# Late Holocene sediment storage in canyons of the Colorado Plateau

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## ABSTRACT

**Field surveys of ten drainage basins 10 to 1,790 km$^2$ in area in the Colorado Plateau (Utah and Arizona) and repeat photography of 156 fluvial environments providing comparative evidence spanning up to 114 yr reveal that two stratigraphic units characterize the alluvial materials on valley floors. An older unit deposited generally between 1250 A.D. (±200 yr) and 1880 A.D. (±20 yr) was dissected by arroyo development by the early twentieth century. A younger unit was deposited generally during the period after approximately 1943 (±5 yr). Rates of sedimentation in the 1943–1980 period were almost twice the rates in the 1250–1880 period. Channel-storage rates during the two periods of sedimentation are related to drainage-basin area by a power function similar to functions relating slope-sediment production and sediment yield to drainage basin area. Storage rates in the 1943–1980 period were about 50% of the rates of slope-sediment production. The amount of sediment stored in the two units exhibits a definable spatial pattern. Source streams (with basin areas upstream <1 km$^2$) consistently passed sediments eroded from slopes through the channel system with little storage. Local streams (with basin areas upstream of 1–1,000 km$^2$) alternatively stored and then evacuated large amounts of sediment in apparent response to climatic and land-use changes. Regional streams (with basin areas upstream of 1,000–10,000 km$^2$) stored or evacuated moderate amounts of sediment in response to events upstream. Inter-regional streams (with basin areas upstream >10,000 km$^2$) alternatively stored or evacuated moderate amounts of sediment in response to upstream evacuations of sediment from the Colorado Plateau, riparian vegetation change, and hydro-climatic changes in mountain watersheds outside the plateau region.**


## INTRODUCTION

The purpose of this paper is to examine the spatial and temporal variation of fluvial sedimentation within drainage basins of the central Colorado Plateau. Since the late 1800s, dramatic changes have occurred in processes of channel deposition and erosion in the region (Fig. 1). Although the cause of these changes has been the subject of intense debate (Cooke and Reeves, 1976; Graf, 1983b), the rates of deposition and the geography of the resulting deposits have received less attention. The emphasis in this paper is on system-wide variations in rates and magnitudes of storage rather than on highly detailed analysis of a few sites. All fluvial processes take place within highly integrated slope and channel systems (Schumm, 1977, p. 2), so that analyses of alluvial deposits in specific sites might be better understood if the evidence could be seen in a general framework encompassing complete drainage basins.

The task of developing generalizations for temporal and spatial changes in sedimentation along channels in the plateau region produces three questions with which this paper is concerned. First, what are the stratigraphic units containing the deposits of the past several hundred years? Much work has already been published concerning nearby areas that may be applicable to the central plateau (summarized by Euler and

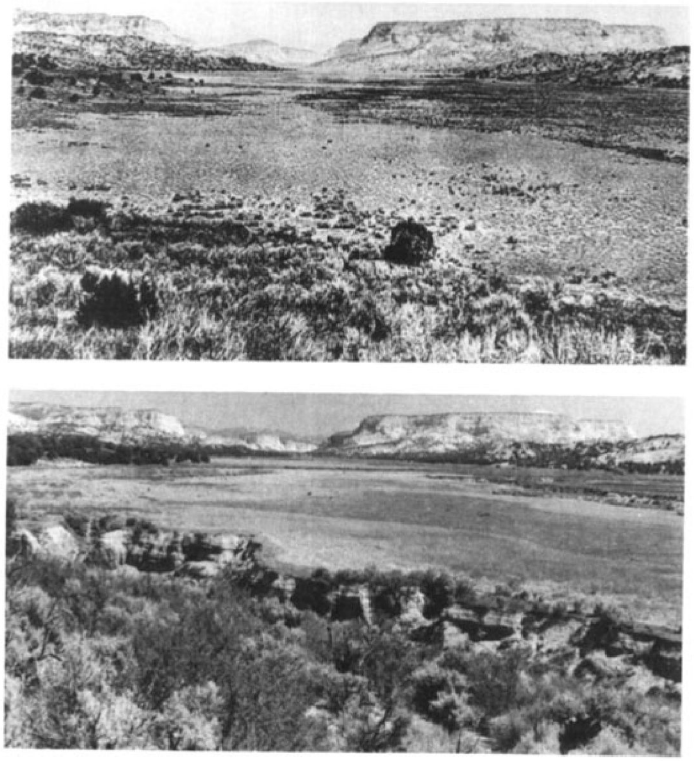

**Figure 1. Views upstream (north) in Johnson Canyon south of its junctions with Needle and Flood Creeks showing valley fill in 1872 and its modern appearance with an arroyo. Above: 1872, photo by J. K. Hillers, U.S. Geological Survey Photo and Field Records Library, Denver, Gregory Photo No. 1272. Below: 1984, photo by author. The alluvial surface shown across the entire canyon floor in the 1872 photograph is the upper surface of unit 1, which forms a broad terrace along channels in the 1984 photograph. [*Note:* although Gregory, 1950, p. 174, dated the earlier view as 1880, Hillers' (1875) journal indicates that he was in the area in 1872.]**

**Additional tabular and map material for this article may be secured free of charge by requesting Supplementary Data 87-27 from the GSA Documents Secretary.**

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others, 1979). Second, what do the amounts of material stored in the alluvial deposits indicate for rates of accumulation and magnitude of the storage term in the sediment budget of the region? The storage term of sediment budgets has been investigated for other environments in North America (Meade and Trimble, 1974; Trimble and Lund, 1982; Graf, 1983c) but not for the Colorado Plateau. Third, what is the spatial distribution of the storage component? Except in the broadest terms (Knighton, 1984, p. 81–84), generalizations about the location of channel storage of materials are lacking.

The Colorado Plateau is an area of epeirogenic uplift characterized by gently dipping sedimentary rocks with locally folded strata and volcanic intrusions (Hunt, 1974). Elevations range from about 900 m along the Colorado River to 3,880 m at the peak of the laccolithic La Sal Mountains. The climate of the region is arid and semi-arid; annual precipitation ranges from less than 150 mm to more than 750 mm and results mostly from summer thunderstorms (Richardson and others, 1981). Vegetation in most of the area is sparse except for riparian zones (Cronquist and others, 1972), modern soils are poorly developed, and bare rock surfaces are common (Wilson and others, 1975).

Ten drainage basins tributary to the middle Colorado and lower San Juan Rivers provided data defining the amounts of alluvium stored along channels (Fig. 2). Basins selected for study have a wide range of drainage areas (0.4 to 1,788 $km^2$), have channels with easily defined bedrock cross sections, and are not in complex lithology. The basins have streams that are entrenched several hundred metres into the plateau with discontinuous accumulations of late Holocene alluvium.

The alluvium frequently forms two sets of paired terraces and associated sediments, stratigraphic units hereafter referred to as "units 1 and 2." Unit 1 is the older of the two units. Canyon floors do not appear to contain alluvium predating unit 1. Unit 1 inundates talus blocks near the canyon walls and consists of fine to coarse sand with massive beds, lenses of fine gravel, buried paleochannels, and weakly developed, discontinuous paleosols. The geomorphic expression of unit 1 in the early 1980s was a terrace with the upper surface 3–10 m above the modern channel or as a broad alluvial fill cut by arroyos. The upper surface is underlain by a weakly developed soil and occasionally has remnants of former channels now separated from the modern channel by arroyo cutting (Hunt and others, 1953, p. 207–211; Graf, 1983a, p. 378–379). The upper surface also has cottonwood trees (*Populus fremontii* Wats.) that began their growth at or near the surface and that were later partially buried by fine overbank sediments. Tree-ring counts indicate that they range between 100 and 130 yr in age (similar evidence was found by Hereford, 1984, for the Little Colorado River). Other vegetation that characterizes the surface includes box elder (*Acer negundo* L.), gambel oak (*Quercus gambelii* Nutt.), Utah

