Use of Radiometric (Cs-137, Pb-210), Geomorphic, and Stratigraphic Techniques to Date Recent Oxbow Sediments in the Rio Puerco Drainage Grants Uranium Region, New Mexico

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ABSTRACT / In the absence of historic geochemical baseline data for the Grants uranium region, environmental changes resulting from uranium mine-mill activities can be determined only by indirect methods. A methodology for determining the age of recent sediments in streams draining the region has been established based on combined geomorphic, stratigraphic, and radiometric dating techniques. Because clay-rich sediments retain possible radionuclides and heavy metals derived from mineralization and mined sources, sample sites which contain fine-grained deposits that both predate and postdate mine-mill activity were located in abandoned-channel segments (oxbows) of major streams draining the eastern Grants uranium region. Aerial photographs (and derivative maps) taken between 1935 and 1971 provided the historical and geomorphic documentation of approximate dates of oxbow formation and ages of alluvial fills in the abandoned-channel segments. Pits were dug at these oxbow sites to determine stratigraphy and composition of the deposits. Samples collected from pit walls and auger holes below the pits were subjected to radiometric analysis by gamma ray spectrometry for the artificial radionuclide Cs-137 and the natural radionuclide Pb-210 as well as other U-238 and Th-232 daughters. Because of the dynamic nature of the system, absolute dating with Cs-137 was not possible but samples could be dated as either pre- or post-1950. The 1950 date is important because it marked the beginning of the uranium exploitation in the region. The Pb-210 dating was not possible because background Pb-210 was very high relative to fallout Pb-210.

Introduction

Environmental effects of mining and milling commonly are difficult to assess because historical baseline water quality and sediment data do not exist. An excellent example of the need for baseline data occurred in western New Mexico in July 1979, when a uranium tailings pond dam broke, releasing 360 million liters of pH 1.5 tailings water containing high concentrations of some trace metals and radionuclides into the Puerco River. The tailings water passed through Gallup, New Mexico (population: 19,000) and was traced downstream for about 90 km (Millard and others 1983; Galliher and Cary 1986). Concern that the spill might be detrimental to the health of humans and livestock living along the stream caused immediate reaction by government agencies, but because of the lack of historical data on the stream, the effects of the spill were difficult to evaluate. Subsequent investigations suggested that long-term effects of mine-dewatering and sediment discharge from mine dumps and mill tailings should also be considered.

The Puerco River drains only the western part of the Grants uranium region, a uranium-bearing area which has provided more than 40 percent of the nation's uranium. Because the spill precluded baseline studies of the Puerco River, baseline studies of the drainages east of the continental divide became even more essential. These drainages include the Rio Puerco of the east (Rio Puerco, in contrast to the Puerco River west of the divide) and its tributaries, the Rio San Jose, and Chico Arroyo (Fig. 1; see further hydrologic description below). The study region included over 250 km of stream length combined for the Rio Puerco and Rio San Jose.

Since 1948, New Mexico has produced more than 40 percent of the nation's uranium, 99.8 percent of

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which came from the Grants uranium region (Rautman 1977). In 1978, there were 35 active uranium mines in the Grants uranium region, as well as five mills capable of handling about 21,000 t of ore per day. The locations of a number of these facilities are shown on a map of the study area in Figure 1.

A population attracted by the recent mining activity is located along the Rio San Jose from the Grants area to Laguna (see Fig. 1), with the bulk of the habitation in the stream valley. The sediments from the San Jose enter the Rio Grande system through the Rio Puerco and are eventually deposited in Elephant Butte Reservoir, a large irrigation storage reservoir heavily used for recreation. It has been estimated that the Rio Puerco contributes more than 50 percent of the sediment load to the Rio Grande in central New Mexico while carrying less than 16 percent of the water (Waite and others 1972; Popp and Laquer 1980).

The age of sampled sediments had to be established in order to provide baseline data on chemical and physical properties of sediments along the streams, and to determine the extent to which active uranium mining and milling operations in the Grants uranium region may be contributing excess trace metals and radionuclides to Rio Puerco and Rio San Jose sediments. Available historical data on Rio Puerco–San Jose channel behavior permitted identification of sites for sampling stream sediments that both predate and postdate onset of uranium mine-mill operations, which began about 1950 (Perkins 1979). Comparison of sediments deposited within the past 30 yr (1950–1980) with earlier sediments from the same area has established man-induced contributions to sediments and provided long-term baseline data on behavior of the affected drainage system.

Procedures used to determine the processes of sediment transport and the ages of the sediments include the following:

1. Geomorphic evaluation of the fluvial transport and depositional system from the uranium mines and mills in the headwaters through the Rio San Jose–Rio Puerco drainage systems, and evaluation of loci of sediment deposition along the drainages.
2. Historical documentation of loci of deposition to aid in determining the age of sediments.
3. Field sampling and sediment characterization along the drainages.
4. Laboratory characterization of grain size and grain mineralogy of sediment samples.
5. Laboratory determination of ages of sediments using radioactive cesium-137 (Cs-137) and lead-210 (Pb-210).

Categories 2 and 5 should corroborate each other in establishing the age of a particular sediment layer.

Radionuclides and heavy metals commonly are adsorbed on clays. Therefore, we looked for thick accumulations of fine-grained sediments which could be dated by comparing historic sequences of maps and aerial photographs. In general, we selected segments of abandoned channels, or oxbows, because they are readily identifiable on aerial photographs, commonly are filled with thick sequences of fine-grained sediments over a coarser channel base, and can be dated in relation to historic photos and by tree rings. Most of the oxbows we chose formed after 1935 and, in one case, after 1957. We also sampled fine-grained sediments trapped in Paguate Reservoir downstream from the Jackpile uranium mine. Analyses of sediments for trace metals and uranium-238 and thorium-232 daughters will be reported in a separate communication.

Radiometric Dating of the Sediments

The use of radionuclides with relatively short half-lives, such as Pb-210 and Cs-137, to date recent sediments is well established (Krishnaswami and Lal 1978). Cesium-137 is an artificial radioisotope formed by nuclear fission and has a half-life of about 30 yr (Lederer and others 1967). This isotope has been introduced into the atmosphere in irregularly varying amounts since nuclear testing above ground began in 1945 (Durham and Joshi 1980). Dating methods based on Cs-137 depend on the imprint of an irregular influx of wet and dry atmospheric deposition in sediment layers or on its absence before 1945 (Krishnaswami and Lal 1978).

Lead-210 is a naturally occurring radioisotope in the uranium-238 decay series with a half-life of approximately 22.3 yr (Lederer and others 1967). The presence of Pb-210 in atmospheric deposition is due to the escape of a fraction of its precursor, Rn-222, from the earth's crust into the atmosphere and subsequent rapid decay to Pb-210, which undergoes deposition like Cs-137. The exponential decay of the atmospherically derived Pb-210 (unsupported Pb-210) can then be used to estimate the age of a sediment layer as long as it is significantly higher in activity than the Pb-210 already present in the soil (supported Pb-210).

