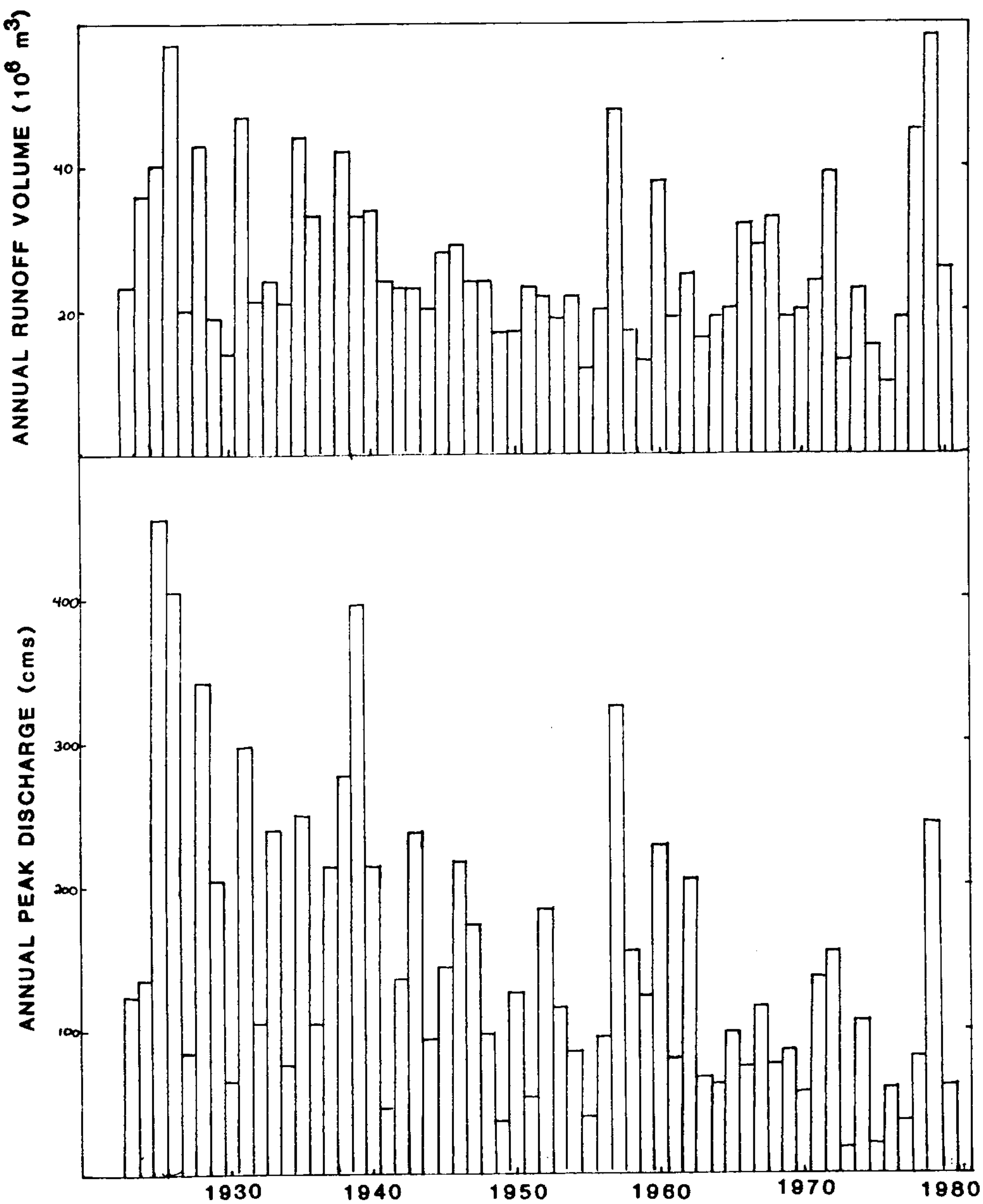


FIGURE 34. Annual runoff volumes and peak discharges for the Paria River at Lees Ferry, Arizona.

decreasing since the 1920's. Floods on the Paria River are responding to a different factor than annual climate, possibly land-use changes and reseeding projects in the headwaters (Chidester and Bruhn, 1949).

Summer thunderstorms of small areal extent generate most of the flash floods in southern Utah, hence the drainage-basin area was considered an important variable. Rivers with large drainage areas should better reflect annual climate in their flood records than rivers with small areas because the influence of individual thunderstorms is lessened. Figure 35 shows the correlation coefficients of annual runoff volume and peak discharge for 34 Colorado Plateau rivers with records greater than 14 years in length plotted by drainage-basin area. No significant relationship was obtained either using the actual data (fig. 35A) or ranks of the data (fig. 35B), the latter reducing any nonlinear influences. Fifty-three percent of the stations studied had rank-order correlation coefficients less than 0.5 (or less than 25% of the variance explained), indicating that annual climate is a poor predictor of the size of the annual flood peak regardless of basin size. Even the high correlation coefficients are suspect; Moenkopi Wash, with a correlation coefficient of 0.84 (fig. 36), exhibits a classic spurious correlation between two clouds of data points (Haan, 1977).

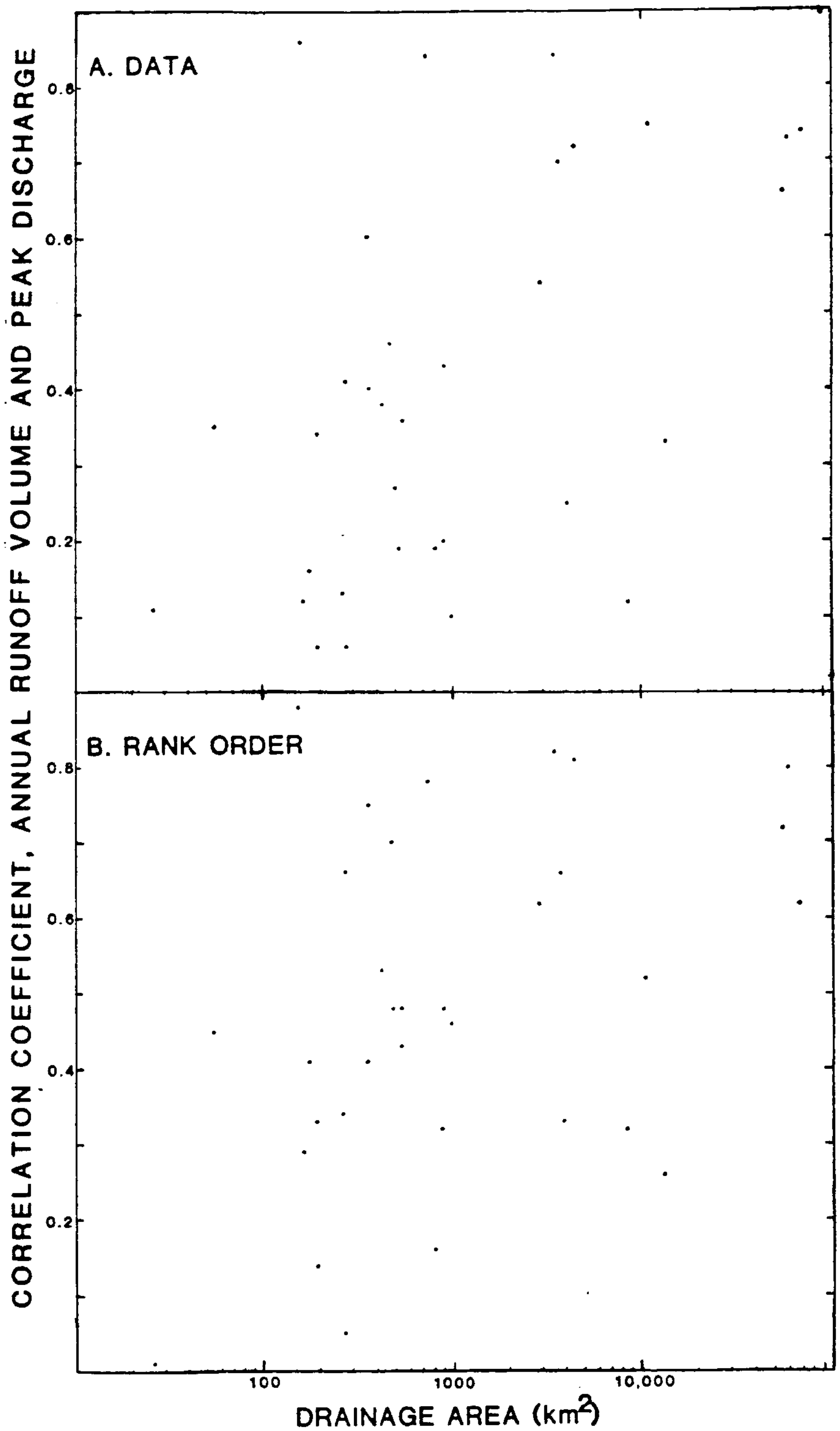


FIGURE 35. Correlation coefficients between annual runoff volume and peak discharge for 34 drainages on the Colorado Plateau.

