Complex-response of a chaparral drainage basin to fire

JEFFREY R. LAIRD and MICHAEL D. HARVEY
Dept. Earth Resources; Colorado State University
Ft. Collins, CO 80523

ABSTRACT Sediment yield from El Oso Creek, a small chaparral-vegetated drainage basin in Arizona, is controlled primarily by wildfires that are followed by significant precipitation. Following a geomorphically-effective fire, hillslope erosion is severe and this causes lower-order tributary aggradation. Concurrently, the highest-order channel degrades and previously stored alluvium is transported from the basin. In the longer term, the tributaries degrade and the main channel aggrades. This aggradation reduces the probability of sediment export from the basin because it increases the volume for subsurface water storage that must be satisfied before surficial, sediment-transporting flows are generated. Soil development across the entire valley floor occurs with time, and this reduces the permeability of the stored sediments, and it increases the probability of sediment export from the basin. Prediction of sediment yield, therefore, can be improved by determining the geomorphic status of the basin.

INTRODUCTION

The ability to predict sediment yields from basins drained by ephemeral-flow channels is important to the design and construction of reservoirs in arid and semiarid regions. Under-prediction of sediment yields can lead to rapid loss of reservoir capacity, whereas over prediction can lead to over-design.

The objective of this paper is to document the complex-response of a small, chaparral vegetation-zone drainage basin, El Oso Creek, to wildfire, and to relate the basin response to fire to sediment yields from the basin.

Prediction of sediment yields in semiarid regions is complicated by the temporal and spatial variability of precipitation events that may be very intense (Thornes, 1974). In contrast to more humid regions, sediment tends to be stored in the channels rather than on the hillslopes, until an event of sufficient magnitude and duration occurs that is capable of transporting the sediment. This flow-dependent episodic removal of sediment results in both temporal and spatial episodes of aggradation and degradation in ephemeral-flow channels and therefore, significant variation in sediment yield. Channel reaches under such flow conditions will be out of phase (Schumm & Hadley, 1957; Schumm, 1961; Kottlowski, *et al.*, 1965). The episodic behavior that is controlled by the temporal and spatial variability of hydrologic events may be further complicated by the presence of geomorphic thresholds and the complex response of the system (Patton & Schumm, 1975; Schumm, 1977, 1979; Bergstrom, 1980; Harvey, 1980). The episodic behavior of ephemeral-flow channels in semiarid regions suggests that they may be inherently unstable (Thornes, 1977), and the resulting sediment yields will be highly variable.

Thornes (1974) has suggested that three types of flow can be recognized: 1) fully integrated flow of the drainage network, 2) axial or main channel flow with no tributary contribution at increasing distances downstream and, 3) asynchronous tributary flow to a dry main channel. Each of the flow types will have significant effects on the morphological characteristics of different channel reaches and on in-channel sediment storage and transport in both time and space (Leopold & Miller, 1956; Schumm & Hadley, 1957; Schumm & Lichty, 1963).

Ephemeral-flow channels are characterized by non-uniform unsteady flow behavior which is coupled with major transmission losses (Keppel & Renard, 1962; Benke & Schiff, 1963; Matlock, 1965; Murphey, et al., 1972; Thornes, 1974, 1977). Streamflow from a basin near El Oso Creek is reported to be 3.6 percent of the measured precipitation, due to losses by infiltration and evapotranspiration (Thomsen & Schumann, 1968).

In semiarid regions, wildfire has been shown to significantly affect sediment yields (Rice, 1973; Wells, 1982) because it increases overland flow and erosion (Brock & DeBano, 1982). Scholl (1975) demonstrated that soils under chaparral vegetation exhibited hydrophobic behavior which further increased runoff. DeBano and others (1976) report that temperature gradients due to fire are responsible for the development of a water repellent layer at depth in the soil. This layer is formed from hydrophobic compounds that are derived from the burning chaparral litter. During a storm event, the soil overlying the water-repellent layer becomes saturated, which leads to the development of overland flow and rills (Wells, 1982). The net result is a significant increase in delivery of sediment to the ephemeral-flow channels.

STUDY AREA

El Oso Creek drainage basin is located in the Tonto National Forest, central Arizona (Fig. 1). It has a drainage area of 2.5 km^2. The basin is located on the east flank of the NE-SW trending Mazatzal Mountains, at an average elevation of 1100 m. Data from the Three Bar Watershed Research Area, which is located 5 km south of El Oso Creek (Fig. 1), was used to extend the data base.

El Oso Creek basin is predominantly underlain by a deeply-weathered, coarse-textured, PreCambrian granite (Fig. 1). Within the granite body are localized zones of more resistant and less-weathered granite. Faulting has produced shear zones comprised of silicified cataclasites. These shear zones provide base level and groundwater controls throughout the basin. A dike of granodiorite, originating from a batholith to the north, crosses the basin and divides it into an upper-elevation, rugged, bedrock-controlled area and a lower-elevation, more gentle, alluviated area. Certain channel reaches are controlled by faults and joints, which strike and dip in two sets: N 25°W and 75 NE, and N 40°E and 40°E (Wilson, 1939).

El Oso Creek lies in one of Arizona's wettest regions within the elevation range of 1000 to 1600 m (Hibbert, et al., 1974). Average annual precipitation is 78.3 cm (US Weather Bureau & NOAA records, Three Bar 'D' data), and it is very seasonally distributed (Fig. 2). Winter precipitation, from October through March, occurs as a result of frontal-type storms, and averages 48.5 cm, or 62 percent of the annual total. The storms are usually of low-intensity, but they may release up to 10 cm of precipitation per day (Hibbert, et al., 1974). Summer precipitation, from April through September, occurs as a result of convective storms, and averages 30 cm, or 38 percent of the annual total. The storms can be intense and erratic, releasing up to 8 cm of precipitation per hour (Hibbert, et al., 1974).

Mean daily temperatures (Fig. 2) have been calculated from data recorded at the Sierra Ancha Experimental Site, which is located 32 km east of El Oso Creek at an elevation of 1555 m. Mean winter-month daily temperatures range from 5°C to 13°C, whereas mean summer-month daily temperatures range from 18°C to 26°C.

The entire drainage basin lies within the chaparral-vegetation zone. Vegetation species are dominated by shrub live-oak (*Quercus turbinella*) and birchleaf mountain mahogany (*Cercocarpas montanus*).