Both Pb-210 and Cs-137 are strongly bound by sediments and tend to remain trapped in a sediment layer which is subsequently buried. Robbins and Edgington (1975) used both Pb-210 and Cs-137 to establish anthropogenic inputs of lead from coal and gasoline to Lake Michigan sediments. Benninger (1978) used

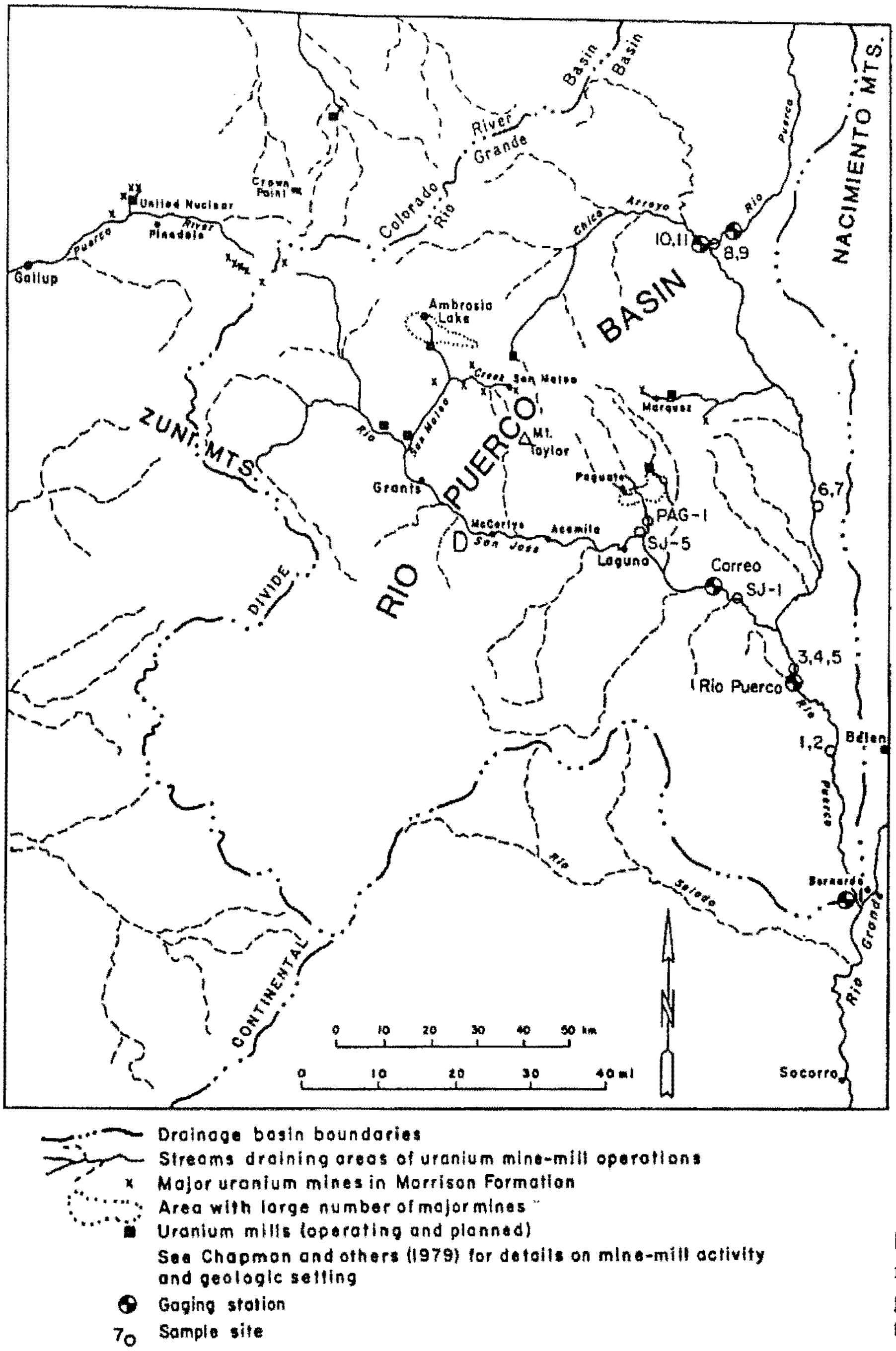

Figure 1. Location of mines and mills of the Grants uranium region, gaging stations, and sample sites in the Rio Puerco drainage basin.

Pb-210 to determine lead fluxes in Long Island Sound, and Smith and Walton (1980) used Cs-137, as well as pollen assemblages to determine the sedimentation rate in a fjord in Quebec. In the previous studies referenced, deposition has been quite regular and continuous in standing bodies of water, and individual sediment samples typically represent a year or more of deposition. A major concern in dating sediments from the ephemeral, high-energy streams in this study has been mixing and redeposition due to the dynamic nature of the system.

An additional problem, shown by a number of authors, is that Pb-210 (Robbins and Edgington 1975; Goldberg and others 1978), Cs-137 (Smith and Walton 1980; Edgington and Robbins 1975), and various other radionuclides are significantly enriched in the finest size fractions—a finding which is in agreement with the greater surface area, cation exchange capacity, and hydrous metal oxide and organic contents of these fractions. As a result, the activities of both Pb-210 and Cs-137 may be significantly affected by the silt and clay content of the samples. Such an effect (which has generally not been significant at sites chosen in previous studies) may be corrected for in a variety of ways. First, the concentration of stable lead or cesium adsorbed by each sample can be determined, and the activities of the Pb-210 or Cs-137 normalized to these values. This approach, however, is based on the assumption that nearly all of the elements in question are present as ions adsorbed onto the surface of the particles and not trapped within the framework of the silicate or metal oxide structures. Such an assumption, although it may be warranted for cesium on account of its large ionic radius, is probably not true for lead, which is scavenged by the hydrous metal oxide phase (Lewis 1977). In addition, a portion of the lead will be of anthropogenic origin, and will not have been added at a constant rate.

Alternately, several samples of identical age—such as surface samples—can be analyzed for Pb-210 or Cs-137, and an attempt made to determine an empirical correlation between the activity of the isotope and the percentages of the different size fractions. This empirical relationship can then be used to normalize the Pb-210 or Cs-137 activities of the remaining samples.

Finally, samples can be chosen which are all of similar lithology, or which can be mechanically separated to remove certain of the size fractions. Coarser sand fractions, for example, could be removed by passing the sample through a screen or sieve of appropriate size, while silt and clay could be removed manually if it is present as discrete, cohesive layers.

Geologic Setting

Drainage Basin Characteristics

The Rio Puerco drainage basin is more than 200 km long, encompassing approximately 18,892 km^2 straddling the boundaries between the Colorado Plateau, Southern Rocky Mountains, and Basin and Range physiographic provinces. The upper portions of the drainage basin are underlain by bedrock (see below), whereas the middle and lower portions are underlain by thick, semiconsolidated deposits in the Albuquerque structural basin. Although most of the drainage basin is less than 2,000 m above sea level, the headwaters lie in the Nacimiento Mountains (up to 3,176 m), the Zuni Mountains (2,821 m), and Mount Taylor (3,345 m) (see Fig. 1). Rio San Jose and Chico Arroyo are the two major subbasins which drain the Grants uranium region. Smaller drainages from the Marquez area drain the easternmost part of the mineralized belt. A particularly important tributary to Rio San Jose is Rio Paguate, which is bisected by the extensive open pit and waste piles of the Jackpile–Paguate uranium mine complex.

Geomorphology of the Rio Puerco and Tributaries

The landscape along the Rio Puerco and its tributaries is quite diverse. Pertinent to this study are the general features of the stream valleys. The valleys consist of (1) the sloping valley margins commonly cut in bedrock or in semiconsolidated basin fill, (2) the valley floor, underlain by thick alluvial deposits, and (3) the incised axial stream channel (arroyo) and related features.

The valley side slopes are dissected by tributaries which transport sediment from the slopes to the valley floor. Some tributaries deposit sediment in alluvial fans along the margins of the valley floor. Others have become integrated with the arroyo system and contribute sediment to the axial stream channel.

The valley floor is relatively flat, consisting of sediment layers built up by flooding from the axial stream when it was not entrenched, and by deposition from the toes of alluvial fans along the valley margins. Valley floors presently are undergoing erosion by lateral and vertical cutting of surface streams (axial arroyos and dendritic tributary arroyos) and subsurface tributaries in pipes (natural cavelike passages through clay-rich sediments).

The Rio Puerco and its major tributaries have developed distinctive geomorphic features within their confined arroyo walls. Rio Puerco Arroyo ranges from 145 to 245 m wide between walls 8 to 13 m high in studied reaches. Geomorphic features within and adjacent to Rio Puerco Arroyo are shown in Figure 2.

