Types and processes of short-term sediment and uranium-tailings storage in arroyos: an example from the Rio Puerco of the West, New Mexico

Jerry R. Miller
Groundwater Section, Illinois State Geological Survey, 615 East Peabody, Champaign, Illinois 61820

Stephen G. Wells
Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131

ABSTRACT

In 1979, United Nuclear Corporation's Churchrock mill tailings dam was breached releasing 1 x 10^3 kg of sediment and 3.5 x 10^6 m^3 of liquid wastes enriched in trace elements and radionuclides into the Rio Puerco of the West, a deeply incised arroyo. Subsequently, the transport and storage of sediment and contaminants along the Rio Puerco was quantitatively studied using geomorphic and chemical techniques. Three short-term (decades) sediment/contaminant storages sites were identified along the Rio Puerco. In decreasing order of maximum potential sediment/contaminant storage capacity, these sites are: floodplain, bankfull channel (channel, upper channel, point bar), and tributary-backwater deposits. The size and location of each storage site depends upon: (1) sediment grain size within the perimeter of the arroyo, (2) meander processes and morphology, and (3) the maximum bankfull-channel width or the rate of lateral migration of the arroyo channel. Preferential storage of silt and clay, assumed to be the chemically active phase of depositional units, occurs in the upper-channel deposits of the bankfull-channel sites.

The total change in channel morphology and lateral position in the Rio Puerco is apparently dependent upon the percent silt and clay in the arroyo perimeter and upon drainage area (discharge). These relations explain downstream increases in aggradation rate and in lateral arroyo erosion which enhance the storage of sediments in lower arroyo reaches. Geomorphic data suggest that the maximum storage of UNC-mill tailings contaminants from the 1979 spill may have occurred in floodplain and upper-channel deposits on meander bends. However, trace-element geochemistry could not be used to locate sites of contaminant concentration five years after the spill, perhaps due to fluvial and eolian reworking and dilution.

INTRODUCTION

The Grants Mineral belt of west-central New Mexico has produced 50 % of the total uranium concentrate in the United States since mining and milling began in the 1950's (Grant, 1981). Concentrate is refined from uranium ore at mills, leaving tailings as a waste product, the majority of which is stored on alluvial valley floors (Wells and Gardner, 1985). The majority of sediment stored in these alluvial valleys typically have residence times of thousands of years (Wells *et al.*, 1983; Bullard, 1983). However, valley floors are typically incised by arroyos which serve as conduits for episodically transporting and storing sediment over decades (Patton and Schumm, 1981). Thus, arroyos and their dynamic nature pose a hazard to the storage of uranium milling wastes on semiarid valley floors, and potentially arroyos can disperse such hazardous wastes down valley should contaminants be accidently released into the fluvial system.

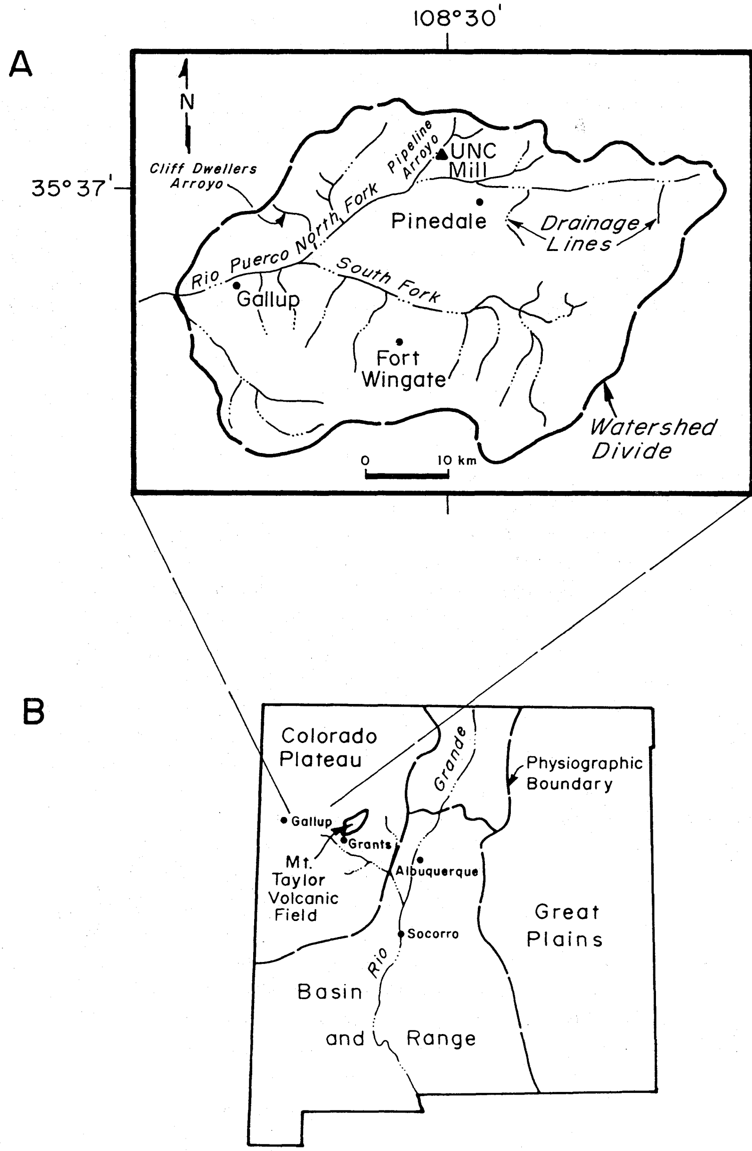


FIG. 1. Location map of the Rio Puerco study area: (A) immediate vicinity of study area, (B) geographic location of study area in New Mexico.

A release of uranium mill-tailing contaminants into an arroyo system occurred in 1979, when United Nuclear Corporation's (UNC) Churchrock mill tailings dam was breached. This event introduced 1×10^3 kg of sediment and 3.5×10^6 m^3 of liquid waste enriched in trace elements and radionuclides into Pipeline arroyo, a tributary to the Rio Puerco of the West (Fig. 1) (Gallaher and Goad, 1981). Subsequently, the Rio Puerco provides an excellent setting to quantitatively assess the transport and storage of sediment and associated uranium mill-tailings contaminants within a deeply incised semiarid arroyo system. The primary purpose of this paper is to elucidate types and potential capacity of storage sites for sediment in an active semiarid arroyo and assess the storage mechanisms of tailings sediments and their associated contaminants released during the 1979 UNC tailings spill.

The study area is located in the headwaters of the Rio Puerco, northwestern New Mexico, approximately 8 km northeast of Gallup on the western side of the continental divide (Fig. 1). This area is characterized by semi-arid, moderate climatic conditions with a mean annual temperature of approximately 9°C and a mean annual precipitation of 270 mm/yr (Von Eschen, 1961). The bedrock of this region consists of inter-tonguing marine and non-marine Cretaceous rocks resting unconformably on continental Jurassic deposits. Within the study area, the Rio Puerco primarily flows over the Cretaceous-age Mancos shale which is overlain by tens of meters of alluvial fill as well as active and interbedded eolian deposits. The northern divide of the watershed is formed by cuestas composed of alternating sandstones and shales of the Mesaverde Group. Dipslopes, formed by the Dakota Sandstone, form most of the watershed's southern divide.

In its natural state the Rio Puerco is a deeply incised, continuous, ephemeral arroyo. However, due to uranium mining the Rio Puerco acquired a perennial character from 1969 to 1986 between its confluence with Pipeline arroyo and its union with the Little Colorado River in Arizona. This perennial character is due to groundwater discharge into the headwaters of Pipeline Arroyo as a result of aquifer dewatering at the uranium mines. Cessation of dewatering in relation to the recent decline in uranium mining operations in the headwaters of Pipeline arroyo has caused the lower reaches of the Rio Puerco to revert to ephemeral conditions. The study area includes both the previously perennial reach, downstream of the Pipeline arroyo, and an ephemeral reach, upstream of the Pipeline arroyo (Fig. 2). The drainage area of this portion of the Rio Puerco is approximately 500 km^2. Average monthly discharge in the perennial reach of the Rio Puerco is 0.2 $m^3\ s^{-1}$, based on U.S. Geological Survey records from 1977 to 1985. The maximum discharge on record during this time is the 12.7 $m^3\ s^{-1}$ event related to the 1979 tailings spill, and this discharge is equal to the 5-year flood event (Gallaher and Cary, in press).