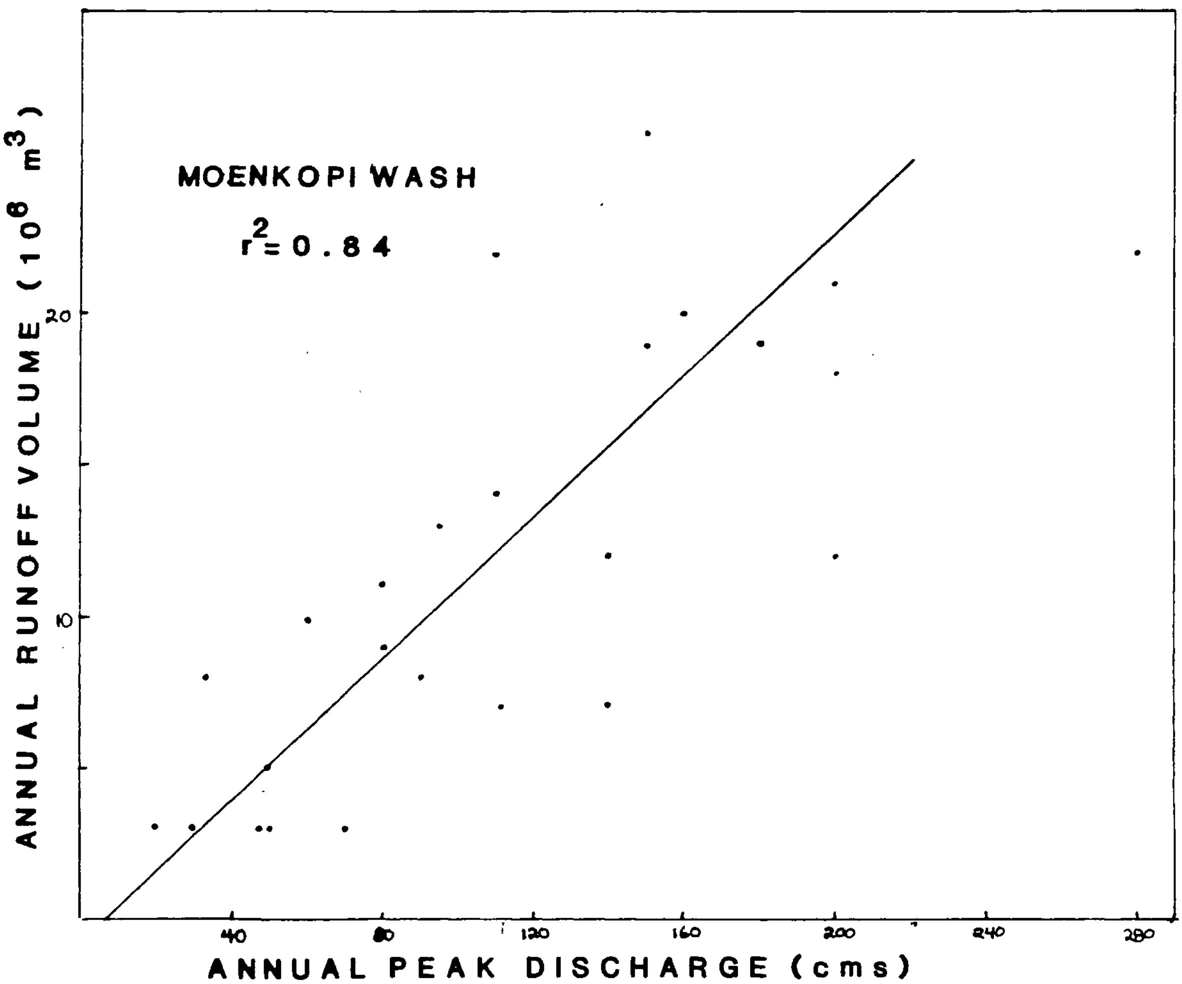


FIGURE 36. Correlation between annual runoff volume and peak discharge for Moenkopi Wash, northern Arizona.

Large Floods and Annual Climate

The relationship between large flood events and annual climate was investigated to determine if extreme events occurred during predominantly wet or dry years. A tree-ring chronology from the Escalante River basin (fig. 37; S. Clark, written comm., 1984) was examined for correlation with historic floods. Large ring-width indices (greater than 1, see dashed line, fig. 37) are inferred to be years wetter than normal, while small ring-width indices indicate the opposite (Stockton and Boggess, 1979). This chronology is similar to that for northwestern New Mexico (Rose and others, 1982), indicating a regional representation. The 1909 general flooding corresponds with the year with the widest rings in the period of 1850 to 1980. However, other large floods, such as the Virgin River floods of 1862, 1889, and 1966; the Kanab Creek flood of 1883; and the Escalante River flood of 1932; occurred in years of normal or slightly wider rings than normal. The large floods in 1896 on the Fremont River and Pack and Mill Creeks (Chapter 1) occurred during a drought year on the Colorado Plateau (Gregory and Moore, 1931; fig. 37).

The dates of the four large historic floods on the Escalante River were compared with the annual precipitation record at Escalante (fig. 4). The floods occurred between 1909 and 1932, a period little different from the rest of the record. The mean annual precipitation for the four

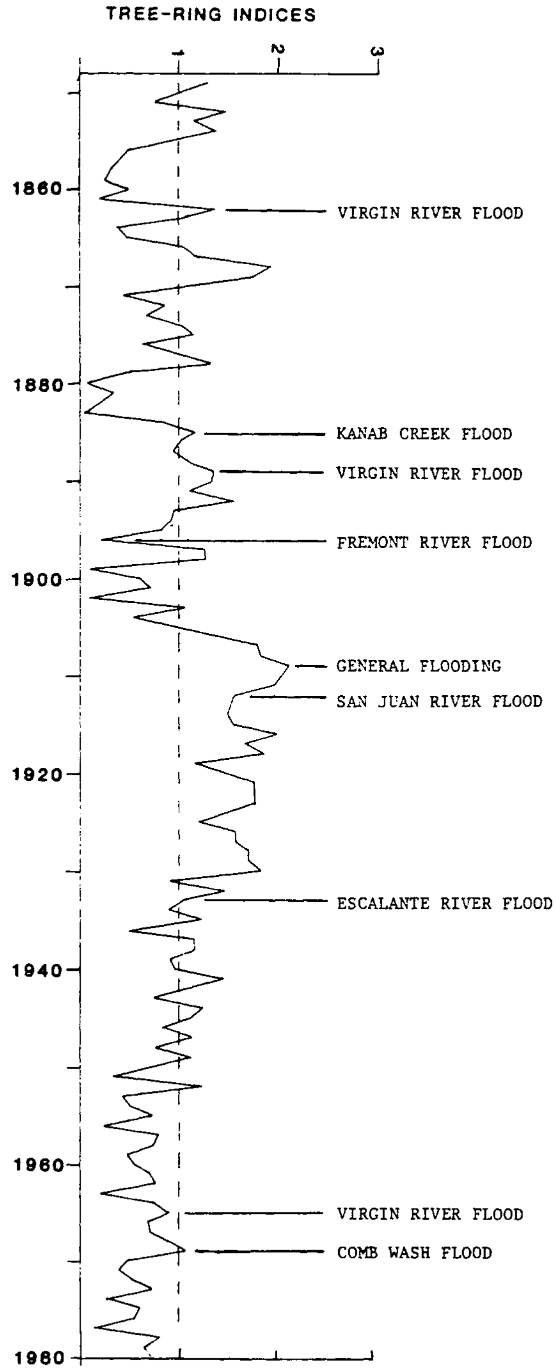


FIGURE 37. Tree-ring width indices for *Pinus ponderosa* from Upper Valley (S. Clark, written comm., 1984).