In June, 1959, the Boulder wildfire burned both the El Oso Creek and the Three Bar drainage basins. Vegetation density was reduced from 65 to 70 percent crown cover to near zero following the fire (Hibbert, et al., 1974). Ten years after the wildfire, vegetation had regained 90 percent of its pre-fire crown cover.

METHODS OF INVESTIGATION

In order to obtain field data on sediment movement and sediment distribution in the El Oso Creek basin, several different field techniques were employed.

Longitudinal profiles and cross-sections were surveyed in the main channel and seven tributaries. Cross-sections were established at 50-meter intervals or just downstream of major tributary confluences.

The main channel suballuvial bedrock profile was determined by seismic refraction. This survey enabled depths and volumes of alluvial fill to be calculated.

Eleven debris dams, constructed from fence posts, wire netting and brush, were emplaced on the main channel and selected tributaries. Dam height was kept below 0.75 m so as to minimize downstream degradation. Cross-sections were established at 1, 5, 10 and 15-meter intervals upstream of the dams, and they were periodically resurveyed in order to determine the volumes of sediment transported to and deposited behind the dams.

Five storage-type rain gages were established along the perimeter of the basin at 200-meter vertical intervals in July, 1984. These were later abandoned following US Forest Service installation of two recording tipping-bucket rain gages and several storage gages in February, 1984.

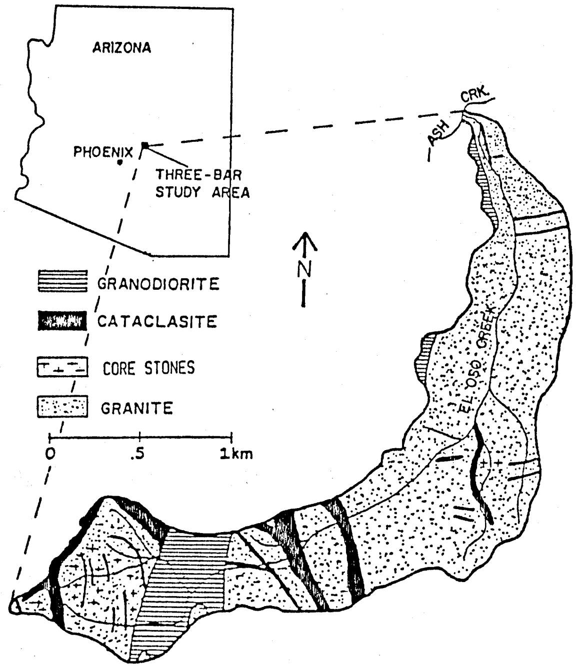

Fig. 1 Location map and bedrock geology of El Oso Creek, located 115 km northeast of Phoenix, AZ. Three Bar Study Area is 5 km south of El Oso Creek.

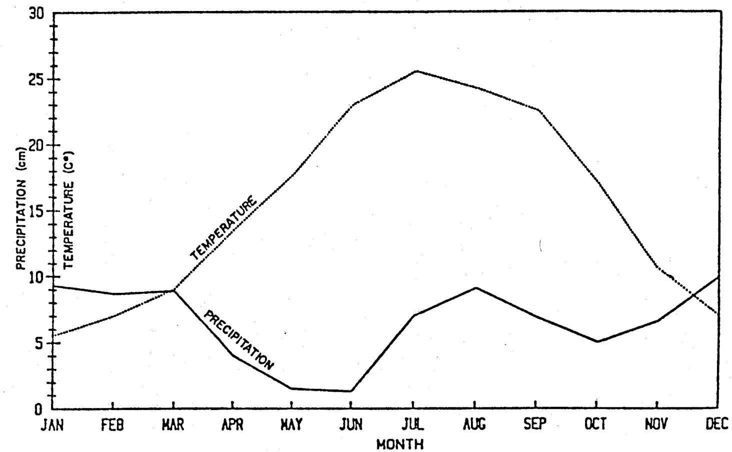

Fig. 2 Averaged monthly precipitation and daily temperatures at El Oso Creek basin.

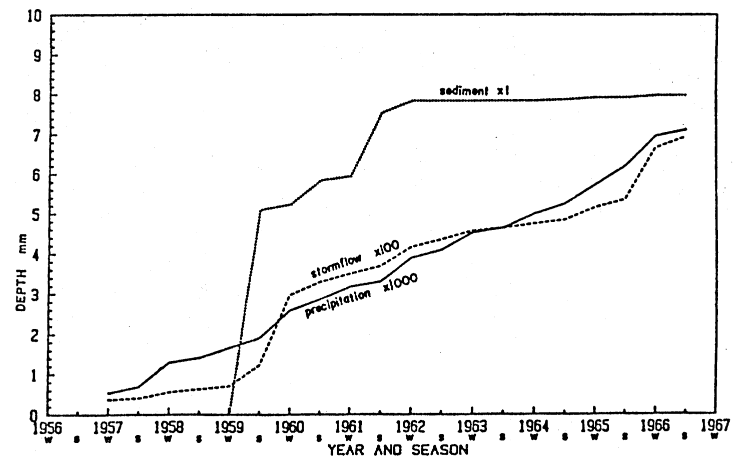

Fig. 3 Cumulative precipitation, stormflow and sediment production of the Three Bar 'D' drainage basin before and following the 1959 wildfire, expressed in mm of depth over the basin area.
s -summer, w - winter.

In 1956, six drainage basins, A to F, in the Three Bar Watershed Research Area were instrumented with rain gages and V-notch weirs by the US Forest Service in order to determine the effects of converting chaparral vegetation to grasses. Following the Boulder wildfire, debris basins were constructed in each basin in order to trap the increased sediment load.

Precipitation, streamflow and sediment production data gathered from basin 'D', which was a control, was used in this study. Because the basin is underlain entirely by granodiorite, is smaller (33 ha), steeper, and has a perrenial spring, the hydrologic characteristics are different from those found in El Oso Creek. For this reason, relationships derived from basin 'D' are used in only a relative sense and cannot be applied directly to the El Oso Creek basin.

In 1983, the US Forest Service obtained low-level aerial photography of El Oso Creek basin at a scale of 1:300. In addition, aerial photos taken in 1959 (pre-fire) and 1967 at a scale of 1:15 840 were obtained and enlarged to a scale of 1:2475. The photos provide a 26-year record of basin conditions before and following the Boulder wildfire, and they were also used to determine the morphometric characteristics of the basin.

