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GEOMORPHOLOGY OF PLUTONIUM IN THE NORTHERN RIO GRANDE

by

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EXECUTIVE SUMMARY

Nearly all of the plutonium in the natural environment of the Northern Rio Grande is associated with soils and sediment, and river processes account for most of the mobility of these materials. A composite regional budget for plutonium based on multi-decadal averages for sediment and plutonium movement shows that 90 percent of the plutonium moving into the system is from atmospheric fallout. The remaining 10 percent is from releases at Los Alamos. Annual variation in plutonium flux and storage exceeds 100 percent. The contribution to the plutonium budget from Los Alamos is associated with relatively coarse sediment which often behaves as bedload in the Rio Grande. Infusion of these materials into the main stream were largest in 1951, 1952, 1957, and 1968. Because of the schedule of delivery of plutonium to Los Alamos for experimentation and weapons manufacturing, the latter two years are probably the most important. Although the Los Alamos contribution to the entire plutonium budget was relatively small, in these four critical years it constituted 71-86 percent of the plutonium in bedload immediately downstream from Otowi.

The annual budgets for sediment in the Rio Grande between 1948 and 1985 show that about 50 percent of the sediment and its associated plutonium that enter the system was stored internally in river deposits. The geographic distribution of these stored materials is related to discontinuous flood plains, fill in abandoned channels, and mid-channel bars. The deposits along the Rio Grande that were laid down in 1951, 1952, 1957, and 1968 are most likely to contain plutonium from Los Alamos. Deposits laid down during the post-1943 period, mapped and dated using aerial photography, field evidence, and vegetation data, are generally less than one meter thick. The deposits along the Rio Grande likely to contain the most plutonium from Los Alamos are those between Otowi and Cochiti Reservoir. Preliminary investigations of a flood plain at Buckman, 5 km downstream from the confluence of Los Alamos Canyon and the Rio Grande, revealed plutonium with isotopic ratios consistent with ratios expected from a combination of plutonium from the laboratory and from fallout.

Data from almost two decades of sampling of the physical riverine environment show that: lowest plutonium concentrations occur in water, greater concentrations occur in bedload sediments and flood plain deposits, and highest concentrations occur in suspended sediment and especially reservoir deposits. Plutonium concentrations in sediments are related to particle size and organic content, while concentrations in flood plain sediments are related to particle size and date of deposition. Computer simulations of sediment and plutonium transport and storage in the Rio Grande indicate that concentrations of Los Alamos derived plutonium in sedimentary deposits along the river are likely to be 100 fCi/gm or less. Empirical data from limited sampling of flood plains indicate concentrations of less than 50 fCi/gm

A prudent, refined monitoring and surveillance program for plutonium in sediments in the vicinity of Los Alamos should be driven by a general philosophy that generally strives to accurately assess the regional plutonium budget and the place occupied in that budget by plutonium from Los Alamos National Laboratory. Such a

policy would emphasize knowledge about the inventory of plutonium in sediment in Los Alamos Canyon, how that plutonium moves to the Rio Grande, how plutonium deposits are distributed along the main river, and how plutonium interacts with the dynamics of Cochiti Reservoir.

A general monitoring and surveillance philosophy for Los Alamos National Laboratory drives specific procedural recommendations. Investigators should explore isotopic ratios for plutonium in sediments outside the laboratory boundaries to assess the laboratory contributions. Sediment samples for the analysis of plutonium content should be collected at regional stream gage sites, and should include suspended as well as bedload samples. Sampling of flood plains between Otowi and Cochiti Reservoir, especially between Los Alamos Canyon and Buckman should be a special priority because of the high probability of occurrence of laboratory-derived plutonium in the deposits. Monitoring of deposits in Cochiti Reservoir should include intensified and regular sampling because it is likely that plutonium from the laboratory and from fallout will continue to enter the reservoir for at least several hundred years.

