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Ephemeral-Stream Processes: Implications for Studies of Quaternary Valley Fills

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Three unstable ephemeral-stream channels (arroyos), which drain source areas that have high sediment yields ranging from predominantly sand (Arroyo Calabasas) to a mixture of sand, silt, and clay (Sand Creek) to largely silt and clay (Sage Creek), were resurveyed to provide data on the rates and mechanics of erosion and sedimentation processes during periods ranging from 14 to 22 yr. Channel morphology changed significantly. Erosion occurred through nickpoint recession and bank collapse, but erosional reaches are separated by aggrading or stable-channel reaches. In general, sediment that is eroded, as the nickpoint recedes upstream, is trapped in the widened channel downstream. In this manner sediment is transported episodically out of these basins during a series of cut-and-fill cycles. The manner by which the channels aggrade and the morphology of the aggraded stable channels are controlled by the sediment type. The wide and shallow channel of Arroyo Calabasas is filled by vertical accretion of sand-size sediment. The narrow and deep channels of Sage Creek and Sand Creek are created by the lateral accretion of cohesive fine-grained sediment. The channel modification and the cut-and-fill episodes are dependent on high sediment yields, and therefore they are independent of subtle climatic shifts. Cut-and-fill deposits that have been created in this manner should not be equivalent in age from basin to basin, and therefore channel trenching and filling in the semiarid western United States during the Holocene need not be synchronous.

INTRODUCTION

The causes and processes of arroyo formation in the semiarid western United States have intrigued investigators since the late 1800s when the present epicycle (Bailey, 1935) of arroyo erosion was thought to have begun. The interest stems from the many geomorphic, archeologic, and land management problems that are directly related to the phenomena of arroyo incision, and their subsequent evolution.

One important problem includes the interpretation of the Quaternary stratigraphy of alluvial fills, their possible climatic significance, and the interrelationship of these valley fills to archeological remains. Traditionally, each alluvial fill has been interpreted as the result of a climatic change (Bryan, 1940; Euler *et al.*, 1979), but more recently it has been demonstrated that alluvial-fill terraces can form in a rapid and complex manner independent of climatic controls (Born and Ritter, 1970; Schumm and Parker, 1973; Womack and Schumm, 1977; Schumm, 1977). The formation of more than one alluvial-fill terrace during a single period of baselevel lowering has been documented both in the laboratory (Schumm and Parker, 1973) and in the field (Womack and Schumm, 1977). This result clearly demonstrates that there need not be a one-to-one correspondence between widespread climate change and alluvial-fill chronologies. Therefore, an appreciation for the rate and manner in which alluvial fills can be deposited and dissected is important for their proper interpretation.

It is still unresolved whether arroyo cut-

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ting and filling is primarily caused by (a) climatic fluctuations (Bryan, 1940; Euler *et al.*, 1979) either to a more humid or to a more arid climate, (b) changes in the relative frequency of rainfall magnitudes (Leopold, 1951), (c) poor land management practices, specifically overgrazing (Swift, 1926; Hastings, 1959; Cooke and Reeves, 1976), or (d) natural geomorphic–sedimentologic processes within a range of climates and over time spans independent of land management practices (Thornthwaite *et al.*, 1942; Schumm and Hadley, 1957; Patton and Schumm, 1975). Probably all of the above are causes but the nature of the prevailing climate and the geomorphic character of the drainage basin can strongly influence which causative factor will be most important.

Solutions to these problems require a thorough understanding of the mechanics of erosion and sedimentation processes that create arroyos and cause their cyclic behavior. The objective of this study is to provide additional information on rates of arroyo cutting and filling as well as to document the evolution of ephemeral-stream-channel morphology through time.

To achieve these objectives, three ephemeral-stream channels studied in 1957 by Schumm (1961) were resurveyed in 1971 (Patton, 1973) and 1979 to evaluate channel changes over these time periods. The channels studied were Sage Creek, South Dakota; Sand Creek, Nebraska; and Arroyo Calabasas and its tributary, Arroyo de los Frijoles, New Mexico (Fig. 1). Only the Sage and Sand creeks' cross sections were resurveyed in 1979. Originally, these channels were selected for study because they drained areas characterized by high sediment yields, the processes of aggradation and erosion were active in different reaches of the same channels, and they exhibited a range of sediment size from largely silt and clay (Sage Creek) to sand (Arroyo Calabasas).

PROCEDURE

Channel longitudinal profiles and cross sections were surveyed with a level and rod. Relocation of previously measured cross sections was difficult and was achieved with varying degrees of success. However, where channel changes were large, the error in relocation of the sections was less significant. Additional cross sections were measured in 1971 for comparison with photographs and observations made in 1957.

Width and maximum depth of the channels were measured in the field. Where depositional berms and point bars were present, the top of the depositional form was used to define the channel depth. Where the arroyo cross section was an entirely erosional rectangular channel, the depth was estimated based on the height of scour marks on the channel margins. Width was measured from bank to bank based on the estimated depth.

Sediment samples were collected from the channel bed and from well-developed

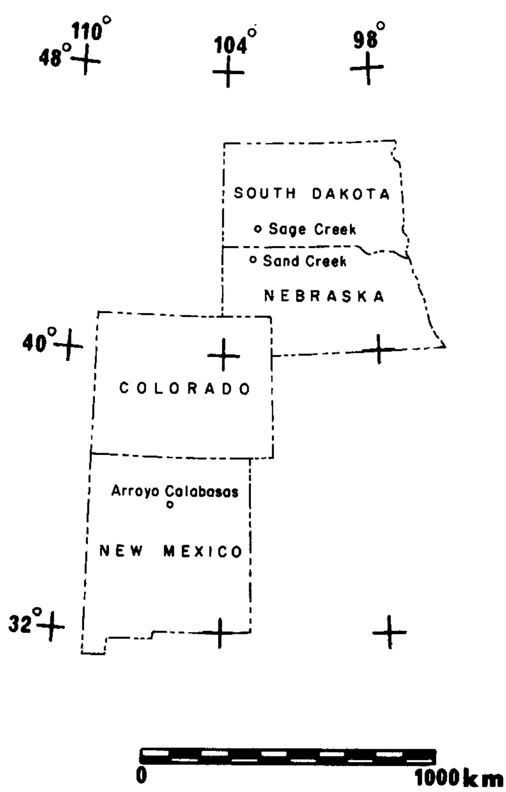

FIG. 1. Location map of study areas.

point bars and berms. These samples are representative of the sediment currently transported by the channel. The alluvium in the Sand Creek valley was sampled with an auger to determine the change in sediment characteristics with depth in the valley fill. Grain-size distribution was obtained using standard techniques (Folk, 1974).

The arroyos documented in this study lengthened by headcut migration. The youngest reach of each channel is nearest a vertical headcut and the channel becomes progressively older downstream. Therefore the evolution of the channel morphology can be documented both at a section through time and in a downstream direction from a nickpoint at a given time. Both techniques were employed in this study.

CHANNEL CHANGES IN THE STUDY AREAS

Sage Creek, South Dakota

Sage Creek, a tributary of the White River, drains a 240-km² area in southeastern Pennington County (Figs. 1 and 2). The creek has its headwaters inside the Badlands National Monument and flows southeastward to the White River. The basin is on the Bouquet Table and Conata 7.5-min U.S. Geological Survey topographic maps.