According to Love and others (1983), the pattern of the inner channel of Rio Puerco Arroyo consists of complex meanders, straight reaches, and slightly arcuate reaches. Some meanders are very elongate, but the overall ratio of stream length/straight line distance (sinuosity) is about 1.5.

Geomorphological-sedimentological features of the inner channel and inner floodplain commonly include sandbars and ripple-marked surfaces along the floor of the inner channel, slightly finer-grained sandbars along the margins of the inner channel (see below), natural levees along the outer margins of the inner channel, a relatively flat floodplain, and coppice dunes. Chutes across point bars or parallel to the inner channel produce relief on the inner floodplain. Lo-

Figure 2. Geomorphic features of Rio Puerco Arroyo and adjacent valley floor in reach downstream from site 5. Letters identify features as follows: (A) the inner channel, (B) point bars along the channel, (C) an inner floodplain which may include oxbows, (D) with sand plugs, (E) where the channel has been cut off, (F) erosional and depositional terraces above the inner floodplain, (G) vertical arroyo walls, (H) remnants of the valley fill within the arroyo (I) gently to steeply sloping eroded slopes, (J) the mouths and alluvial fans of soil pipes and tributaries, and (K) uneroded valley floor.

cally, adjacent to the inner channel, is a subhorizontal zone where sheet flow occurs during large floods (Shepherd, 1976). Tamarisks commonly are the dominant vegetation, although willows and cottonwoods are common locally. In broad reaches of the arroyo, tamarisks die out away from the margins of the inner channel and rabbit-brush and four-winged saltbrush dominate.

Sediments accumulate along modern streams in several depositional environments. Sediments are deposited in channel-marginal bars, along the margins of point bars, in low areas along the inner floodplain, and in cutoff channels (oxbows). Oxbows are likely to accumulate the thickest and most fine-grained deposits, so they were sought for study. The oxbow filling process may take 15 to 30 yr in the Rio Puerco.

Tributaries commonly have steeper gradients and have less well-developed channel and inner floodplain features than the Rio Puerco.

Sources of Sediment, Radionuclides, and Heavy Metals

The drainage basin is underlain by a variety of rocks and less consolidated deposits (Table 1). Point-counts of 212 township and range line intersections in the drainage basin on the geologic map of New Mexico (Dane and Bachman 1965) were used to estimate the relative proportions of rocks exposed. The late Tertiary and Quaternary sediments are derived from sources which continue to contribute sediments to the drainage. Thus, sediments reworked from relatively young basin fill are similar to sediments presently being shed from the headwater areas.

About three percent of the drainage basin is underlain by Todilto Limestone and Morrison Formation, the two major uranium host rocks of the Grants uranium region (the amount of *mineralized* rocks at the surface is estimated to be much smaller than one percent of the drainage basin area).

Table 1. Percentages of geologic units exposed in the Rio Puerco drainage basin.

Unit	Percent
Thick Late Quaternary sediments (8% Holocene fill)	9.4
Upper Tertiary and Quaternary basin fill	6.1
Upper Tertiary and Quaternary volcanics	17.0
Lower and Middle Tertiary sediments and volcaniclastics	6.6
Cretaceous sandstones, shale, and mudstones	40.6
Jurassic sandstone, mudstone, limestone, and gypsum	4.7
Triassic mudstone and sandstone	5.7
Upper Paleozoic limestone, mudstone, sandstone	7.5
Precambrian igneous and metamorphic rocks	2.4
Total	100.0

Uranium prospects and mines in the eastern part of the Grants Mineral Belt are discussed by McLemore (1982, 1983), Hilpert (1969), Rautman (1980), Perkins (1979), and Hatchell and Wentz (1981). Most surface occurrences of uranium mineralization are sites of mines or prospects. Many of the mines and mineral occurrences are underground and have little surface expression other than man-made disturbance. A survey of abandoned mines and prospects (Anderson 1981) revealed that few prospects had extensive surface disturbance with elevated amounts of radioactivity. With several notable exceptions, there appear to be few concentrated surface sources for radionuclides and heavy metals from the Grants uranium region.

Uranium is also found in Eocene Baca Formation along the southern margin of the drainage basin (Chamberlin 1981). Uranium mineralization is localized along the eastern margin of the Ladron Mountains (McLemore 1982) and in Cerro Colorado, an exhumed volcanic complex near the Rio Puerco west of Albuquerque (Hilpert 1969).

Other rocks which may produce above-background trace elements or radionuclides within the drainage basin include sedimentary copper deposits along the front of the Nacimiento Mountains (Kaufman and others 1972), fluorite (-sulfide) deposits in the Zuni Mountains (Goddard 1966), and trace-metal-bearing coal and humate deposits of Cretaceous formations (Bachman and others 1959; Siemers and Waddell 1977; New Mexico Bureau of Mines and Mineral Resources unpublished coal data files).

Another possible source of radionuclides and trace metals has been mine dewatering. Discharges to the Rio Puerco above its confluence with the San Jose are approximately 22.7 m^3/s and to tributaries of the San Jose, about 13.2 m^3/s (Perkins and Goad 1980). Concentrations of trace metals and radionuclides in mine discharges and local stream waters and sediments which are high or exceed New Mexico groundwater standards have been reported (New Mexico Water Quality Control Commission 1982; Brandvold and others 1981; Popp and Laquer 1980; Dreesen and others 1982). Any of this material entering the drainage systems may be moved downstream.

Possible Reworking of Sediments Within the Drainage Basin

Recycling (retransporting) previously deposited sediments may account for much of the dilution of sediments derived from primary sources in the drainage basin. Recycling of grains may occur on several scales, including (1) episodic transport and deposition of loose sediment within the modern channel, (2) recycling modern sediment by eroding twentieth-century bank and floodplain deposits, (3) recycling earlier valley fill by lateral erosion of arroyo walls, (4) recycling earlier valley fill by vertical erosion at the base of the modern channel, and (5) erosion of valley fill by tributaries. No data are available regarding episodic transport of sediment within the modern channel, but bars are deposited and are reworked by later floods. The distance individual grains are transported probably is related to the size of the grains (whether they are part of the bedload or suspended load) and the stream power of individual floods. Some marshy areas along the modern Rio San Jose above Laguna (see Fig. 1) act as natural sediment traps.

In order to assess the amount of lateral erosion of both twentieth-century deposits (floodplain) and earlier valley fill, a 10-km stretch of the Rio Puerco between some of the sample sites (1 and 5) was analyzed by determining the course of the inner channel on 1:4,800 scale maps produced in 1979 by the Army Corps of Engineers. About 77 percent of the length of the inner channel was between banks which appeared to be relatively stable (neither eroding nor receiving sediment). About 9 percent of the length of the channel appeared to be impinging on twentieth-century deposits and, in some cases, clearly cutting into the inner floodplain. The inner channel impinged directly onto exposures of older valley fill along 14 percent of the channel.

Vertical cutting into older deposits is difficult to assess because commonly the channel floor is covered with loose sandy sediment or with water. In early fall 1982, however, a relatively large flood removed loose sediment from some reaches of the Rio Puerco and it was possible to see that the channel locally rests on older valley fill. Nonetheless, it is not yet possible to estimate what proportion of the channel length is eroding older valley fill.

Pipes and small incised tributaries contribute reworked valley fill directly onto the inner floodplain and to the inner channel. Larger tributaries recycle sediments from the valley margins as well as valley fill directly into the inner channel.

Hydrology of the Rio Puerco and its Tributaries

The Rio Puerco is an ephemeral stream throughout much of its length, flowing only in response to precipitation and snowmelt. Water discharge and sediment transport data from five United States Geological Survey gauging stations along with long-term records within the Rio Puerco drainage basin were analyzed to determine the size and frequency of floods and the general behavior of the Rio Puerco. The stations included Bernardo (1940–1982), Rio Puerco (1934–1976), Rio Puerco above Chico Arroyo (near Guadalupe) 1951–1980. Rio San Jose at Correo (1943–1980), and Chico Arroyo (1943–1980) (see Fig. 1). In general, the Rio Puerco flows in the spring and during the summer thunderstorm season (July–September). The annual number of days of flow decreases downstream. All stations are marked by great fluctuations in the amount of flow each year (see Fig. 3).