Sediment samples were collected from the channel surface at each surveyed cross-section, from trapped dam sediment and from paleosols that were observed in the valley-fill at incised reaches. Grain size distributions were then determined.

A simple falling-head infiltrometer, constructed from a clear plastic tube with centimeter graduations, was used to measure the relative infiltration rates into the alluvium and the paleosols on a seasonal and locality basis. The tests were conducted by measuring the time elapsed for 20 cm of water to drain out of a 3 mm hole in the base of the infiltrometer.

RESULTS

basin morphometrey

Table 1 lists averaged values of morphometric variables for sub-basins grouped according to elevation and aspect. Potential relationships between these morphometric variables were investigated, but they did not show strong correlations. Patton and Schumm (1975) suggested that morphometric relationships established for larger basins may not apply to smaller basins because local factors exert a controlling influence. In addition, drainage basins in which one area or component is out of phase with another cannot be expected to show the strong correlations that might be found in basins that are in a more quasi-equilibrium state (Schumm, 1977).

hydrology

In El Oso Creek, four separate flow events occured during the summer and winter of 1984. In all cases, flow was limited to tributaries and short reaches in the main channel downstream of tributary confluences. Two of the events were characterized as asynchronous tributary flow and the remaining two events as axial flow (Thornes, 1977).

Table 1 Basin morphometric values (means:x and standard deviations:s) for El Oso Creek basin, for all sub-basins, and for sub-basins grouped on the basis of aspect and elevation.

Zone		No. Obs.	Basin Area (km^2)	Drainage Density (km/km^2)	Stream Frequency ($seg./km^2$)	Channel Slope (%)
El Oso Creek		1	2.19	22.0	238	13.6
All Sub	x	65	0.032	23.5	286	29.0
Basins	s		0.034	14.8	209	7.3
Upper	x	8	0.0483	15.9	158	30.8
Basin	s		0.0414	6.1	53	6.7
Middle	x	20	0.017	24.8	326	27.8
North	s		0.008	11.8	202	6.2
Middle	x	16	0.0515	16.8	125	30.8
South	s		0.0458	4.5	64	9.1
Lower	x	6	0.0221	17.7	207	27.8
West	s		0.0097	3.8	80	5.3
Lower	x	15	0.026	28.4	506	28.9
East	s		0.024	7.4	185	6.4

Perrenial spring flow was observed in the lower reach of the main channel, which is characterized by a narrow valley, bedrock outcrops, extensive dikes and incision following the 1959 fire. A perennial spring was also found in one of the tributaries in a shear zone. The groundwater in the basin alluvium originates from basin surface infiltration and from groundwater further up the mountain flank, which then flows down through faults and joints.

A series of infiltration tests were conducted in May, 1985. Average infiltration rates are presented in Table 2. Tests were conducted on channel alluvium, boulder bar alluvium, where depth to the bedrock was less than 15 cm, fan alluvium, where vegetation density was greater, and on the paleosols. Infiltration rates are greatest for the deep channel alluvium and least for the paleosols.

Table 2 Means and standard deviations of infiltration rates.

Location	Channel Alluvium	Fan Alluvium	Boulder Bar Alluvium	1959 soil Surface
No. obs.	50.	9.	9.	4.
Mean (cm/sec)	0.39	0.29	0.26	0.13
Std. dev.	0.09	0.09	0.08	0.01

Seasonally averaged precipitation and runoff/rainfall ratios for three-year periods before and after the 1959 fire in the Three Bar 'D' basin show an initial increase following the fire and then a decrease (Table 3). Increased runoff following a fire in chaparral vegetation is common, as a result of both reduced vegetation cover and the presence of hydrophobic compounds in the soil (Rice, 1973; DeBano, *et al.*, 1979).

Table 3 Three Bar 'D' total seasonal storm precipitation and runoff/rainfall ratios (Ro/Rf) averaged over 3-year periods before and following the 1959 wildfire. W-winter, S-summer.

Period	Number of Storms	Precip mean (cm)	Precip std dev	Ro/Rf mean (cm)	Ro/Rf std dev
W 57-59	36	35.2	42.1	0.018	0.024
W 60-62	30	52.0	51.5	0.055	0.087
W 63-65	27	44.1	37.3	0.023	0.025
W 66-68	24	68.8	80.8	0.060	0.061
W 69-71	23	40.9	26.4	0.028	0.026
S 57-58	16	25.6	19.8	0.008	0.015
S 59-62	19	28.6	18.8	0.096	0.120
S 63-65	23	32.8	21.6	0.017	0.020
S 66-68	20	26.0	23.2	0.019	0.022
S 69-71	22	37.7	43.2	0.009	0.009

Figure 3 shows cumulative precipitation, stormflow and sediment production from the Three Bar 'D' basin for the years 1957-1966. Before the 1959 fire, no measurable sediment was produced and stormflow was minimal in comparison to the precipitation . Following the fire, sediment production increased dramatically, to a level which was equivalent to a depth of 5 mm over the basin. By 1962, measurable sediment production had reduced to pre-fire levels. Stormflow also began to decrease three years after the fire, but it did not reach pre-fire levels by 1967, eight years after the fire. In part, this was due to the lower density and crown cover of the resprouting chaparral vegetation, resulting in less transpiration (Hibbert, US Forest Service, personal communication)

sediment sources

The predominant source of main channel sediment is from degradation and bank failure of the tributary channels. Scour, lateral erosion and bank failure have also occured within the main channel, but no recent erosion was documented by the cross-section resurveys.

Dry ravel is the process contributing the majority of sediment to the tributary channels and to a lesser extent, to the main channel. During the summer, deposits of dry ravel material were common along the base of the channel banks, but these deposits were removed by the winter flows.

Extensive rills were observed on the interfluves, some up to 20 cm in depth. Overland flow is rare on steep, well drained chaparral slopes (Krammes, 1969; Rice, 1973), but Wells (1982) proposed a mechanism for formation of these rills following a fire. Hydrophobic compounds are driven by high temperature gradients down into the soil layer (DeBano, 1976). These compounds condense on the cooler soil particles at depths ranging up to 6 cm, and they form a layer, up to 5 cm thick, of significantly reduced permeability. Precipitation on the hillslope saturates the soil above this impervious layer, which eventually causes overland flow and rill formation. The rills may eventually cut through the impervious layer and allow the water to seep into the colluvium, thereby terminating further flow in the rills.