Methods

Eleven arroyo cross sections (six ephemeral and five perennial) were measured at approximately equal intervals along the Rio Puerco (Fig. 2) using a tape, transit, and stadia-rod. Measurements collected included a detailed survey of channel cross-sectional morphology as well as total cross-sectional width, total cross-sectional depth, bankfull-channel width, and hydraulic radius (Fig. 3). Scour-and-fill chains patterned after Leopold *et al*. (1964) were emplaced in the modern floodplain and bankfull-channel at 50-cm increments at ephemeral cross sections of the Rio Puerco. Several months after initial measurement, the Rio Puerco cross sections were re-surveyed to determine changes in cross-sectional area. Black-and-white vertical aerial photographs at an approximate scale of 1:30,000 were compared photogrammetrically with 1:24,000 scale color air photographs to assess changes in the planform of the channel during this period.

At each cross section five sediment samples were collected from the perimeter of the arroyo. Particle-size distribution analysis was performed on cross-section samples using normal pipetting and sieving techniques outlined by Folk (1974). The weight-percent silt and clay within the arroyo perimeter, or M value (Schumm, 1961), were then calculated for each cross section.

Fluvial stratigraphic units were defined on the basis of sediment size, lithologic composition, and sedimentary structure. Material from each

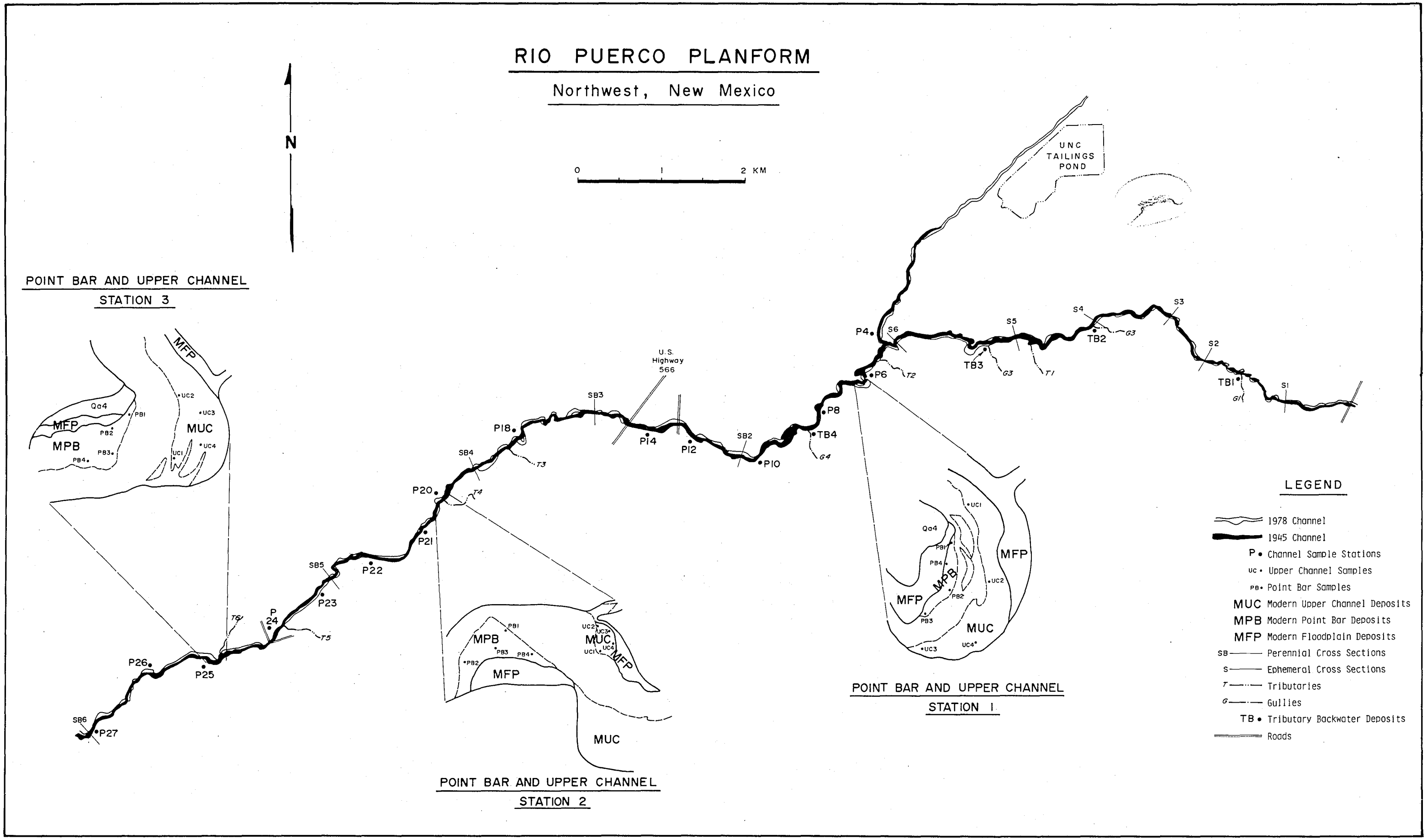


FIG. 2. Planform map of the Rio Puerco study area showing: (1) the 1945 and 1978 channel of the Rio Puerco, (2) cross-section locations, and (3) sediment-sample station locations. Note stream flow is from east to west.

Table 1. Summary of elemental sensitivities using procedures outlined by Husler (1984).

Element	Sensitivity (ppm)
Ba	5.0
Cd	0.07
Cu	0.5
Mo	0.02
Se	0.04

stratigraphic unit was sampled. Channel sediments were collected at 16 stations located at approximately equal intervals along the Rio Puerco (Fig. 2). Sampled sediments (adjacent to six of these channel stations) included floodplain, channel, point-bar, and tributary backwater deposits. In addition, seven major tributaries upstream of backwater deposition were sampled (Fig. 2). At each sample station, sediments were collected from the upper 10 cm of the deposit surface. Floodplain material was also collected at 50 cm and 10 cm depths below land surface. These samples were analyzed for grain-size distribution, clay mineralogy, and six trace elements including barium (Ba), cadmium (Cd), magnesium (Mg), copper (Cu), molybdenum (Mo), and selenium (Se). Analyses were performed only on silt- and clay-size fractions, which are assumed to be the chemically active sediment phase of the depositional units (Novo-gradic, 1983). Thus, the chemical concentrations reported in this paper for each sample is higher than the true concentration of the bulk sample which also composed of sand. Chemical analyses were performed using procedures outlined by Husler (1984), and all analyses were conducted using a Perkins and Elmer 303 atomic spectrophotometer. Sensitivities for each element are listed in Table 1.

SEDIMENT STORAGE SITES

The relative residence time of sediment stored in semiarid valley floors has been subdivided into three scales on the basis of relative and absolute ages as well as the areal distribution of depositional units: long-, intermediate-, and short-term storage sites (Miller, 1985) (Fig. 3). Long-term storage sites include extensive late-Pleistocene and Holocene valley fill; whereas, intermediate-term storage sites include historic-age (<150 years) inset fills within the confines of the arroyos which are cut into the valley fills. Short-term sites involve sediment that is transported and deposited along the active channel system both yearly and up to 50 years in the floor of the arroyo (Figs. 3 and 4). This paper focuses primarily on the short-term storage of arroyo sediments and uranium tailings waste. Three short-term storage sites identified within the perennial and ephemeral reaches of the Rio Puerco include bankfull-channel, floodplain, and tributary backwater deposits (Fig. 4).