ACKNOWLEDGEMENTS

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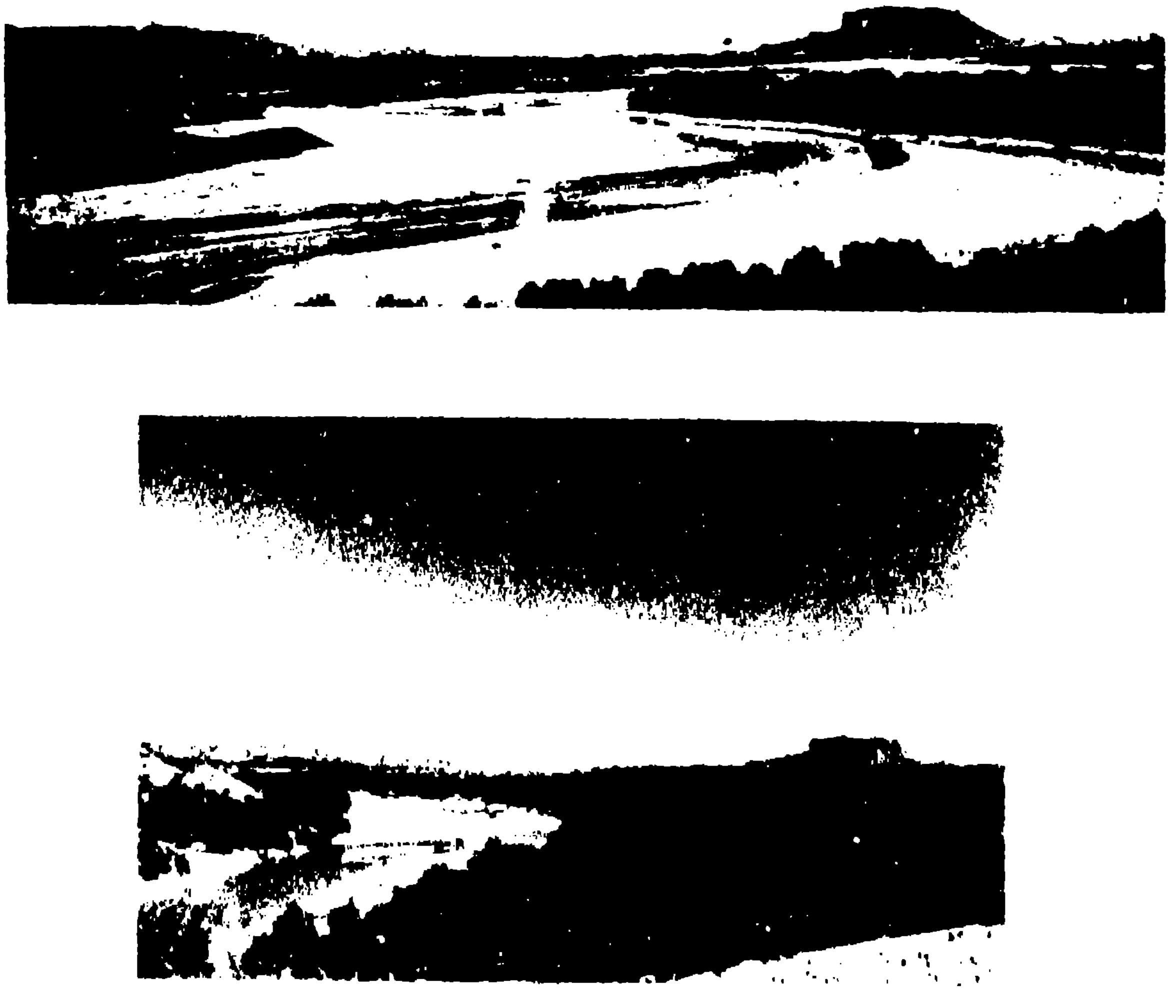


Figure 1.1 The changing environment of the Rio Grande is seen along the stream immediately north of Otowi Bridge, New Mexico. Above, looking north from the east bank of the river about 1910 (Photo 3700, Museum of New Mexico); below, same view in 1991 showing a much narrower channel, filling of the meander on the right with sediment, and much more dense gorwth of cottowood trees (W. L. Graf Photo 104-17)

PART 1. INTRODUCTION

CHAPTER 1. INTRODUCTION

1.1 The Basic Issue

Plutonium occurs throughout earth environmental systems, though usually in quantities so small that they are barely detectable. The toxic characteristics of the artificial element require the identification of those few locations where the highest concentrations are likely to occur. Because almost all plutonium released to the environment is ultimately attached to soil and sediment particles,[1] the behavior of natural transport systems such as water and sediment flows provide the key to understanding the ultimate geographic disposition of the element.[2] The general purpose of the work discussed in this book is to explain the distribution of plutonium in the Northern Rio Grande system of northern New Mexico and southwestern Colorado (Figure 1.2) by forging a link among available data and general principles of environmental sciences such as hydrology, geomorphology, and radioecology.