Formation of the rills causes a significant contribution of sediment to the channels following a fire. The present depth of the rills is greater than the maximum depth at which they initially could form (ie; 11 cm), indicating subsequent overland flow and erosion.

Large boulders of granodiorite, up to 1 m long, were observed in the main channel as far as 2 km downstream from their only source, the granodiorite dike. A debris flow seemed to be the only plausible process that could transport these boulders so far downstream from their source. Field evidence, consisting of a boulder lodged on the upstream side of a dead tree, whose surface had burned down to the 1959 pre-fire surface, confirmed that a debris flow had followed the wildfire. The fire had set up favorable conditions for a debris flow to occur, a phenomena common in recently burned chaparral drainage basins (Rice, *et al.*, 1982).

sedimentology

Sediment in El Oso Creek is predominantly composed of very coarse sand and gravel, with an overall median size of 2.11 mm. The sediment is poorly sorted, with an averaged standard deviation of 3.4 mm, and it is positively skewed. Averaged grain-size statistics for tributaries, the main channel and a paleosol are listed in Table 4. Sediment is coarser in the main channel than in the tributaries, a result of the loss of energy, due to transmission losses and lower gradients, needed to transport the coarse particles in the main channel.

Table 4 Averaged grain size distribution statistics for individual and all tributaries, main channel reaches and total main channel, and entire basin.

Channel	No. Obs.	Median (mm)	Sorting (mm)	Skew	Silt-Clay (%)
Trib 3	4	2.1	3.24	0.314	2.59
Trib 4	5	2.28	3.97	0.358	2.37
Trib 8	20	2.09	3.33	0.410	1.18
Trib 17	8	2.44	3.23	0.341	1.10
Trib 24	4	1.24	3.48	0.393	1.47
Trib 38	4	1.42	3.58	0.389	1.08
Trib 40	22	1.67	3.24	0.390	1.57
Trib 44	16	1.25	3.59	0.426	1.87
All Tribs	83	1.79	3.40	0.392	1.55
Main Chan					
0-1550 m	35	2.22	3.08	0.385	1.37
1550-3410 m	35	2.48	3.14	0.409	2.00
3410-4550 m	11	2.99	3.15	0.352	1.93
4550-4945 m	5	2.32	3.41	0.426	1.62
Tot Main	86	2.43	3.13	0.393	1.71
Basin	170	2.11	3.27	0.392	1.63
Paleosol	1	2.40	5.29	0.363	5.87

Exposures of the alluvial fill were observed throughout the basin in terraces and eroded banks. Horizontal bedding, an indication of deposition predominantly during transitional

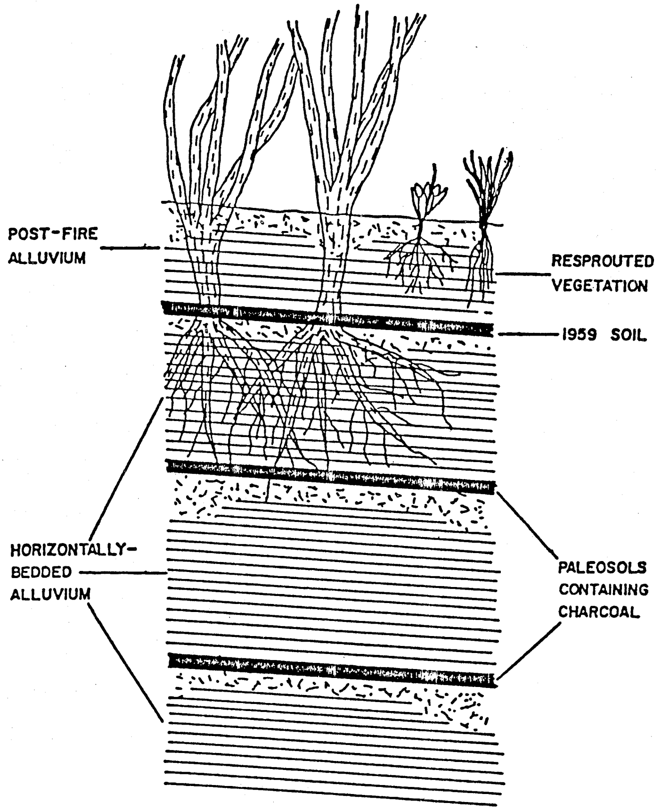

Fig. 4 Idealized diagram of horizontally-bedded alluvium and intervening paleosols in El Oso Creek alluvium.

plane bed sheet flow (Simons, et al., 1965), was the only type of primary sedimentary structure observed in these exposures (Fig. 4).

Also observed at these exposures were up to three paleosols (Fig. 4). The upper soil was the pre-1959 fire surface. There is abundant charcoal found on top of this soil and there is 10 to 30 cm of fire-induced alluviation above the soil. Chaparral plants, which were rooted in the soil, aıe now growing through and above the overlying alluvium. Older paleosols that contain charcoal were also observed in the alluvial fill. Separating these paleosols is horizontally-bedded alluvium. The presence of the paleosols and the intervening alluvium, which is very similar to the post-1959 sedimentation sequence, suggests that fire has been a significant factor controlling basin sedimentation.

sediment storage

The main channel can be characterized as having three components (Fig. 5), which are characterized by their potential

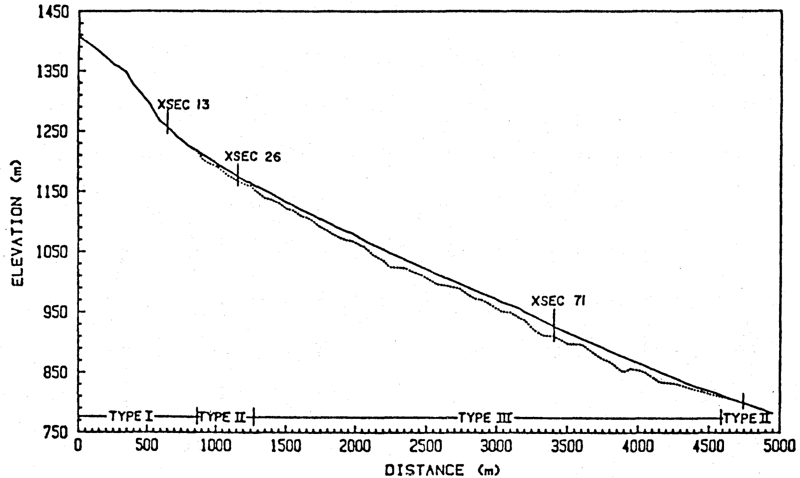

Fig. 5 El Oso Creek longitudinal profile and sub-alluvial bedrock profile. The channel is divided into the three reach types. A represen-ative cross-section of each is shown in Fig. 6.