Commonly, there is a loss of water in a downstream direction as floods lose water to the channel floor and banks (Heath 1983). As in other streams, the duration becomes longer and the size of floods becomes less peaked downstream.

Flow data were analyzed to determine possible numbers of overbank flood events which have taken place in the past 30 yr. Unfortunately, the analysis turned out to be complicated. First, the channel and banks have changed through time, so the amount of flow necessary to overtop the banks has not remained constant. Second, the gauge records report mean daily flow and flood peaks greater than base flow. At some gauging stations, base flow (defined by the United States Geological Survey as a flood with a recurrence interval of 1.15 yr) was redefined every few years, so discharges which were considered to be floods changed by as much as 127 m^3/s through the years of records. Moreover, there is no clear relationship between daily flow and peak discharge (see Popp and others 1983 for details). Nonetheless, it was possible to estimate the number of overbank events at each site since 1950 or later. For example, we estimate that more than 22 floods have occurred at site 1 (Fig. 1) since 1957 (when the site probably became an oxbow).

The Rio Puerco is infamous for large discharge and high sediment loads. At the gauging station near Rio Puerco, maximum discharge (September 23, 1929; stage 5.5 m) was estimated to be 1,070 m^3/s, which destroyed the railroad bridge along with the stream gauge. Suspended sediment loads up to 680,000 ppm have been recorded at Bernado, and loads up to 400,000 ppm are not uncommon (Nordin 1963).

Experimental Methods and Procedures

Selection of Sample Sites

In order to select sample sites, the general sources and transport directions of sediments were determined by examination of maps and aerial photographs and by field reconnaissance of the drainages. The maps used included 1:250,000 and 1:100,000 scale maps of the region, and 1:24,000 and 1:62,500 scale maps of segments of the drainage basin and 1:500,000 and 1:24,000 geologic maps. Sites were selected on the basis of (1) their location within the drainage basin, (2) the degree of development of abandoned channels which have been active loci of deposition during the past 40–50 yr and contiguous active stream channels for comparison, and (3) accessibility. The general areas considered for site location were (A) upper part of the Rio Puerco upstream from all uranium mines, (B) central part of Rio Puerco in reaches of possible influence of mines and natural radionuclides, (C) downstream portions of Rio Puerco where radionuclides would have to have been transported, and (D) along major tributaries directly downstream from mine activity and natural exposures of mineralized rocks (see Fig. 1).

Locations of sample sites were chosen on the basis of comparing the position of the inner channels of streams on early maps and aerial photographs with later photographs. As summarized above, because metals and radionuclides are adsorbed on clays, we looked for thick deposits of fine-grained sediments, particularly in oxbows formed after 1935 and, in some cases, after 1954. We also selected a sample site in the delta of Paguate Reservoir, a small impoundment 7 km downstream from the Jackpile uranium mine. In each case, the time of oxbow formation could be bracketed by comparing dated sequences of photographs (e.g., between 1935 and 1954, between 1947 and 1954, or between 1954 and 1972).

Age of Samples

The age of the cutoffs was partially determined by examination of aerial photography. Historic photographs (Happ 1948, plate 4) were used at one site (site 9, Fig. 1) to help determine the age of the site. In the

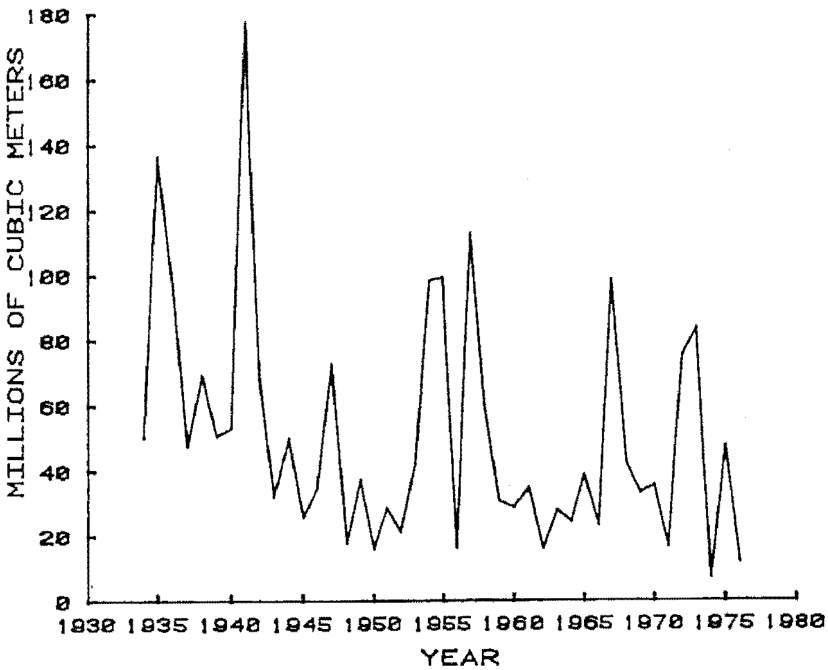

Figure 3. Annual water year flow for a representative gaging station-Rio Puerco at Rio Puerco. See sites 3–5 on Figure 1.

field, archeological and historical items were sought in relation to the sample sites. Unfortunately, the only site which yielded a historic artifact (portion of old, light-gauge rail for railroad) was unsuitable for sampling due to lack of floods after cutoff. Recently, it was shown that tamarisks can record annual rings and that deposits may be dated by analyzing where and when tamarisk germination took place (Hereford 1984). This technique was used successfully on the sample site which had the least time control (Heath 1983, Site 2, Fig. 1). Surveyors' notes, historical accounts, and archeological studies (Betancourt 1980; Love and others 1983) were useful in determining long-term behavior of the Rio Puerco, but were not used for selecting sample sites. The 1938 date for construction of Paguate Reservoir was provided by the Laguna Tribal Agency.

Surveying Procedures

Topographic profiles across arroyos, detailed stream gradient determinations, and detailed profiles across inner channels were done by surveying with a theodolite (commonly a 20-second instrument with a 7.62-m rod). In two locations, profiles across the inner channel were measured with metric tapes. Elevations were calculated to the nearest centimeter. Horizontal distances were measured to the nearest foot and converted to meters.

Estimation of Bank-Full Discharge at Ungauged Locations

Williams (1978) investigated numerous methods of estimating bank-full discharge. He found that definition of *bank-full* varied from method to method and that few of the previously proposed techniques came close to predicting measured bank-full discharge in his more extensive data set. Williams found that the best estimators of bank-full discharge (Qb) were the bank-full cross-sectional area of the stream (Ab, in m^2) and the slope (S, dimensionless, m/m):

$$Qb = 4.0Ab^{1.21}\, S^{0.28}$$

The equation has a standard error of 0.174 log units or an average standard error of 41%. It accounts for 96% of the sums of squares of log Qb (Williams, 1978). Williams indicated that there appears to be more error for streams with small bank-full discharges (which would include the Rio Puerco). In spite of the large possible error of the estimate, the equation is better than other presently available techniques (including the popular Gaukler-Manning equation, Williams, 1978).

Examination of Sediments and Sampling Procedures in the Field

Sampling at sites consisted of taking 2-kg samples of typical surface deposits near a designated sample site and digging and augering below the surface. Commonly, the pits dug to expose stratigraphy and sedimentary structures were 1.5 m deep, 2 m long, and 0.75 m wide. Approximately 2-kg sediment samples were taken in vertical succession from each unit of interest exposed in the walls of the pits. Once the floor of the pit had been cleaned, two auger holes were sunk approximately 40 cm apart using a 7.62-cm-diameter auger which took 15-cm incremental samples. Possibly contaminated material at the very top of each sample was discarded, as was any contamination visible on the sides of the sample. Samples from the same depth in both holes were combined in order to insure at least 2 kg of sample for lab work. Depths of each hole were checked during sampling to insure that the same intervals were being sampled in both holes. Augers disrupt the sample in part, but chunks of sediment remain intact to aid description of each sample interval. The Munsell color (chroma and hue), grain size, and texture of each sample were described in the field along with sedimentary structures and other notable features (such as organic remains and evaporite crystals within the matrix). The sample number and description were recorded in one or more notebooks, and the sample was placed in a plastic sample bag and sealed.