Between 1945 and 1952 Los Alamos National Laboratory handled large amounts of plutonium as part of the Manhattan Project (the effort to construct the first atomic weapons) and as part of the weapons programs related to the early years of Cold War. During the conduct of these weapons programs, the laboratory emptied untreated plutonium waste into the alluvium of Los Alamos Canyon.[3] After 1952, the laboratory released relatively small amounts of treated plutonium waste. The vertical movement of plutonium through the alluvial materials has been largely limited to the upper 10 m.[4] Horizontal movement of the contaminants involved much larger dimensions. The plutonium was adsorbed onto sedimentary particles, so that the fate of those sediments is also the fate of the plutonium. Natural processes of erosion have resulted in substantial movement of contaminated sediments through the canyons. Research during the 1960s and early 1970s showed that surface flows within the laboratory boundaries had redistributed at least some of plutonium since the war years.[5] Laboratory researchers later estimated that fluvial (river-related) processes in Los Alamos Canyon had probably removed significant quantities from the laboratory area by carrying the plutonium into the Rio Grande.[6] They predicted that early in the twenty first century, almost all of the plutonium would be emptied from Los Alamos Canyon into the Rio Grande.

During the 1990s, increasing national concern for environmental quality and a more stringent regulatory system require the design and maintenance of effective monitoring and surveillance programs to account for environmental contaminants such as plutonium. Los Alamos National Laboratory has an extensive store of data collected from a variety of environments, but the processes in Los Alamos Canyon and the Rio Grande indicate a need for improved understanding of the river systems that move and store the plutonium. Present sampling programs aimed at active river sediments have not detected plutonium in concentrations above those expected from fallout alone.[7] Therefore, either the plutonium from the laboratory has been dispersed by river processes, or the sampling effort has not yet identified the storage sites for

Figure 1.2 The general location of the Rio Grande in New Mexico and Colorado.

plutonium.

A major issue in designing an effective contaminant sampling program for river systems is an understanding of the context within which the processes operate. Rivers behave in a variable fashion over periods of decades, so that contaminants introduced to the system at one time (when diluting, uncontaminated sediments are available in large quantities) may be less significant than at other times (when only small quantities of diluting sediments are available). Deposition of potentially contaminated sediments is geographically discontinuous, a factor that influences the choice of sample sites in an effective sampling program. Although the Northern Rio Grande system is relatively rich in data describing river processes,the data have not heretofore been interpreted for the purpose of explaining contaminant movement and storage. Little information is available that describes the geographic distribution of dated sediments and landforms that might be plutonium storage sites.

The geographic components of hydrology (the science of water) and geomorphology (the science of earth-surface processes) offer useful principles for explaining the dynamics of river systems that transport and store radionuclides. Unfortunately, specific theoretical and applied work in these sciences for explanation of the physical mobility of radionuclides is poorly developed. While the biological sciences have developed radioecology as a distinct body of knowledge pertaining to the dynamics of radionuclides in life forms, hydrology and geomorphology have spawned only an embryonic literature concerning the dynamics of radionuclides in physical environments. Scientifically and legally defensible sampling programs and explanations for their findings therefore require reinterpretation of hydro-geomorphic principles in light of their radiological implications.

The study area for this work will be referred to in the following pages as the "Northern Rio Grande," a term which includes the main stream and its tributaries from Española (essentially the confluence with the Rio Chama) to San Marcial (the headwaters of Elephant Butte Reservoir south of Socorro). Although there are no formally accepted definitions of the terms, "Upper Rio Grande" as used by residents and writers in New Mexico often refers to the river north of Española, a usage adopted in this work. This work does not use the term "Middle Rio Grande" (except where it is part of a proper name of an organization) because it has had a variety of usages in official government parlance, generally referring to some segment of the river between Cochiti and San Marcial.

1.2 Specific Objectives

In an attempt to simultaneously develop general principles and to contribute to the practical aspects of an informed sampling program for the Northern Rio Grande, this work has the following specific objectives. The results of this effort will be general enough for use in other, similar environments by using the Rio Grande in northern New Mexico as a representative example. The specific objectives are as follows:

1. Briefly outline the physical environmental context of the Northern Rio Grande. The

river channel processes affecting plutonium mobility operate within a particular matrix of landforms, soils, geology, climate, and vegetation. The geographic variability of these subsystems partly explains the behavior of the entire river system.

2. Specify the mass budgets of surface water and river sediments in the Northern Rio Grande system. Although the water transports little plutonium, it is the primary vehicle for energy in the system, and its variability in terms of total annual flows and flood peaks strongly influences the movement of sediment through the system. The sediment is important because plutonium is strongly adsorbed onto sedimentary particles. No process explanation can be effective unless it is couched in a clear understanding of the magnitudes of mass transfers in the general system.

3. Define and explain the major changes in system operation for the Northern Rio Grande from the 1940s to the 1980s. Hydro-climatic changes and the construction of major engineering works in the region have significantly altered the channel processes of the river from the 1940s to the 1980s. Channels, near-channel landforms, and deposits reflect these changes and are potential storage sites for plutonium.