Floods shown are described in Chapter 1 with dates given in Appendix 1.

years 1909, 1916, 1927, and 1932 was 440 mm, or about 50% higher than the mean annual precipitation of 295 mm for the entire record. However, while 1927 had the highest annual precipitation in the record (551 mm), 23 other years had a higher annual precipitation than the 346 mm in 1909. Four years had a higher annual precipitation than the 449 mm in 1932. The mean annual precipitation for 1909-1932, a period of increased flood frequency, was 315 mm, or only 7% greater than the mean annual precipitation for the entire record. The coefficients of variation for the 1909 - 1932 period and the rest of the record are 0.28 and 0.33, indicating little difference in variability between the periods.

Floods, therefore, are not necessarily related to local or regional annual climate. Channel changes on the Colorado Plateau were initiated during the 47 years from 1862 to 1909, a period when the climate as inferred from tree-ring widths was highly variable (fig. 37). No trends are apparent in this period which greatly differentiate it from periods before or after (see Rose and others, 1982). While large floods on the Escalante River occurred during years of greater than normal annual precipitation, other years with higher precipitation did not have large floods. Therefore, annual climate is not an appropriate factor for assessing the cause for climate change on the Colorado Plateau.

Summer Precipitation at Escalante

Floods on the Escalante River occur primarily in the month of August (table 12). Fluctuations in the number and intensity of summer storms, therefore, may be a climatic cause for floods. Rainfall records have been kept at Escalante from April 1901 to the present although some data is not published in "Climatological Data for Utah" (e.g. Thiessen, 1910). An analysis of the available records suggests a subtle change in summer precipitation in the period of 1909 to 1932.

Monthly Precipitation

A contour map of monthly precipitation at Escalante (fig. 38) illustrates a shift in the seasonality of precipitation. While annual precipitation has not changed, the amount of precipitation during July and August has decreased after 1932. The densely packed contours characterizing July and August in the period 1909 - 1932 suggest a period of wetter-than-normal summers (fig. 38). Only the summer of 1955 appears to have the same amount of summer precipitation as the period of 1909 - 1932. However, densely packed contours in October and November after 1932 suggest that precipitation shifted to the fall months, probably falling as snow at higher elevations, maintaining the annual precipitation totals.

Correlograms of monthly precipitation (not shown) revealed no significant inter- or intra-annual

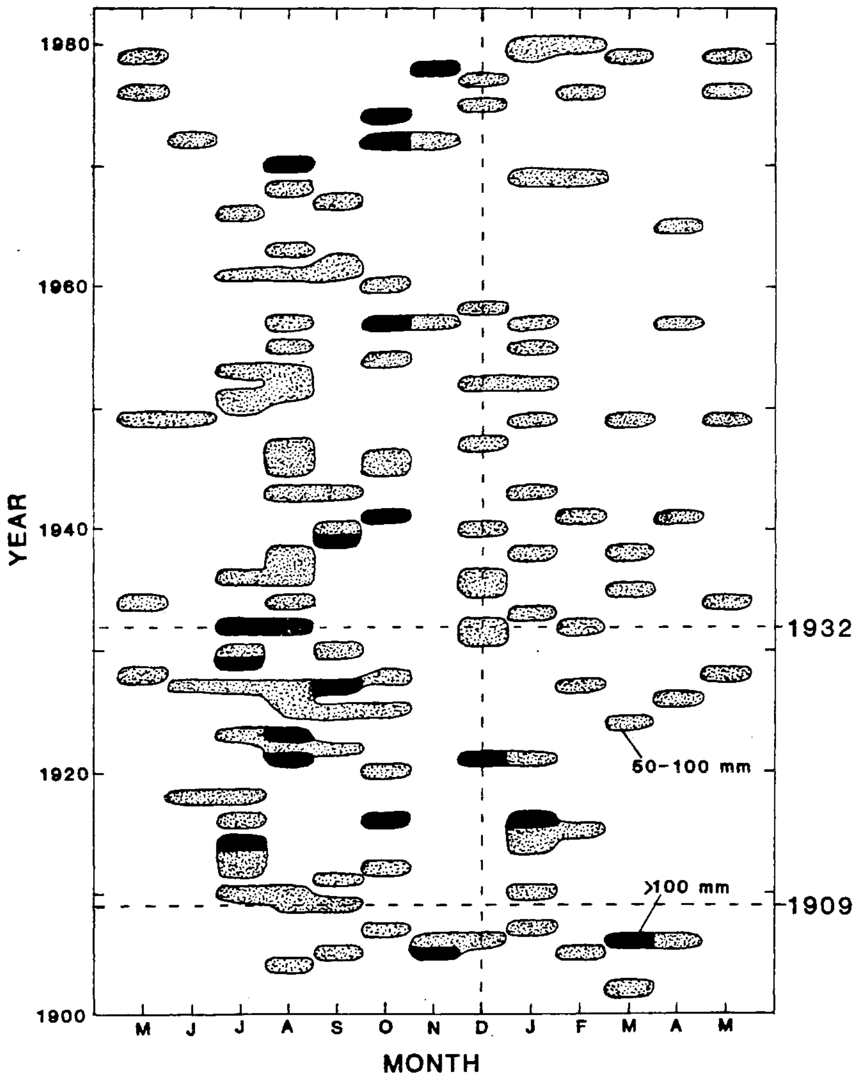


FIGURE 38. Contour map of monthly precipitation for Escalante, Utah, from 1902 to 1982.

relationships. The highest correlation coefficient among monthly precipitation was for March and April, with r = 0.3. August precipitation had correlation coefficients close to zero for every month except December, with r = 0.2. The lag-1 inter-annual correlation coefficient for August precipitation was -0.05, with the largest r-value in 7 lags equalling -0.373 (lag 3). These results indicate no persistence in precipitation amounts month-to-month or for August year-to-year. Variability in the monthly precipitation is larger than any subtle changes in intra- or inter-annual precipitation.

Summer Precipitation

An analysis of summer precipitation revealed a possible subtle change which could be responsible for the large floods. Precipitation during the summer months of June-September (fig. 39) is highly variable during the period of 1909-1932 and less variable during the rest of the record. Coefficients of variation of 0.54 for 1909-1932 and 0.39 for the rest of the record denote the magnitude of the change. The mean summer precipitation for 1909-1932 was 36% larger than the summer precipitation during the rest of the record.

Daily precipitation records, although fragmentary, suggest a change in the intensity of storms (fig. 39). The period of 1909-1932 had more frequent, large storms than the rest of the record. Four daily precipitation totals

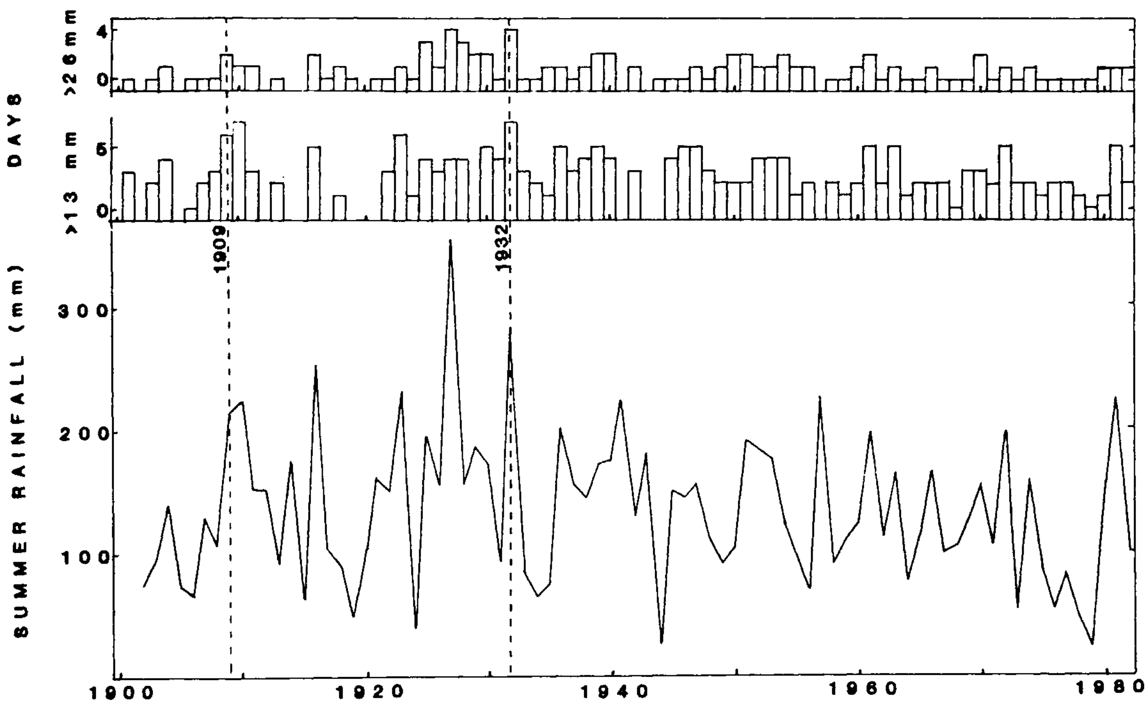


FIGURE 39. Total summer (July-September) rainfall and frequency of rainfall intensities for Escalante, Utah.