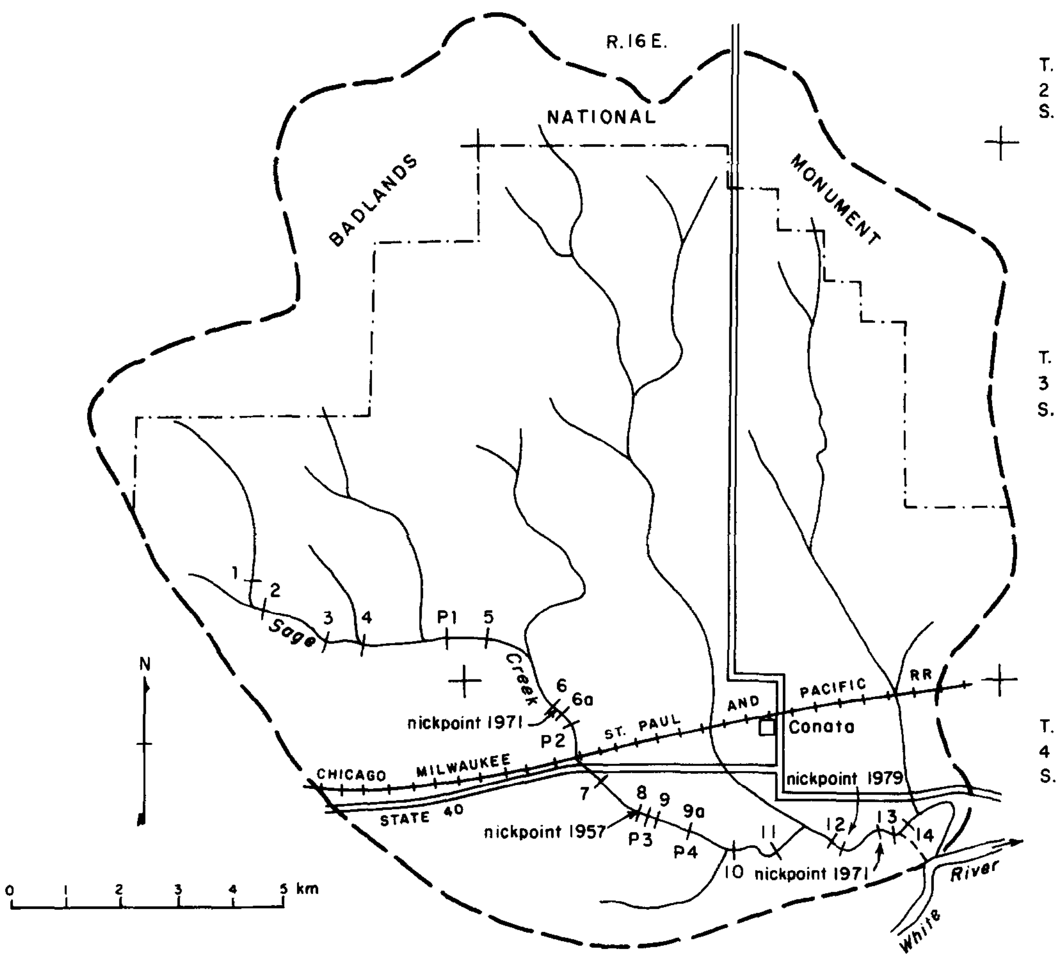

FIG. 2. Map of the Sage Creek drainage basin. Numbers show locations of cross sections measured in 1957, 1971, and 1979. Photograph stations (Px) and location of nickpoints in 1957, 1971, and 1979, are also shown.

Based on a 20-yr climate record at Interior, South Dakota, 11.3 km west of the drainage basin, the average annual precipitation is 397 mm (Table 1). Snowfall averages 625 mm. Temperature ranges from an average daily high of 33.3°C in July to an average daily low of −11.7°C in January. The climate is semiarid (Thornthwaite, 1941). Prior to 1957, the average annual precipitation was 435 mm and since 1957 the precipitation has averaged 377 mm, a difference of almost 60 mm less per year.

Except for unvegetated badlands in the headwaters, vegetation is predominantly grass with cottonwood trees growing along the channels. The land is used to graze cattle and to raise hay.

The basin is underlain by the Brule and Chadron Formations of the White River Group of Oligocene age. In its headwaters, Sage Creek is eroding into the Brule Formation of Late Oligocene age, an interbedded siltstone and sandstone. Farther downstream, Sage Creek has eroded through the Brule Formation into the underlying interbedded sandstone and mudstone of the Chadron Formation (King and Raymond, 1971).

The easily eroded bedrock and the lack of vegetation in the badlands combine to provide Sage Creek with large quantities of sediment and, except where the creek is eroding laterally into the Chadron Formation, it is flowing across and eroding into an alluvial fill. The alluvium is characterized by high percentages of silt and clay and a correspondingly small median grain size (Table 2).

Previous investigation. Schumm (1961) concluded that the fine-grained sediment load supplied to Sage Creek caused it to aggrade by the plastering of fine cohesive alluvium along the sides of the channel. By this process the channel width was reduced while the depth of the channel changed only slightly. Thus, width/depth ratios decreased during deposition. With reincision, the width/depth ratio initially declines but

TABLE 1. PRECIPITATION DATA

Station	Length of record (yr)	Precipitation (mm)												
		Annual	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Interior, South Dakota	20	397	4	11	17	41	78	94	55	34	31	18	6	8
Fort Robinson, Nebraska	70	443	11	14	24	52	79	78	53	40	36	29	13	14
Santa Fe, New Mexico	72	362	17	19	21	28	37	30	59	48	43	28	18	14
Santa Fe Airport, New Mexico	15	274	8	11	14	17	18	24	46	61	33	25	6	12

TABLE 2. CHANNEL AND SEDIMENT CHARACTERISTICS, SAGE CREEK, SOUTH DAKOTA, 1971

Cross section	Distance between sections (km)	Channel gradient (m/m)	Width (m)	Depth (m)	Width/Depth ratio F	Median-grain size D_{50} (mm)	Silt–clay in the channel (%)	Silt–clay in the banks (%)	Weighted mean % silt–clay
6		0.0001	8.8	2.9	3.0	0.001	87.0	41.0	68.8
6a	0.45	0.0017	4.7	0.6	7.83	0.009	93.5	84.9	91.7
7	2.10	0.0022	7.3	0.9	8.1	0.0022	87.0	61.5	79.5
8	1.58	0.0031	14.3	1.5	9.5	0.068	62.0	64.7	62.5
9a	1.34	0.0023	7.9	1.4	5.6	0.22	9.0	85.7	28.7
11	1.93	0.0023	7.6	1.7	4.5	—	100.0	65.9	89.3
12	2.22	0.0017	6.4	2.1	3.0	0.0017	100.0	95.0	98.0
13	1.01	0.0010	12.5	1.3	9.6	0.0012	95.0	98.1	95.5

rapidly increases as bank erosion and collapse rewiden the channel.

In 1957 the channel of Sage Creek was a raw gully at cross sections 8 and 9 (Fig. 3). In a downstream direction from these cross sections the channel became increasingly filled with sediment. The channel of Sage Creek was nearly completely aggraded near the confluence with the White River. The actual aggradation process is a progressive backfilling of the channel in an upstream direction. The construction of two earthfill dams and the rapid stabilization of the channel by vegetation suggested that the lower portion of Sage Creek would continue to aggrade.