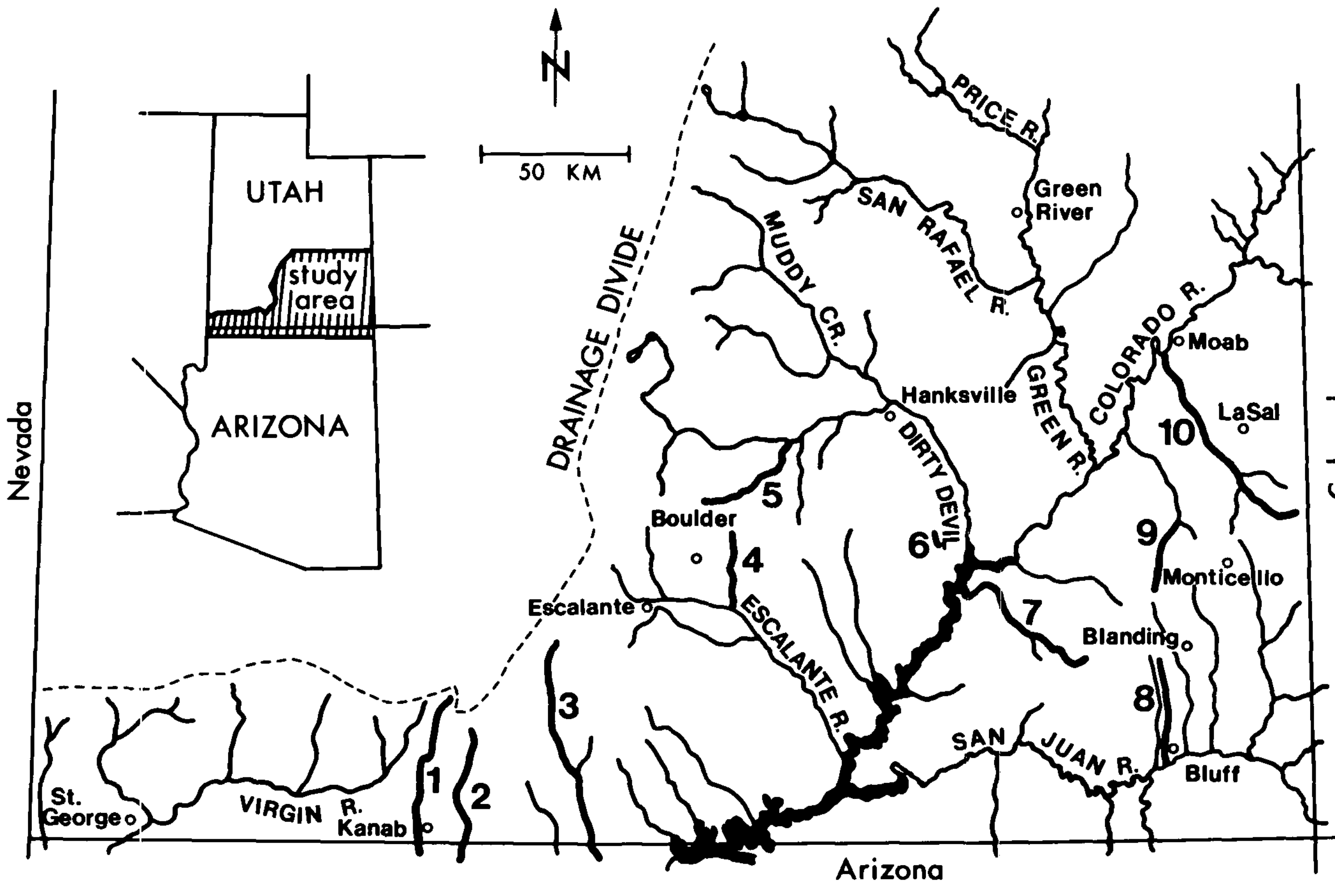


**Figure 2. Location map showing canyon systems used for measurement of sediment volumes. (1) Kanab Canyon above Fredonia, Arizona. (2) Johnson Canyon above U.S. Route 89A in Arizona. (3) Paria River above "The Narrows." (4) The Gulch above its junction with the Escalante River. (5) Pleasant Creek above its junction with the Fremont River. (6) Hog Springs Canyon above its junction with North Wash. (7) White Canyon above the maximum pool elevation of Lake Powell. (8) Butler Wash above its junction with the San Juan River. (9) North Cottonwood Canyon above its junction with Indian Creek. (10) Kane Springs Canyon above its junction with the Colorado River.**

juniper [*Juniperus osteosperma* (Torr.) Little], and big sagebrush (*Artemisia tridentata*).

Inset below unit 1 terraces are the forms and deposits of a younger unit 2. Arroyo incision into unit 1 frequently removed alluvium to bedrock, and younger deposits have partially filled the resulting void. Unit 2 is usually 1 to 3 m thick and consists of coarse gravels and cobbles overlain by fine sediments. The fine sediment is apparently the product of overbank flooding and representative of a typical fining-upward stratigraphic sequence (Allen, 1970, p. 141–142; Leeder, 1982, p. 146). Historical photographs indicate that these materials began to accumulate in the early 1940s after the general erosional episode (all year dates in this paper are A.D. unless otherwise noted). Roads made by heavy machinery during the period of uranium prospecting from 1947 to the late 1950s (described for the area by Taylor and Taylor, 1970) are found on the upper surface of unit 2. In addition to cottonwood trees no more than 30 yr old, the surface vegetation commonly includes tamarisk (*Tamarix chinensis* Lour.), russian olive (*Elaeagnus angustifolia* L.), and golden rabbitbrush (*Chrysothamnus nauseosus*). Frequent erosive floods since 1980 have entrenched channels into unit 2.

## METHODS

### Means of Correlation

The identification and correlation of depositional units in the canyon-floor alluvium of the study area depend on geomorphic and stratigraphic relationships. The relationships of the terraces to each other and the stream channel, the height of the terrace surfaces above the modern channel, and surface characteristics of the terraces provide their initial identification. Soil development on surfaces provides a means of differentiation where sets of terraces are incomplete. Vegetation communities also aid differentiation of surfaces, with each surface exhibiting a generally recognizable community. Cutbanks resulting from channel erosion expose sediments for stratigraphic comparisons.

Dating of sediments and their associated surfaces was made possible by a variety of indicators. Carbon for radiometric dating was available from cottonwood and juniper trees buried at the base of the sediments. Cottonwood trees growing on surfaces provided sequences of tree rings for estimation of dates of germination on surfaces of up to more than a century in age (Everitt, 1968). Tamarisk trees provided similar evidence for surfaces up to about 40 yr in age. Human artifacts provided date-related evidence spanning at least the past 1,000 yr. Hearth sites constructed on alluvial surfaces (many of them now buried) are especially common in the central plateau region and are related to Anasazi and Fremont cultures of the period prior to about 1300 A.D. (Ambler, 1976; Gunnerson, 1969). Artifacts of subsequent Indian occupants are relatively rare. Early Anglo-American inhabitants left wagon roads, utensils, and remains of dwellings on older terraces, and uranium prospectors during the 1950s marked younger terraces with survey stakes and mechanically improved roads (Taylor and Taylor, 1970). Historical photographs also provide date-specific information on near-channel accumulations (Graf, 1978; Hereford, 1983, 1984).

### Calculation of the Sediment Budget

After the units of alluvium are identified, differentiated, and dated, it is possible to measure their volumes and estimate rates of accumulation. Comparison of rates of accumulation with estimates of rates of slope-sediment production and sediment yield from the basins provides insight into the sediment budgets for the basins. Only processes directly connected with channels (input from slopes, storage, channel output) were considered, although complex movement and storage of sediment clearly occurs on slopes as well (Gilbert, 1877; Dutton, 1882).

Slope-sediment production refers to that sediment which leaves the hillslopes of a basin and enters the channel system. Comparison of sediment-yield maps by soil surveyors (Wilson and others, 1975) with standard geologic maps of the region (Wilson and Moore, 1969; Hintz, 1980) permits estimation of the annual slope-sediment production for modern processes. Bulk density was assumed to be 1,100 $kg/m^3$ in accordance with Bureau of Reclamation procedures (Oka, 1962, p. 7). The area of the various bedrock units exposed in the drainage area above each site was multiplied by the expected slope-sediment production for that unit and summed with similar calculations for all the other major units. This total divided by the total drainage area provided the mean slope-sediment production for the basin. This method permitted an accounting of geologic variation within each study basin.