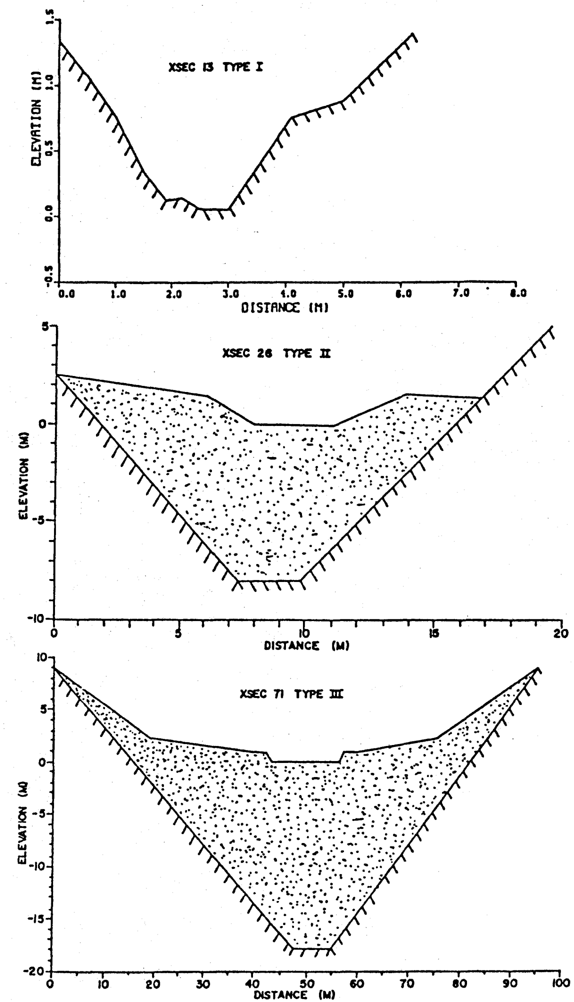

Fig. 6 Representative cross-sections from each of the three reach types of Fig. 5. Note changes in vertical and horizontal scales for each cross-section.

for sediment storage. The three components are defined as follows:

Type 1 - Available energy exceeds sediment delivery rate; therefore sediment is never stored in this zone.

Type 11 - Available energy may or may not exceed sediment delivery rate; therefore sediment may be periodically stored and flushed from this zone.

Type 111 -Available energy is exceeded by sediment delivery rate; therefore, this zone always stores sediment.

Sub-surface valley cross sections were estimated by projecting the valley slopes at each cross-section down until they intersected at the depth of alluvium, which was determined by seismic refraction (Fig. 6). Sediment volumes were estimated by extrapolating the subsurface valley cross-sections to the midpoints between adjacent cross-sections in both the upstream and downstream directions. Total volume of the valley fill was calculated at 2.5 million m^3.

Thirty-six sub-basins within the El Oso Creek basin are actively forming alluvial fans on the valley floor and often directly into the main channel (Fig. 7). The fans comprise 6.4 percent of the total basin area. Average fan surface area is 5000 m^2, with a standard deviation of 3400 m^2. Most of the alluvial fans are located in the middle and lower elevations of El Oso Creek basin, where the type 2 and 3 reaches or zones are located (Fig. 5). Because the upper drainage basin has more resistant bedrock and a greater vegetation density, sediment production is less than in the lower basin, while the steeper slopes in the upper basin reduces the number of potential sites for sediment storage. These two factors combined limit the number of alluvial fans in the upper basin.

Longitudinal profiles of main channel reaches are convex, where channel-intruding fans are forming locally steepened gradients. Headcuts are incising upstream through the convexities, as the main channel attempts to establish an equilibrium gradient.

channel changes

Field investigation, analysis of a series of aerial photographs and cross-section resurveys revealed that the geomorphic state of the channels in the basin was out of phase in 1984-1985, with the tributaries degrading and the main channel aggrading. It became obvious that the 1959 Boulder wildfire had significantly altered the basin sedimentation regime.

Comparison of the 1959, 1967 and 1983 aerial photographs shows that Ash Creek, to which El Oso Creek drains, was a wide, vegetated and aggraded channel before the 1959 fire. By 1967, Ash Creek had incised, which lowered baselevel, and caused tributary incision. The incision had migrated 1875 m up El Oso Creek by 1967. The 1983 aerial photographs showed that degradation of Ash Creek and its tributaries had continued. Repeated cross-section surveys in El Oso Creek during 1984 and 1985 revealed that the tributaries were still