Channel changes 1957–1971. Between surveys the channel reach between sections 3 and 6 had not undergone any drastic changes. A recent veneer of sediment which partially buried vegetation on the point bars and berms indicated that aggradation was slowly continuing. This aggradation is presumably related to the low channel slope. Channel width/depth ratios are intermediate between low values associated with fully aggraded reaches and high values corresponding to erosional reaches. These intermediate values represent a trend toward aggradation.

The greatest morphologic change occurred downstream from section 6 and only this reach of channel will be discussed in detail (Fig. 3). Data on channel morphology and sediment characteristics in 1971 are in Table 2.

At section 7 the channel had incised 3.0 m since 1957 (Fig. 3), and a nickpoint had eroded upstream over 4 km from its position at section 8 in 1957 to its location near section 6 in 1971 (Fig. 2). A 2.1-m nickpoint at section 6a separated the aggrading upstream reaches above section 6 from the eroding channel downstream.

At section 8 the width of the channel had increased from 6.7 m in 1957 to 14.3 m in 1971 (Figs. 3 and 4). The trapezoidal channel present in 1957 has been modified

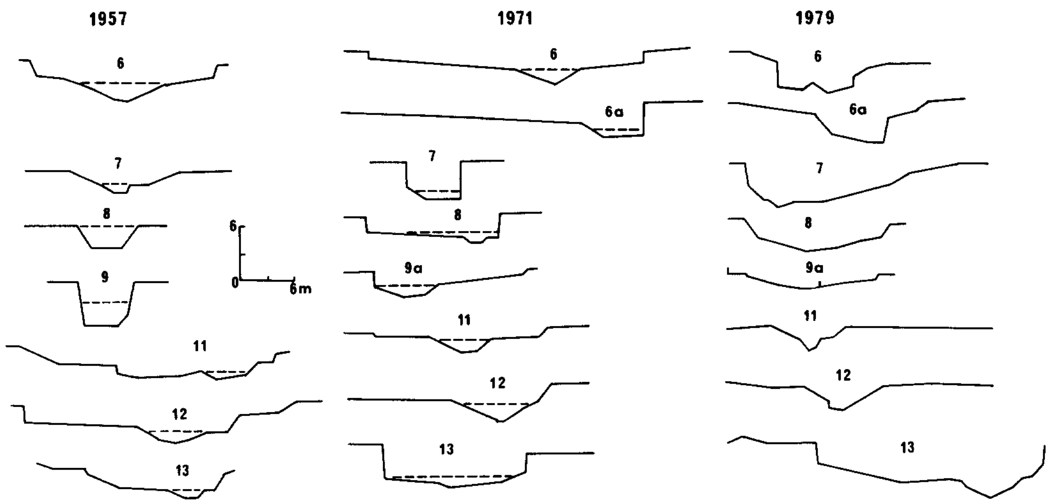

FIG. 3. Sage Creek cross sections measured in 1957, 1971, and 1979. Numbers refer to locations on Figure 2. The dashed lines represent the measured channel width.

through deposition of alternate bars and has developed a meandering thalweg channel. The alternate bar deposition represents the incipient stages of aggradation at this cross section.

Cross section 9 was not accurately relocated and section 9a measured in 1971 corresponds to photograph station 4 (Fig. 2) of Schumm (1961). In 1957 this reach of channel showed signs of aggradation. The channel floor was 4.9 m below the valley surface in 1957 (Fig. 3). In 1971 the channel was 2.9 m below the valley surface (Fig. 3) and deposition was occurring on both sides of the channel, decreasing its width to 7.9 m from a maximum width of 16.2 m based on the top width of the channel at the elevation of the valley floor. Therefore since 1957 the reach of channel between sections 9 and 9a has widened and subsequently infilled with sediment. Downstream from section 9a, cross sections 11 and 12 indicate that the channel continued to fill in.

Between sections 12 and 13, a 1.5-m headcut separated the narrow upstream channel from a wide flat-floored gully downstream cut into the valley fill to depths of 5 m. The channel downstream from section 13 no longer follows its old 3-km-long course, but instead follows a new 1-km course to the White River (Fig. 2). The increase in gradient caused by this diversion is the cause of the incision and erosion of the previously stable alluvial fill between sections 12 and 13. The small dams built on lower Sage Creek are probably responsible for diverting the course of the stream, increasing the channel gradient and accelerating the reincision process. Reincision would occur naturally, as it has upstream, when aggradation processes had sufficiently oversteepened the gradient of channel (Schumm, 1961).

Channel changes 1971–1979. Between 1971 and 1979, the cycle of cutting and filling observed during the 1957 to 1971 period has continued. Again, no major changes were observed in the upstream reaches above section 5. The vertical headcut which was positioned between sections 6 and 6a in 1971 has eroded headward over the past 8 yr and section 6 has been trenched (Fig. 3). The headcut is no longer a single vertical drop but is now a series of small steps distributed over a reach of channel. The effect of this erosion can be traced about 0.5 km upstream from the position of the headcut in 1971.

Downstream from cross section 6a aggradation has continued. Section 7 has

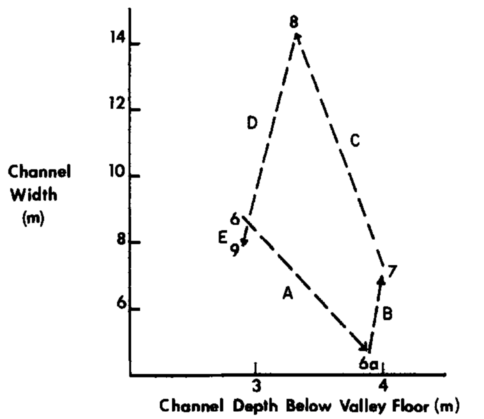

FIG. 4. Graph illustrating the erosion and aggradation of a reach of Sage Creek. Numbers on the graph refer to cross sections measured in 1971. The sequence in a downstream direction, sections 6 to 9, is as follows. (A) Channel incision by headcut recession forming a deep narrow trench; (B) channel widening and slight aggradation caused by bank caving (C) channel widening and aggradation caused by lateral planation and point bar formation. (D) channel narrowing and aggradation as a result of sediment deposition forming berms on both sides of the channel as the reach fills in. This sequence of events is illustrated spatially along a reach of the channel, but the sequence of events could be plotted for a single cross section through time.

widened and at section 8, which was sufficiently wide for aggradation to start in 1971, berms have developed on both sides of the channel. Between sections 9 and 12 the channel remains nearly the same as in 1971, but at section 12 the channel has been scoured presumably by a small headcut which has migrated upstream through this reach. The major headcut which was immediately above section 13 in 1971 is now only 300 m downstream from section 12. This 2-m-high nickpoint has migrated 0.7 km upstream in the past 8 yr.

The evolution of channel morphology through a cut-and-fill cycle can be observed by studying 1971 sections 6 to 9a (Figs. 3 and 4). At section 6a channel width is a minimum after incision but increases rapidly with bank caving (section 7) and as the banks are undermined by the lateral cutting of the stream (section 8). Sediment delivery to the channel is high during the channel-widening process. However, the tendency for deposition is also increased during this process because of the increased resistance to flow in the wider channel. Sediment concentration probably also increases because of greater water losses through the larger wetted perimeter. This process would be less important on Sage Creek because of the fine-grained sediment in the channel perimeter, but some infiltration losses can be expected during the initial wetting of the desiccated channel margin. Therefore the process that causes the high sediment discharge eventually produces a channel morphology and sediment concentration conducive to deposition.