Sample Handling in the Laboratory

In the laboratory, 450 ml of material were removed from each sample, using a riffle splitter with 1-cm openings. Any pebbles coarser than 1 cm were also removed at this point, as were any clay balls (armored mud balls), twigs, and similar objects.

A series of additional, smaller samples were further characterized by a variety of techniques. These included wet-sieving through 80- and 230-mesh U.S. Standard stainless steel sieves (mesh openings 175 and 63 μ, respectively), examination of the size fractions under a 400× optical microscope, determination of the percentage of clay-size material in the finest size fraction, X-ray diffraction analysis of clay-size fractions and selected sand-sized material, and chemical analysis. It was found that copper contamination was significant if brass sieves were used, so it was necessary to use stainless steel sieves.

Determination of Pb-210 and Cs-137

The previously obtained 450-ml splits were mixed to ensure homogeneity and transferred to plastic Marinelli beakers. These were sealed with tape, and, if Pb-210 analysis was desired, allowed to stand for a minimum of two wk to allow for Rn-222 and, hence, Pb-214 ingrowth. Procedures for Pb-210 followed those of Schery (1980) as adopted by Dehn (1983) and Novo-Gradac (1983).

Activities of the radioisotopes Pb-210, Pb-214, and Cs-137 used for dating were obtained by gamma spectrometry, using an N-type, high purity, low background lithium-doped germanium detector. The gamma spectra were obtained using one of three lead-shielded Ortec Gamma-X spectrometers linked to a 4096-channel pulse-height analyzer. Minimum counting times for Cs-137 and Pb-210 were 4,000 and 16,000 s, respectively, and the energy range of the spectra in both cases was approximately 0.1500 keV. For low levels, counting times of about 40,000 s were found to be sufficient.

The efficiency of each detector at a number of different energies was determined by counting several sediment samples impregnated with known quantities of nine radionuclides (Reference Standard QCY,44, Amersham Corp., Amersham, England). As the efficiencies were found to be largely unaffected by the mean grain size of the sediment matrix of the standards, values obtained from a mixture of equal quantities of medium sand and silty clay were used. Efficiencies at other energies were found by interpolation, using programs provided for this purpose by Nuclear Data Corporation (ND 6600, 1980).

The areas of the Pb-210 peak at 46.5 keV were calculated using a peak area extraction program also provided by Nuclear Data Corporation (1980). The areas of selected peaks were checked visually to verify the accuracy of the program, and to verify that these peaks had been adequately resolved from neighboring peaks in the spectrum.

Activities of each isotope (in pCi/g) were calculated from the peak areas, sample weights, and branching ratios, using previously determined efficiencies at these energies. The branching ratios for measured Pb-210, Pb-214, and Cs-137 decays were taken to be 4.05 percent, 37.2 percent, and 84.6 percent, respectively (Erdmann and Soyka 1979). Where necessary, corrections were made for the presence of peaks at the same locations in background spectra.

Both Pb-210 and Pb-214 peaks were clearly resolved by gamma spectrometry, with full peak widths at half the maximum peak height above background (FWHM) of approximately 1.1 and 1.3 keV, respectively. Peak shapes were consistently Gaussian, and centroid energies were in good agreement with one another and with published values (National Council on Radiation Protection 1978), again indicating that no significant interferences were present.

Cs-137 peaks were occasionally less clearly resolved, because of the greater FWHM (approximately 1.7 keV) and the presence of a neighboring peak at 665 keV. The iterative nature of the peak area calculation, however, does appear to accurately separate the peaks in most cases. In the remaining cases (marked by small Cs-137 activities and atypical centroid energies of FWHM values), visual estimation of the peak areas was occasionally necessary.

Because of the random nature of the individual radioactive decays, the measured activities were subject to statistical uncertainties which were inversely proportional to the square root of the number of decays measured. It was possible, for example, to halve the uncertainty in a particular measurement by increasing the counting time by a factor of four. The typical counting times of 1.5–24 h for Cs-137 and 4–48 h for Pb-210, Pb-214, and Cs-137, thus, reflect an attempt to balance the relative errors of the activity measurements against the counting required. (For example, the longer counting times within each range often correspond to those samples which, on account of their grain size or depth, could expect to have relatively low Pb-210 or Cs-137 activities). Counting times of about 12 h were finally adopted. This time allowed counting statistics to generate relative errors of usually less than 10 percent, even for the low level isotopes.

In addition to statistical errors, the measured activities may also be subject to systematic errors in the peak areas and efficiencies used, due to such factors as differences in self-absorption between sand and clay samples. The resulting relative errors are expected to be on the order of 10 percent and will vary depending on both the nuclide and the detector. Although such systematic errors should not significantly affect any Cs-137 dating, they would seriously affect the accuracy of Pb-210 dating of any sample in which supported Pb-210 levels are high, or in which unsupported Pb-210 levels are low due to age. This difficulty may be partially overcome by dealing with the ratio of Pb-210 to Pb-214, rather than the difference between the two values. In accordance with the radiometric decay equation, this ratio will decay exponentially with time to a value of unity in any closed system.

Finally, the measured Pb-214 activities will be subject to a further systematic irror due to differences in the rate of radon emanation with depth. Continual escape of gaseous Rn-222 from a sample can, over time, substantially lower the amount of supported Pb-210 present. After sealing of a sample, however, Rn-222 (and, hence, Pb-214) would reequilibrate at a higher level. The calculated Pb-210/Pb-214 ratio, which, like the calculated unsupported Pb-210 activity is based on assumed secular equilibrium between the measured Pb-214 and supported Pb-210, would, therefore, be too low in those samples nearest the surface. To estimate the magnitude of this error, a previously counted sand sample was unsealed and allowed to stand for two weeks, then recounted. The decrease in the measured Pb-214 activity was found to be 0.21 $\pm$ 0.04 pCi/g, or 27 percent. The resulting increase in the measured Pb-210/Pb-214 ratio, if statistical variations in the Pb-210 activities were neglected, would be 0.40. The typical increase for finer-grained samples would presumably be less.

Results and Discussion

Geological Description of Sample Locations

Figure 4 shows a typical pair of sample sites on dated pairs of aerial photographs, along with changes in channels and development of oxbows. These photographs illustrate the changes in sedimentation and growth of vegetation along the drainage as well. The sample sites in relation to present topographic profiles within Rio Puerco are illustrated in Figure 5. These figures show that the oxbow sites are separated from the present (1982) inner channel by at least dozens of meters, a factor which should influence frequency of overbank flooding and grain size of deposits.

Detailed descriptions of stratigraphy and sedimentary structures of each pit and auger hole are given in Popp and others (1983). In general, deposits at the surface of the present inner channel of the Rio Puerco and Rio San Jose depend on the magnitude of previous floods and whether the most recent flood scoured the channel base or deposited fresh sediments. Fresh sediments consisted of gravelly sand in ripples and bars along the lowest parts of the inner channel, with thin silt and clay drapes deposited on top, particularly in low areas between bedforms. Margins of the inner channel received fine sand displaying a variety of sedimentary structures, primarily horizontal laminations, climbing ripples, and silty-clay drapes. In pits and auger holes beneath the channel surface, and in scoured reaches, the deposits tended to be in units 10–20 cm thick, and more fine-grained (fine sand, silt, and clay) than the modern surficial deposits of the channels. These fine-grained units are not scoured valley fill because the Cs-137 content (see below) demonstrates that they have been deposited since 1950. They apparently were deposited during low flows and lateral accretion during lateral migration of the inner channel.