For purposes of general comparison with rates of fluvial sediment yield and storage, a collective description of the calculated slope-sediment production for all of the study areas as a group is desirable. As a generalization of the ten study streams, the following function accounted for 70% of the variability in slope-sediment yield:

$$Y_s = 1200\ A_d^{1.0}, \qquad (1)$$

where $Y_s$ = rate of slope sediment yield in $m^3/yr$ and $A_d$ = drainage area in $km^2$. Mean slope-sediment production is about 1200 $m^3/yr/km^2$ (2.5 acre ft/$mi^2$), corresponding to a rate of general surface lowering of about 0.12 cm/yr. This rate is slower than rates of about 1.0 cm/yr reported for badlands erosion in the Chaco River Basin by Wells and others (1983, p. 183), probably reflecting the widespread occurrence of more resistant sandstones in the central plateau. Equation 1 is highly generalized and masks the variability of slope-sediment production that occurs from one basin to another.

Gaging stations on streams in the plateau region are few in number and have limited records. The only lengthy records are those on the Colorado, Green, and San Juan Rivers which are not representative of the smaller tributaries. For ungaged streams, the present study uses a function calculated for the southwestern United States (Strand, 1975):

$$Q_s = 1130\ (A_d)^{0.77}, \qquad (2)$$

where $Q_s$ = sediment yield in $m^3/yr$ and $A_d$ = drainage area in $km^2$. Equation 2 includes data from the entire Colorado River Basin from drainage areas ranging from 25 to 1,550 $km^2$. Note that equations 1 and 2 estimate annual rates.

The accuracy of calculations for rates of slope-sediment production and fluvial-sediment yield represent first approximations rather than highly precise determinations. The function for slope-sediment production (equation 1) is a summary of more accurate evaluations for each study stream. The over-all average figure of 1,200 $kg/km^2/yr$ appears to be a reasonable figure, given sedimentation rates observed in small reservoirs (King and Mace, 1953), and when applied in another context to the entire central plateau, the function provides predictions that are reasonable in view of the sediment records on major streams (Graf, 1985). The function for fluvial sediment yield (equation 2) is widely used by the Bureau of Reclamation for estimation purposes (Strand, 1975). Its coefficient is probably less reliable than its exponent which is typical of several studies (Gottschalk, 1964, p. 17.12–17.13; Branson and others, 1981, p. 146).

An additional indication that the functions are reasonable is that for basins of less than 100 $km^2$, predictions of slope-sediment production and fluvial-sediment yield are similar in magnitude, a condition observed for an instrumented watershed in Arizona (Renard, 1980; Renard and Laursen, 1975). The difference between the two functions for larger basins may not be as great as it appears because the exponent in equation 1 may be less than unity as a result of colluvial storage on footslopes, a feature not investigated here. In any event, equations 1 and 2 provide reasonable first approximations in the absence of more reliable methods.

Storage rates were computed by dividing the volumes of the deposits by the assumed length of time required for deposition. Surveys of 114 cross sections along the ten study streams allowed measurement of the volume of sediment stored in each of the stratigraphic units. Along each study stream, a similar downstream sequence of deposits occurred. In the headward portions of the tributaries, relatively little sediment was stored, and so these areas were ignored in the storage analysis. In each canyon, the cross section farthest upstream was located where terraces and their associated sediments first became identifiable. The cross section farthest downstream was surveyed where the terrace converged with the channel, where the stream joined a master stream, or where the depositional units became small and spatially discontinuous.

Surveys of the cross-sectional dimensions of the depositional units provided the basic input into volumetric calculations. The vertical distance from the top of unit 1 to the bedrock floor was measured with a tape or by optical ranging methods if bedrock was present in the floor of the stream channel. Otherwise the vertical extent of the unit was determined by seismic survey, using a Soil Test Model MD-50 Mini-Scout Seismograph (Gardiner and Dackcombe, 1983, p. 55). Width of the bedrock cross section was surveyed at the level of the surface of unit 1 in the field by triangular survey or from aerial photography. Seismic surveys and observations of canyon cross sections where alluvial materials do not obscure the bedrock confirmed that the bedrock cross section was usually rectangular. The rectangular shape is probably the product of vertical joints which result in blocky disintegration of many of the sandstones of the Glen Canyon Group, which underlies much of the region.

Cross-sectional area of each unit at each site was the product of the width and depth. The total volume of units 1 and 2 for a given stream and its basin was

$$U = 0.5\,(A_i + A_j)\,L_{i,j}, \qquad (3)$$

where U = total amount of stored sediment in unit 1 or 2 ($m^3$), A = cross-sectional area of unit 1 or unit 2 surveyed at a site ($m^2$), L = longitudinal profile length between sites (m), and i,j = sequential sites along the profile.

Equation 3 accounts only for sediment added to a given cross section during deposition. The equation does not account for coincidental erosional losses, so that it describes the gross amount deposited in a given episode rather than the net value given by deposition minus erosion. Equation 3 implicitly assumes that the cross-sectional area old channel that

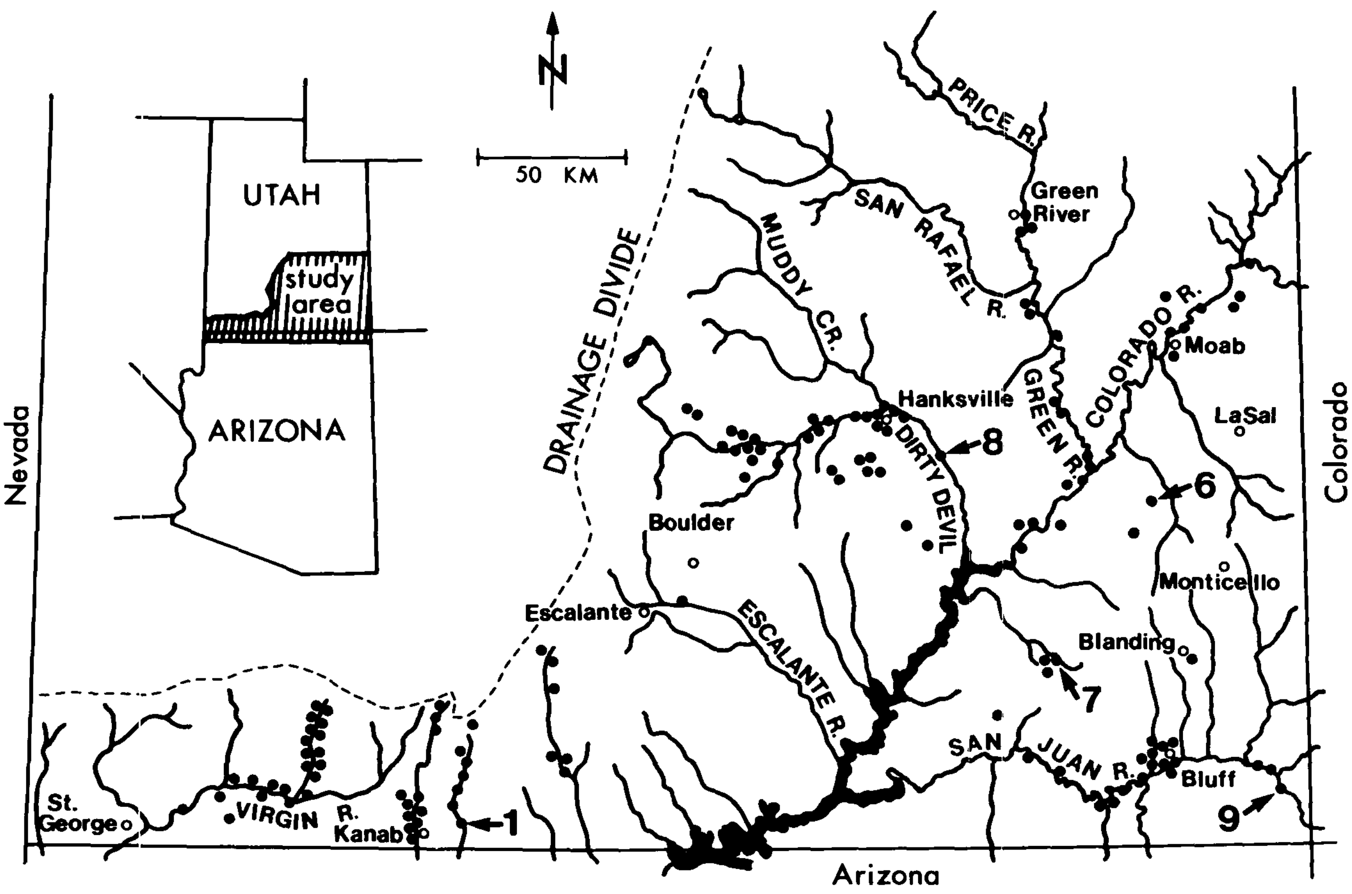


**Figure 3. Locations of historic rephotography sites used for the analysis of recent fluvial changes. Each dot represents a pair of photographs, a historical view 40–114 yr old and an identical modern (1980–1984) view. Numbered dots correspond to locations and figure numbers of historical-modern pairs included in this paper.**