As the channel continues to widen, flows no longer impinge on the steep banks and depositional berms are formed along both banks, reducing channel width (section 9a). Vertical aggradation accompanies the lateral accretion of sediment as shown by the decreasing depth below the valley floor between sections 7 and 9a. Deposition continues until the channel achieves a more stable form. Sage Creek transports predominantly fine-grained sediment and its most stable form is a narrow deep channel, such as section 6 or 12 (Schumm, 1960). This stable form apparently limits the minimum dimensions of the channel, and unlike arroyos which transport coarser-grained sediment, Sage Creek never aggrades completely to the level of the valley floor. Also, because of the impervious nature of the sediment, infiltration of runoff into the channel is low and flow probably does not decrease as rapidly downstream as it does in sand-bed ephemeral-stream channels. This relative increase in flow length results in slower rates of sedimentation over a longer reach of channel.

The cut-and-fill process described here is an example of a negative feedback mechanism that can be observed either at a single cross section through time or in a downstream direction (Fig. 4). Figure 4 illustrates that in this case, a simple relationship between channel width and depth of the arroyo below the valley floor can be used to summarize the complex interaction between channel morphology and water and sediment discharge.

Sand Creek, Nebraska

Sand Creek drains an area of 67 km^2 in northern Dawes and Sioux counties, Nebraska, northeast of the town of Crawford (Figs. 1 and 6). The creek flows eastward from the Pine Ridge escarpment to its junction with the White River, northeast of Crawford. No large-scale topographic maps are available for the basin.

Based on a 71-yr climate record at Ft. Robinson, 4.8 km southwest of Crawford, the average annual precipitation is 448 mm (Table 1). Average annual precipitation prior to 1952 was 451 mm, and during the 14 yr between 1957 and 1971 it was 436 mm. The temperature ranges from an average of −4.8°C in January to 21.7°C in July. The region lies on the eastern border of the semiarid rangeland in North America (Thornthwaite, 1941).

The headwaters of the drainage basin are badlands, with little vegetative cover. The vegetative cover over the remaining area is predominantly grass, although along the stream channel, cottonwood trees are numerous. The drainage basin is used primarily for grazing cattle.

The area is underlain by the siltstones and sandstones of the White River Group. Along the Pine Ridge escarpment these rocks are exposed and their erosion creates the badland topography previously mentioned, which in turn produces a high sediment load of clay, silt, and sand to Sand Creek.

Previous investigation. Schumm (1961) described the channel of Sand Creek as stable between sections 4 and 6, and as rapidly aggrading between sections 7 and 9 (Figs. 5, 6, and 7). The percentage of silt and clay in the channel sediment was minor except in the aggrading reaches, where because of the reduced channel slope fine-grained sediment was deposited (Table 3). In the aggrading reaches, the reduced channel dimensions cause overbank flooding and deposition across a large portion of the valley floor. In the Sand Creek valley the aggradational reach (between sections 7 and 10) can be easily identified on aerial photographs because it corresponds to the section of the valley that is covered with recently deposited light-colored sediment which has buried the vegetation and filled the channel. Downstream from section 9 the channel was completely filled with sediment. However, downstream from the aggrading reach there was headward erosion into the valley fill, and the channel was narrow and deep at section 10.

Channel changes 1957–1979. In 1971 the reaches of channel upstream from cross section 4 continued to widen by undercutting the stream banks. At cross section 4 the channel remained stable over the time period with the only noticeable change being the encroachment of vegetation on the lower point bar. The most spectacular channel changes occurred downstream from section 4 where rapid deposition filled the channel (Fig. 6). At section 6 up to 2 m of sediment was deposited in the channel bed (Fig. 7). Because overbank flooding is substantially increased in the reach of maximum deposition, the actual width/depth ratio of the flow is probably much greater than that indicated for the channel alone. Downstream from section 6 the channel was completely filled and there was an anastomosing network of shallow depressions across a broad vegetated valley. The changes in the longitudinal profile of the stream channel indicate the amount of sediment deposited in this reach between 1957 and 1971 (Fig. 8).

In 1979 the reach of channel between sections 4 and 6 has continued to aggrade slowly. The greatest change that has occurred is the rapid colonization of the low banks of the channel by vegetation. At section 6 the channel is entirely choked with willows.

Deposition in this reach is enhanced because there is no major tributary contribu-

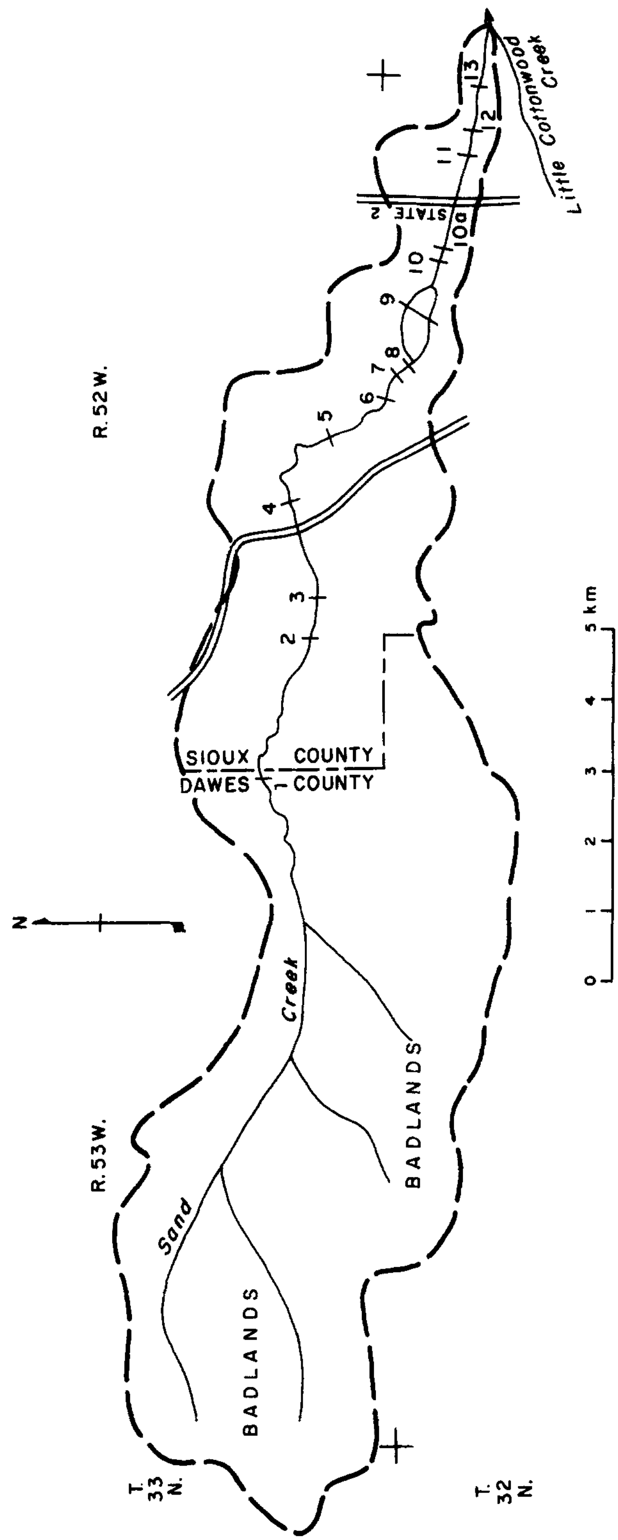

FIG. 5. Map of the Sand Creek drainage basin. Numbers indicate locations of the cross sections measured in 1957, 1971, and 1979.