Bankfull-Channel Site

Bankfull-channel sites can be subdivided locally into active-channel, upper-channel, and point-bar sites (Fig. 2). Active channel sites include sediment within the thalweg of the arroyo and are therefore subjected to a higher

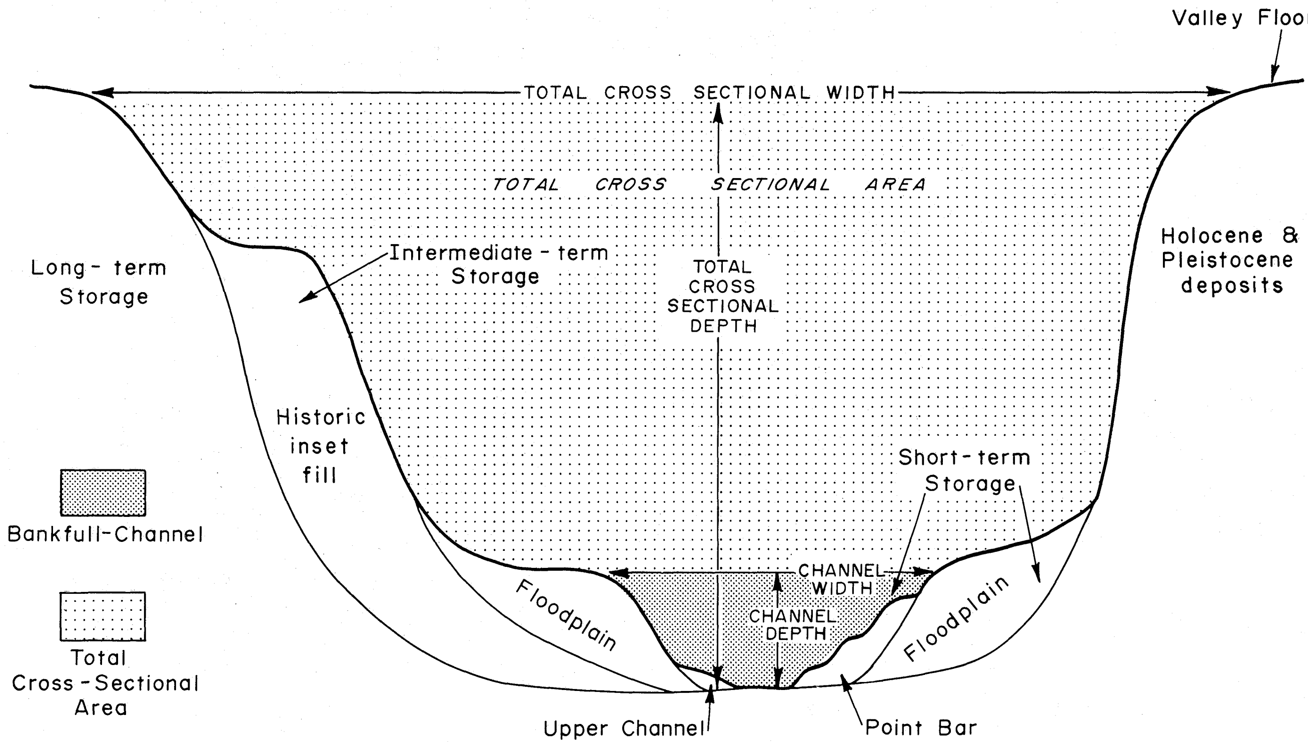


FIG. 3. Diagrammatic cross section showing: (1) channel morphology measurements, (2) differences between total and bankfull cross-sectional area and (3) long-term, intermediate-term, and short-term storage sites along the Rio Puerco.

frequency of transport and redeposition. Along the perennial reach the sediments in the active channel were continuously inundated flow related to mine dewatering between 1969 and 1986. Sediments within these sites consist predominantly of fine-to-coarse sand with an average silt/clay content of 7.3 %. Locally, the channel reaches, up to 3 m in length, are veneered with pebble-size clasts. Upper-channel and point-bar storage sites occur locally between the active channel and the margin of the floodplain (Fig. 2). Point-bar sites are only associated with meander bends. Upper-channel sites occur at any position topographically below the floodplain and higher than the active channel. They are typically found in wide reaches directly across the channel from point bars (Fig. 2) and rarely occur along the ephemeral reach upstream of the Pipeline arroyo confluence. Upper-channel and point-bar deposits consist of sandy-to-silty clay and have an average silt/clay content of 47.2 and 25.0 %, respectively.

The width:depth ratio of the bankfull-channel sites in the ephemeral reach vary between values of 6 and 14; whereas, the perennial reach is characterized by width:depth ratios of 20 to 75. The change in the channel geometry not only reflects discharge frequency but also the type of sediment transported in the two reaches. Upstream of tributary T1 near the confluence with Pipeline arroyo (Fig. 2), channel sediment is derived from shale units of the Mesaverde Group exposed north of the arroyo. Tributary T1 and many of those downstream supply sandy sediment derived from the Dakota Sandstone and other sandstone-rich formations exposed south of the arroyo. A change from predominantly clay-rich to sand-rich sediment source areas influences the percentage of silt/clay content within the bankfull-channel perimeter, or values of M (Schumm, 1961). Values of M change from approximately 30 to 60 % to 15 % or less in these two reaches. Seasonal variations between (high-runoff and low-runoff periods) in width:depth ratio in the ephemeral section was less than 20 % and in the sandy perennial section was as much as 75 %. Thickness of the bankfull-channel deposits varied from zero over bedrock exposures to at least 60 cm.

In 1978 values of sinuosity and meander wavelength of the bankfull channel in the clay-rich ephemeral reach were > 1.17 and < 280 m, respectively. In the sandy perennial reach these values were < 1.16 and between 280 and 500 m, respectively. Based upon a comparison with the 1945 air photographs, the average sinuosity and meander wavelength changed +0.01 m and +23.0 m for the clay-rich and sand-rich reaches, respectively. The number of point bar sites in the sinuous ephemeral reach varied from 12 to 15 and from 5 to 9 in the sandy lower reach between 1945 and 1978. These relations indicate that the channel form was relatively stable over decades and was not significantly altered by uranium-mine dewatering processes in the sandy lower reaches. Similar trends relating to channel silt/clay content, arroyo stability, and aquifer dewatering effects have been noted for other arroyos in northern New Mexico (Mills and Gardner, 1983).

Floodplain Sites

Floodplain storage sites of the Rio Puerco are topographically below and confined by the arroyo walls (Figs. 3 and 4) and have an average silt/clay content of 41.2 %. The thickness of deposits in floodplain storage sites range between 0.40 and 1.2 m. These storage sites are most extensive near meander bends, downstream of collapse-blocks of the arroyo wall, or along reaches where meander wavelength of amplitude have changed (Figs. 2 and 4). Floodplain width increases downstream from the clay-rich ephemeral section to the sand-rich perennial section where widths locally exceed 90 m. This increase is related to the relatively greater amounts of channel migration and