exceeded 26 mm during the summers of 1927 and 1932, the former a year with a suspected large flood and the latter the year of the largest historic flood on the Escalante River. The four years with the highest number of storms exceeding 13 mm are 1909, 1910, 1923, and 1932 (fig. 39). Total number of storms, defined as the number of days with trace or greater precipitation, appeared to be related more to the observer changes than to any climatic factor.

High daily precipitation totals do not necessarily indicate the occurrence of a flood. Daily totals of 56 and 55 mm were recorded in August, 1947 and 1955, yet large floods did not occur. A daily total of 82 mm recorded in July, 1932, was related to a relatively minor flood, but the daily total for the August 27, 1932, flood was only 31 mm. Only 41 mm of precipitation was recorded the day of the disastrous August 1909 flood. Point precipitation records do not necessarily reflect basin-wide conditions because of the strong orographic components of summer precipitation. However, the Escalante precipitation record suggests some subtle shifts which may be responsible for the large flood events and channel change.

Implications of the Climatic Record

A concentration of precipitation in the summer months and a subtle shift in the intensity of summer precipitation may be responsible for the generation of large floods, and ultimately the initiation of an arroyo, on the Escalante River. The period of 1909 - 1932 had higher summer precipitation and more intense storms than the rest of the period of record; the arroyo in Upper Valley was initiated and fully coalesced during this period (Chapter 3) in response to large flood events (Chapter 2). No other, widely applied climatic index (e.g. annual precipitation) could explain the anomalous 1909 - 1932 period.

A shift to more high-intensity and less low-intensity summer storms has been proposed as the cause for arroyos in New Mexico (Leopold, 1951b) and possibly for southern Arizona (Cooke, 1974). Similar kinds of changes have been observed in records from Santa Fe, New Mexico, and Tucson, Arizona, as is found in the Escalante record. However, the timing of the changes is not in phase among the sites. Data in Leopold and others (1966) indicate that the period of 1855 to 1880 is anomalous in the New Mexico record, and the period of 1909 - 1932 does not appear unusual. Cooke (1974) found significantly higher intensities of precipitation, with no change in annual precipitation, during the period of 1866 - 1916 compared with 1917 - 1966 for southern Arizona. The Escalante precipitation record, therefore, is unusual with its later shift in intensities, although lack of pre-1901 data precludes a statistical comparison with Leopold's (1951b) and Cooke's (1974) data.

Climatic change, in the form of shifts in intensity and seasonality of precipitation, is a possible cause for the initiation of the arroyo on the Escalante River. Several data deficiencies reduce the certainty of this conclusion, however. The Escalante precipitation record is of insufficient length to determine if a similar subtle shift occurred prehistorically with or without an associated arroyo. Tree-ring widths, the only available climatic proxy before 1901, indicate favorable growing conditions between 1905 and 1925 (fig. 37) which is not reflected in the annual or summer precipitation records (figs. 4 and 39). Inspection of Rose and others' (1982) and the Escalante (S. Clark, written comm., 1984) tree-ring records revealed other time periods of sustained, above-average ring widths in the periods of 1825 - 1830, 1715 - 1725, and 1615 - 1621 AD. Large arroyos apparently did not form on the Escalante River during these periods as indicated in the stratigraphic record (see Chapter 3).

CHAPTER 5

THE CAUSE OF THE ARROYO IN UPPER VALLEY

The detailed record of historic and prehistoric channel changes in Upper Valley provides an opportunity to test hypotheses for the cause of arroyos. Poor land-use practices, a subtle climatic shift, the random occurrence of a large flood, and/or intrinsic geomorphic processes could have induced the initiation and coalescence of the arroyo between 1909 and 1940. The purpose of this chapter is to briefly describe some hypothetical scenarios, and to ascertain whether a cause can be determined for the arroyo in Upper Valley.

Scenarios of Arroyo Formation

Land-Use Practices

Poor land-use practices were associated with the initiation and coalescence of the arroyo in Upper Valley (fig. 40). Grassy meadows described in 1872 were replaced with sagebrush by 1893 in response to overgrazing. Native vegetation on the floodplain was cleared for agricultural fields, and the pre-arroyo channel was modified with headgates and canals for irrigation works. Both the

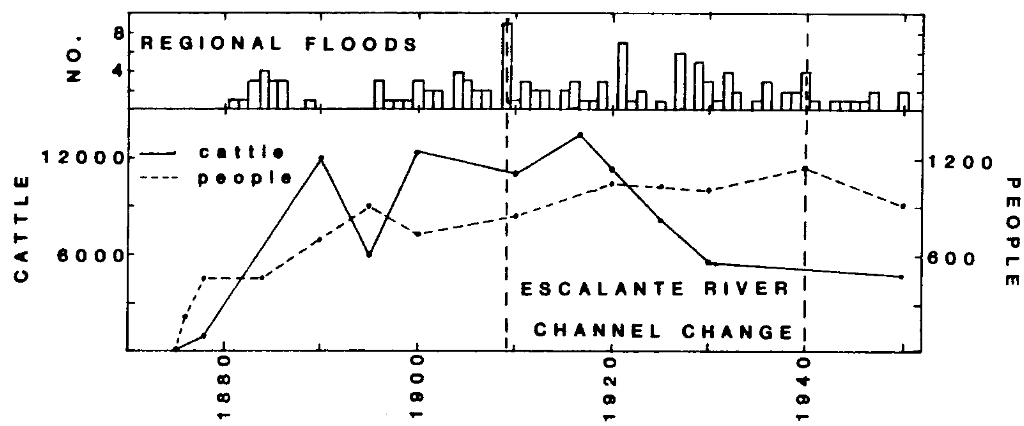


FIGURE 40. Association of population and cattle numbers with floods and channel change on the Escalante River.

Population and cattle numbers are from Table 9. Floods were compiled from Appendix 1.

population of Escalante and the peak in livestock grazing were at their maximum levels between 1910 and 1920, at the start of the arroyo incision. Moreover, reductions in livestock numbers and reseeding projects are associated with the lack of significant channel change between 1940 and 1984.

Land-use practice is a compelling hypothesis for the cause of arroyos. Its chief detraction has been the alleged lack of human influences associated with paleoarroyos (Bryan, 1940; Leopold, 1976). Recent studies (e.g. Betancourt and Van Devender, 1981) have demonstrated human-induced vegetation changes by the Anasazi in Chaco Canyon, New Mexico. The presence of aboriginal artifacts in flood deposits (Chapter 2) indicates the direct association of Fremont or Anasazi Indians with the largest paleoflood around 900 yrs BP. Although no evidence is available to support aboriginal-induced watershed changes associated with the paleoarroyo in Upper Valley, prehistoric land-use effects cannot be summarily dismissed as negligible.

In this hypothetical scenario, land-use practices caused a severe modification of watershed and floodplain conditions on Upper Valley Creek. The late-August, 1909, storm dropped intense rainfall on grass-impoverished slopes, leading to more rapid runoff and higher runoff volumes than occurred from similar storms prior to settlement. The runoff was concentrated in a channel destabilized with irrigation works, and the cleared floodplain provided less flow resistance, causing higher flow velocities and bed-shear stresses. The resulting erosion would not have occurred from the 1909 storm if land-use practices had not destabilized the hydrologic system.