once existed on the surface of unit 1 can be disregarded because its cross-sectional area was insignificant in comparison to the total area occupied by the sediments. Historical photography (Fig. 1), General Land Office Surveys, and accounts by early observers (Gregory, 1917, 1938, 1950; Gregory and Moore, 1931) clearly indicate that channels were small in relationship to the total valley width. Tributaries were disregarded (except in the Paria River system where storage in Cottonwood Canyon was included) because they contained little or no stored materials (Kitchen Corral, Park, and Deer Springs washes were not included because they enter the Paria below the downstream limit of this investigation). The modern arroyo cavity was assumed to have eroded from unit 1 materials and to have originally been filled by such sediment. The same general procedure provided volume data for unit 2.

The calculations reported in this paper have variable error factors that are impossible to accurately assess. The estimates of slope-sediment production are likely to have a standard error of about 50%, whereas the estimates of fluvial sediment yield are probably more reliable because they derive from a function describing direct measurements. The surveyed volumes of stored sediment probably have a 10% standard error. The date of initial deposition of unit 1 is variable, and the age of 630 yr (standard error of about 20%) serves as a maximum. The age of unit 2 deposits is probably accurate to within about 5 yr. These errors may combine to produce concluding estimates that are correct only within an order of magnitude.

### Cartographic and Photographic Sources

Plots of the sites of surveyed cross sections on aerial photography and topographic maps permitted along-stream measurements between cross sections. Drainage basin areas were plotted on topographic maps and measured with a polar planimeter. Aerial photography was also useful in preliminary general delineations of the alluvium, but in most cases, field investigations defined precise limits.

Repeat photography at 156 locations provided additional information regarding processes during the past century (Fig. 3). Comparisons of historical photographs (dating mostly from 1871 to 1939) with modern photographs (1980–1984) reveal the effects of recent fluvial processes (Malde, 1973). I have rephotographed 138 sites (examples of paired photos published in Graf, 1982, 1983a, this paper), Baars and Molenaar (1971, p. 90–97) provided four pairs, Baars (1973, p. 66–69, 84–85, 90–91) provided four pairs, and Shoemaker and Stevens (1975, p. 113–122) provided ten pairs. Only seven of the ten study basins are represented in the historical photography, but the collection extends over the entire range of stream sizes considered here and includes additional stream systems throughout the central Colorado Plateau. Sources of the historical images include the U.S. Geological Survey, U.S. Soil Conservation Service, Utah State Historical Society, University of Utah Marriott Library, Denver Public Library Western History Collection, and the Colorado State Historical Society. For a review of repeat photography techniques, see Graf (1984), Klett and others (1984, p. 11–52), and Rogers and others (1984).

The historical and modern conditions of the channels were assessed as either eroding, depositing, or transporting (neither erosion nor deposition apparently dominant). Eroding conditions were indicated by steep side-walls along arroyos and channels, mass-movement structures along channel margins, lack of riparian vegetation in the channel, and exposure of surfaces that were buried in previous photographs. Depositing conditions were indicated by meandering, narrow channels, burial of surfaces exposed in previous photographs, and newly established and expanding coverage of channel surfaces by riparian vegetation. Transporting conditions were indicated by lack of change between paired photographs, and the presence of undisturbed trees several decades in age along the channel margins.

TABLE 1. DATES OF SETTLEMENT AND CHANNEL EROSION IN PARTS OF THE CENTRAL COLORADO PLATEAU

| Stream | Settlement | Earliest date | |
|---|---|---|---|
| | | Settlement | Erosion |
| Santa Clara | Santa Clara | 1855[1] | 1861[2] |
| Lower Virgin River | St. George | 1861[3] | 1862[4] |
| Middle Virgin River | Rockville | 1859[5] | 1862[6] |
| Long Valley | Mt. Carmel | 1868[7] | 1883[8] |
| Upper Virgin River | Orderville | 1864[9] | 1885[10] |
| Kanab Creek | Kanab | 1858[11] | 1872[12] |
| Upper Paria River | Cannonville | 1875[13] | 1890[14] |
| Middle Paria River | Paria | 1865[15] | 1883[16] |
| Escalante River | Escalante | 1876[17] | 1890[18] |
| Pleasant Creek | Notom | 1882[19] | 1896[20] |
| Fremont River | Giles | 1882[21] | 1896[22] |
| Mill Creek | Moab | 1855[23] | 1896[24] |

*Note:* table provides only earliest date of reported erosion; many areas experienced extensive erosion at later dates. Examples include Kanab Creek which was reported as eroding in 1872 (Robinson, 1970, p. 141) but which experienced "the great washout" in 1883 (Robinson, 1970, p. 139). The Escalante River near Escalante experienced some erosion in 1890 (Bailey, 1935, p. 350), but extensive cutting occurred in 1909 (Laing and Stockton, 1976). Mill Creek began incision in 1896 (Tanner, 1976, p. 269) but was extensively eroded in 1905 (Tanner, 1976, p. 200).

1. Larson, 1961, p. 38; 2. Larson, 1961, p. 44; 3. Larson, 1961, p. 4; 4. Larson, 1961, p. 357; 5. Woodbury, 1950, p. 149; 6. Woodbury, 1950, p. 151; 7. Bailey, 1935, p. 350; 8. Bailey, 1935, p. 350–351; 9. Robinson, 1970, p. 302; 10. Larson, 1961, p. 363; 11. Robinson, 1970, p. 12; 12. F. S. Dellenbaugh, cited by Robinson, 1970, p. 141; 13. Gregory and Moore, 1931, p. 29; 14. Bailey, 1935, p. 350; 15. Robinson, 1970, p. 270; 16. Bailey, 1935, p. 350; 17. Woolsey, 1964, p. 31; 18. Bailey, 1935, p. 350; 19. Carr, 1972, p. 119; generally Snow, 1977; 20. Hunt, 1939; 21. Carr, 1972, p. 120; 22. Gregory, 1918; 23. Tanner, 1976, p. 55; 24. Tanner, 1976, p. 269.

## RESULTS

### Fluvial Deposits

Unit 1 appears to have been deposited after an extensive erosion episode which generally occurred sometime around 1250 A.D. Euler and others (1979) reported widespread evidence of such erosion followed by deposition, and archeologic evidence in the study canyons substantiates this interpretation. In some limited areas, unit 1 may contain undifferentiated slope deposits, but exposures generally reveal that the unit was deposited on bedrock surfaces or lapped over easily distinguished talus accumulations. Lower and middle portions of unit 1 contain artifacts of the last Anasazi occupation which ended in the period 1200–1300 A.D. (Gregory, 1950, p. 172). In addition, a buried cottonwood stump, rooted at the base of unit 1 in Hog Springs Canyon, yielded a radiocarbon date (A-3665) of 630 ± 80 $^{14}C$ yr B.P. Initiation of deposition of unit 1 was not everywhere synchronous. Older dates from the Escalante drainage (Patton and Boison, 1986; Boison, in press) contrast with younger dates from other areas. Deposition of unit 1 in The Gulch, for example, may have been relatively late as indicated by a cottonwood stump rooted near the base of unit 1 in The Gulch yielded a date of 260 ± 80 $^{14}C$ yr B.P. Euler and others (1979) reached similar conclusions concerning variability of the date of deposition.

In the 1700s and 1800s, the surface of unit 1 was apparently stable or slowly aggrading. For example, in 1776 Escalante (1776, p. 78) reported that Indians were irrigating fields from shallow channels on the surface of what was probably unit 1 in the Virgin River basin. During Anglo-American settlement of the southwestern and south-central plateau, narrow streams meandered on the surface of unit 1 (Woodbury, 1950, p. 140 for the Virgin River; Cleland and Brooks, 1955, p. 135–141 for the Paria River). In 1880 Dutton reported that Johnson Canyon was "slowly filling with alluvium . . . in some cases a smooth floor of alluvium extends from side to side" (Fig. 1; Dutton, 1880, p. 228–229). Gilbert (1872, p. 76) reported similar conditions for Kanab Canyon in 1872.