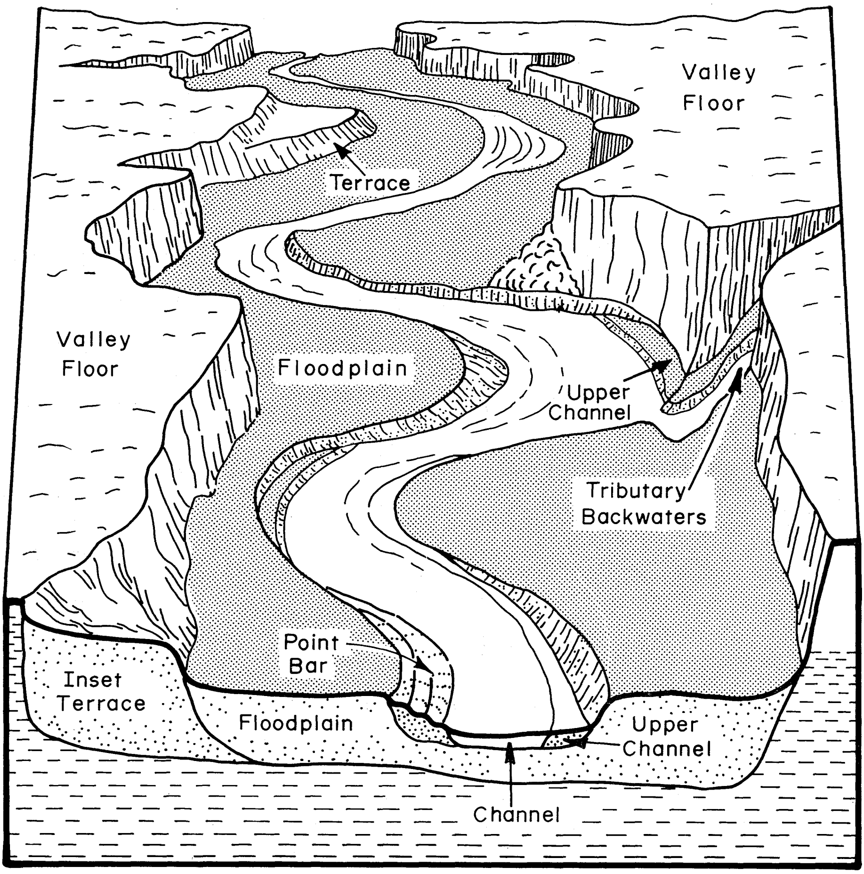


FIG. 4. Short-term sediment/contaminant storage locations along the Rio Puerco (modified from Love, 1983).

floodplain development below station S5 near tributary T1 (Fig. 2). Average rates of lateral migration of the arroyo floor between 1945 and 1978 are estimated to be 0.7 and 1.1 m yr^{-1} for the ephemeral and perennial reaches, respectively. Similar trends in the relation of lateral migration of arroyos to sand and silt/clay content has been seen throughout the semiarid valley floors of northwestern New Mexico (Wells and Gardner, 1985).

Tributary-Backwater Sites

Tributary-backwater deposits occur near the confluences of incised tributary arroyos and the main stem of the Rio Puerco and consist of interbedded sand, silt, and clay layers. The average percent silt/clay content for the backwater deposits is 45.3 %. Thicknesses of the deposits vary from approximately one meter at the confluence to zero where they pinchout upstream in the tributary. The amount of sediment storage in these sites is a function of the number of tributaries along the reach and the relatively topographic position of the tributary channel floor to that of the main stem. Those tributaries graded to the channel floor of the Rio Puerco may experience greater frequency of backwater flooding; whereas, the steep gradient or

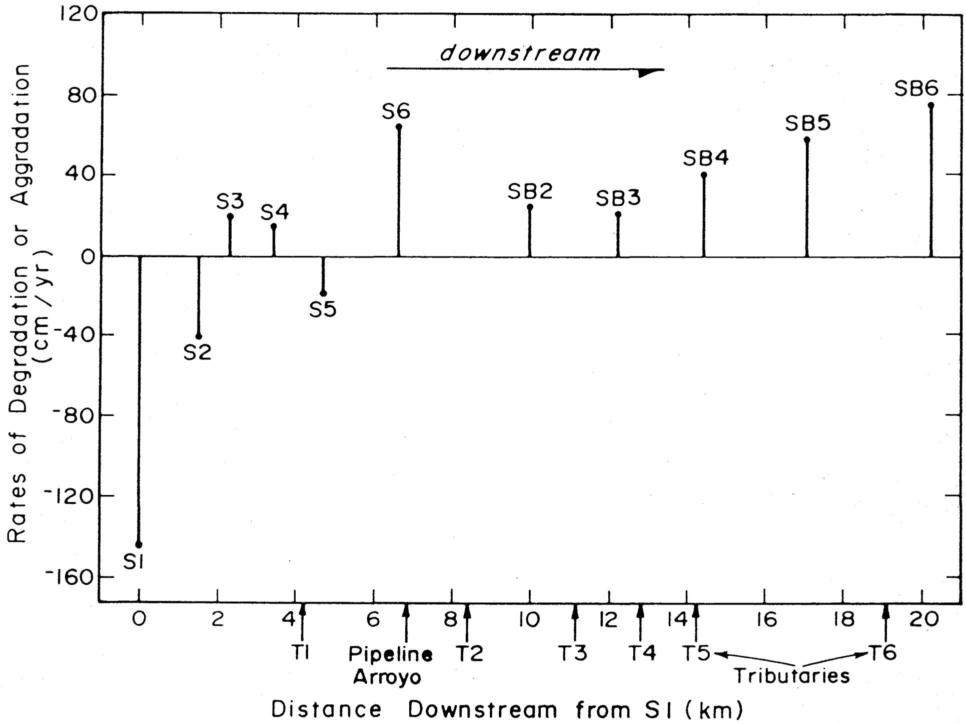


FIG. 5. Variation in total aggradational and degradational rates with distance downstream of cross-section S1. Cross-sections S1 and S2 are degradational, cross-sections S3, S4, and S5 are stable, and cross-sections SB2 through SB6 are aggradational. Aggradation at cross-section S6 was enhanced by backwater deposition from the perennial reach.

topographically high tributary floors only experience less frequent large floods. The residence time of these sediments is also controlled by the frequency of tributary flooding and flushing of sediments out of tributaries. Near this study area, backwater deposits composed of perlite clasts which are related to a perlite-mine tailings release into an arroyo near Grants, New Mexico have remained in storage for nearly 30 years (Miller, 1985). This indicates that residence time of sediments deposited at tributary-backwater sites typically exceed the residence times of floodplain and channel sediments and may approach the intermediate-term scale.

SEDIMENT STORAGE POTENTIAL

The maximum potential storage of sediments in each of the short-term sites depends upon the size and geometry of the depositional units. Field mapping of these sites suggest the following ranking in relative storage capacity of sediments with the Rio Puerco arroyo: (1) floodplain deposits, (2) channel deposits, (3) upper-channel deposits, (4) point-bar deposits, and (5) tributary-backwater deposits (Miller, 1985). As mentioned above, floodplain sites are far more extensive within the sandy reach, and therefore sediment storage potential increases down the arroyo in response to changes in the type of sediment within the arroyo. The significant increase in sand content

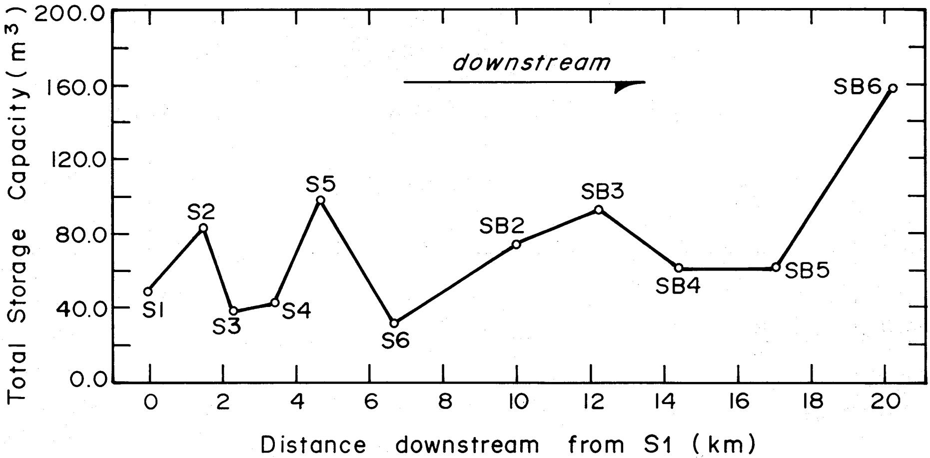


FIG. 6. Graph of total storage capacity versus distance downstream of cross-section S1 for 11 cross sections of the Rio Puerco; see Fig. 2 for location.

enhances the mobility of the channel allows for greater lateral storage (broader floodplains). Although the channel forms have remained relatively stable over the past 40 years, arroyo floors (predominantly floodplain) in the lower reach of the Rio Puerco in the study area have experienced the greatest change in lateral position (Fig. 2).