Climatic Shift

A subtle climatic shift in the seasonality and intensity of summer precipitation was associated with the period of 1909-1932, wherein the arroyo was initiated and probably fully coalesced. A larger number of intense summer storms in highly variable but generally wetter summers manifested this change. Because of the short length of the precipitation record (81 years) and lack of correlation with tree-ring records, the uniqueness of this subtle change over the last 2000 years could not be determined.

In this scenario, a subtle climatic change induced channel changes in Upper Valley. Rainfall in the summer, the only season for floods on the Escalante River, increased in total amount and intensity between 1909 and 1932. General storms, such as cutoff lows and tropical storms, were more frequent in late August, leading to high, basin-wide rainfall on already saturated watersheds. The resulting floods had peak discharges far greater than floods before or after this period, leading to an erosion of the channel bed which would have occurred without the concurrent, poor land-use practices.

Land-Use and Climatic Shift

A synthesis of the preceding two hypotheses can be formulated as causes for the Upper Valley paleo- and modern arroyos. In this scenario, periodic changes in summer precipitation have induced the formation of small arroyos such as the paleoarroyo in Upper Valley. Land-use practices, however, caused severe watershed changes by 1900. When the latest climatic shift occurred between 1909 and 1932, the floods became larger and more erosive than during the preceding changes. This scenario can be used to explain the size difference between the large modern arroyo, with associated poor land-use practices, and the relatively small paleoarroyo, with presumably less severe Anasazi and Fremont land-use practices.

Random Flood Events and Positive Feedback

The August-September 1909 storm induced floods on all the rivers in southern Utah, a unique event in 120 years of historical record (fig. 41). In this scenario, the 1909 storm was an extreme event random in time unrelated with the subtle climatic shift. Runoff from saturated hillslopes was sustained over several days during the four-day storm, causing unprecedented erosion of the channel bed which would have occurred regardless of poor land-use practices. The post-storm channel consisted of a series of unstable, headward-eroding knickpoints which coalesced during successive, smaller floods. Decreased flow resistance and

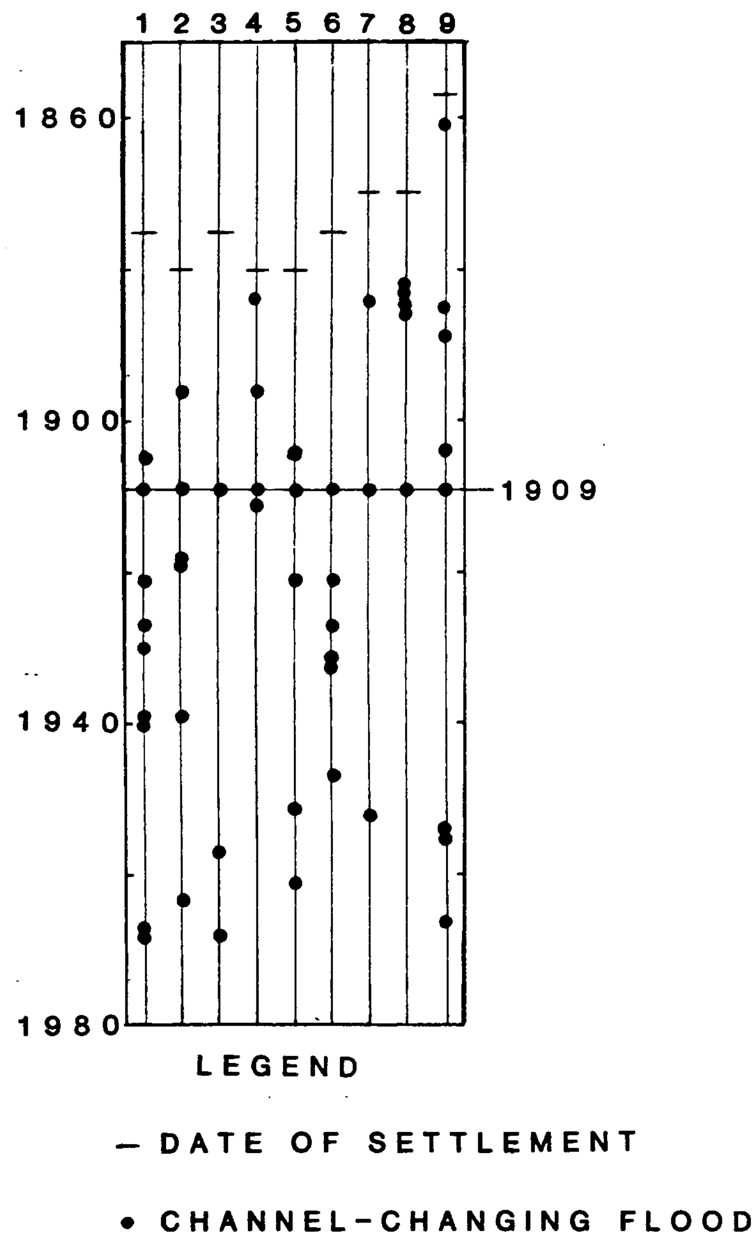


FIGURE 41. Years of channel-changing floods in southern Utah.

Dates are given in Chapter 1 and Appendix 1. 1.-- Price River, 2.-- Pack and Mill Creeks, 3.-- San Rafael River, 4.-- San Juan River, 5.-- Fremont River, 6.-- Escalante River, 7.-- Paria River, 8.-- Kanab Creek, 9.-- Virgin River.

increased hydraulic efficiency due to channelization caused a large increase in the peak discharge of the post-1909 floods. The subtle climatic change between 1909 and 1932 could have played a role in the rapid coalescence of the arroyo, but the initiation was due solely to a random, extreme storm event. The succeding large floods resulted primarily from the positive feedback of increased hydraulic efficiency resulting from the 1909 flood.

Intrinsic Geomorphic Processes

Land-survey notes and the diaries of the Thompson Expedition (Chapter 3) indicate the presence of discontinuous ephemeral-stream channels in Upper Valley before 1892. These headcuts -- at Liston Flat and the Birch-Upper Valley Creek confluence (fig. 21) -- were located where tributaries entered the main channel. "Critical valley oversteepening" (Schumm and Hadley, 1957) may have occurred through tributary addition of sediments to Upper Valley Creek's floodplain at these sites. From observations, the highest arroyo walls on Upper Valley Creek are near the major tributaries of Birch Creek, Allen Canyon, and South Hollow (see fig. 21).

This scenario follows the argument presented by Schumm (1979; fig. 42). Episodic erosion is the dominant control of channel change on Upper Valley Creek. The channel floodplain became increasingly unstable after the

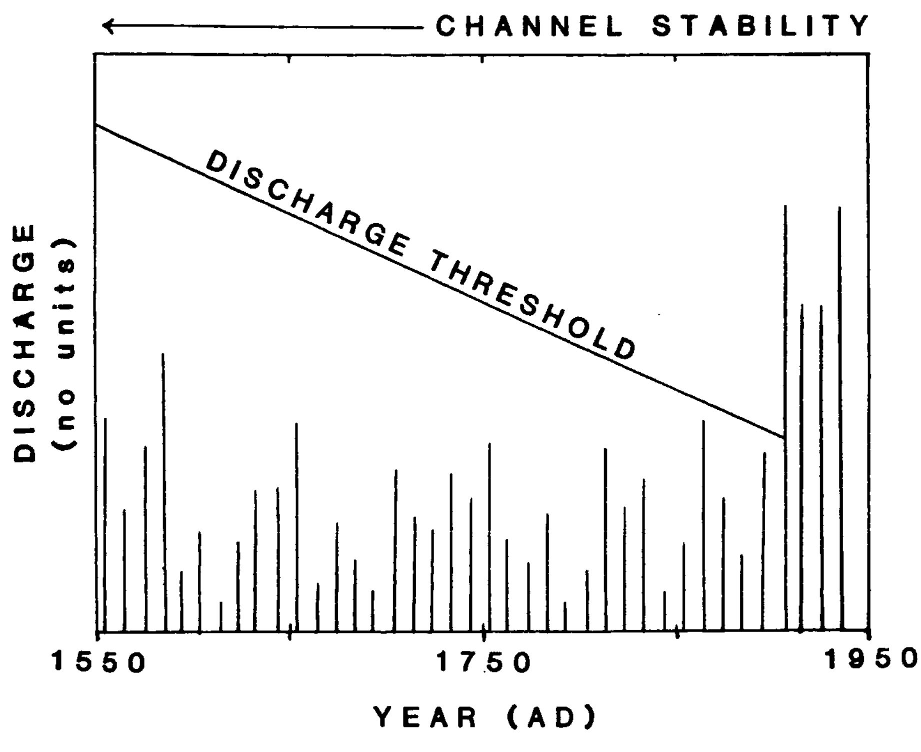


FIGURE 42. Scenario of increasingly unstable floodplains and decreasing "discharge threshold" for the Escalante River.

filling of the paleoarroyo approximately 400 yrs BP. Excessive deposition of sediments at tributaries to Upper Valley Creek created an unstable valley slope because the base level of the bedrock canyon had not changed. A "discharge threshold" required for net erosion of the channel decreased with time. Large floods which would not have eroded the stable floodplain eroded headcuts into the unstable floodplain in the late 1800's. The 1909 storm "exceeded the threshold" of floodplain resistance to erosion, leading to coalescence of an arroyo which would have inevitably formed (fig. 42).