Arroyo development terminated deposition of unit 1 during about 1880 (±20 yr). Entrenchment usually occurred by headcut recession during periods of high discharges or flash floods (Robinson, 1970, p. 138–141 provided a typical example). Because local flooding was the immediate mechanism for erosion, exact synchroneity should not be expected in dates of initial incision (Table 1; see Bryan, 1925, for similar analysis for other areas). During the period 1880–1900, the central plateau experienced

TABLE 2. TENTATIVE CORRELATIONS AMONG STRATIGRAPHIC UNITS

| Area | Reference | Older unit | Younger unit |
|---|---|---|---|
| Central Plateau | This study | Unit 1 | Unit 2 |
| Central Plateau | Bailey, 1935 | Original surface | (1) |
| Escalante Basin | Patton and Boison, 1983 | Low alluvial fill | Flood plain |
| Paria Basin | Hereford, in press | Cottonwood Terrace | Flood plain |
| Little Colorado River | Hereford, 1984 | Cottonwood Terrace | Flood plain |
| Southern Plateau | Hack, 1939, 1942 | Naha Formation | (1) |
| Southern Plateau | Euler and others, 1979 | Upper Y, Z units | "a" unit |
| Chaco Canyon | Hall, 1977 | Post-Bonito | Historic |
| Chaco Canyon | Wells and others, 1983 | QaVIIa unit | QaVIIb unit |

*Note:* (1) Unit 2 correlative not yet deposited at the time of the referenced research.

increased frequency of flooding (Laing and Stockton, 1976). The result of arroyo development was the creation of unit 1 terraces. For example, Gregory (1917, p. 130) noted that in the early twentieth century "each valley is bordered by a single set of terraces which is increasing in length by headward erosion and in height by downcutting." Downcutting was halted only by bedrock exposure, leaving entrenched channels bounded by the steep walls of the unit 1 terrace (for a general description of conditions in 1931–1934, see Bailey, 1935).

Unit 2 deposits were laid down on the floor of the arroyo excavated in unit 1 materials. Initial deposition of unit 2 sediments occurred generally in the early 1940s as indicated by ring counts of tamarisk trees rooted in the base of the sediments (see also Hereford, 1984, 1986). Cottonwood trees sprouted on the upper surface of unit 2 in the early 1960s, indicating some stability of the materials. Bottles, cans, plastic, survey stakes from uranium prospectors, and photographic evidence (Graf, 1982, Figs. 9.7 and 9.8) show that unit 2 deposits are features of the post-1940 period.

Use of correlation techniques outlined in the methods section above, along with the age-related evidence, permit tentative correlation of units 1 and 2 in this study with stratigraphic units described in nearby areas by other workers (Table 2). Similar correlations for areas near the central plateau have been published by Euler and others (1979, p. 1097), who found from a wide range of localities that deposits apparently correlative to unit 1 date from about 1250 A.D., although there are exceptions (for example, ~200 yr earlier in Chaco Canyon according to Wells and others, 1983, p. 181). Therefore, calculations in this study adopt 1250 A.D. (±100 yr) as the date of initial deposition of unit 1. Deposition terminated about 1880 (±20 yr). Deposition of unit 2 probably began about 1943 (±5 yr). For the purposes of this paper, calculations terminate in 1980. This chronology is similar to periods of erosion and deposition reviewed for the southwestern United States by Dunne and Leopold (1977, p. 691).

## Regional Sediment Budget

Table 3 shows a wide range in slope-sediment production among the ten study basins. Those basins containing extensive areas of poorly consolidated fine-grained rocks (generally Chinle, Moenkopi, and Mancos Shale) exhibit the highest yields. The amount of material reaching channel systems is probably less than the calculated production, however, because of unknown amounts of storage on footslopes. Colluvial fans and aprons are common features of valley and canyon side slopes in the central Colorado Plateau, and they may account for an amount of material that is of the same order of magnitude as the alluvium.

Annual rates of sediment storage calculated for unit 1 during the 630-yr period 1250–1880 are generally much less than the rate of slope sediment supply (Table 3). The high storage rates for Kanab and Johnson canyons reflect the high rates of slope sediment supply from the Wasatch, Kaiparowits, Winsor, Carmel, Navajo, and Entrada Formations in their headwaters (Gregory, 1950, p. 162), and contributions from the Carmel Formation (Hintz, 1980). Those canyons with low rates of accumulation in unit 1 have low rates of slope-sediment production or lack storage space along channels. For example, White Canyon has its headwaters in the resistant rocks of the laccolithic Abajo Mountains and receives little sediment input. White, Kane Springs, and Pleasant Canyons have steep, deeply incised courses with narrow floors and have relatively little space for sediment storage.

Accumulation of the materials in unit 2 during the 37-yr period from 1943 to 1980 was generally two to four times more rapid than the rates of accumulation in unit 1 (Table 3). Wells and others (1983, p. 186) reported a similar increase in rates of sedimentation between correlative units in Chaco Canyon. The increased rates may be the combined result of at least three influences. First, human activities probably affected the near-channel

TABLE 3. GENERAL SEDIMENT BUDGETS OF TEN DRAINAGE BASINS IN THE CENTRAL COLORADO PLATEAU

| Drainage basin | Drainage area ($km^2$) | Rates ($m^3/km^2/yr$) | | | | Total volume stored $10^6 m^3$ | |
|---|---|---|---|---|---|---|---|
| | | Slope sediment | Fluvial yield | Storage Unit 1 | Storage Unit 2 | Unit 1 | Unit 2 |
| Hog Springs | 10 | 360 | 670 | 220 | 660 | 1,360 | 235 |
| Butler Wash | 147 | 660 | 360 | 260 | 310 | 24,200 | 1,680 |
| The Gulch | 158 | 420 | 350 | 87 | 200 | 8,700 | 1,180 |
| N. Cottonwood | 285 | 400 | 310 | 89 | 180 | 16,000 | 1,920 |
| Pleasant Creek | 300 | 760 | 300 | 51 | 130 | 9,610 | 1,390 |
| White Canyon | 709 | 160 | 250 | 19 | 66 | 8,610 | 1,720 |
| Johnson Creek | 760 | 860 | 250 | 420 | 60 | 202,000 | 1,680 |
| Kanab Creek | 814 | 1,000 | 240 | 1,200 | 670 | 635,000 | 20,200 |
| Kane Spring | 1,682 | 470 | 210 | 14 | 42 | 14,900 | 2,600 |
| Paria River | 1,788 | 620 | 200 | 77 | 300 | 86,300 | 19,700 |
| Mean | 665 | 510 | 320 | 140 | 260 | | |
| Stand. dev. | 629 | 260 | 140 | 140 | 230 | | |

*Note:* rates reported with two significant digits, volumes with three. Means and standard deviations calculated from original data omitting the obvious outlier of Kanab Creek.