4. Develop mapping techniques to identify the locations of river deposits likely to contain variable amounts of plutonium. Methods to date the deposits are also required because releases of plutonium from laboratory and fallout sources varied from year to year. The mapping and dating methods rely on connections between the hydro-geomorphic systems and riparian vegetation.

5. Explore eleven limited but representative reaches of the Northern Rio Grande to understand the nature of sediment storage in the system and to identify useful sampling environments. Because the length of river possibly of interest is more than 300 km, detailed analysis of a limited number of relatively short reaches replaces costly investigation at great detail of the entire length.

6. Use the water and sediment mass budgets with previously collected radiological data to construct a regional budget for plutonium in the surface environment. Because of the quality of radiological data, this effort is only a first approximation, but it is useful in outlining the relative roles of laboratory and fallout contributions and provides an order of magnitude picture of the plutonium system.

7. Use the geographic analysis of the distribution of sediment storage to make estimates of the distribution of plutonium in storage in the river system. A distributional analysis is the foundation of an effective, rational sampling program

8. Design a simple, effective, inexpensive, defensible sampling program based on the preceding points. Such a program consists of a series of guidelines useful for

radiological professionals but understandable to the educated layperson.

9. Assemble a data bank for the physical system of the Northern Rio Grande that can serve as supporting document for public discussions about policy-making for the Northern Rio Grande. The data from diverse sources can also be used by others to address their own research questions.

1.3 Related Research

Although most radioecological literature views "soils and sediments" as a general catchall term, from a geomorphologic perspective the terms connote specific environmental components. Soils are surface materials with organic and inorganic components that host living organisms. Soils may develop on materials that have been transported and deposited, or they may develop *in situ* as the result of weathering of bedrock. Sediments are unconsolidated surface materials that have been transported and deposited. The difference is significant from a radioecological standpoint because soils may receive contaminants either from atmospheric fallout or from direct surface additions. Alternatively, sediments might also receive such inputs, but they also may contain contaminants collected elsewhere that have been subsequently transported along with the sediments. Sediments have the additional property of sorting that occurs during transport (especially by flowing water), so that physical separation of small or light weight particles from large or heavy ones is common. Because heavy metals and radionuclides tend to adsorb to higher concentrations on the finest particles, the natural variability of sediments is reflected in variability of contaminant concentrations. Heavy metals and radionuclides also have an affinity for organic materials which may be a significant component of soils, but which may be entirely absent from sediments.

The purpose of the following pages is to outline the generally available scientific literature concerning the relationship between river sediments and the contaminants of radionuclides and heavy metals. Soils are mentioned only in relationship to this general theme. The literature review is not exhaustive, but rather is designed to define the primary threads of research that have emerged. The review includes heavy metals and radionuclides for two reasons. First, if only radionuclides are considered, the literature is so limited that few well defined threads have yet emerged. A clearer picture is available if heavy metals are included. Second, heavy metals and radionuclides are likely to behave in a similar manner in rivers because most radionuclides important for long-term environmental quality are heavy metals.

Surface materials, whether soil or sediment, are the major reservoir of heavy metals and radionuclides in the natural environment. Of all the various organic and inorganic compartments in the natural environment, sediments almost always contain the largest quantities of heavy metals.[8] In river systems, water quality is the most immediate concern because of its use for human consumption, but river sediment generally contains concentrations of heavy metal pollutants several orders of magnitude higher than water.[9] Radionuclides have a similar distribution, and researchers have often concluded that soils and sediments are the major repository for plutonium.[10] For example, in contaminated forest ecosystems at Oak Ridge, Tennessee, and Los Alamos, New Mexico, more than 99 percent of the plutonium is contained in the soil and surface sediments.[11] The biotic components of the systems contain less than one percent. The compartmentalization of other heavy metals in rivers is similar: a global survey has shown that more than 90 percent of most heavy metals in the river systems is carried in the sediment load.[12] Variability of plutonium concentrations in soils and sediments is greater than in the biotic compartments,[13] so that small sample volumes or numbers are problematic.[14] Radionuclides that find their way into biotic systems usually do so from soils and sediments.[15]

Of all the actinides, plutonium is the most-studied element in terms of its behavior in the natural environment. Much of the previous work has focused on chemical characteristics and has shown that at pH values of most natural soils and sediments, plutonium may be chemically unstable until it is adsorbed onto soil particles. Thereafter the element becomes generally stable in chemical terms. Reviews of the chemical properties of plutonium indicate that fallout and industrial plutonium behave similarly, and that the most important soil properties affecting plutonium chemical mobility are pH, together with clay, calcium carbonate, manganese, iron, and organic content.[16]