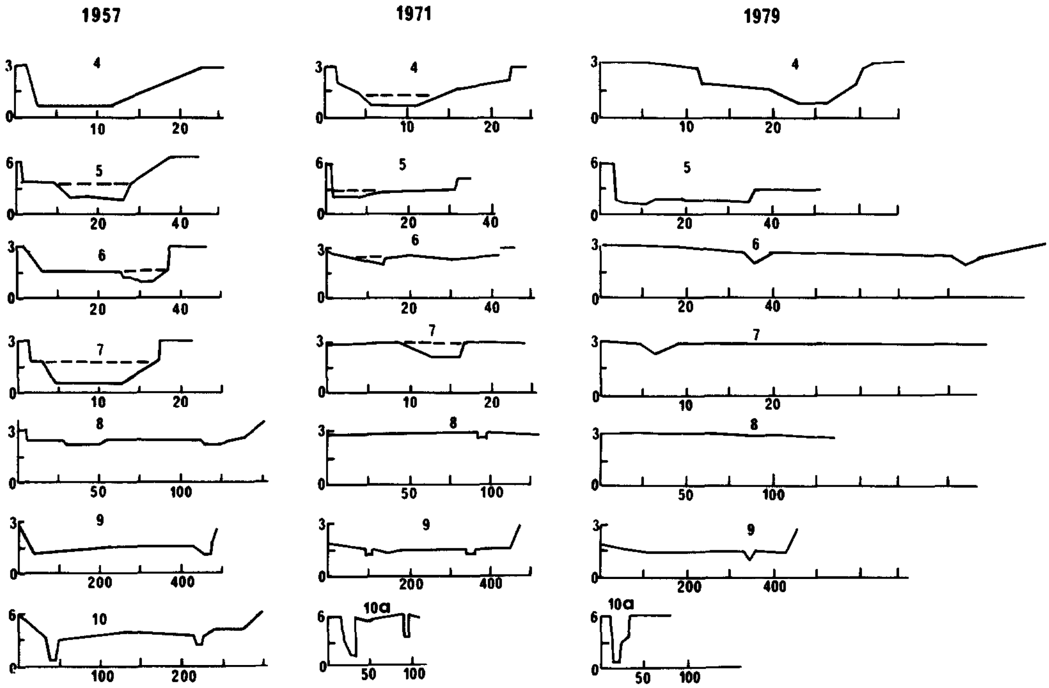

FIG. 6. Sand Creek cross sections measured in 1957, 1971, and 1979. Dashed lines represent the measured channel width at each section. Note the changes in scale (meters).

tion. This causes sediment concentration to increase rapidly because water is lost to evaporation and infiltration into the pervious sand-bed channel (Hadley and Schumm, 1961; Schumm, 1961). The increase in sediment concentration accelerates the aggradation process. Again, as in Sage Creek, deposition is related to channel width. Wide reaches on Sand Creek aggrade as sediment is deposited across the channel floor and plastered onto the banks. Once deposition begins, the associated de-

FIG. 7. Photographs of cross section 6 taken in 1957 (A) and 1967 (B). Over 2 m of sediment has filled in this cross section in the 14-yr interval between the 1957 and the 1971 surveys. Downstream is to the left in both photos.

TABLE 3. CHANNEL AND SEDIMENT CHARACTERISTICS, SAND CREEK, NEBRASKA, 1971

Cross section	Distance between sections (km)	Channel gradient (m/m)	Width (m)	Depth (m)	Width/depth ratio F	Median-grain size D_{50} (mm)	Silt–clay in the channel (%)	Silt–clay in the banks (%)	Weighted mean % silt–clay
4		0.0025	10.7	0.5	21.4	0.33	19.1	66.6	22.9
5	1.83	0.0010	10.7	0.6	17.8	0.28	30.2	2.9	28.2
6	1.19	0.0004	7.3	1.1	6.6	0.0625	53.0	91.9	61.7
7	0.51	0.0025	3.0	0.8	3.7	0.022	99.3	99.6	99.4
8	0.42	0.0025	1.8	0.3	6.0	0.021	87.9	99.9	90.9
9	1.08	0.0029	2.1	0.3	7.0	0.0027	100.0	99.8	99.9
10a	1.77	0.0050	7.92	1.1	7.2	0.52	2.0	72.9	16.3

crease of stream gradient promotes further deposition and the channel backfills (Fig. 8). With a declining stream gradient the median grain size of the deposited sediment also decreases, as indicated by the auger samples at four localities along the aggrading stream channel (Fig. 9). With aggradation the channel of Sand Creek narrows and becomes shallower until it is filled to the level of the valley floor.

With continued deposition upstream, the toe of the alluvial-fill deposit becomes increasingly steep, inducing renewed erosion (Patton and Schumm, 1975). This is precisely what has happened on Sand Creek downstream from section 9. In 1971 a 4-m-high headcut had eroded 455 m upstream from its position in 1957. Two smaller nickpoints downstream lowered the channel an additional 2.4 m. The channel created by this erosion is an extremely deep and narrow trench because of the cohesive silts and clays in the alluvial fill that accumulated when the valley floor was aggrading through deposition of suspended sediment.

In 1979 the headcut had advanced another 550 m. The headcut was actually moving as three distinct headcuts across the valley floor, the largest being about 7 m deep. These three headcuts have eroded the alluvial fill down to the underlying bedrock. The upstream progression of the headcuts is accelerating, and eventually the thick alluvial fill upstream will be removed.

Arroyo Calabasas, New Mexico

Arroyo Calabasas, a tributary of the Santa Fe River, has a drainage area of about 125 km² with its headwaters north of the town of Santa Fe (Fig. 10). The confluence of Arroyo Calabasas and the Santa Fe River is near the Santa Fe Municipal Airport. The drainage basin is shown on the following 7.5-min U.S. Geological Survey topographic maps: Santa Fe, Aqua Fria, Turquoise Hill, Tetilla Peak, and Montoso Peak.

Based on a 72-yr record at Santa Fe, the

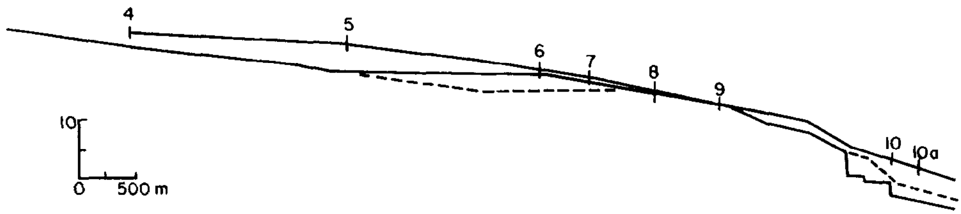

FIG. 8. Longitudinal profiles of Sand Creek. The upper solid line is the profile of the valley and the lower solid line is the channel profile measured in 1971. The dashed lines are the channel profile in 1957. Note the steepened valley profile between sections 9 and 10 where reincision of the valley fill is occurring. In the maximum reach of aggradation between sections 5 and 7 the channel gradient is substantially reduced.

average annual precipitation is 352 mm at an elevation of 2225 m (Table 1). The weather station at the airport at an elevation of 1920 m recorded an average annual precipitation of 274 mm for a 15-yr period of record. Between 1957 and 1971, the annual precipitation averaged 381 mm at the higher weather station which is about 30 mm above the long-term average. The climate of the drainage basin is classified as semiarid (Thornthwaite, 1941).