Deposits of cross-laminated fine sand in units up to 1 m thick dominate the upper margins of the inner

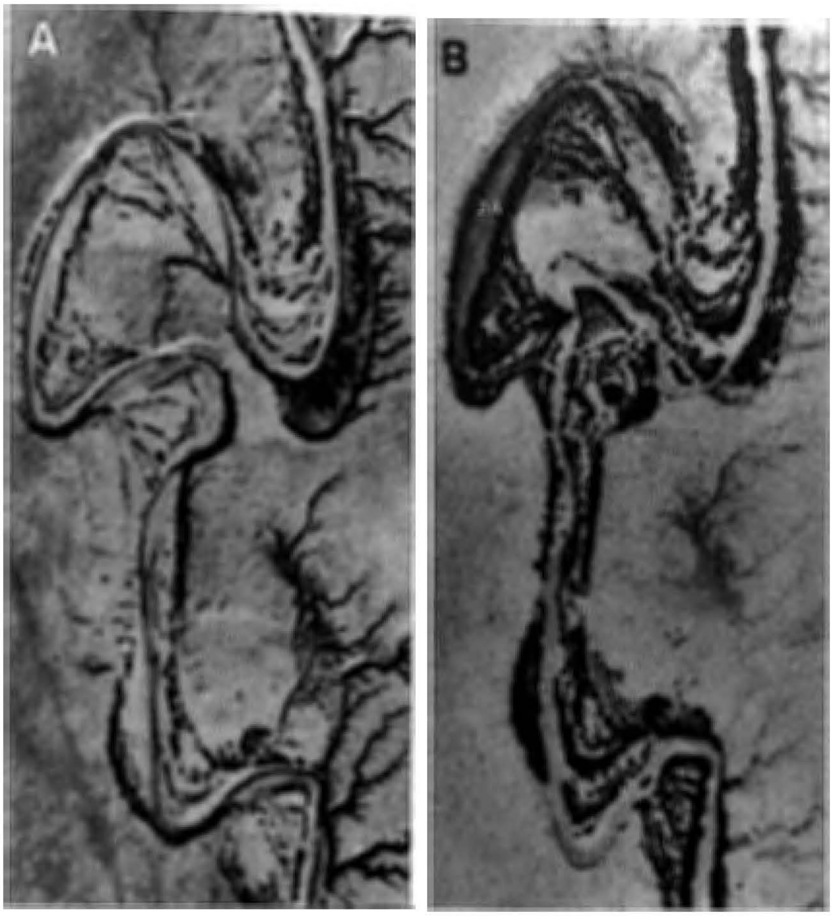

Figure 4. Aerial photographs of the area including sites 1 and 2 taken in 1954 (A) and 1979 (B). Site 2A has been cut off as an oxbow.

channel and adjacent natural levees and floodplain. Few silt and clay deposits occur in this zone that is reached by most bank-full flood events. The lack of silty-clay drapes is somewhat unexpected because the streams ordinarily carry quantities of suspended sediment. Perhaps the silt and clay do not have an opportunity to settle out in discrete layers in these channel-margin areas.

Further from the present inner channel, depending on presence of tributary gullies debouching onto the inner floodplain, sedimentation may be dominated by small alluvial fans deposited by these tributaries. These deposits generally are poorly sorted sand and clay. Clasts commonly consist of fine sand and clay platelets (reworked from older valley fill and not disaggregated during short-distance transport).

In most oxbow sites selected for study (Figs. 6, 7), deposition of clay was minor compared to deposition of units of fine sand and silt and deposition of tributary fans. Apparently, conditions for quiet settling of clay were not common in these oxbows. This may have been due to several factors, including processes of oxbow formation, gradients within the oxbows, frequency of major overbank events from the inner channel, and rapidity of alluvial fan deposition from tributary gullies. These results were not expected considering the amount of silt and clay in most streamflows and considering that tests in the first oxbow site indicated that thick clay sequences might be common.

Oxbows generally had at least one zone of coarse sand and gravel 2–5 m below the present surface, possibly indicating the base of the abandoned channel. In fact, the coarse sand and gravel were more ubiquitous in the oxbows than along the present inner channel, perhaps indicating a change in stream regime. On the other hand, coarse sand and gravel lie below other facies in most auger holes within the arroyo of Rio Puerco. These deposits probably are left from receding flows after scour of the arroyo below the present level during the large floods of 1929 (Heath 1983).

The stratigraphy of the fill sampled in Paguate Reservoir is dominated by clay, with thin interbeds of silt and fine sand. The sand and silt may reflect proximity of distributary channels during part of the period of aggradation of the delta. The clay layers reflect sub-

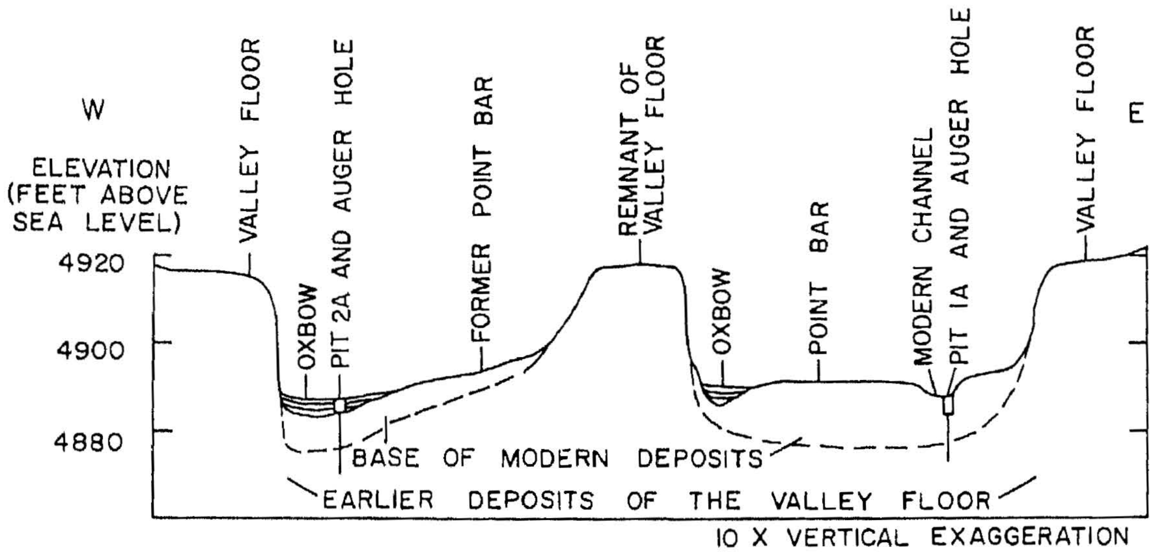

Figure 5. Cross section of Rio Puerco Arroyo at sample sites 1A and 2A.

Figure 6. Sample site 3A in oxbow and edge of tributary fan (February 1981).

aqueous settling of clay within the reservoir in low, ordinarily subaerial interdistributary areas on top of the delta after it prograded into the reservoir.