In highly acidic conditions ($1 < pH < 2$) most of the soluble plutonium occurs in ionic form.[17] In alkaline conditions ($pH > 8$), plutonium becomes relatively unextractable.[18] The fixation of plutonium in soils and sediments is most strongly developed with clay particles, and high cation exchange capacity results in rapid adsorption onto soil particles when clay is present.[19] Calcium bentonite rapidly fixes a variety of forms of plutonium,[20] and the fixing properties of calcium are especially pronounced in near-neutral or slightly alkaline pH conditions, those most commonly encountered in the natural environment.[21] Organic material also accelerates the fixation of plutonium, and in soils with greater than about three percent organic content, the impact of organics on plutonium binding dominates other considerations.[22] In aquatic environments, manganese and occasionally iron behave as scavanging agents for plutonium.[23] In some coastal sediments, more than 85 percent of the plutonium is associated with iron or manganese coatings on particles.[24] Whatever the process of fixation, however, most chemical studies indicate that plutonium adsorbed onto soil particles is generally unavailable to plants: only up to about 10 percent may become involved with organic processes.[25]

The overall effect of these chemical activities resulting in rapid and secure fixation in most natural settings is to produce a distinct vertical distribution of plutonium in soils and sediments. Fallout plutonium and plutonium released onto soils surfaces by industrial processes are highly concentrated near the surface. In the Savannah River area, for example, 84 percent of the soil plutonium is within 5 cm of the surface, and 90 percent is within 15 cm.[26] Concentration of fallout plutonium in Japanese soils declines exponentially with depth, and more than 80 percent of the plutonium 239, 240 is within 10 cm of the surface.[27]

In soils some plutonium moves vertically, partly because of physical movement of small particles with adsorbed plutonium. The rate of movement depends on soil particle-size distributions. In German soils vertical movement is 0.8 - 1.0 cm per year.[28] In dryland conditions near Trinity Site, New Mexico (site of the first nuclear detonation), 20 years after the initial release, about 50% of the soil plutonium had moved from the 0 - 5 cm layer to the 5 - 20 cm layer.[29] At a geomorphological scale, such movement is inconsequential because it is slow and has little effect on the horizontal mobility of the materials.

Process studies, rather than static mapping approaches, are a key to the development of sampling or monitoring programs, explanation of observed distributions of contaminants, and predictions of future distributions because the sediments that contain most of the contaminants are highly mobile, especially on time scales of several decades. In just one storm event at Los Alamos, surface water runoff transported one to two percent of the entire sediment-bound inventory of plutonium.[30] The geomorphic literature related to radionuclides and heavy metals has developed five distinct avenues of inquiry and explanation for these processes: 1) slope processes, 2) drainage basin processes, 3) channel processes, 4) flood-plain processes, and 5) general mass budget approaches.

Geomorphic studies of contaminants in slope processes have focused on the transport and storage of cesium-137 by using the radionuclide as a tracer for erosion studies. Cesium-137, produced primarily during atmospheric detonations of nuclear weapons, occurred as global atmospheric fallout, with peak rates of deposition in the northern hemisphere in 1957-1959, 1962-1964 (major peak), and 1974.[31] Because the cesium strongly adsorbed onto soil particles (especially the clay),[32] and because it was rarely taken up by vegetation, the element concentrates in the upper soil layer. Overland water flows that erode the soil also erode its associated cesium burden, so that in limited areas the amount of cesium remaining is an indication of the amount of erosion since it was added to the soil.[33] The difference between cesium added to the soil (usually directly related to annual precipitation in the United States) and the concentrations measured at a later date (adjusted for radioactive decay) is an indication of the magnitude of erosion.[34]

Numerous case studies using this cesium method have refined understanding of soil loss rates.[35] Loss rates can be mapped using cesium to define regions and locations of maximum erosion rates.[36] Cesium occurrence in the vertical profile of sedimentary deposits and the destination of soil materials eroded from slopes have also provided insight into sedimentation rates along footslopes and stream courses.[37] Despite these advances using cesium as an indicator of erosion processes, there are no basin-wide studies that use an understanding of the processes to explain the distribution of cesium. No cesium mass budgets have been published in the readily accessible literature, although that literature may be extensive and detailed enough to permit the develop of such budgets. The major value of the cesium-erosion literature for the present work is that it demonstrates how slope processes deliver fallout radionuclides to rivers for further transport.