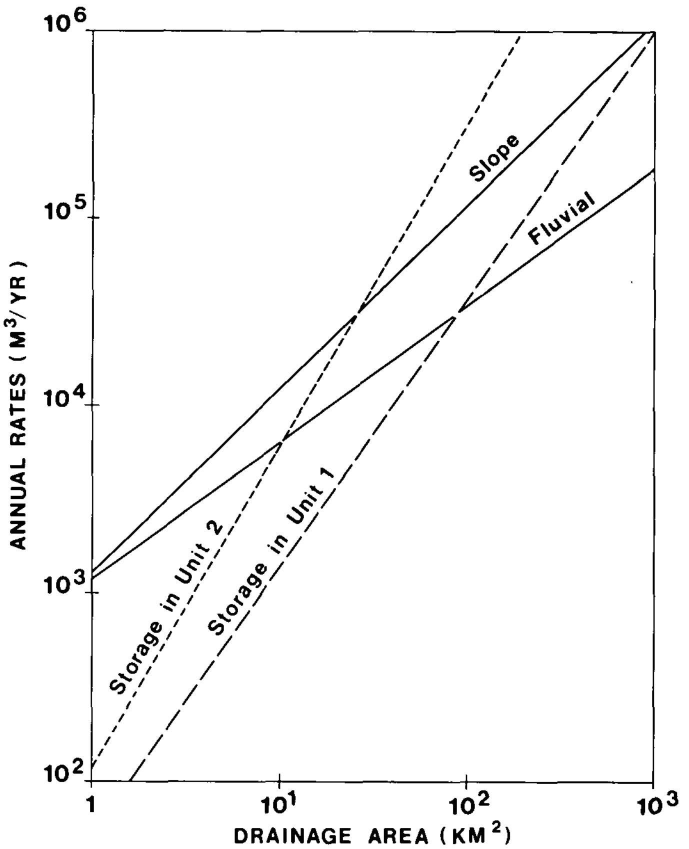


**Figure 4. Comparison of annual process rates for ten local-scale (drainage areas 1–1,000 km$^2$) streams in the central Colorado Plateau. $Y_s$ = slope-sediment production (equation 1 in text). $Q_s$ = fluvial sediment yield (equation 2 in text). Storage functions calculated from mean coefficients and exponents in Table 4. Coefficients were divided by length of time for accumulation in respective units (630 yr for unit 1 and 37 yr for unit 2) to convert volume functions to rate functions for comparison. Note that storage rates for more recent unit 2 are higher than older unit 1, and that in reaches with large drainage areas upstream storage rates exceed rates of slope sediment production. Remobilized alluvuial materials may make up the difference but cannot be assessed.**

environment by construction and maintenance of structures that promote sedimentation. Second, the invasion of exotic riparian vegetation such as tamarisk and Russian olive may have accelerated rates of sediment accumulation (Hadley, 1961; Graf, 1978). Third, there is no reason to assume that the rates for the 600-yr accumulation of the primary unit were uniform, and so the rate for the 37-yr period of the secondary unit sedimentation may represent short-term values that would decline if the sedimentation continued for several centuries. The pulsating behavior of sediment transport mechanisms may further complicate interpretation of short-term storage rates (Howard, 1982; Schumm and others, 1982).

When storage rates are compared to rates of slope-sediment production, the geomorphologic significance of channel storage in the central Colorado Plateau becomes apparent. Deposition rates for accumulation of material in unit 1 generally were less than rates of slope sediment production and fluvial sediment yield from the basins (Table 3). During the relatively brief period of unit 2 sedimentation, an average of 51% of the slope-sediment production were stored along the channels. In addition to changes in instrumentation for measurement of suspended sediment in large streams and climatic changes, the initiation of the storage process in unit 2 about 1943 may in part explain the dramatic decline in fluvial sediment yield in the Colorado River in the Grand Canyon (noted by Smith and others, 1960; and by Oka, 1962).

The components of the sediment budget shown in Table 3 do not balance (that is, fluvial-sediment yield does not exactly equal the difference between slope-sediment production and storage) for at least three reasons. The function for fluvial-sediment yield does not account for geologic variation, but improved functions are not available. Remobilized alluvium originally stored on canyon floors is not accounted for, although it may explain rates of storage in some large basins that exceed rates of slope-sediment production (Fig. 4). For particular systems, furthermore, the general age estimate for unit 1 may be too large because it is a maximum estimate.

### Spatial Variation of Sediment Storage

The late Holocene sediments in units 1 and 2 are distributed in the downstream direction in the ten study streams in a particular arrangement. In headwaters, the units are absent or present in only small quantities, but the quantity of stored sediment increases rapidly in mid-basin reaches where drainage areas upstream are 1–1,000 km$^2$. Farther downstream, the amount of stored sediment at each cross section rapidly declines and commonly approaches zero in those reaches with 1,000–10,000 km$^2$ drainage area upstream. Except for the through-flowing rivers, there are very few basins in the central plateau with drainage areas in the range 2,500–10,000 km$^2$, and so observations in this range are limited.

Mid-basin areas therefore play a pivotal role in the total sediment budget. The geographic significance of these mid-basin areas is that they are the locations of maximum stream power (Graf, 1983a). They are also the locations of major fluctuations in stream power that produce episodes of erosion and deposition.

The relationship between the amount of stored sediment and drainage basin area is complex. Although the total volume of sediment stored in White Canyon is less than in other cases, the basin has a spatial distribution of material that is typical of all of the basins in the study area and serves as a useful example. A polynomial describes the relationship between the amount of sediment stored at each cross section and the upstream drainage area (dashed line in Fig. 5). Cumulative volume of stored sediment, however, is related to drainage-basin area by a simpler power function (exemplified by the solid line in Fig. 5):

$$U = a\,(A_d)^b, \qquad (4)$$

where U = cumulative volume of stored sediment in either unit 1 or unit 2 (m$^3$), $A_d$ = drainage area (km$^3$), and a, b = empirically derived constants.

The downstream distribution of stored materials reflects the influences of sediment supply, stream power, and factors related to the regional master streams. Small amounts of sediment occur in upstream areas because little material is supplied to the stream. Large amounts of sediment are stored in the middle reaches where stream power is great and where it fluctuates from one time to another, triggering deposition or erosion (Graf, 1983a). In the downstream reaches, downcutting by the Colorado River and tectonic uplift have resulted in steep gradients in many of the tributary canyons, producing narrow, incised streams and little sediment storage.

Table 4 shows that equation 4 fits data from the ten study streams well, that the relative rates of change (indicated by the exponent b) are similar throughout the study canyons, and that the similarity between canyons is less for unit 2 than for unit 1. Variation in basin area explains

TABLE 4. REGRESSION ANALYSIS RELATING TOTAL CUMULATIVE VOLUME OF STORED SEDIMENT TO DRAINAGE AREA UPSTREAM (EQUATION 4)

| Stream | Unit 1 | | | | | Unit 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | $r^2$ | F | $s_{y \cdot x}$ | a | b | $r^2$ | F | $s_{y \cdot x}$ |
| Hot Springs | 19,800 | 1.96 | 0.91 | 30.94 | 0.07 | 12,286 | 1.47 | 0.90 | 28.16 | 0.06 |
| Butler Wash | 109,000 | 1.07 | 0.95 | 263.55 | 0.09 | 25,322 | 0.82 | 0.94 | 202.81 | 0.08 |
| The Gulch | 11,700 | 1.27 | 0.95 | 85.25 | 0.14 | 15 | 2.27 | 0.86 | 29.95 | 0.42 |
| N. Cottonwood | 29 | 2.27 | 0.96 | 115.84 | 0.10 | 0.6 | 2.46 | 0.93 | 71.48 | 0.14 |
| Pleasant Creek | $10^{-5}$ | 5.43 | 0.91 | 62.81 | 0.45 | $10^{-5}$ | 4.67 | 0.92 | 68.18 | 0.37 |
| White Canyon | 13,300 | 0.97 | 0.97 | 554.53 | 0.06 | 11 | 1.84 | 0.91 | 158.01 | 0.43 |
| Johnson Creek | 95,100 | 1.13 | 0.84 | 44.32 | 0.16 | 12 | 1.83 | 0.98 | 320.59 | 0.10 |
| Kanab Creek | 10,200 | 1.70 | 0.99 | 366.89 | 0.09 | 11 | 2.23 | 0.98 | 200.59 | 0.16 |
| Kane Spring | 800 | 1.38 | 0.83 | 52.65 | 0.64 | 580 | 1.18 | 0.79 | 41.30 | 0.62 |
| Paria River | 3,740 | 1.22 | 0.78 | 24.26 | 0.46 | 217 | 1.53 | 0.72 | 17.61 | 0.68 |
| Mean | 29,900 | 1.42 | 0.91 | 170.81 | 0.21 | 4,270 | 1.74 | 0.89 | 118.94 | 0.30 |
| Stand. dev. | 41,700 | 0.46 | 0.07 | 185.62 | 0.21 | 8,860 | 0.54 | 0.09 | 106.42 | 0.24 |

*Note:* all $r^2$ values significant at the 0.05 level of confidence. Values for a reported with three significant digits; calculations of over-all means and standard deviations conducted with original data, with Pleasant Creek exlcuded. Symbols: a = regression coefficient, b = regression exponent, $r^2$ = coefficient of determination, F = F statistic, $s_{y \cdot x}$ = standard error of the estimate in log form.

90% of the variation in the cumulative amount of stored sediment (mean $r^2$ = 0.90, n = 20, significant at the 0.01 level of confidence; standard deviation of $r^2$ values is only 0.08). This high degree of predictability results from the spatial regularity of the deposits (for example, open circles in Fig. 5) and obviates the need for large numbers of sample cross sections along each stream.