Storage potential within the channel is also a function of vertical changes in the channel position as determined by local rates of aggradation and degradation, which have been calculated for the 11 cross-section stations on the Rio Puerco (Fig. 5). Nearly all stations below the high-sand influx tributary (T1) experienced aggradation during the high-runoff season, and the rate of aggradation increased down arroyo (Fig. 5). The reach above tributary T1 experienced relative stability with minor local degradation and aggradation Such trends imply that channel reaches with high values of M do not readily store sediment by either vertical or lateral accretion; whereas, those reaches with low values of M can store sediment by lateral and vertical accretion.

The total capacity to store sediment within the arroyo is a function of the cross-sectional size of the arroyo per meter length of stream (Fig. 3). Although the total capacity to store sediments within the upper ephemeral reach is similar to the lower sandy reach (Fig. 6), less sediment is actually stored due to relative immobility of channel reaches with high M values. The increased storage of sediment within the sandy reach has not significantly reduced the total storage capacity due to the greater laterally mobility of the arroyo floor in the sandy reaches (Figs. 2 and 5).

Channel mobility, as measured by the total cross-sectional change occurring over the study period (ΔCSA), was quantified at selected cross-sections on the upstream clay-rich reach (stations S1-S4) and on the downstream sandier reaches (stations S5, S6, SB2, SB4-SB6) (Figs. 2 and 7). Those cross-sections with silt/clay content, or M values, greater than 30 % were either degradational (negative ΔCSA values) or stable; increasing silt/clay content apparently increased channel stability (Fig. 7A). Channel cross-sections with low M values (< 20 % silt/clay content) were predominantly aggradational (positive ΔCSA values) (Fig. 7A), and these reaches had the highest absolute values of ΔCSA. In addition, the sandy channel reaches have ΔCSA values which increase with drainage area (Fig. 7B). Channel stability in sandy reaches on the Rio Puerco decreases with increasing drainage, or

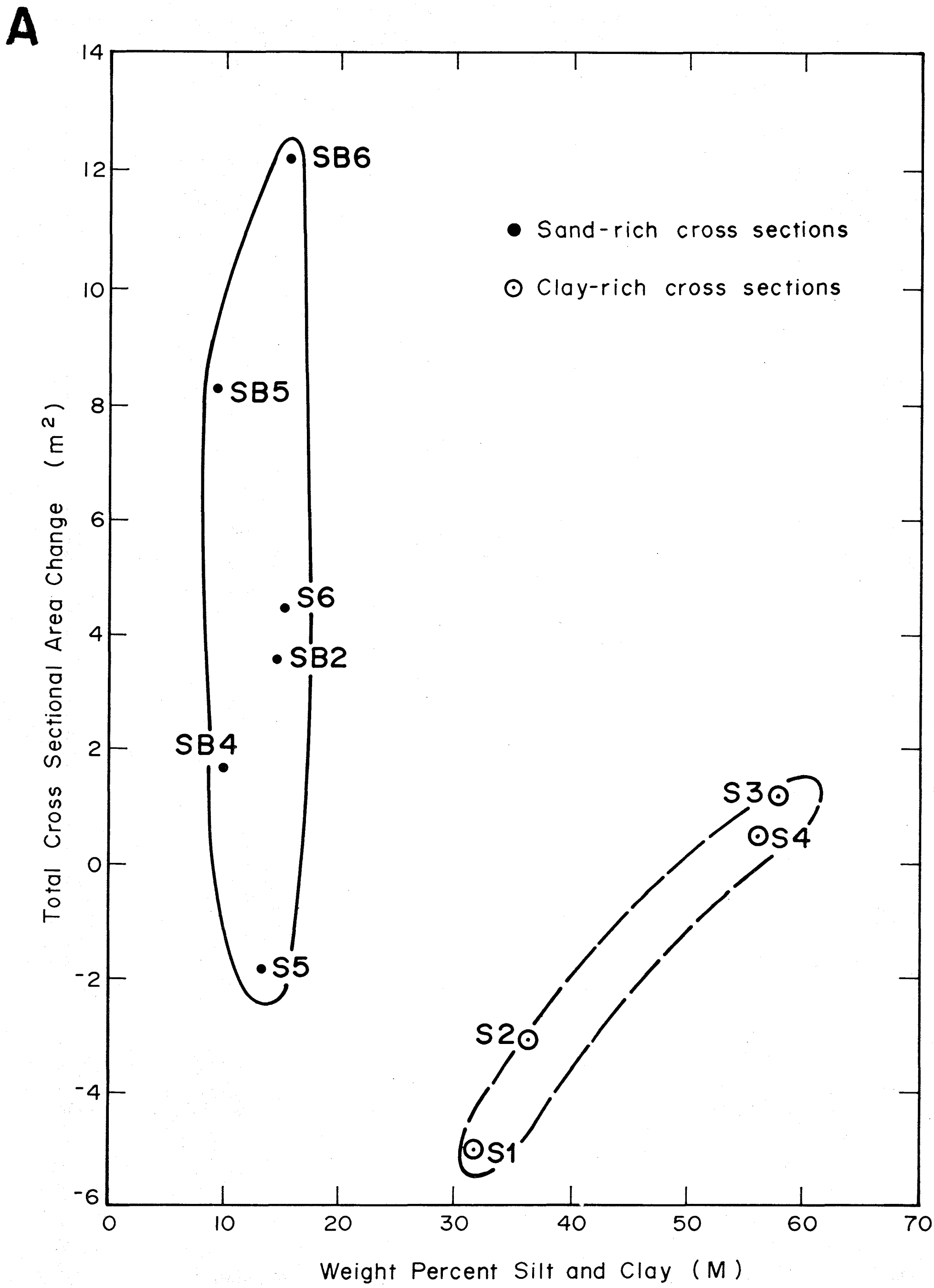


FIG. 7.A. Total change in cross-sectional area versus weight percent silt and clay in the arroyo perimeter (M). Note cross-sections S1 through S4 are in silt- and clay-rich reaches; whereas, cross-sections S5 through S6 are in sandy reaches.

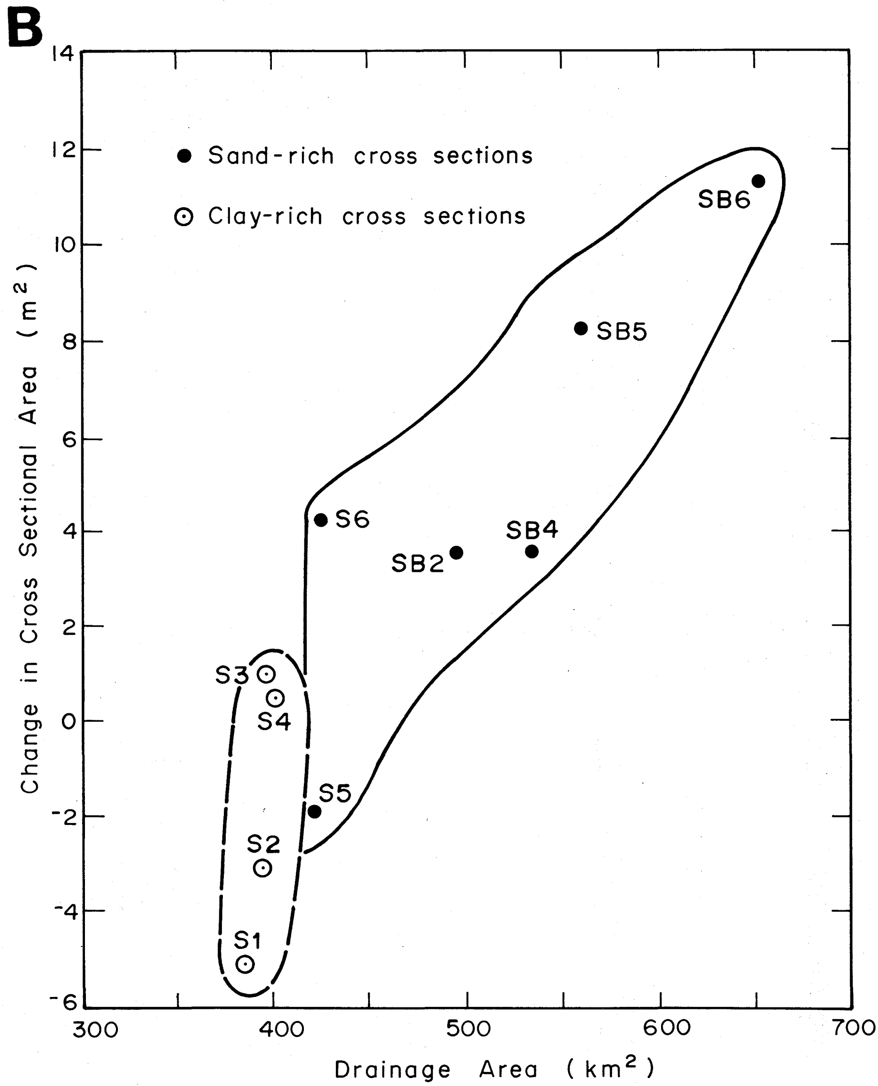


FIG. 7.B. Total change in cross-sectional area versus drainage area for 10 surveyed cross sections of the Rio Puerco. Note cross-sections S1 through S4 are in silt- and clay-rich reaches; whereas, cross-sections S5 through SB6 are in sandy reaches. Drainage area is substituted for discharge since discharge for events of similar recurrence intervals could not be determined at each cross section.