No incidental discarded waste or other datable material was found in the sample sites, so ages of oxbow formation and subsequent deposits could not be refined by artifactual contents. At sites 1 and 2, which had the least age control, Heath (1983) counted

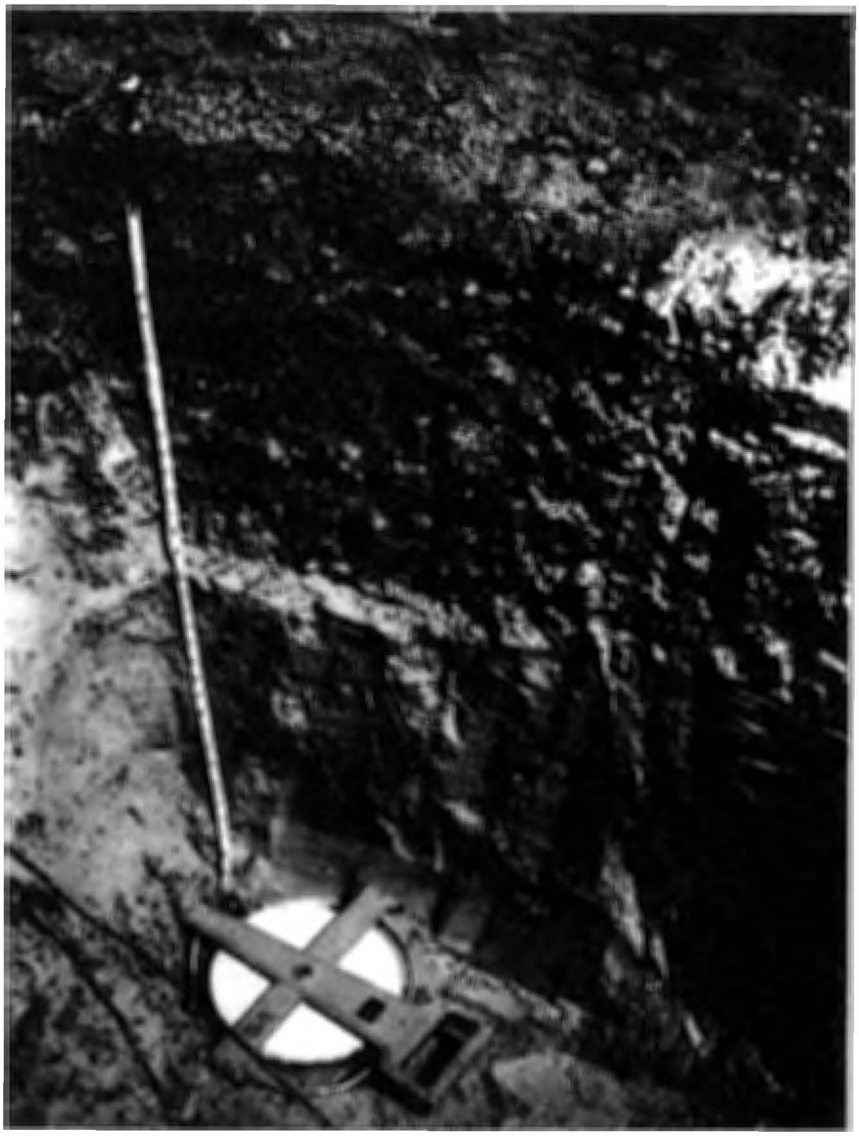

Figure 7. Stratigraphy of pit at site 7. Note change of deposits at 50 cm.

growth rings of tamarisk germinated on the margins of new portions of the inner channel and determined that the channel had formed about 1957.

Stream Discharge Estimates

The cross-sectional areas of bank-full discharge and slopes of reaches near the sample sites (estimated using a theodolite) are presented in Table 2, along with a possible range in bank-full discharge for each locality. Caution should be used in interpreting these numbers, however, because the hydraulic geometry (width, depth, gradient, etc.) of the Rio Puerco changes along each reach and changes with each flow. Studies of the Rio Puerco channel (Young 1982) determined that more than 90 percent of the channel along the lower Rio Puerco has shifted laterally since 1954. The shape of the channel has changed as well, from being relatively wide with low banks and unvegetated point bars in the 1930s to being relatively narrow with high banks in the 1980s.The change in channel shape affects the magnitude and frequency of overbank floods and the efficiency of transport of sediments.

Sediment Dating

Use of Cesium-137. Dating methods based on Cs-137 depend on detecting the imprint of an irregular influx of the radioisotope beginning in the early 1950s. Also, the absence of the isotope in a sediment layer indicates a pre-1950 date because the isotope is strongly bound to sediments. Typical Cs-137 analyses with depth at oxbow sites and the Paguate Reservoir site are shown in Figure 8.

Table 2. Estimates of "bank-full" discharge for Rio Puerco at three locations and Rio San Jose at one location. For site location, see Figure 1.

Site location	Cross-sectional area (m^2)	Slope (m/m)	Bank-full discharge (m^3/s)	Minimum no. of floods since 1950
1	16.8	.00095	17.2	22
5	38.2	.0013	51.1	22
6	97.9	.0011	152.3	18
8	50.8	.0033	93.6	8
SJ 1	16.3	.0057	27.6	—

Two major trends are evident from the Cs-137 data presented in Figure 8. The first observation is that the oxbow sites shown (2, 7, 9) all exhibited Cs-137 levels significantly lower than found at lake and estuarine sites cited in the literature (Krishnaswami and Lal 1978). Most samples ranged from 0.1 to 0.3 pCi/g with the highest value at 0.73 pCi/g, while values from more typical sites with steady and unperturbed depositional environments are in the 0.5 to 2.0 pCi/g range (Robbins and Edgington 1975; Benninger 1978; Smith and Walton 1980). This illustrates the dilution of dry deposition-derived Cs-137 with older sediments from channel walls resulting in overall lower Cs-137 activity and, subsequently, more difficulty in finding peaks in activity which could be associated with dates of historically high atmospheric nuclear testing. The highest activities were found in samples from the Paguate Reservoir delta (Fig. 8), which was the only nonstream site. The depositional environment in the Paguate delta was less subject to dilution by older sediments and should be expected to yield higher Cs-137 activities. Seceral peaks of activity were noted in the Paguate Reservoir auger samples, but a more detailed analysis of a new core would be needed to corroborate the data.

Secondly, because all the core samples eventually went to zero Cs-137 activity with depth, it is apparent that the major usefulness in dating using Cs-137 is that the absence of the isotope in the lower cores indicates sediments predating 1950, which is also the date of inception of uranium mining activity. Establishment of the 1950 cutoff date is all that is necessary for the purposes of identifying trace metal and radionuclide concentrations from historic sediments for comparison with sediments deposited in the post-mining era.

The stratigraphic evidence from all of the oxbow sites from the Rio Puerco (2, 7, and 9, Fig. 8) where sand/silt/clay from the oxbow deposits grade to sand and gravel suggest a 1950 horizon at approximately the same position as the disappearance of Cs-137. The

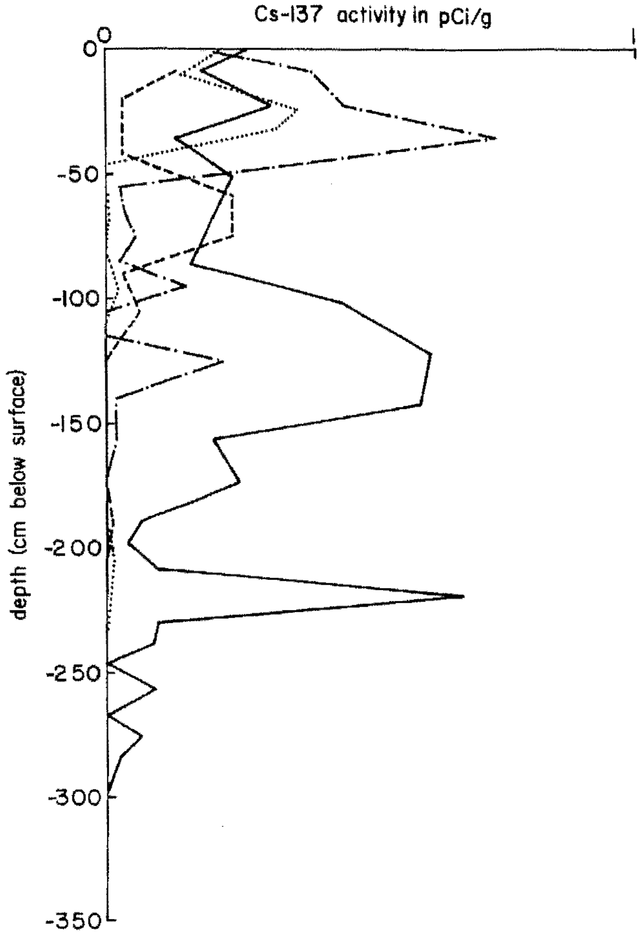

Figure 8. Cs-137 activity with depth. See Figure 1 for site locations. — · — · — · = Paguate Reservoir; – – – – – – = oxbow site 9; ——— = oxbow site 2; · · · · · = oxbow site 7.

data are summarized in Table 3. The data from sites 2 and 9 show an overlap in the 1950 cutoff from Cs-137 evidence and stratigraphic evidence for the location of the base of the oxbow deposits. At site 7, the evidence suggests large dilution effects from a soil pipe outlet from the channel wall located close to the auger hole.