The vegetation in the drainage basin is determined by elevation-controlled precipitation (Spiegel and Baldwin, 1963). Vegetation varies from grassland at 1830 to 2135 m to juniper at 1980 to 2285 m, and to pinyon pine at 2285 to 2440 m (Spiegel and Baldwin, 1963).

The drainage basin is underlain by basin-fill sediments of the Santa Fe Group of middle (?) Miocene to Pliocene or Pleistocene age. The headwaters of the basin are underlain by the Tesuque Formation of middle Miocene to early Pleistocene age, a conglomeratic silty sandstone (Spiegel and Baldwin, 1963). The lower part of the basin is underlain by the Ancha Formation of middle Miocene to early Pleistocene age, an unconsolidated deposit of silt, sand, and gravel up to 90 m thick (Spiegel and Baldwin, 1963). The western portion of the basin is covered by basalt (Fig. 10).

The grain size of the alluvium reflects the coarse-grained sedimentary source rocks in the basin. The average median grain size for 15 channel samples is 0.69 mm. The channel samples contain only minor percentages of silt and clay, whereas the banks contain up to 50% silt and clay, which provides cohesion and bank stability (Table 4).

Previous investigation. Schumm (1961) noted that because of the small percentage of silt and clay in the bed of the channel, aggradation occurred by the filling of the channel from the bottom to the top with no plastering of fine alluvium on the sides of the channel. Vertical headcuts occurred only where the valley had been completely aggraded allowing the deposition of finer

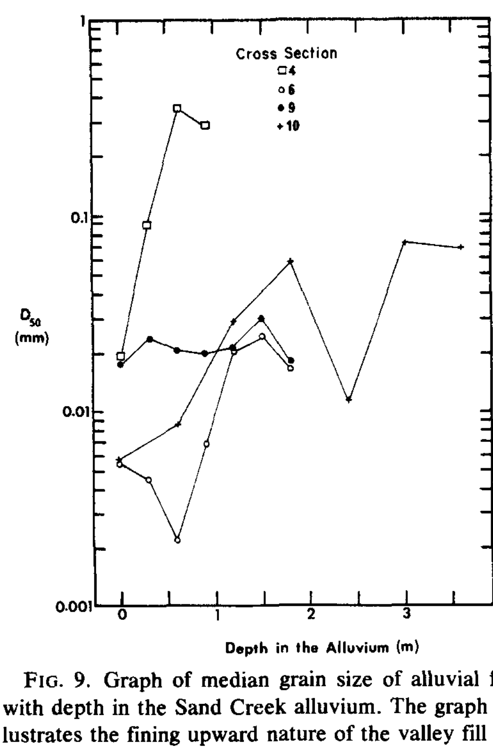

FIG. 9. Graph of median grain size of alluvial fill with depth in the Sand Creek alluvium. The graph illustrates the fining upward nature of the valley fill as aggradation proceeds and channel slope is reduced.

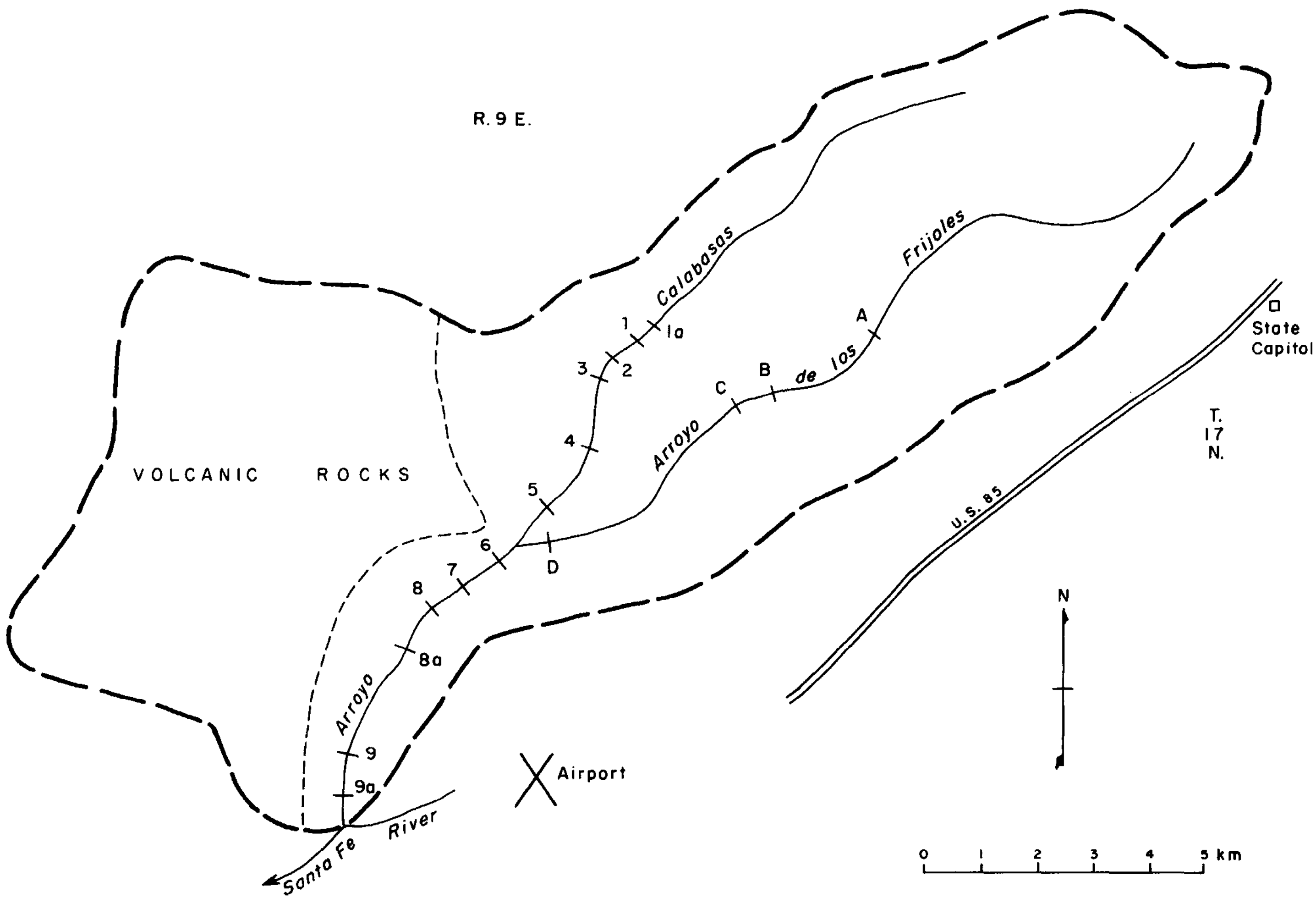

FIG. 10. Map of Arroyo Calabasas drainage basin. Numbers show locations of the cross sections measured in 1957 and 1971.