What Caused the Arroyo?

As the preceding scenarios indicate, several hypotheses can be proposed as the cause for the arroyo on the Escalante River. None of these hypotheses can be completely rejected. Each is based on some direct evidence obtained from the Escalante River basin, emphasizing some evidence and de-emphasizing other evidence. However, innate problems with the methodology, missing information, and lack of hypothesis testing preclude determination of a cause.

All of the proposed causes for the arroyo are based on circumstantial evidence without a direct, causal link with the arroyo. Although many studies have demonstrated the ramifications of intense land-use on watersheds (e.g. Marston, 1952), the effect of shifts in vegetation induced from poor land-use practices is not readily determined. The amount and spatial distribution of watershed changes on Upper Valley Creek are not known due to insufficient records, and the influence of any changes in increasing peak discharges or destabilizing floodplain conditions is therefore speculative.

The subtle climate shift during the period of 1909 to 1932 is a compelling cause for the arroyo. However, no evidence is available to indicate that prehistoric shifts in climate of equal or greater magnitude have occurred <u>without</u> initiating an arroyo. Tree-ring records, the only available proxy for extension of climatic records, do not indicate the subtle change. Lack of an appropriate proxy for climate, therefore, precludes a testing of this hypothesis.

The intrinsic-geomorphic-processes and random-flood-event scenarios are beset with similar problems. Quantification of "critical valley oversteepening" is extremely difficult, and "thresholds" may vary significantly within a single river system (Begin and Schumm, 1984). The timing of the random-flood event with respect to the instability of the floodplain is uncertain. Moreover, it is speculative whether or not a flood of a certain magnitude would scour the Upper Valley Creek floodplain without land-use effects.

Despite the uncertainty concerning causality, several factors are associated with the initiation of the modern arroyo on the Escalante River. A large flood, induced from a storm during a period of subtle climatic shift, initiated headcuts which coalesced during successive floods into a large, continuous arroyo. Poor land-use practices also were associated with the initiation of the arroyo, but their influences are unclear and speculative. The modern arroyo is the largest channel to form on Upper Valley Creek in 1600 years. A smaller paleoarroyo was initiated around 1100 yrs BP.

A nonstationarity in the frequency of large floods is associated with the paleo- and modern arroyos. A series of four modern floods and 3 to 5 paleofloods radiocarbon dated from 1200 to 900 yrs BP occurred during periods when arroyos were present on Upper Valley Creek. The association of paleofloods with a paleoarroyo, the initiation of an arroyo on the Escalante River during a large flood, and historic evidence of floods initiating arroyos on every river in southern Utah during the historic period indicate that unusual, large flood events are the principal agents of channel change on the Colorado Plateau. Future research on arroyos should concentrate on the climatic, anthropologic, and geomorphic significance of large flood events in the initiation of arroyos in the geologic past.

APPENDIX 1. Dates of historic floods on 10 rivers or regions of southern Utah.

YEAR	CEDAR CITY CREEKS	VIRGIN RIVER	KANAB CREEK	PARIA RIVER	ESCALANTE RIVER	FREMONT RIVER	SAN JUAN R. AND TRIBS	SAN RAFAEL RIVER	PACK & MILL CREEKS	PRICE RIVER
1850										
1851	*****									
1852										
1853	9/3									
1854										
1855										
1856										
1857		*****								
1858										
1859										
1860										
1861		1/8,1/18,2/4								
1862										
1863										
1864										
1865										
1866										
1867										
1868										
1869										
1870	7/25		*****	*****						
1871										
1872	9/2									
1873										
1874										
1875					*****			*****		*****
1876										
1877										
1878										
1879										
1880						*****	*****		*****	
1881		8/11								
1882			8/30							
1883		7/21	7/29	7/?						
1884			3/12	3/13			3/16,6/18			
1885		7/4	9/10				SPRING			8/23
1886			4/12,8/18-31				SPRING			
1887										
1888										

Dates were compiled from many sources, principally Woolley (1946) and Butler and Marsell (1972). Dates for channel-changing events are underlined.

APPENDIX 1. Dates of historic floods on 10 rivers or regions of southern Utah (continued).

YEAR	CEDAR CITY CREEKS	VIRGIN RIVER	KANAB CREEK	PARIA RIVER	ESCALANTE RIVER	FREMONT RIVER	SAN JUAN R. AND TRIBS	SAN RAFAEL RIVER	PACK & MILL CREEKS	PRICE RIVER
1889		12/7-15								
1890										
1891										
1892										
1893										
1894										
1895										
1896			7/5			9/22			9/22	
1897								9/12		
1898									10/7	
1899								7/30		
1900						9/9			9/3	
1901		8/2				8/4				
1902		7/25,8/13								
1903										
1904	7/22	7/21,7/26				8/16				
1905		8/24						8/26		8/24
1906		8/20		8/13						
1907	8/12,8/21									
1908										
1909		9/1	9/1	9/1	8/29,8/31	9/1	9/4	9/2	9/2	8/31
1910									7/22	
1911						10/?	10/7		9/?	
1912		10/12		SUMMER						
1913								9/8		7/19
1914										
1915	7/25						8/26			
1916					10/6?	11/6			8/13	
1917								10/8		
1918									6/28	
1919									8/2	8/20,9/7
1920										
1921	8/20				8/31	9/3	9/?	7/17		7/29,8/23
1922										8/21
1923				7/23					8/16-29	
1924										
1925			10/5							
1926										
1927			9/13		8/27,9/13?		9/10			7/4-21, 9/12-13
1928										

Dates were compiled from many sources, principally Woolley (1946) and Butler and Marsell (1972). Dates for channel-changing events are underlined.

APPENDIX 1. Dates of historic floods on 10 rivers or regions of southern Utah (continued).

<u>YEAR</u>	CEDAR CITY <u>CREEKS</u>	VIRGIN <u>RIVER</u>	KANAB <u>CREEK</u>	PARIA <u>RIVER</u>	ESCALANTE <u>RIVER</u>	FREMONT <u>RIVER</u>	SAN JUAN R. <u>AND TRIBS</u>	SAN RAFAEL <u>RIVER</u>	PACK & MILL <u>CREEKS</u>	PRICE <u>RIVER</u>
1929				8/2			9/23	8/3		8/3,9/21
1930	8/13	8/8							<u>8/7</u>	
1931					<u>8/31</u>					
1932				8/21	<u>7/12,8/20,8/27</u>					
1933								7/12		8/26
1934										
1935								9/4		
1936	7/11	9/2							9/2	
1937										
1938		3/3				8/30				
1939									<u>8/28</u>	<u>9/9</u>
1940			8/7	9/6						<u>8/13,9/13</u>
1941							10/14			
1942										
1943										8/5
1944						8/18				
1945						9/2				
1946		10/31								
1947					<u>8/28</u>			8/22		
1948										
1949										
1950						8/?				7/21
1951					7/27-31	<u>8/4</u>				8/4
1952		6/3		<u>8/26</u>		7/28		7/27		
1953	7/14	8/1		9/9	7/18				7/23,8/27	
1954		8/4,<u>10/8</u>							8/13	10/8
1955	7/29	<u>8/25</u>	8/4						5/22,7/27	
1956										
1957			8/20	8/20,9/21				7/19,<u>8/6</u>	7/8,8/6,8/20	8/7
1958	7/23		9/12				9/12			
1959					8/2	11/4				
1960										
1961	8/10	9/17	7/4,9/?	8/1-4		<u>8/23</u>			7/30,8/26	7/5,9/10
1962							9/20			
1963	8/19			8/31		9/1	8/30		7/22,<u>8/8</u>	
1964	8/4	8/12	8/12					8/2		
1965	8/18	9/7				8/18		8/25	9/5,10/15	
1966		<u>12/6</u>			7/30				8/31	
1967	7/16,9/25				8/2			5/25,8/8	<u>6/5</u>,9/5	
1968	8/8					8/1	<u>8/1</u>	8/1,8/11	<u>8/1</u>	
1969	7/23	1/25						8/29,9/9	6/24	

Dates were compiled from many sources, principally Woolley (1946) and Butler and Marsell (1972). Dates for channel-changing events are underlined.