Once radionuclides attached to sediment particles enter stream channels, their fate becomes intertwined with channel processes. A large scale effort at exploring the connection between channel processes and radionuclide transport was a research project coordinated among several workers by the U.S. Geological Survey during the early 1960s. The two primary topics in this work were investigations of dispersion of radionuclides suspended in flowing water, and processes related to bed materials. Controlled experiments in flumes,[38] in a wide range of natural streams,[39] and in the Clinch River, Tennessee showed that if the contaminants were released at a point, downstream processes would disperse the suspended materials.[40] As distance increased away from the point of injection, concentrations of contaminants declined exponentially.[41]

The U.S. Geological Survey work also explored bedload processes related to radionuclides. Although the highest concentration of contaminants per unit weight occurred in the fine particles, significant quantities also adhered to the larger bed sediments, mostly through a process of cation exchange.[42] The bottom sediments of the Clinch River emerged as a significant component of the radionuclide storage in the river system.[43] Bedload transport models therefore became important in predicting the movement of the contaminants, and research in the Clinch River as well as in the North Loup River of Nebraska, using marked tracer sediment, improved understanding of the bedload transport process.[44] The Survey also conducted some research using radioactive tracers in sediment in conveyance channel of the Rio Grande near Bernalillo, but the results apparently never appeared in formal publications.[45]

Studies of radionuclides and heavy metals in transit through river channels languished after the U.S. Geological Survey projects. Radioecologists, however, correctly identified the importance of fluvial sediment transport for contaminants. Research by biologic and geoscientists at Los Alamos has highlighted the importance of runoff in transporting plutonium in the surface environment,[46] and has demonstrated the importance of physical transport of plutonium in making the element available to life forms.[47] Evidence collected in investigations of plutonium and cesium-137 in Los Alamos Canyon have shown that stream sediments were the major reservoir of radioactivity from waste disposal activities of Los Alamos National Laboratory, and that runoff processes were moving the sediments downstream.[48] In a more general sense, radioecologists have indicated that "the distribution of transuranic elements from point sources at nuclear facilities typically produces decreasing concentrations with distance from the source."[49]

While applicable to short term atmospheric and suspended river sediment processes in highly controlled conditions, this statement is probably not true for most natural river systems. Because contaminants preferentially adhere to the fine sediments that are sorted by fluvial processes,[50] most streams operate to produce unequal geographic distributions of contaminants. L. J. Lane and T. E. Hakonson offered an enrichment ratio, borrowed from agricultural researchers,[51] to account for the resulting variations in concentrations.[52] They and their associates then used engineering based models of hydraulic processes to further illuminate the probable mechanisms of transport in small to medium channels and predicted the movement of contaminated sediments through Los Alamos Canyon.

A geomorphological approach to the contaminant-sediment transport problem complements engineering-based interpretations. The distribution of thorium-230 downstream from an accidental spill in the Puerco River, New Mexico, does not decrease with distance from the source as might be predicted by the standard diffusion models.[53] On the time scale of several weeks, the wave-like distribution of thorium concentrations in the downstream direction might result from the movement of contaminated sediment through the system in pulses, a phenomenon commonly observed in rivers.[54] On a shorter time scale, the wave-like downstream distribution of thorium results from geographic variation in the ability of the stream to transport heavy metals and sediment.[55]

Australian researchers have also investigated radionuclide transport in rivers, most with regard to mill tailings.[56] Explanation of the distribution of contaminated sediments through river systems in Australia depended upon an understanding of 1) characteristics of the sedimentary environments along the channels, 2) physical properties of the contaminated sediments that influenced their transport, and 3) mixing of contaminated and uncontaminated materials.[57] Researchers argued that environmental managers and planners could take these generalizations into account in a general if not in a precise, quantitative way.[58]

Although little published research is available pertaining to fluvial transport of radionuclides, more information appears in the literature regarding other heavy metals. Using a commonly held definition for heavy metals as those elements with a positive chemical valence and a density equal to or greater than 4.5 g per cu cm,[59] all the elements in the periodic table beyond actinium (that is, the actinide series which includes uranium and plutonium) are "heavy metals." The significance of this definition is that all heavy metals behave similarly from the perspective of physical transport in rivers. Although the metals may exhibit a variety of chemical mobility characteristics, they all adsorb onto sedimentary particles,[60] and those particles are likely to be distributed by physical processes into depositional patterns that result from sorting by weight.

The geographic and geomorphologic implications of high density for heavy metals are connected to the shear stress required to move the particles with adsorbed metals. Particles of common quartz, for example, have a density of 2.65 g per cu cm, while those of plutonium dioxide have a density of 11.46 g per cu cm.[61] Standard, widely accepted hydraulic principles provide the means of outlining the relationship between flowing water and sedimentary particles,[62] and their application indicates particles of plutonium dioxide require 6 times more shear stress for initial motion than quartz particles of similar size.