The range of exponent values for unit 1 (0.97–2.46 in Table 4, excepting Pleasant Creek) is particularly small in view of the variety of geologic conditions, canyon morphology, and rates of slope-sediment production. The exponent values for unit 2 are slightly more variable but are similar to those for unit 1. The increased variability in unit 2 may reflect the short period of accumulation.

The function relating sediment storage to basin area (equation 4) has the same form as those relating slope-sediment production (equation 1) and fluvial-sediment yield (equation 2) to basin area (Table 4; Fig. 4). The

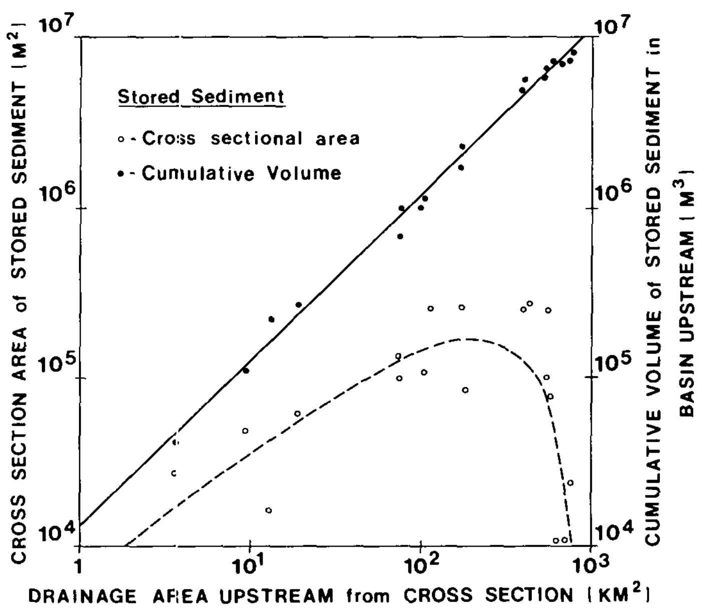


**Figure 5. Spatial variation of unit 1 sediment storage in White Canyon. Open circles represent cross-sectional area of stored sediment at various measurement sites. The dashed line is a parabolic function fitted to the data represented by open circles by least squares: $y = 31.5 + 1.2\,x - 0.002\,x^2$. Solid dots represent the cumulative volume of unit 1 sediment stored in the basin above the same measurement sites, generalized by the solid line defined by a power function fitted by least squares: $y = 13{,}200\,x^{0.97}$. Note the logarithmic scales.**

largest amounts of storage relative to basin area occur in Kanab Creek, Johnson Canyon, Hog Springs Canyon, and Butler Wash. All receive large influxes of sediment from the easily erodable Carmel and Morrison Formations (Haynes and others, 1972, Hackman and Wyant, 1973). Although the Paria River carries the highest recorded sediment concentration in the Colorado Plateau (a recorded instantaneous value of 646,000 ppm: Beverage and Culbertson, 1964), it stores only modest amounts. The smallest amounts of storage relative to basin area are in Kane Springs Canyon (no. 10 in Fig. 2) which heads in resistant laccolithic areas (Williams, 1964). The remaining basins are similar regarding the sediment-volume–drainage-area relationship.

## Generalizations from Photographic Evidence

Repeat photography confirms the variability and significance of sediment storage in medium-sized basins. The 156 relocated historical photographs show that during the past century the smallest channels or source streams (basin areas of less than 1 km²) are sources of sediment and rarely store it (Fig. 6). They appear relatively insensitive to environmental change. In local streams (drainage areas 1–1,000 km²), storage has been common with extensive deposits of units 1 and 2 and dissection by arroyo cutting (Fig. 7). Apparently these mid-basin areas alternatively store and evacuate sediment, and respond to land management or climatic changes specific to the Colorado Plateau.

Analysis of the repeat photography indicates that regional streams (drainage areas 1,000–10,000 km²) occasionally store modest amounts of sediment and respond mostly to events in upstream tributaries in the Colorado Plateau region (Fig. 8). Streams of this size are few in number in the plateau region and probably play only a minor role in the regional sediment budget, because units 1 and 2 generally occur only as small discontinuous deposits along them.

Inter-regional streams (drainage areas greater than 10,000 km²) extend beyond the Colorado Plateau region and are represented by the Green, Colorado, and San Juan Rivers. Although deposits along these large rivers were not measured in this study, previous workers have found that the amount of material in storage is relatively small in relationship to their drainage areas, and that most of the material is mobilized during floods, and so it is not in long-term storage (Miser, 1924, p. 67–71; Gregory, 1938, p. 102). These large rivers apparently respond partly to upstream events in the plateau tributaries and partly to events in distant mountain areas that supply the majority of their water (Miser, 1924). Channel changes are exemplified by the San Juan River. In the 1890s, it was a sandy braided channel (Perkins and others, 1968, p. 59), probably sustained by receiving massive inputs of sediment from eroding tributaries (Miser, 1924, p. 67–71). When runoff from the Rocky Mountain source areas declined after the early 1940s (Oka, 1962), the channel narrowed and established a mildly meandering pattern (Fig. 9). In those reaches of

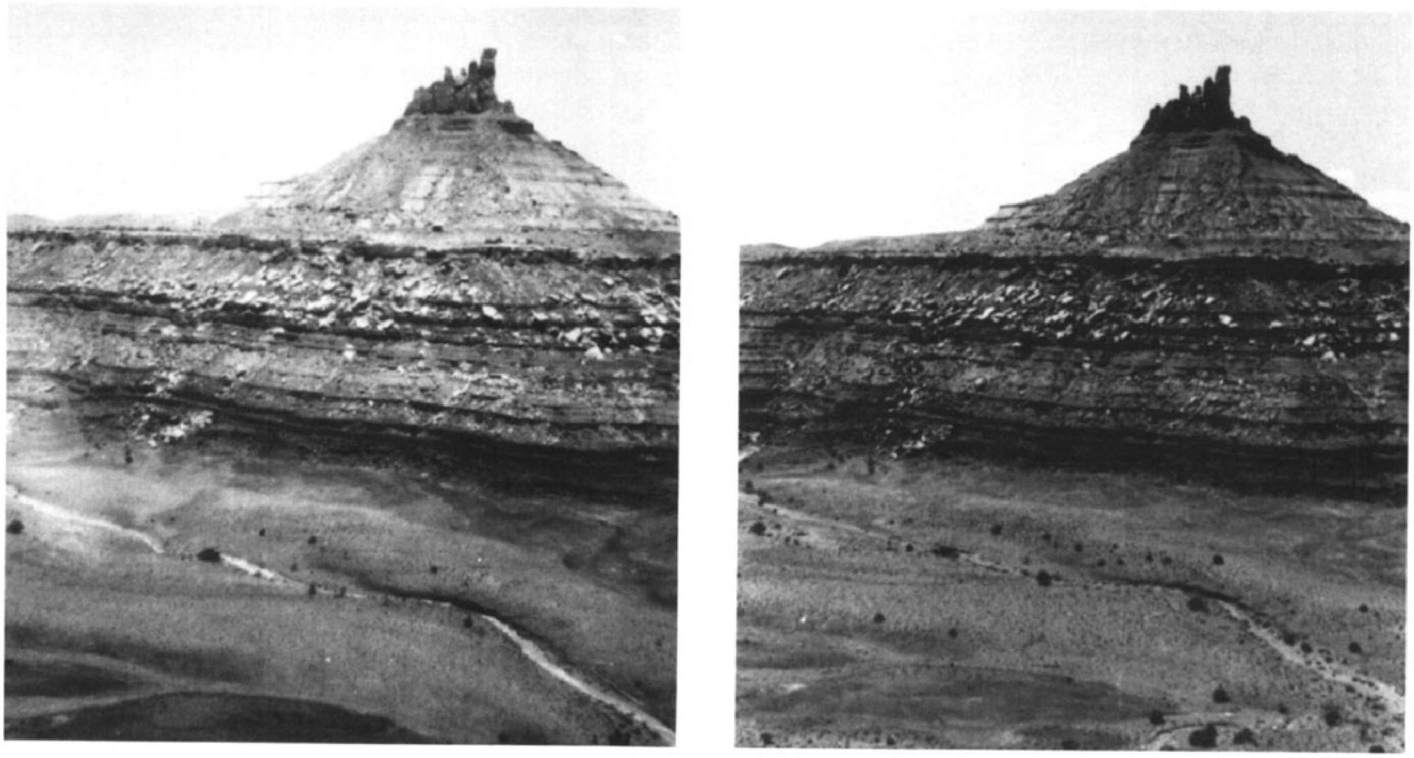

**Figure 6. A source stream draining Bogus Pocket near the southeast corner of Canyonlands National Park, Utah. View from the flank of South Sixshooter Peak looking northwest toward North Sixshooter Peak. Left: 1927, photo by Arthur A. Baker, U.S. Geological Survey Photo and Field Records Library, Denver; Baker Photo No. 237. Right: 1983, photo by author. Note lack of change in channel storage, which is minimal in both views.**

the largest streams confined by narrow canyon walls, channel changes have been less dramatic. Channel narrowing after 1940 was common, related partly to reduced runoff and partly to vegetation changes (Graf, 1978).