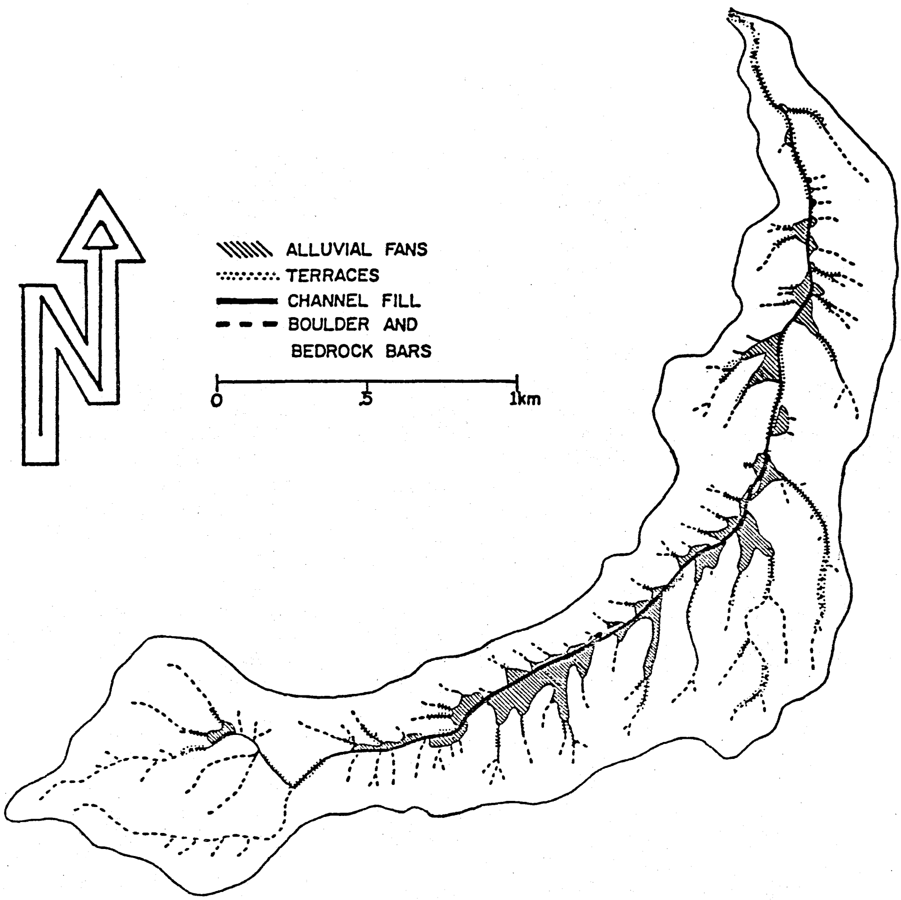

Fig. 7 Map of El Oso Creek basin showing sites of sediment storage.

Table 5 Contributing basin area, precipitation data expressed as volumes from the contributing areas, and volumes of sediment trapped at debris dams. --- dams not installed.

Dam	Basin Area (km^2)	12/13/84 - 1/7/85 Precip (m^3)	12/13/84 - 1/7/85 Sediment (m^3)	1/8/85 - 5/30/85 Precip (m^3)	1/8/85 - 5/30/85 Sediment (m^3)
36	0.524	61 320	2.1	168 310	0.0
71	1.920	197 880	0.0	420 865	0.0
1-17	0.036	3 861	0.0	7 245	0.0
2-38	0.017	---	---	2 520	0.0
9-40	0.096	10 272	13.0	16 630	0.0
17-40	0.036	---	---	6 740	0.0
2-44	0.111	13 550	1.3	16 780	0.0
11-44	0.035	---	---	5 850	0.0

degrading, but the main channel was aggrading, as sediment was flushed from the tributaries.

The 1959 aerial photograph shows that the tributary alluvial fans were present before the fire, but they were much more heavily vegetated and appeared to be relatively inactive in comparison to the fans shown on the 1983 aerial photographs. The pre-fire tributary channels were also heavily vegetated, and there was no evidence from the 1959 aerial photograph of major surficial flow. By 1967, many of the fans had incised in response to the main stem degradation. In addition, the upper reaches of the tributaries were degrading in response to the depleted sediment sources on the hillslopes. By 1983, tributary sediment that was eroded from the upper reaches was being transported through the incised fans and was building new fans out into the main channel. Incision had not occured in response to the mainstem degradation on some fans, and these have continued to aggrade, often causing the tributary fan-surface channels to shift to lower elevations.

sediment yield

Table 5 presents data on sediment-volumes trapped behind the debris dams, with total precipitation during the intervals between surveys. The greatest volumes of trapped sediment were in the tributaries, where most sediment was transported in the upper reaches (dams 9-40, 17-40, 11-44). Less sediment was transported to the tributary fans (dams 1-17, 2-38, 2-44) and less still was transported within the main channel (dams 36, 71). Also evident from Table 5 is the seasonal distribution of sediment yields, with sediment being transported predominantly during the winter months because, during that season, surficial flows are more common.

Changes in cross-section areas were determined by resurveys in 1984-1985. These changes in cross-section areas were extrapolated to the midpoints between adjacent cross-sections in both the upstream and downstream directions to derive sediment yield data (Table 6). The surveys show that most reaches of the tributaries are degrading, and bank failure is occuring. Fans are aggrading in the lower reaches of tributaries. In the the main channel (Fig. 5), the upper 900 m reach is also degrading due to a reduction in sediment supply. The next 2490 m reach downstream, beginning where channel-fill begins, is aggrading. Cross-sections downstream of this aggrading reach have been surveyed only once, but field observations suggests that the main channel continues to aggrade for another 1380 m downstream, at which point groundwater resurfaces. The main channel is degrading from this point downstream to the confluence with Ash Creek.

Table 6 shows that over half of the main channel aggradation can be accounted for by the seven degrading tributaries, but these seven tributaries represent only 11 percent of the tributaries. It seems reasonable to conclude that the tributary channels are producing more sediment than is being deposited in the main channel. Therefore, the majority of eroded tributary sediment is being stored on the fans and on the valley floodplain, and it is not reaching the main channel.

Table 6 Erosion (-) and deposition (+) volumes as determined by cross-section resurveys on the main channel and tributary channel and fan reaches.

Channel Reach	Reach Length (m)	January 1985 Bed (m^3)	January 1985 Bank (m^3)	May 1985 Bed (m^3)	May 1985 Bank (m^3)
Upper Main	900	-123	0	0	0
Lower Main	2490	+1086	-18	+45	0
Trib 3	142	0	0	0	0
Trib 4	185	-5	0	0	0
Trib 8	970	-256	-8	+18	0
Trib 40	935	-374	-47	0	0
Trib 40 Fan	90	+416	0	+13	0
Trib 44	850	-437	0	-17	0
Trib 44 Fan	40	+37	0	0	0

Upstream of the Ash Creek confluence, the post-fire incision of El Oso Creek has formed a continuous terrace for 1600 m. Over 29 000 m^3 of alluvium are estimated to have been eroded from this reach and transported out of the basin into Ash Creek since the 1959 fire.

DISCUSSION

Fires occur cyclically in the Arizona chaparral vegetation and they are reported to have a return period of between 50 and 100 years (Pase & Brown, 1982). However, not all fires produce the same response as the 1959 Boulder wildfire. It appears that for a fire to be geomorphically significant, it must be followed by significant precipitation events. This was the case in June, 1959, in El Oso Creek, when the fire was followed by 75 cm of precipitation during the next 6 months, a 60 percent increase over the average precipitation for this period. The presence of the three sedimentation units, each of which consists of a charcoal-containing paleosol with overlying horizontally-bedded alluvium, in a region where soil development takes much longer than the 50 to 100-year return period for wildfire, suggests that the combination of wildfire followed by significant precipitation, is much less frequent than the frequency of wildfire itself.