At a larger scale, the movement of sediments and attached metals through stream systems creates a particular geography of concentrations downstream from sources. K. E. Carpenter, a fisheries biologist, first recognized the significance of river channel processes in metal transport.[63] Her work in the Welsh lead and zinc mining districts led to later studies in the same region that indicated some materials were temporarily deposited before remobilization, indicating that internal storage along and near channels was a source of pollutants.[64] Further analyses in a variety of streams in Europe, Great Britain, and the United States showed that, within channels, the downstream decline in concentrations could be modeled using simple distance decay functions.[65] In active sediments, this phenomenon is partly the product of mixing and dilution with uncontaminated sediments.[66]

Heavy metal concentrations are usually highest in the finest stream sediments,[67] and in most rivers the finest materials accumulate in flood plains. As a result, much research by fluvial geomorphologists interested in metals has focused on flood plains as repositories for the metals--wherein each layer of sediments and associated metals are often the products of individual flood events.[68] As sediments accumulate and bury previous deposits, a vertical stratigraphy develops with varying amounts of metals in each layer. Metal content can indicate the date of emplacement of individual strata if the date of introduction of the pollutant in the system is known.[69] Channel and flood plain studies have been concerned with a variety of common heavy metals, usually copper, zinc, lead, and cadmium, but the conclusions are probably applicable to those chemically stable elements of the actinide series, particularly some forms of plutonium and americium. Unlike humid-region rivers where flood plains are the focus of storage, in some dryland rivers highest metal concentrations may occur in active channels where frequent additions by flows inject metals more often than in overbank areas.[70]

Sediments and attached heavy metals and radionuclides that originate from erosion of hillslopes or waste sites therefore do not simply enter river systems and move directly to seas, oceans, or reservoirs. Considerable internal storage in channel sediments and on flood plains reduces the amount of output from the system. However, attempts to construct mass budgets of heavy metals or radionuclides for entire river systems have been uncommon, partly because of lack of data. Such budgets require information on the water and sediment fluxes over large areas, because the movement of these materials determines the movement of the contaminants. Water and sediment data are expensive to collect and are not generally available in the same locations or regions for which reliable metal or radionuclide data are available. There are, however, at least four regional budget studies dealing with heavy metals. In Europe, investigators derived aspatial budgets (those with compartments for various components of the environment without geographic identity) for lead, copper, zinc, nickel, chromium, and cadmium for the 4,488 sq km basin of the Ruhr River.[71] A more general geographically correct budget for mercury is available for the Upper Colorado River Basin in the 279,500 sq km drainage area above Lake Powell in the western United States.[72] In the Netherlands sediment and soil sampling has produced aspatial budgets for lead, copper, zinc, and cadmium for the River Geul, a 350 sq km watershed.[73] An investigation of lead and arsenic along a 121 km study reach of the Belle Fourche River in South Dakota revealed that flood plains have stored one third to one half of the metals entering the system from mine tailings.[74]

Regional budgets for radionuclides are not available for river systems, though budget studies for parts of the environment have used limited compartmental approaches. Estimates of the yield of fallout plutonium from hillslope erosion into rivers suggest that less than 10 percent probably exited the rivers to the oceans.[75] Lakes, reservoirs, channel sediments, and flood plains must store the remaining 90 percent. Small scale, probabilistic, agricultural-based models have predicted rates of removal of plutonium from a 33 sq km watershed at the Nevada Test Site in studies that bordered on budgetary approaches.[76] Efforts to model movement of plutonium in Los Alamos Canyon have also contained some mass budgetary perspectives.[77] However, none of the previous work on radionuclides has attempted a detailed, regional, geographically specific budget for a large watershed.

This brief review indicates that the formal literature on the physical mobility of heavy metals and radionuclides in river systems is sparse. The few studies in print indicate that monitoring and surveillance efforts, construction of theoretical explanations, and practical prediction for the distribution of contaminants in the river-channel environment must take into account the following *established* generalizations for radioactive contaminants that are heavy metals:

1. Contaminants adhere to sedimentary particles and do so to greatest concentrations in the finest material.

2. Once adsorbed onto sedimentary particles, most metal contaminants (including plutonium) remain relatively stable, especially in environments with high pH conditions.

3. Contaminants are more dense than most natural sedimentary particles and therefore fluvial processes are likely to preferentially sort and deposit them.

4. River systems store large quantities of sediments and associated contaminants in flood plains and along channels, especially in those systems undergoing aggradation.

5. Contaminants exist in most river systems either as a result of erosion of waste disposal sites or by the addition of global atmospheric fallout.

6. There is considerable geographic variation in the concentration of contaminants in river systems as a result of geographically and/or temporally discontinuous sedimentation and variable transport rates.