discharge. Channel stability and sediment storage potential along given arroyo reaches are directly influenced by the sediment type in the arroyo walls and floor which affect channel erodibility as well as size of the drainage basin which controls discharge properties. The type of sediment in which the arroyo has developed is a function of the source-area lithology, and therefore, source-area lithology indirectly influences the sediment storage potential in the Rio Puerco arroyo.

TRANSPORT AND STORAGE OF URANIUM-MILL TAILINGS IN ARROYOS

During the 1979 breach of the UNC mill-tailings dam, liquid waste and contaminated sediments (tailings sediment) were released into Pipeline arroyo. However, a larger volume of tailings sediments were deposited on the valley floor as a fan immediately below the dam and did not reach Pipeline arroyo (Gallaher and Cary, in press). Most of the liquid effluent and some tailings sediment were carried approximately 90 km downstream into west-central Arizona (Gallaher and Goad, 1981). Discharge for the dam-failure event decreased downstream from 12.7 to 4.5 m^3 s^{-1} over a distance of approximately 8 km (Gallaher and Cary, in press). Liquid wastes were contained within the Rio Puerco arroyo downstream of Pipeline arroyo and were observed inundating the arroyo floodplain surface. However, little alteration in floodplain or bankfull-channel morphology occurred as a result of the tailings release (Gallaher and Cary, in press).

The calculated discharges of the tailings release indicate that the sediment would have been deposited over the floodplain and into the tributary-backwater sites. The maximum areal distribution of the contaminanted tailings sediments should have occurred on the floodplains. Scouring and filling of the bankfull-channel sites during the spill may have resulted in storage of tailings sediment within the arroyo channel. Since silt/clay size fractions are assumed to be the chemically active sediment phases and are most likely to concentrate the contaminants (Novo-gradic, 1983), contaminated sediment may have been stored in upper channel deposits which have the highest average silt/clay content. In addition, decreasing discharge downstream during the tailings spill and increasing aggradation rates downstream (Fig. 5) may have resulted in increased storage of tailings sediments in the distal reach of the Rio Puerco within the study area.

Geochemistry of Rio Puerco Sediments

The chemical composition of uranium mill tailings at the Churchrock Mill is not known. However, it is assumed that the UNC mill-tailings pile is a contaminant point source for many trace elements associated with uranium mill tailings (Dreesen et al., 1978) including Ba, Cd, Cu, Mo, and Se. Assuming that tailing contaminanted sediment accidentally released in 1979 were stored in floodplain and channel sites, selected samples from storage sites were chemically analyzed for these five elements. Analyses were performed in order to determine whether these elements could be used to trace the storage sites of uranium mill-tailings released into a fluvial system from a point source.

Sediments within the short-term storage sites are composed predominantly of kaolinite and traces of smectite and illite clay minerals. The homogeneity of clay mineralogy within these short-term storage sites suggest that changes in clay composition are not responsible for differences in elemental concentration (Miller, 1985).

Figure 8 compares downstream concentrations of channel, floodplain, and tributary deposits. Tributary samples were collected upstream of backwater deposition and are thought to provide background concentration data for the drainage basin. This is due to the fact that tributary sediments are likely to be representative of the chemical concentration possessed by drainage basin soils, alluvium, and bedrock.

Figure 8 illustrates that there are not systematic downstream increases or decreases in concentration of the five elements analyzed. Background levels in the various tributaries downstream are not significantly different than the concentrations in the floodplain or channel. Only selenium concentrations within the tributaries are relatively higher than the channel or floodplain. In general, channel concentrations were slightly higher than

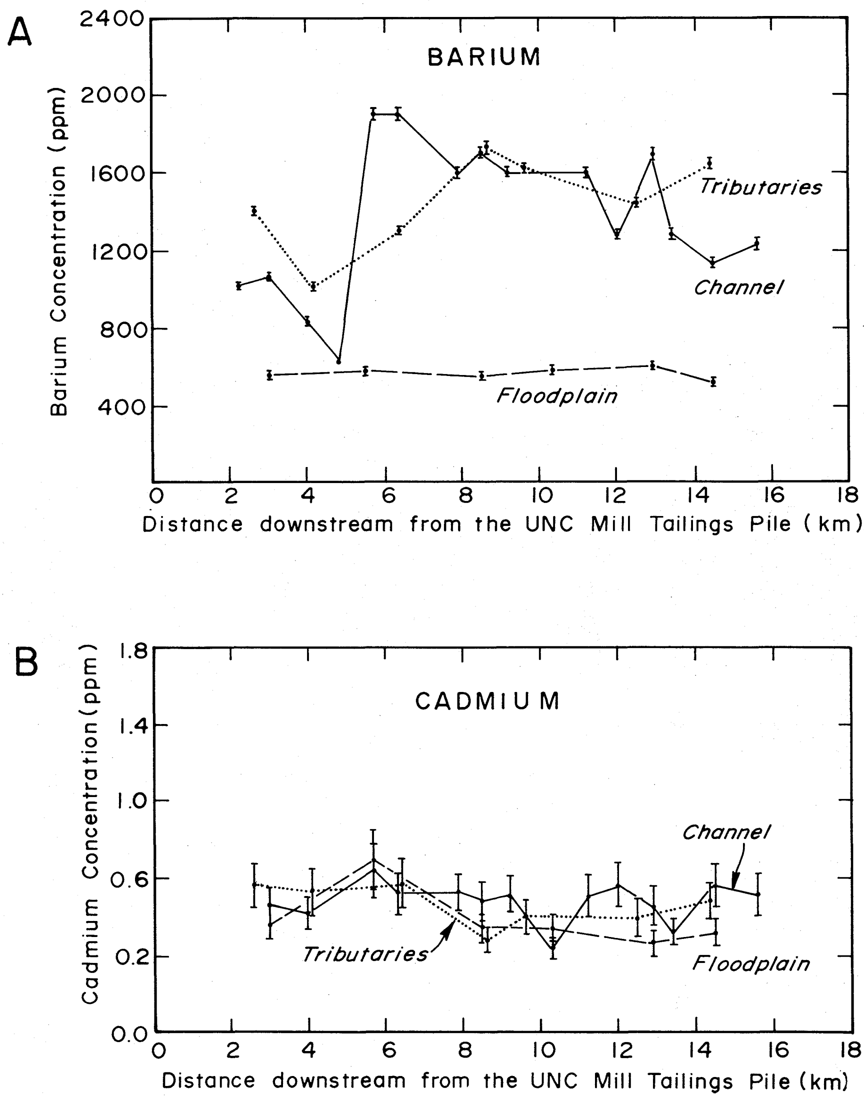
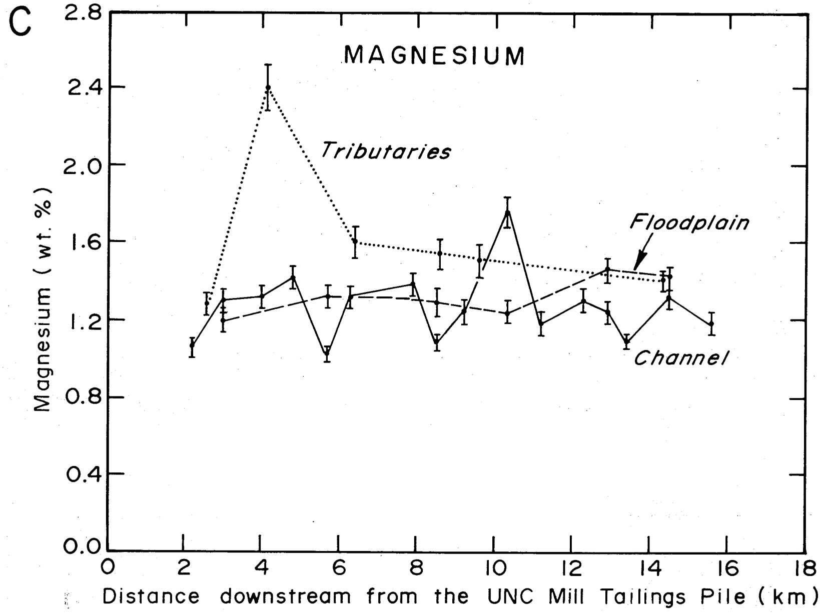