Comparison of the three sets of aerial photographs (1959, 1967, 1983), which cover a 26-year period before and following the fire, shows a cyclic but complex basin response to fire. Before the 1959 fire, the basin was in a relatively quiescent state, in which all channels were aggraded, surficial flow was relatively rare, and there were relatively low rates of sediment delivery to the channels from the well vegetated slopes.

Following the fire, the main channel degraded in response to increased surface runoff and upstream migration of a nickpoint from the confluence with Ash Creek. Tributary channels initially aggraded in response to the large amounts of sediment delivered from the rilled and impermeable hillslopes. As the slopes revegetated and the sediment sources were depleted, tributaries began to incise, thereby delivering sediment to the main channel, which then aggraded.

In-channel vegetation was dense in the pre-fire main channel, as observed from the 1959 aerial photograph, and dominated by salt cedar (Tamarisk gallica). The 1967 aerial photograph shows almost no vegetation in the channel, whereas the 1983 aerial photograph reveals channel-vegetation density at about 70 percent of the pre-fire vegetation density level.

In-channel vegetation can effect sedimentation several ways. First, it increases channel roughness, which will then reduce the stream velocity and its abilty to transport sediment. Second, the vegetation can act as a sieve, effectively trapping the sediment. Third, vegetation colonizes and stabilizes channel bars and banks, increasing their resistance to erosion. Finally, salt cedar can send roots directly to the water table, which will reduce the volume of stored water through transpiration (Robinson, 1958). The reduction in stored subsurface water increases the volume of subsurface water storage that needs to be satisfied before surface flows can be generated.

As stated above, 2.5 million m^3 was estimated as the total volume of basin fill. A value of 30 percent porosity was reported by Cohen (1963) for similar alluvial material. Using this value, a potential groundwater storage volume of 750 000 m^3 exists in the basin fill. This volume is equal to a depth of rainfall of 34 cm over the drainage basin.

Obviously, surficial flow of any significant duration could not be generated in El Oso Creek if this great volume of subsurface water storage must be satisfied first. However, the presence of the paleosols under the floodplain and the channel floor act as hydraulic discontinuities, which will decrease the rate of infiltration. Behnke and Schiff (1963) reported that hydraulic conductivities in coarse uniform sands can be reduced up to 90 percent with the introduction of a limiting layer of finer sand. Thus, the paleosol will act as a limiting layer, enabling the overlying alluvium to become saturated and surficial flow to be generated (Tables 2 and 4).

The 1959 pre-fire soil horizon can be found throughout the valley bottom buried beneath post-1959 fire alluvium. Rates of soil formation under the climatic and vegetation conditions found in the basin are not known, but certainly a period of relative basin stability is required. Vegetation is an important factor in soil development and its presence would help to provide the required channel stability for development of a valley-bottom soil.

At present, the main channel is aggrading and vegetation density is increasing. Surficial flows are relatively rare, due to the great quantities of water lost to infiltration as a result of the increased capacity for water storage in the alluvium. Providing that no further major disturbances to the basin occur, a new soil horizon will develop on the valley floor and within the main channel.

Aggrading channels have been shown to develop steepened gradients (Schumm, 1977). Both channel steepening and soil development processes are occuring in El Oso Creek. The first process to cause the threshold of channel stability to

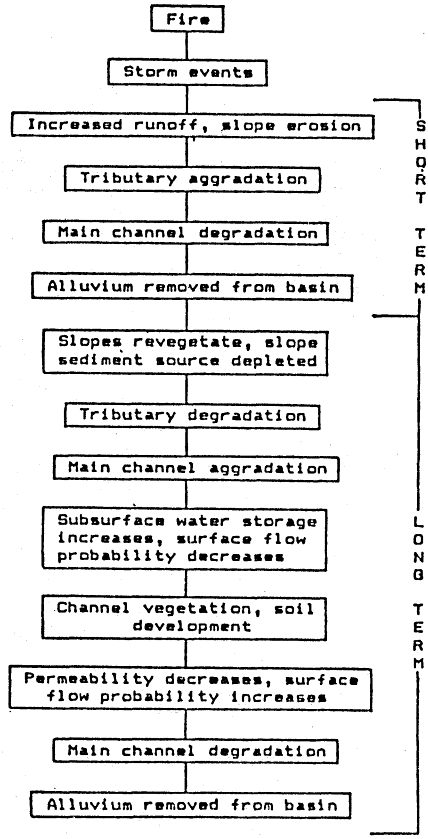

Figure 8: Summary of short- and long-term basin complex-response to fire.

be exceeded is not known. But with both processes occuring simultaneously, the time required to reach that threshold will be less. Nevertheless, in this basin, fire, followed by significant precipitation, seems to be the dominant control over aggradation and degradation.

CONCLUSIONS

Sediment yield for El Oso Creek, which drains a deeply weathered granitic source area, is controlled primarily by the combination of fire followed by significant precipitation. However, the fire-induced sediment production is out of phase with sediment yield from the basin. Following a fire, erosion of the hillslopes is severe, as a result of reduction in vegetation cover and hydrophobic behavior of the soils. Sediment is delivered to the lower-order tributaries, and they aggrade, with a consequent reduction in sediment delivery to the main channel. Simultaneously, the increased runoff causes the main channel to degrade, and sediment that was derived from longer-term storage is exported from the basin. Within a fairly short period of time (ie; 8 years), the tributaries begin to degrade as sediment delivery to them is reduced. The main channel then begins to aggrade, and this reduces the probability that a storm of a given magnitude and frequency can generate surficial flow that is capable of transporting sediment from the basin. This positive feedback promotes stability of the system, which allows vegetation to colonize the aggraded main channel, thereby permitting pedogenesis to begin. However, soil development reduces the permeability of the already over-steepened main channel, and this increases the probability of surficial flows. Significant sediment yield from the basin can occur when a geomorphic threshold is exceeded, by either another fire followed by precipitation, or by a large-magnitude hydrologic event. The short- and long-term effects of the 1959 Boulder wildfire in El Oso Creek are summarized in Figure 8.

The complex and cyclic response of this drainage basin to fire demonstrates the difficulty of predicting the effects of fire and land-use changes on sediment yields in a semi-arid region. However, sediment yield predictions may be improved by determining the geomorphic status of the basin as it adjusts to the effects of a geomorphically significant fire.

ACKNOWLEDGEMENTS. We wish to thank Dr. Burchard Heede of the U. S. Forest Service, Rocky Mountain Forest and Range Experimental Station at Tempe, Arizona, for his considerable assistance. We also would like to thank Dr. Aldon R. Hibbert and Dr. Leonard DeBano, also with the U. S. Forest Service at Tempe, Arizona, for their assistance. Finally, we would like to thank Dr. Stanley Schumm at Colorado State University for his review and comments.