TABLE 4. CHANNEL AND SEDIMENT CHARACTERISTICS, ARROYO CALABASAS AND ARROYO DE LOS FRIJOLES, NEW MEXICO, 1971

Cross section	Distance between sections (km)	Channel gradient (m/m)	Width (m)	Depth (m)	Width/depth ratio *F*	Median-grain size D_{50} (mm)	Silt–clay in the channel (%)	Silt–clay in the banks (%)	Weighted mean % silt–clay
Arroyo Calabasas									
1a		0.0119	12.8	1.16	11.0	0.780	0.6	98.0	15.5
3	0.98	0.0107	25.0	0.30	83.3	1.500	0.1	42.8	1.1
4	0.82	0.0128	—	—		0.780	11.7	—	—
5	1.71	0.0099	—	—		0.011	91.0	—	—
6	0.95	0.0066	17.4	0.91	19.1	0.860	0.4	—	—
7	0.79	0.0089	24.4	0.91	26.8	0.660	0.3	74.7	5.8
8	0.98	0.0100	78.1	0.61	128.0	0.310	1.5	7.7	1.8
8a	0.80	0.0065	11.6	1.31	8.8	1.150	0.1	90.3	16.7
9	2.20	0.0072	—	—		0.480	63.4	—	—
10	0.43	0.0101	13.7	0.61	22.4	0.500	7.9	69.9	12.0
Arroyo de Los Frijoles									
B	—	0.0150	36.6	0.76	48.1	1.50	0.3	49.7	2.3
C	0.68	0.0150	29.0	0.46	63.0	0.46	0.1	—	—
D	2.25	0.0110	20.4	1.07	19.1	0.80	5.0	97.2	13.7

alluvium on top of the coarser channel sediment. The silt and clay deposits provided the necessary cohesion to maintain the vertical headwall of the nickpoint.

In 1957, the Arroyo Calabasas at sections 3, 4, and 5 was completely filled with sediment (Fig. 11). A large reach of Arroyo Calabasas between sections 3 and 5 was a stable, vegetated valley floor with no major channel. Near the junction of Arroyo Calabasas and Arroyo de los Frijoles a headcut was beginning to erode into this stable portion of the valley. Obviously little sediment is transported through this reach of Arroyo Calabasas. Instead, Arroyo de los Frijoles appeared to be responsible for transporting the sediment which nearly filled the sandy channel to the level of the valley downstream at section 8. Between sections 8 and 9 the channel was completely filled and the valley was undissected with the exception of a small discontinuous gully. A headcut was also eroding the valley floor near the confluence with the Santa Fe River.

General channel changes 1957–1971. In 1971 an earthfill dam upstream from section 1 on Arroyo Calabasas was trapping sediment delivered from upstream and sediment-free water was locally eroding the channel downstream. Deposition downstream from section 1 filled the channel

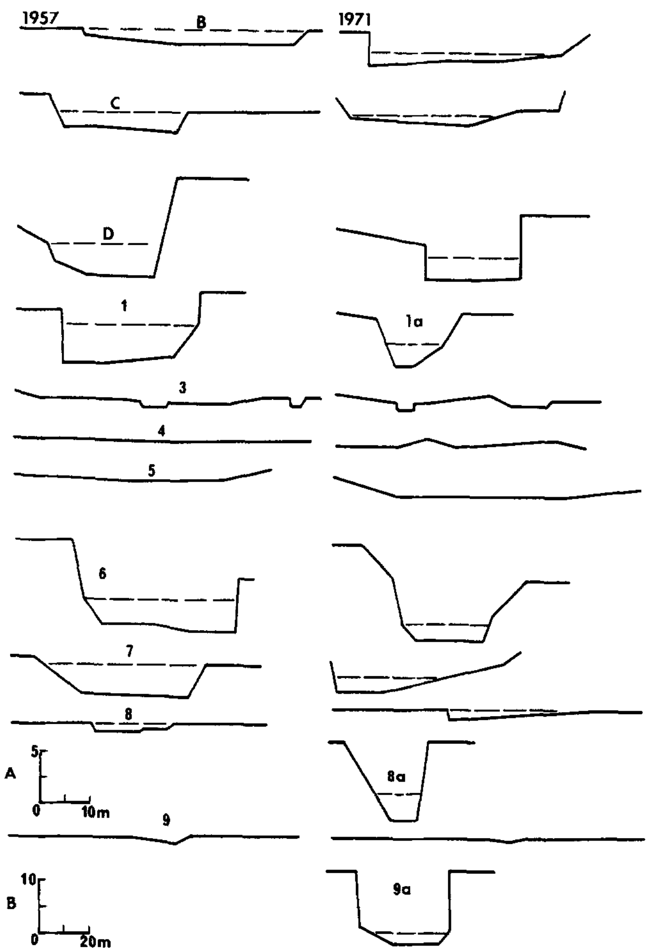

FIG. 11. Arroyo Calabasas and Arroyo de Los Frijoles cross sections measured in 1957 and 1971. Arroyo de Los Frijoles cross sections are indicated by capital letters. Scale B applies only to sections 3, 4, 7, 9, 9a. Dashed lines represent the measured channel width of each section.

to the level of the valley floor at sections 3, 4, and 5. There was no erosion on the headcut upstream from the junction with Arroyo de Los Frijoles. At section 6a immediately downstream from the confluence there was evidence of renewed erosion in the form of scour holes and eroded channel banks. This is probably caused by the increased sediment-free water discharge from Arroyo Calabasas. Downstream from section 6 the channel was progressively filled and at section 8 the stream was completely filled and sand was being deposited across the entire valley floor (Figs. 11 and 12).

The short discontinuous channel downstream from section 8 in 1957 had eroded headward into the aggraded reach immediately upstream. Although a vertical headcut was maintained, as it eroded through the cohesive vegetated alluvium at section 8, the vertical headcut could not be maintained in the coarser alluvium upstream. Instead, the reach of maximum erosion is represented by a local steepening of the channel gradient created by the nickpoint recession between sections 8 and 8a. The dashed line on the longitudinal profile at section 8a represents the profile of the valley in 1957 (Fig. 13). At section 9 the valley is unchanged since 1957. Directly downstream the lower headcut has eroded approximately 365 upstream since 1957.

Channel gradients have decreased where erosion has recently occurred, as at section D on Arroyo de los Frijoles and at section 8a on Arroyo Calabasas. Conversely, channel gradients are steepest immediately downstream from reaches where deposition is greatest as at section 8 on Arroyo Calabasas (Table 4).

Width/depth ratios vary greatly, and it is valid only to state that where deposition has filled the channel to the level of the valley, width/depth ratios are a maximum and where renewed erosion has occurred width/depth ratios are near a minimum.

DISCUSSION

The three small drainage basins that have been studied have one attribute in common. The main ephemeral-stream channels in each basin are undergoing simultaneous erosion and deposition. Erosion is primarily in the form of headcut incision and recession. It is also evident that a large percentage of sediment that is eroded as the headcut recedes, is trapped in the widened channel downstream. These processes were observed in 1957 (Schumm, 1961), and the same processes were still operating,

FIG. 12. Aerial view of Arroyo Calabasas between sections 7 and 8a. Downstream is to the left. Note sand splaying across the floodplain of the arroyo at section 8. Recently incised reach of channel (section 8a) can be seen on the left-hand side of the photograph.