FIG. 8. Variations in barium (A), cadmium (B), magnesium (C), copper (D), molybdenum (E), and selenium (F) concentrations within the channel, floodplain, and tributary depositional units of the Rio Puerco with distance downstream from the UNC mill tailings dam (Fig. 2). Note tributary samples were collected upstream of backwater deposition and floodplain concentrations are the average of three samples collected at the surface as well as 50 cm and 100 cm depths below ground surface. Vertical bars represent calculated variations in elemental concentration determined from duplicate analyses.



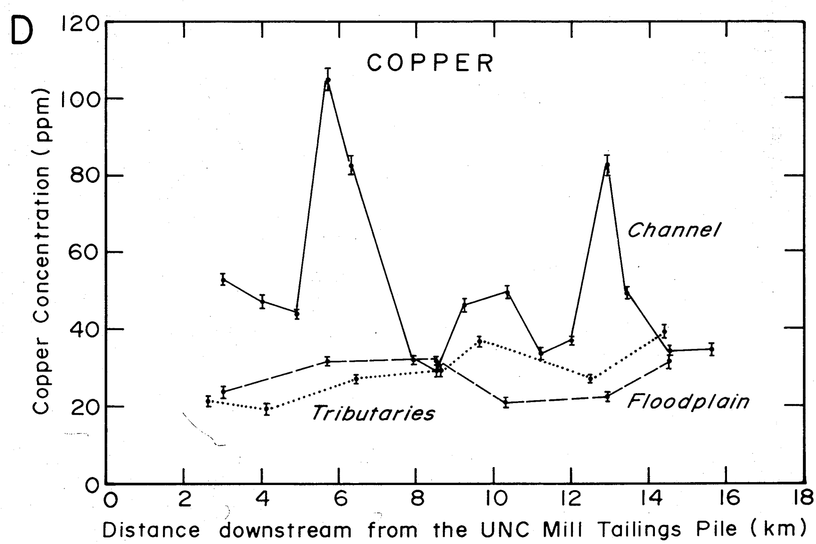
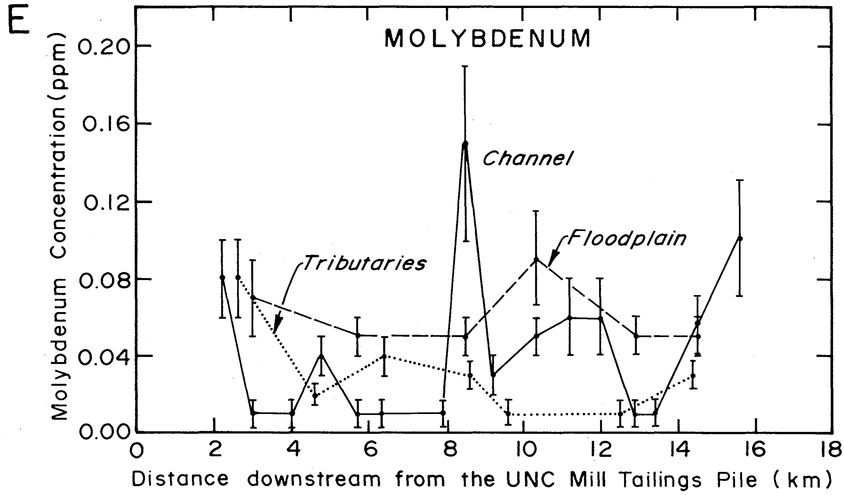


FIG. 8. (CONTINUED)



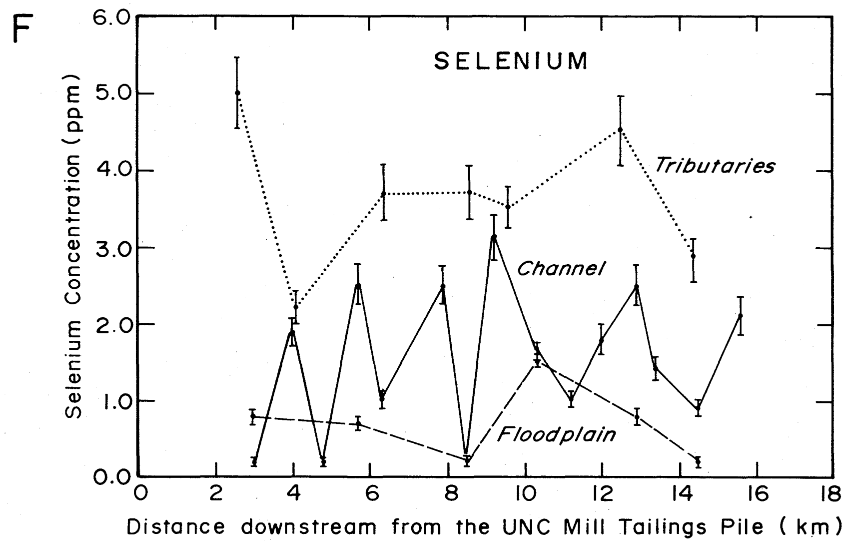


FIG. 8. (CONTINUED)

floodplain samples, excluding Mo which was almost consistently higher in concentrations along the Rio Puerco floodplain than in the channel. Elemental concentrations within the upper-channel and point-bar samples are also extremely variable at a station and downstream (Table 2 and Fig. 2). No systematic change in concentration with depth below the surface was found (Miller, 1985).

The geochemical data suggests that the sediment/contaminants introduced into the Rio Puerco in 1979 may be diluted to near background levels. Both coal and shale contain high concentrations of these elements and variations in the quantities of coal and shale at the storage sites may cause the variations

Table 2. Summary of elemental concentration of selected point-bar samples (A) and upper-channel samples (B) from the Rio Puerco; see Figure 2 for sample locations.

A.

Samples	Ba	Cd	Cu	Mg	Mo	Se
PB1,1	1530	0.68	32.5	1.44	<0.02	2.8
PB1,2	900	0.50	25.0	1.42	0.04	<0.4
PB1,3	1230	0.41	28.0	1.50	<0.02	<0.4
PB1,4	1500	0.31	28.0	1.54	0.02	3.9
PB2,1	1695	0.42	37.0	1.50	<0.02	4.6
PB2,2	1650	0.53	34.0	1.54	0.32	2.4
PB2,3	1580	0.42	37.0	1.60	<0.02	4.6
PB2,4	620	0.48	20.7	1.56	0.04	1.7
PB3,1	1570	0.72	27.0	0.98	0.04	4.4
PB3,2	1670	0.44	20.0	1.54	0.04	4.6
PB3,3	1570	0.48	40.0	1.36	0.12	3.5

Point-bar samples (PBx,y) - silt and clay analysis
PB = point bar deposit
x = station number
y = sample number

B.