REFERENCES

Behnke, J.J. & Schiff, L. (1963) Hydraulic conductivity of uniform, stratified and mixed sands. J. of Geophys. Res. 68, 4769-4775.

Bergstrom, F.W. (1980) Episodic behavior in steep terrain. MSc Thesis, Colorado State Univ., Fort Collins, CO.

Brock, J.H. & DeBano, L.F. (1982) Runoff and sedimentation potentials influenced by litter and slope on a chaparral community in central Arizona. USDA For. Serv. Gen. Tech. Report PSW-58, 372-377, Pac. SW For. and Range Exp. Stn., Berkeley, CA.

Butcher, G.C. & Thornes, J.B. (1978) Spatial variability in runoff processes in an ephemeral channel. Z. Geomorph. Supp, Band 29, 83-92.

Cohen, P. (1963) Specific-yield and particle-size relations of Quaternary alluvium, Humboldt River Valley, Nevada. USGS Water-Supply Paper 1669-M.

DeBano, L.F. (1973) Chaparral soils. In: Living with the Chaparral (Proc. Riverside Symp. 1973) 19-26. Sierra Club.

DeBano, L.F., Savage, S.M. & Hamilton, D.A. (1976) Transfer of heat and hydrophobic substances during burning. Soil Sci. Soc. of Am. J. 40, 779-782.

DeBano, L.F., Rice, R.M. & Conrad, C.E. (1979) Soil heating in chaparral fires; effects on soil properties, plant nutrients, erosion and runoff. USDA For. Serv. Res. Paper PSW-145, Pac. SW For. and Range Exp. Stn., Berkeley, CA.

Harvey, M.D. (1980) Steepland channel response to episodic erosion. Ph.D. Dissertation, Colorado State Univ., Fort Collins, CO.

Hibbert, A.R., Davis, E.A. & Scholl, D.G. (1974) Chaparral conversion potential in Arizona, part 1: water yield response and effects on other resources. USDA For. Serv. Res. Paper RM-126, Rocky Mtn. For. and Range Exp. Stn., Fort Collins, CO.

Keppel, R.V. & Renard, K.G. (1962) Transmission losses in ephemeral stream beds: J. Hydraul. Div. ASCE. 88, 59-68.

Kottlowski, F.E., Cooley, M.E. & Ruhe, R.V. (1965) Quaternary geology of the Southwest. In: Quaternary of the United States (ed. by H.E. Wright, Jr. & R.B. Morrison) 287-298 Princeton Univ. Press, Princeton, NJ.

Krammes, J.S. (1969) Hydrologic significance of the parent granitic material of the San Gabriel Mountains, California. Ph.D. Dissertation, Oregon State Univ., Corvallis, OR.

Leopold, L.B. & Miller, J.P. (1956) Ephemeral streams-hydraulic factors and their relation to the drainage net. USGS Prof. Paper 282-A.

Matlock, W.G. (1965) The effect of silt-laden water on infiltration in alluvial channels. Ph.D. Dissertation, Univ. Arizona, Tucson, AZ.

Murphy, J.B., Diskin, M.H. & Lane, L.J. (1972) Bed material characteristics and transmission losses in an ephemeral stream. In: Ariz. Acad. Sci. Hydrol. Sec. (Proc. Prescott meeting, May 1972) v 2, 455-472.

NOAA, Climatological data for Arizona, annual summaries (1950-1955).

Pase, C.P. & Brown, D.E. (1982) Interior Chaparral. Desert Plants 4, 95-98.

Patton, P.C. & Schumm, S.A. (1975) Gully erosion, Northern Colorado: a threshold phenomenon. Geology 3, 88-90.

Rice, R.M. (1973) The hydrology of chaparral watersheds. In: Living with the Chaparral (Proc. Riverside Symp. 1980) 27-34. Sierra Club.

Rice, R.M., Ziemer, R.R. & Hankin, S.C. (1982) Slope stability effects of fuel management strategies - inferences from Monte Carlo simulations. USDA For. Serv. Gen. Tech. Report PSW-58, 365-371, Pac. SW For. and Range Exp. Stn., Berkeley, CA.

Robinson, T.W. (1958) Phreatophytes. USGS Water-Supply Paper 1423.

Schumm, S.A. (1961) The effects of sediment characteristics on erosion and deposition in ephemeral stream channels. USGS Prof. Paper 352-C.

Schumm, S.A. (1977) The Fluvial System. Wiley, N.Y.

Schumm, S.A. (1979) Geomorphic thresholds: the concept and its applications. Inst. of Brit. Geogr. Trans. 4, 485-515.

Schumm, S.A. & Hadley, R.F. (1957) Arroyos and the semiarid cycle of erosion. Am. J. Sci. 255, 161-174.

Schumm, S.A. & Lichty, R.W. (1963) Channel-widening and floodplain construction along the Cimarron River in Southwestern Kansas. USGS Prof. Paper 352-D.

Simons, D.B., Richardson, E.V. & Nordin Jr., C.F. (1965) Sedimentary structures generated by flow in alluvial channels. In: Primary Sedimentary Structures and Their Hydrodynamic Interpretation (ed. by G. V. Middleton) 34-52. SEPM Spec. Pub. no. 12.

Thomsen, B.W. & Schumann, H.H. (1968) Water resources of the Sycamore Creek watershed, Maricopa Cty., Arizona. USGS Water-Supply Paper 1861.

Thornes, J.B. (1974) Speculations on the behavior of stream channel width. In: Discussion Paper No. 49, London Sch. Econ., Dept. Geogr.

Thornes, J.B. (1977) Channel changes in ephemeral streams: observations, problems and models. In: River Channel Changes (ed. by K. J. Gregory), 317-333, Wiley-Interscience, N.Y.

US Weather Bureau, Climatological data for the United States, annual summaries (1915-1949).

Wells III, W.G. (1982) Some effects on erosion processes in coastal Southern California. In: Erosion and Sediment Transport in Pacific Rim Steeplands (Proc. Christchurch Symp., 1982) 305-322. IAHS Publ. no. 132.

Wilson, E.D. (1939) PreCambrian Mazatzal Revolution in Central Arizona. Geol. Soc. Am. Bull. 50, 1113-1164.