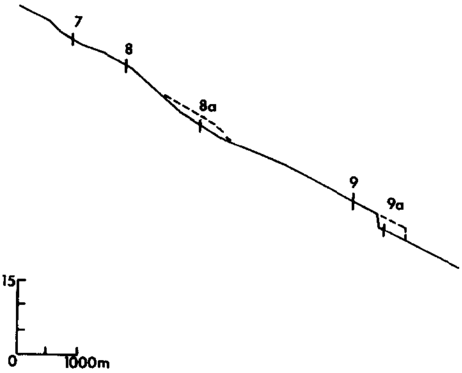

FIG. 13. Longitudinal profile of Arroyo Calabasas between section 7 and the confluence of the Santa Fe River downstream from section 9a. Solid line is the channel profile measured in 1971, dashed lines are the channel profile measured in 1957.

although on different reaches, in 1971 and 1979.

Between 1957 and 1971 the annual precipitation remained near the average for the Sand Creek and Arroyo Calabasas basins. Annual rainfall was below average during this period for the station near Sage Creek, but these data are not statistically meaningful because of the short period of record. Unfortunately, data on individual storms and runoff hydrographs are not available for these basins and the direct impact of rainfall-runoff variations on the erosional and depositional processes cannot be determined. But it appears that ephemeral-stream cutting and filling is operating independently of any subtle short-term climatic fluctuations.

Comparisons of photographs of the basins taken in 1937, 1957, 1971, and 1979 indicate only limited change in the vegetation cover. The most obvious change is the increased vegetation along rapidly aggrading channel reaches. This is probably the result of water spreading over the flood plain as flood flows spill out of the nearby aggraded channels and increase the soil moisture of the flood plain. Land use has remained constant between 1957 and 1979, and there is no evidence of any substantial revegetation in the headwaters of the basins. Therefore, the processes observed appear to be natural under the present climatic regime and with the present vegetative cover.

Arroyo cutting and filling has been suggested as the normal means by which sediment is transported out of semiarid drainage basins, which have naturally high sediment yields (Schumm and Hadley, 1957). This study supports this suggestion that arroyo cutting and filling may be fundamental processes in semiarid regions whose rates can be strongly influenced, but which can neither be initiated or stopped, by slight vegetation changes or subtle climatic fluctuations. The mechanics of erosion and deposition in Sage Creek illustrate the inherent nature of this geomorphic process. In 1971 there were two reaches of channel nearly aggraded to the valley floor. Below each depositional reach was an erosional reach. The channel in the erosional reach eventually widened to the point that it began to trap the sediment being produced in the zone of maximum erosion upstream. The process of renewed deposition is enhanced by the downstream increase in sediment concentration in ephemeral-stream channels (Hadley and Schumm, 1961). Therefore, the greater the distance from the nickpoint, the greater the sediment concentration and the greater the rate of deposition. Also, sediment which was efficiently transported through degraded channels with its low width/depth ratio and high hydraulic radius is trapped in the widened channel downstream. The mechanics of the erosion process, therefore, result in a channel configuration that induces deposition. A similar process of erosion and sedimentation was observed on Polacca Wash in Arizona (Thornthwaite *et al.*, 1942).

Our observations of arroyo cutting and filling have direct implications for Quaternary stratigraphic studies of alluvial fills in the semiarid western United States. First, a paleochannel exposed in an alluvial fill does not require that an entire drainage system was gullied simultaneously or that a continuous channel was ever formed. Instead, as demonstrated in this paper, erosion in one valley reach is often balanced by an aggradational reach downstream. Therefore, the occurrence of incised valley reaches, as inferred from stratigraphic studies, does not preclude the fact that there may have been equally significant reaches of deposition in that valley. Incised channels are easily recognized in the valley fills but correlation of these paleochannels with less distinct stable valley floor deposits may not be possible. An additional complicating factor is that several alluvial deposits can be formed during a single period of arroyo trenching (Schumm and Parker, 1973; Womack and Schumm, 1977). The sedimentologic–geomorphic model of arroyo cutting, with its inherent complexity, suggests that a lack of synchrony of incision between adjacent arroyos should be expected. Therefore, we would urge caution in the attempt to explain all cut-and-fill arroyo cycles with a strictly regional climatic model (Euler *et al.*, 1979).

It is possible to find support for this concept in the literature. For example, Martin (1963), in his detailed study of the pollen record of the southwest, accepted the thesis that arroyo cutting and filling was synchronous throughout the Rocky Mountain west (Martin, 1963, p. 69). Based on this assumption, he attempted to correlate distinctive suites of pollen adapted to low water tables in the alluvial fills during periods of erosion. Periods of deposition were dominated by other vegetation types when valley filling occurred which raised water tables and created a wetter flood-plain environment. Based on the pollen record he concluded that arroyo cutting occurred during periods of heavy summer rainfall (Martin, 1963). However, he also pointed out several pollen records which did not correspond to his overall trend and which indicate that during channel cutting on one stream deposition was occurring on other streams (e.g., Matty Wash; Cinega Creek; p. 59). This discrepancy is readily explained by the simultaneously operating processes of erosion and deposition within any valley as illustrated by the arroyos described in this paper.

The primary argument for the simultaneous trenching of alluvial fills during the Holocene is that subtle widespread climatic shifts were responsible for alternating periods of valley erosion and deposition (Bryan, 1940; Leopold and Miller, 1954; Leopold, 1976). However, more recent climate models indicate that significant changes in climate can occur within climate changes are not subtle but instead are rapid transitional changes which separate periods of quasi-stable climate (Bryson *et al.*, 1970).

For example, there is evidence of drought in Iowa and Nebraska in the 13th and 14th centuries while, during the same period, there is evidence of increased rainfall in Oklahoma and the Texas panhandle (Bryson *et al.*, 1970). In the southwest the position of the Pacific front is crucial to the climate of the semiarid grasslands (Bryson *et al.*, 1970). The position of this front induces a greater inflow of moisture from the Gulf of Mexico to the east of the front with a resulting increase in summer rainfall. Conditions to the west of the front would be correspondingly more arid. Evidence for exactly this variability is documented in Arizona where the period of maximum postglacial warmth was humid in southeast Arizona because of increased summer rain and dry in the Mohave Desert to the west because of summer drought (Wells and Berger, 1967; Wells, 1970). More recently, Hall (1977) has also demonstrated the lack of synchronous climate shifts in the southwest during the Holocene. His reinvestigation of Chaco Canyon indicates that the period of maximum aridity in northwestern New Mexico may have begun nearly 2000 yr before the period of maximum aridity in southern Arizona (Hall, 1977).

If the more recent evidence of climate change is correct, then certainly a strict climatic model cannot be used to explain any hypothesized simultaneous period of arroyo trenching throughout the Southwest. Love (1979), for example, concludes that, although tree-ring evidence shows many minor climatic fluctuations, there has not been a major climatic change in the Chaco Canyon area for thousands of years. However, the alluvial record is complex, and records three magnitudes of channel change. The major changes probably reflect climate or baselevel change, but the modern channel changes and Holocene cut-and-fill cycles probably do not. Therefore, we suggest that arroyo cutting may not have been synchronous throughout the West and that, based on geomorphic investigations of arroyo inception and evolution, regional correlations of Holocene alluvial fills in the western United States may not be valid. Instead we suggest that where sediment yields are high and the resulting ratio of sediment discharge to water discharge is high, arroyo cutting and filling is a natural sequence of events by which sediment is episodically transported out of the drainage system (Schumm, 1977). Therefore, a complex alluvial chronology can be expected, the major components of which can reflect major climate change but the details of which are the result of the sediment transport processes within the drainage basin.

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