Samples	Ba	Cd	Cu	Mg	Mo	Se
UC1,1	690	0.52	23.0	1.52	0.04	<0.4
UC1,2	590	0.54	21.0	1.62	0.02	0.9
UC1,3	1550	0.53	20.0	1.44	0.68	4.2
UC1,4	--	--	--	--	--	--
UC2,1	690	0.41	21.0	1.30	0.04	1.9
UC2,2	2150	0.68	19.0	1.28	0.10	4.6
UC2,3	2190	0.54	21.5	1.24	<0.02	4.2
UC2,4	645	0.51	22.5	1.62	--	--
UC3,1	590	--	--	1.52	0.02	--
UC3,2	1650	0.28	29.5	1.36	0.08	3.3
UC3,4	1550	0.31	21.5	1.28	0.04	3.9

Upper-channel samples (UCx,y) - silt and clay analysis
UC = upper channel deposit
x = station number
y = sample number

in the elemental concentrations (Table 2). It is not surprising that dilution of contaminanted sediment would occur during the time interval between the spill and the data analyses (five years) when considering the rates of scour and fill in the bankfull channel. However, concentrations within the flood-plain might be expected to remain elevated for longer periods due to longer-term storage than that of channels. It is equally possible that the elements selected for analysis were poor tracers of uranium-mill tailings since no data is available on the composition of the tailings. Geochemical analysis of dissolved concentrations of Mo and Se immediately after the spill closely approximated the concentrations of the UNC tailings-point liquid (Gallaher and Goad, 1981). In addition, groundwater levels and chemistry 15 km downstream along the Rio Puerco responded to the spill. The limited data base precludes any tentative conclusions concerning the long-term storage of sediment/

contaminants and aspects of the water quality. However, it is possible, as suggested by Gallaher and Goad (1981), that dissolved concentrations of tailings contaminants were sobed to sediment which have been diluted and redistributed subsequently along the arroyo channel and floodplain. In addition, eolian reworking of floodplain sediments and their transport out of the arroyo floor in the broad lower sandy reaches would enhance dilution and redistribution of the tailings sediments as well as the fluvial processes.

CONCLUSIONS

We conclude from our study of sediment/contaminant transport and storage within an arroyo setting the following six aspects:

1. Three short-term sediment/contaminant storage sites occur along the Rio Puerco, and in decreasing order of relative volumetric storage capacity they are: (a) floodplain, (2) bankfull-channel, upper-channel, point-bar, and (3) tributary slackwater deposits.
2. The volume and residence time of short-term sediment/contaminant storage sites along the Rio Puerco are controlled by: (1) sediment grain-size in the perimeter of the arroyo, (2) channel meandering and meander morphology, and (3) the quantity of lateral migration since entrenchment of the channel below the valley floor level and the resulting maximum bankfull-channel width of the incised channel.
3. The change in total cross-sectional area an channel stability is dependent upon drainage area (discharge) and the percent silt/clay in the arroyo channel perimeter.
4. Assuming that silt/clay is the chemically active phase of depositional units, the order of preferential contaminant storage in short-term storage sites from, greatest to least, is: (1) upper channel, (2) tributary backwater, (3) floodplain, (4) point bar, and (5) channel deposits.
5. Geomorphic data for the Rio Puerco suggests that the maximum storage of uranium mill-tailing sediments from the 1979 UNC tailings spill may have been on floodplains and in upper-channel deposits at meander bends.
6. Trace-element geochemistry was not useful in determining sites of contaminant concentration along the Rio Puerco five years after the tailings. This may be due to post-spill dilution and masking with elemental concentrations related to the local bedrock.

ACKNOWLEDGMENTS

This study was financed, in part, by the Department of Energy, in cooperation with Argonne National Laboratory, through a grant entitled, "DOE Master's Thesis Program on Nuclear Waste Management." Special thanks also go the B. Feilberg for his field and laboratory assistance and to Drs. D. Brookins and L. McFadden for their assistance with the interpretation of the geochemical data.

REFERENCES

Bullard, T.F. (1983) Bedrock influences on the late Quaternary alluvial history and evolution of the Kim-me-ni-oli Wash drainage basin. In American Geomorphological Field Group Guidebook, Chaco Canyon Country, (ed. by S.G. Wells, D.W. Love, and T.W. Gardner), p. 79-91.

Dreesen, H.A., Lynn, M., & Kelley, N.E. (1978) Contaminant transport, revegetation, and trace element studies at inactive uranium mill tailing piles. In Uranium Mill Tailings Management, v. 1, p. 111.

Folk, R.L. (1974) Petrology of sedimentary rocks. Hemphill Publishing Company, Austin, Texas, 184 p.
Gallaher, B. & Cary, S. (in press) Impacts of uranium mining on surface and shallow groundwaters, Grants mineral belt, New Mexico. New Mexico Environmental Improvement Division Report, Santa Fe, New Mexico.
Gallaher, B. & Goad, M. (1981) Water-quality aspects of uranium mining and milling in New Mexico. In Environmental geology and hydrology in New Mexico (ed. by S.G. Wells & W. Lambert). New Mexico Geological Society Special Publication No. 10, p. 85-92.
Grant, P.R. (1981) Overview of energy resources in New Mexico. In Environmental geology and hydrology in New Mexico (ed. by S.G. Wells & W. Lambert). New Mexico Geological Society Special Publication No. 10, p. 15-20.
Husler, J. (1984) Analytical methods for the analysis of rocks, ores, and minerals: Unpublished report: Departmental Procedures, University of New Mexico, Department of Geology.
Leopold, L.B., Wolman, M.G. & Miller, J.P. (1964) Fluvial processes in geomorphology. W.H. Freeman and Company, San Francisco and London, 522 p.
Love, D.W. (1983) Quaternary facies in Chaco Canyon and their implications for geomorphic-sedimentologic models. In American Geomorphological Field Group Guidebook, Chaco Canyon Country, (ed. by S.G. Wells, D.W. Love, and T.W. Gardner, p. 195-206.
Miller, J.R. (1985) Sediment storage, transport, and geochemistry in semiarid fluvial and eolian systems: applications to long-term stability and potential dispersal patterns of uranium tailings in the Grants Mineral belt, New Mexico. M.S. Thesis, University of New Mexico, 160 p.
Mills, A.M. & Gardner, T.W. (1983) Effects of aquifer dewatering on an ephemeral stream, San Juan Basin, New Mexico. In American Geomorphological Field Group Guidebook, Chaco Canyon Country, (ed. by S.G. Wells, D.W. Love, & T.W. Gardner), p. 57-66.
Novo-gradic, K. (1983) Trace metal and radionuclide distribution in recent sediments of the Rio Puerco, Rio San Jose, and Paguate Reservoir in the Grants Mineral belt. M.S. Thesis, New Mexico Institute of Mining and Technology, 133 p.
Patton, P.C. & Schumm, S.A. (1981) Ephemeral-stream processes: Implications for studies of Quaternary valley fills. Quaternary Research, v. 15, p. 24-43.
Schumm, S.A. (1961) The effects of sediment characteristics on erosion and deposition in ephemeral stream channels. U.S. Geological Survey Professional Paper 352-C, p. 31-72.
U.S. Department of Commerce (1974-1982) Climatological summary of Gallup and Grants, New Mexico. Climatography of the United States, No. 20-29.
Von Eschen, G.F. (1961) Climatological summary of Gallup Station 1938-1960. National Climatic Center, Asheville, North Carolina, p. 31.
Wells, S.G., Bullard, T.F., Smith, L.N. & Gardner, T.W. (1983) Chronology, rates, and magnitudes of late Quaternary landscape changes in the southeastern Colorado Plateau. In American Geomorphological Field Group Guidebook, Chaco Canyon Country, (ed. by S.G. Wells, D.W. Love, & T.W. Gardner), p. 177-186.
Wells, S.G. & Gardner, T.W. (1985) Geomorphic criteria for selecting stable uranium tailings disposal sites in New Mexico: New Mexico Energy Research and Development Institute Technical Report NMERDI 2-69-1112, v. 1, 353 p.