Therefore, none of the oxbow sites can provide unequivocal data for silts and clays deposited before 1950 although the data strongly suggest the approximate oxbow depths. We were apparently too accurate in pinpointing oxbows which were formed and filling about 1950 when we should have looked for oxbows created in the 1940s before the mining and Cs-137 activities began. The older sands and gravels lying below the oxbow deposits contain little clay and, consequently, have a much lower adsorption capacity for trace metals and radionuclides. The Paguate Reservoir site data shown in Table 3 provides an unambiguous Cs-137 cutoff well above the bottom of the auger hole

Table 3. Oxbow sediment depths and Cs-137 disappearance in cores.

Site[a]	Depth of oxbow sediments[b]-cm	Depth below which Cs-137 is absent-cm
2	190–240	224–280
7	51	31–41
9	100	55–112
Paguate	>220[c]	120–165

[a] Site 2 is downstream from mining and milling activity. Site 7 is above the confluence of the Rio San Jose and Rio Puerco, and site 9 is upstream from all mining/milling activity. The stream distance between sites 2 and 9 is 185 km. (See Fig. 1) Paguate is a reservoir site immediately downstream from an open pit uranium mine.

[b] Essentially determined by position in core where fine sand/silt/clay layers grade to sand and gravel.

[c] The auger penetrated the water table at 220 cm before reaching the reservoir deposit base.

(also see Fig. 8). The disappearance of Cs-137 is at 165 cm and the hole extends to 220 cm.

Use of Pb-210. The decay of atmospherically derived Pb-210 (unsupported Pb-210) has also been used to date sediment cores, again in relatively unperturbed depositional environments such as Lake Michigan (Robbins and Edgington, 1975) and Quebec fjords (Smith and Walton, 1980). Figure 9 summarizes Pb-210 analyses in cores from sites 2, 9, and Paguate Reservoir. The data at site 2 (Fig. 9) are typical of oxbow sites downstream from the mining and milling activity with a slow, steady decrease of activity to a background of around 1–1.2 pCi/g. The Cs-137 cutoff appears at sample 24 at site 2 (260 cm), which is the point below which little Pb-210 change occurs. Unfortunately, the background is high and, when coupled with dilution by sediments from arroyo walls and side channels, the dating of these sediments using Pb-210 is not possible. However, the evidence suggests that excess Pb-210 is contributed from the mining region because the core at site 9 (upstream from mining and milling, Fig. 9) yields essentially flat, background levels of Pb-210 throughout the core (1–1.2 pCi/g).

The Pb-210 data from the core taken in Paguate Reservoir are startling in that by far the highest Pb-210 values (~18 pCi/g) of approximately 20× background were found in the upper sections of the core (Fig. 9). The Pb-210 values then quickly reverted to high background (1.0–1.5 pCi/g) after the first 41 cm of core. The high Pb-210 concentrations in the upper sediments of this core are clearly associated with nearby upstream open-pit uranium mining releasing sediments which have been trapped in undiluted sediments in the reservoir delta. However, dating using

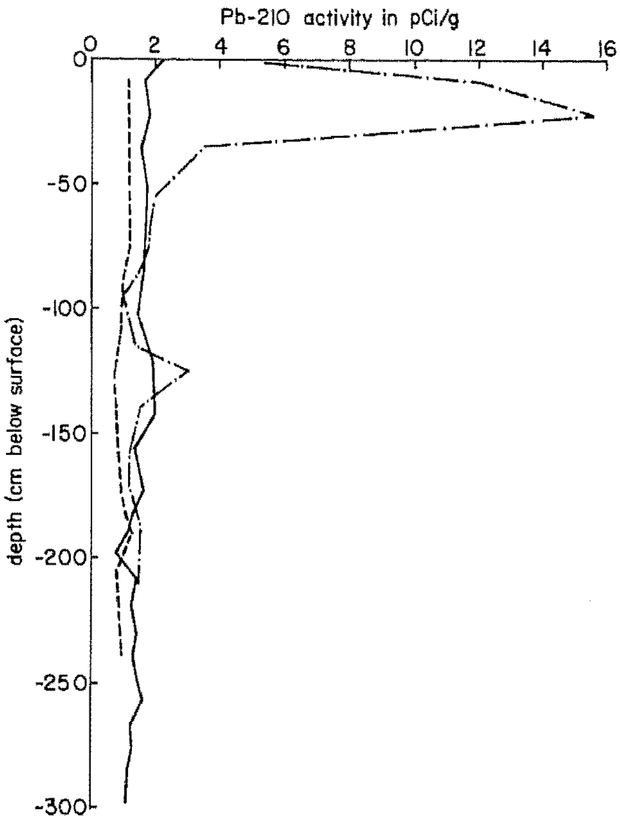

Figure 9. Pb-210 activity with depth. —·—·—· = Paguate Reservoir; – – – – – – = oxbow site 9; ——— = oxbow site 2. See Figure 1 for site locations.

the Pb-210 isotope is again not possible because the nonatmospherically derived Pb-210 is so high.

Summary and Conclusions

In the absence of historic geochemical baseline data for the Grants uranium region in New Mexico, environmental changes resulting from uranium mine-mill activities can only be determined by indirect methods. A similar problem exists in many areas but is especially evident in arid regions of the western United States where development of mineral resources has preceded attempts to estimate impacts. We have developed a methodology for determining the age of recent sediments in ephemeral streams draining the Grants region of New Mexico, based on combined geomorphic, stratigraphic, and radiometric dating techniques. Because clay-size and clay-mineral-rich sediments retain radionuclides and heavy metals derived from mineralization and mined sources, sample sites that contain fine-grained deposits that both predate and postdate mine-mill activity were located in abandoned-channel segments (oxbows) of major streams draining the eastern Grants uranium region. Aerial photographs and derivative maps made between 1935 and 1978 provided the historical and geomorphic documentation of approximate dates of oxbow formation and ages of alluvial fills in the abandoned-channel segments. Pits dug at these oxbow sites revealed the stratigraphy and composition of the deposits. Refinements in dating the sediments may be possible using dendrochronology and flood data to determine ages of oxbow strata.

Samples collected from pit walls and auger holes below the pits were subjected to radiometric analysis by gamma ray spectrometry for the artificial radionuclide Cs-137 and the natural radionuclide Pb-210 for the purpose of dating the sediment layers. Because of the dynamic nature of the system, absolute dating with Cs-137 was not possible, but samples could be dated as either pre- or post-1950. The 1950 date is important because it marks the beginning of uranium mining activity in the region. Lead-210 dating was not possible because background Pb-210 was high relative to fallout Pb-210.

Sediments dated by Cs-137, stratigraphic, and historic techniques were analyzed for radionuclides and trace metals which may be derived from uranium ores and will be the subject of another article. Recent sediments at Paguate Reservoir clearly show elevated levels of Pb-210 in sediments dated after the mid-1950s, where sediments from the Jackpile uranium mine have been trapped in the reservoir fill.

Using the independent methods of historical and geomorphic procedures and gamma ray spectrometry, we have been able to establish the age of sediments in oxbow and reservoir cores in ephemeral streams draining a major mining region in central New Mexico. The results of this study will allow estimation of the impact of mining and milling in the region and should be widely applicable in similar geographic regions.

Acknowledgments

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