APPENDIX 1. Dates of historic floods on 10 rivers or regions of southern Utah (continued).

YEAR	CEDAR CITY CREEKS	VIRGIN RIVER	KANAB CREEK	PARIA RIVER	ESCALANTE RIVER	FREMONT RIVER	SAN JUAN R. AND TRIBS	SAN RAFAEL RIVER	PACK & MILL CREEKS	PRICE RIVER
1970			7/18				9/6			
1971										
1972							10/20			
1973										
1974										
1975		7/29								
1976										
1977										
1978										7/11
1979										
1980		9/10				9/10			9/7	9/11

Dates were compiled from many sources, principally Woolley (1946) and Butler and Marsell (1972). Dates for channel-changing events are underlined.

APPENDIX 2. Radiocarbon dates from the Escalante River, south-central Utah.

Depth (cm)	Lab[1] Number	Radiocarbon Date (yrs BP)	13C	Material[2] Dated	Rating[3]	Notes[4]
		UPPER VALLEY SECTION #1				
65	A-3792	190±90	-25.5	C	(2)	
220	A-3791	1090±100	-25.3	CB	(2)	
370	AA-993	1640±90	---	C	(5)	
525	A-4060	1590±110	-26.5	CH	(2)	
		UPPER VALLEY SECTION #2				
125	A-4059	121±1.6 PMC (1959-61 AD)	-24.8	C	(5)	
240	A-4020	109±1.3 PMC (1957-8 AD)	-23.1	C	(2)	
170	A-4021	106±1.1 PMC (1957-8 AD)	-22.4	CB	(2)	
		UPPER VALLEY SECTION #3				
LEFT CHANNEL						
24	A-4116	103±1.4 PMC	-16.0	OL	(3)	
RIGHT CHANNEL						
110	A-4061	470±60	-22.9	O	(1)	
366	A-4117	420±90	-23.4	O	(1)	
439	A-4114	470±120	-24.2	O	(1)	
CENTER						
379	A-4115	106±1.6 PMC (1957 AD)	-24.6	CB	(2)	Erroneous Date
		PINE CREEK, KM 34.9				
30	A-3465	135±1.5 PMC (1962 OR 1975-6 AD)	-22.9	CB	(2)	
50	A-3466	186±2.5 PMC (1963-4 AD)	-25.0	CB	(2)	
245	A-3467	192±1.9 PMC (1963-4 AD)	-25.1	CB	(2)	
363	A-4018	131±1.3 PMC (1962 AD)	-25.8	CB	(2)	

APPENDIX 2. Radiocarbon dates from the Escalante River, Utah (continued).

Depth (cm)	Lab[1] Number	Radiocarbon Date (yrs BP)	^{13}C	Material[2] Dated	Rating[3]	Notes[4]
		THE ALCOVE, KM 38.3				
LEFT INSET						
64	A-3988	102±1.1 PMC (MODERN)	-22.8	O	(1)	
96	A-3793	150±80	-24.4	O	(1)	
135	A-4003	210±90	-23.9	O	(1)	
MAIN DEPOSIT						
20	A-4001	980±80	-23.1	O	(1)	
64	A-4002	1150±110	-23.4	O	(1)	
135	A-4054	1210±100	-24.4	O	(1)	
160	A-3987	1680±60	-23.8	W	(4)	
190	A-3468	1480±100	-25.5	CH	(2)	
220	A-3794	2080±70	-22.9	CH	(2)	
DOWNSTREAM TERRACE						
60	A-4019	430±100	-24.3	O	(1)	
90	A-4004	550±90	-24.2	O	(1)	
		ANASAZI ALCOVE, KM 42.9				
SECTION #1						
61	A-4056	350±110	-23.4	O	(1)	Cattle dung
92	TX-5107	260±110	---	O	(1)	
144	TX-5105	1400±90	---	O,C	(2)	
180	TX-5106	2590±860	---	O	(1)	
187	TX-5104	310±70	---	O,C	(5)	Disturbed
SECTION #2						
65	TX-5102	1030±70	---	C	(2)	
130	A-4057	1500±110	-25.5	C	(2)	
220	TX-5103	830±60	---	C	(2)	
SECTION #3						
50-70	A-4058	1100±120	-9.3	O	(4)	*Zea mays*

APPENDIX 2. Radiocarbon dates from the Escalante River, south-central Utah (continued).

Depth (cm)	Lab[1] Number	Radiocarbon Date (yrs BP)	13C	Material[2] Dated	Rating[3]	Notes[4]
		BOWINGTON ARCH, KM 61.9				
70	TX-4121	100±80	---	W	(4)	Patton
		ARCH BEND, KM 66.8				
SLACKWATER DEPOSIT						
25	A-3464	1170±60	-22.8	C	(6)	
TERRACE						
95	A-3505	1958	-24.6	C	(2)	
		ORTHOGONAL CANYONS, KM 78.9				
WATERFALL HOLLOW						
160	A-3460	117±1.3 PMC (1958 AD)	-25.7	C	(5)	
SLACKWATER DEPOSIT						
145	A-3461	230±100	-25.8	CB	(2)	
165	A-3462	145±1.4 PMC (1962 AD)	-25.6	CB	(2)	
185	A-3463	129±1.1 PMC (1960-2 AD)	-24.3	CB	(2-5)	
		SILVER FALLS CANYON, KM 101.0				
100	TX-4123	140±150	---	C	(5)	Patton
		CANON BONITO				
48	TX-4122	130±130	---	O	(4)	Patton

APPENDIX 2. Radiocarbon dates from the Escalante River, south-central Utah (continued).

Depth (cm)	Lab[1] Number	Radiocarbon Date (yrs BP)	13C	Material[2] Dated	Rating[3]	Notes[4]
		STEVENS ARCH BEND, KM 168.8				
UPSTREAM SECTION						
0	TX-5101	580±230	---	O	(1)	*Quercus* leaves
148	A-4107	280±120	-22.3	O	(1)	
327	A-4106	260±100	-24.6	O	(1)	
DOWNSTREAM SECTION #1						
32	TX-5098	400±50	---	W	(4)	
55	A-4113	100±0.6 PMC (MODERN)	---	O	(1)	
75	A-4055	510±110	-24.6	O	(6)	
DOWNSTREAM SECTION #2						
94	A-4108	930±60	-25.0	C	(6)	
DOWNSTREAM SECTION #3						
55	TX-5099	440±120	---	O	(6)	
DOWNSTREAM SECTION #4						
220	TX-5100	60±80	---	C	(6)	

1. A -- University of Arizona Isotope Geochemistry.
   AA -- University of Arizona TAMS Accelerator Facility.
   TX -- University of Texas at Austin.

2. C -- charcoal; CH -- charcoal from local hearth; CB -- charcoal from burned horizon (red scorch zone); W -- transported wood; O -- transported leaves and twigs; OL -- accumulated organic litterfall, not transported.

3. Ratings were (1) transported leaves and twigs directly entrained in the deposit; (2) charcoal from local hearth or burned horizon; (3) organic mats in alluvial settings which probably accumulated over a period of years; (4) transported wood, probably significantly older than the

APPENDIX 2. Radiocarbon dates from the Escalante River, south-central Utah (continued).

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deposit to be dated; (5) transported and possibly redeposited charcoal; (6) organic material not in direct association with a deposit but which provides an age constraint.