Changes of process through time as documented by repeat photography show a clear spatial pattern (hypothesized in Fig. 10). Information for the period 1250–1880 is from unit 1 deposits; 1880–1943 with its apparent division about 1910, from photographic evidence and sources listed in Table 1; and 1943–1980, from unit 2 deposits and photographic evidence. A broadly defined "wave" of sediment appears to have moved through the drainages from about 1880 to about 1943 as indicated by the shift of depositional processes to basins successively larger in scale (similar waves documented in other regions by Meade and Trimble, 1974; Trimble and Lund, 1982). Erosion began in local-scale streams and generated changes which propagated themselves downstream through the drainage system.

**Figure 7. Upper White Canyon, a local-scale stream in Natural Bridges National Monument, Utah. View looking upstream (northeast) with Sipapu Natural Bridge in the background. Left: 1915 photo by W. H. Hopkins, Colorado State Historical Society, Photo No. F-42,783. Right: 1984, photo by author. Note that in the earlier view no sediment was stored on the right bank which was composed of exposed Cedar Mesa Sandstone, whereas significant amounts of unit 1 sediment on the left bank supported riparian vegetation. In the later view, the previous right bank has been buried by deposition of unit 2 sediment and the left bank has been severely eroded.**

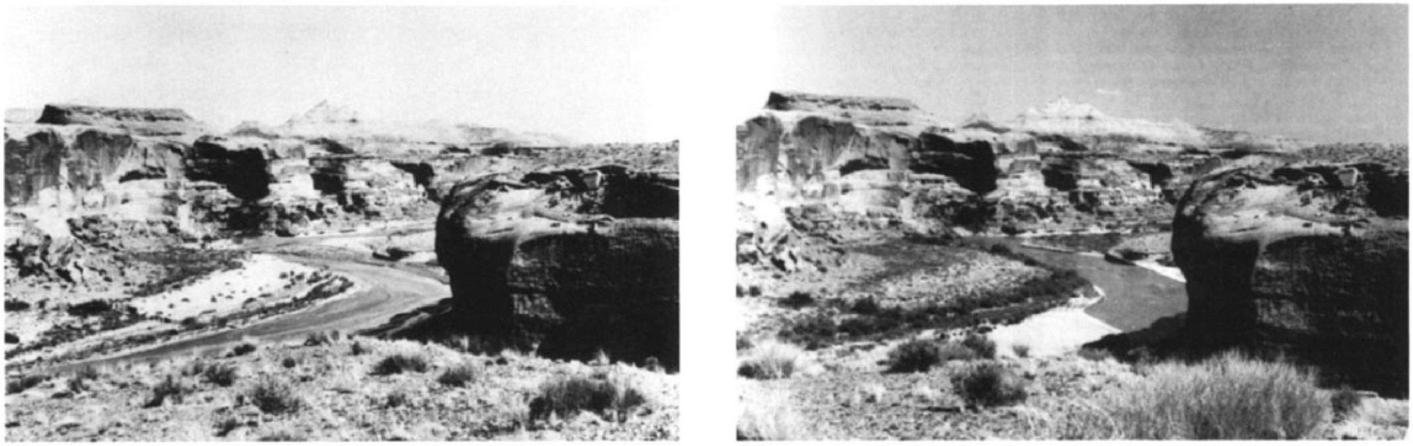

Figure 8. Angel Cove on the Dirty Devil River, a regional-scale stream in eastern Wayne County, Utah; view looking southeast, downstream. Left: 1939, photo by Charles B. Hunt, U.S. Geological Survey Photo and Field Records Library, Denver, Hunt Photo No. 873. Right: 1982, photo by author. Note stabilization of flood-plain and point-bar areas and similar channel dimensions in both photos.

Figure 9. The San Juan River, an inter-regional stream, near Aneth, Utah; view looking west with Casa del Eco Mesa in the background. Left: 1929, photo by Herbert E. Gregory, University of Utah, Marriott Library, Photo No. P2000, 9-2103,G,819. Right: 1983, photo by author. Note the 1-km-wide ribbon of sand representing the channel in the earlier view that in the later view has been stabilized by riparian vegetation (and perhaps controlled releases from Navajo Dam), resulting in a straight, narrow channel.

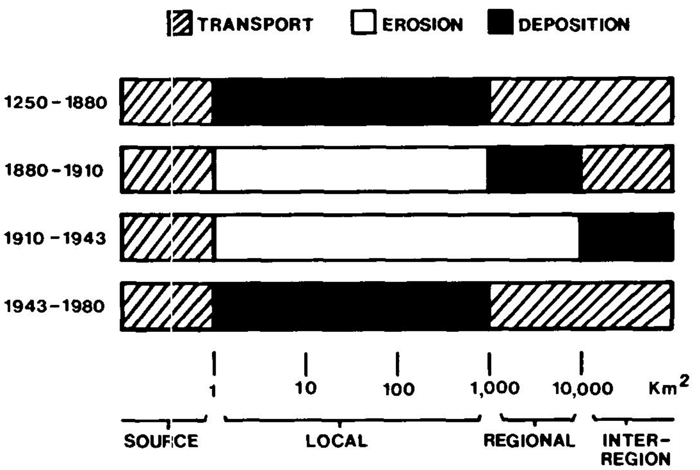


Figure 10. Time (dates approximate; see text) and scale diagram showing generalized changes in fluvial processes in central Colorado Plateau streams as interpreted from deposits and rephotography sites in Figure 3.

## CONCLUSIONS

Tentative answers to the original questions concerning fluvial processes in the central Colorado Plateau are as follows. First, late Holocene alluvial deposits in the central Colorado Plateau are characterized by two stratigraphic units. Unit 1 generally was deposited between 1250 (±100 yr) and 1880 (±20 yr), consists mostly of fine sand, and forms terrace surfaces 3–10 m above modern channels that were produced by arroyo development. Unit 2 generally was deposited between 1943 (±5 yr) and 1980 and consists of boulder and gravel layers overlain by silts and fine sands. The units have correlatives in adjacent areas of the plateau.

Second, materials in the latest Holocene unit were deposited at rates equal to about 50% (during the later period of deposition) of the likely rates of slope-sediment production. Rates of deposition in the later unit were two to four times the rates in the older unit. The cumulative amounts of sediment stored along channels in the two units are related to drainage-basin area upstream by power functions similar to those functions relating slope-sediment production and fluvial-sediment yield.

Third, the amounts of material stored in the two late Holocene units vary in a distinct spatial pattern. Source streams, headwaters channels, and small tributaries with drainage areas of less than 1 km$^2$ store little sediment. Local streams with drainage areas of 1–1,000 km$^2$ store large quantities of sediment and experience radical changes in deposition and erosion processes as a result of changing distributions of stream power (Graf, 1983a). Regional streams with drainage areas of 1,000–10,000 km$^2$ have small discontinuous accumulations of stored sediment and respond to processes operating in the smaller plateau rivers upstream. The large inter-regional rivers with drainage areas of greater than 10,000 km$^2$ store small amounts of sediment relative to their large drainage areas. They respond partly to changes in sedimentologic processes in local plateau tributaries and partly to changes in hydrologic processes in mountain areas that provide most of their runoff. The processes of sediment transport and storage in streams of the Colorado Plateau are therefore discontinuous in time and space.

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