4. Date A-4115 was considered erroneous on the basis of stratigraphic position with respect to six other radiocarbon dates (A-3791, AA-993, A-4060, A-4061, A-4117, A-4114). Date A-4056 (Anasazi Alcove) was in direct association with post-settlement cattle dung. TX-5104 was dated from an inset of sediment against the older slackwater deposit at Anasazi Alcove. Peter C. Patton collected and dated material used in this dissertation from Bowington Arch, Silver Falls Canyon, and Cañon Bonito.

APPENDIX 3. Gaging stations used in flood-frequency analysis for the Colorado Plateau.

Station Number	Name	Record Length (yrs)	Skew Coefficient	Drainage Area (km^2)	Mean Elevation (m)
	DRAINAGES NEAR MOAB, UTAH				
09181000	Onion W. nr. Moab	14	-0.81	49	1839
09183000	Courthouse Wash	24	0.41	421	1466
09182600	Salt Wash	14	-0.17	10	1679
09185200	Kane Springs Canyon	15	-0.10	46	2018
09184000	Mill Creek	36	-0.23	195	2185
09185500	Hatch Wash	22	0.18	983	1996
09187000	Cottonwood Wash	17	-0.20	299	2326
	PRICE RIVER BASIN				
09310500	Fish Creek	44	-1.41	156	2810
09312800	Willow Creek	20	-0.03	163	2619
09314500	Price R. Woodside	38	-1.32	3989	1978
	SAN RAFAEL RIVER BASIN				
09318000	Huntington Creek	71	-0.42	492	2899
09324500	Cottonwood Cr.	52	-0.02	539	2884
09326500	Ferron Creek	47	0.20	358	2850
09327600	Ferron Cr. trib.	11	-0.13	3	2032
09328500	San Rafael River	47	-0.56	4330	2106
	TRIBS. NEAR GREEN RIVER, UTAH				
09314200	Miller Creek	13	-0.64	161	2146
09314400	Coleman Wash trib.	10	-0.32	9	1689
09315150	Saleratus W. trib.	15	-0.09	26	1545
09315200	Saleratus W. trib	15	-1.09	11	1623
09315400	Saleratus Wash	10	1.55	312	1655
09315500	Saleratus Wash	22	-0.07	467	1630
09315900	Browns W. trib	14	0.19	10	1387
09316000	Browns Wash	19	-0.27	194	1698
09328050	Dry Wash	15	-0.36	36	1926
09328300	Sids Draw	14	-0.37	46	1945
09328720	Old Woman Wash	10	-0.67	46	1661
09328200	Buckhorn Draw trib.	10	0.99	15	1951
09328600	Georges Draw	15	-0.25	17	2137
09328700	Temple Wash	10	-0.35	99	1716
09328900	Crescent Wash	10	0.63	61	1884

APPENDIX 3. Gaging stations used in flood-frequency analysis on the Colorado Plateau (continued).

Station Number	Name	Record Length (yrs)	Skew Coefficient	Drainage Area (km^2)	Mean Elevation (m)
	DRAINAGES NEAR HITE, UTAH				
09333900	Butler Canyon	16	-0.96	38	1570
09334000	North Wash	21	-0.13	353	1646
09334400	Fry Canyon	16	-1.11	54	1905
09334500	White Canyon	21	0.02	715	1856
	DIRTY DEVIL RIVER BASIN				
09330100	Sulfur Cr. Torrey	10	-2.61	20	2300
09330120	Sulfur Cr. Fruita	16	-0.21	147	2256
09330200	Pleasant Creek	14	-0.35	210	2432
09330300	Neilson Wash	15	-0.78	58	1472
09329900	Pine Cr. Bicknell	16	0.00	270	3000
09331500	Ivie Creek	24	-0.62	130	2704
09330500	Muddy Creek	39	-0.13	272	2854
09330400	Fremont R. Hanks.	15	-0.14	4924	2271
09333500	Dirty Devil River	35	-0.82	10810	2012
	ESCALANTE RIVER BASIN				
09336400	Upper Valley Creek	16	0.54	137	2323
09336000	Birch Creek	15	-0.05	93	2463
09337000	Pine Creek	31	0.23	176	2710
09337500	Escalante River	22	-0.59	810	2448
09338000	E.F. Boulder Creek	20	-0.27	55	3387
09338000	E.F. Deer Creek	19	0.41	5	3387
09338900	Deer Creek	16	-0.01	163	2341
09339200	Harris Wash	10	-0.95	363	1881
	SAN JUAN RIVER BASIN				
09371100	Teec Nos Pos Wash	9	-1.56	42	2316
09372000	McElmo Creek	32	0.19	897	1920
09372200	McElmo Creek	11	2.08	1872	1890
09378700	Cottonwood Wash	24	-0.33	531	2079
09378720	Cottonwood Wash	10	1.34	884	1905
09378950	Comb Wash	10	-0.91	27	1756
09379000	Comb Wash	10	1.63	736	1847
09379030	Black Mtn. Wash	13	-0.60	210	1804
09379060	Lukachukai Cr. tr.	13	0.60	4	1774
09379100	Long House Wash	13	-1.19	4	2109

APPENDIX 3. Gaging stations used in flood-frequency analysis on the Colorado Plateau (continued).

Station Number	Name	Record Length (yrs)	Skew Coefficient	Drainage Area (km^2)	Mean Elevation (m)
09379200	Chinle Creek	18	0.98	8548	1908
09379300	Lime Creek	15	-0.97	83	1634
09379560	El Capitan Wash	13	-0.81	15	1734
	WAHWEAP CREEK BASIN				
09379800	Coyote Creek	15	-1.14	231	1558
09379820	Buck Tank Draw	10	0.96	14	1533
	PARIA RIVER BASIN				
09381100	Henrieville Creek	20	0.60	88	2170
09381500	Paria R. Cannon.	21	0.39	570	2100
09381800	Paria R. nr Kanab	15	0.30	1670	1948
09382000	Paria R. Lees F.	59	-0.33	3655	1875
	LITTLE COLORADO BASIN				
09383020	House Rock W. trib.	10	-0.67	9	1612
09396400	Dead W. trib.	13	-0.26	3	1750
09395850	Black Cr. trib.	13	-2.85	1	2226
09400290	Teshbito W. trib.	13	-1.34	42	1957
09400300	Teshbito Wash	13	-1.50	149	1914
09401220	Cedar W. Cameron	9	-0.61	1446	1677
09400560	Oraibi W. trib.	13	-1.15	5	1835
09400565	Polacca W. trib.	12	-1.21	5	2100
09400100	Ganado W. trib.	13	-0.88	29	2063
09403800	Bitter Seeps W. tr.	13	0.15	7	1561
09404070	Little Red House W.	13	0.29	57	1981
09400200	Steamboat W. trib.	13	-0.22	1	2057
09400580	Castle Butte Wash	12	-0.02	14	1707
09401245	Klethla Valley tr.	13	-1.28	2	2051
09401300	Hamblin Wash trib.	13	0.54	1	1798
09401370	Hamblin Wash trib.	13	3.07	5	1341
09402100	Forest Boundary W.	13	2.03	2	1890
09403750	Sagebrush Draw	13	-0.42	2	1707
09401400	Moenkopi Wash	38	-1.10	3400	1774
	COLORADO RIVER MAINSTEM				
09403000	Bright Angel Creek	50	0.12	262	2252

APPENDIX 3. Gaging stations used in flood-frequency analysis on the Colorado Plateau (continued).

Station Number	Name	Record Length (yrs)	Skew Coefficient	Drainage Area (km^2)	Mean Elevation (m)
		KANAB CREEK BASIN			
09403500	Kanab Creek	16	-1.52	187	2210
09403600	Kanab Cr. nr Kanab	14	-0.21	513	2152
09403700	Johnson Wash	14	-1.79	614	2032
09403780	Kanab Cr. Fredonia	16	-0.59	2810	1859
		VIRGIN RIVER BASIN			
09406300	Kanarra Creek	23	0.89	26	2423
09404500	Mineral Gulch	14	-0.63	20	1862
09406800	South Ash Creek	14	-0.03	36	2198
09406000	Virgin R. at Virgin	66	0.10	2428	1951
09405500	N.F. Virgin River	59	-0.04	891	2240
09415000	Virgin R. Little.	52	0.19	13200	1585

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