Important *unresolved* issues include the following:

1. It is not clear whether channel sediments or flood plain sediments contain higher concentrations of contaminants (the flood plain materials are generally finer, but the channel materials may experience more contaminant input).

2. The distribution of contaminants in flood plains is not clear for those rivers undergoing radical channel change, especially channel shrinkage with lateral accretion rather than simple vertical flood plain accumulation.

3. The relative importance of industrial versus atmospheric inputs for radionuclides over distances greater than a few km is not known for most systems.

4. The rates of change for transport and storage for contaminants is not known except for a few relatively small and isolated systems.

5. The connections among rates of energy expenditure, geographic distribution of energy, and the resulting distribution of contaminants are not clear.

Because soils and sediments are the major reservoir for heavy metals and radionuclides, and because they are mobile, geographic and geomorphologic analyses of surface processes are critical to understanding the distribution of the contaminants. Radioecologists recognize the need for surface process studies: "Water flow...can and does act as an important agent of radionuclide concentration and redistribution".[78] Environmental geochemists recognize the same need: "studies of geomorphology...are basic to a deep understanding of the geochemistry of landscapes".[79] For plutonium, an international review of research showed that "physical transport mechanisms become significant when compared with chemical transport mechanisms."[80] A summary review of heavy metals in general concluded "A proper understanding of the dynamics (erosion, transportation, sedimentation) is not only essential within most sedimentological contexts but additionally for the prediction of the fate of sediment-bound contaminants."[81] Geomorphologists, however, have yet to explore the subject of heavy metal or radionuclide dynamics to any significant degree. While geochemists have developed techniques using stream sediments as indicators of ore body locations,[82] process specialists have generated only a few studies of the subject.

Analysis of the distribution of plutonium in the Northern Rio Grande system thus takes place with a background of some general knowledge, but with significant theoretical gaps. In some previous work, information from the contaminants has provided clues about geomorphic change, as in the case of the cesium 137 approach to quantifying hillslope erosion In the case of rivers such as the Rio Grande, however, theoretical structures and empirical data are stronger for the geomorphic system than for the plutonium system Therefore, the present research attempts to define and explain geomorphic processes first, and then uses that understanding to unravel the likely fate of the contaminant

Figure 2.1 Ashley Pond [illegible] Los Alamos, which [illegible] buildings of the school [illegible]

CHAPTER 2. PLUTONIUM AND LOS ALAMOS

2.1 History of Plutonium

The plutonium in the Northern Rio Grande is entirely artificial. Small amounts of plutonium may have formed in exceptionally rich uranium deposits in south-central Africa, but for practical purposes until its manufacture in 1939 the element did not occur in the earth environment. Although the detailed story of the origins of plutonium are beyond the scope of the present work, an outline of that history aids in understanding issues surrounding plutonium in the Northern Rio Grande in the late twentieth century. The purposes of this chapter are to review the origins of plutonium and to briefly examine the nature of the element.[1]

Modern nuclear physics, which would ultimately lead to the production of plutonium, began with the publication of the discovery of X-rays by Wilhelm Conrad Rontgen in 1896. His work showed that the physical world was much more complicated than previously thought, and that energy could be emitted from substances. In the same year Henri Becquerel of Paris showed that uranium emitted radiation, and soon thereafter Marie and Pierre Curie coined the term "radioactivity" to describe the emissions they recorded from two newly discovered elements, radium (named after its radiative properties) and polonium (named after Marie Curie's home country of Poland).[2] Between 1898 and 1902, Ernest Rutherford of Cambridge University and later McGill University, explored processes of radioactive decay that generated free electrons (beta radiation) and bursts of energy (gamma radiation), discovering that some elements changed their basic properties during the emission. He termed these changes "transmutation," and laid the philosophical foundations for understanding atomic structure.[3]

The transmutation of elements was significant, because knowledge about the number and types of elements in the natural world was expanding rapidly in the late nineteenth century. Between 1894 and 1900 William Ramsey enlarged the periodic table with an entire family of elements that were inert gases, and by 1903 more than a dozen radioactive elements were known. In 1903 it was obvious that the decay process explained many observed elemental changes. Americans Bertram B. Boltwood and Herbert N. McCoy showed that radium descended from uranium and Otto Hahn connected several types of thorium. Rutherford moved his research to the University of Manchester in 1907, and there, along with Hans Geiger, he began to assess the rates of emission and decay processes. Geiger later developed the now familiar instrument that bears his name for the purpose of counting emissions.[4]

Niels Bohr joined Rutherford, and together they developed a comprehensive theory to describe and explain the structure of atoms.[5] Between 1908 and 1920 the outline of the theory evolved to include alpha radiation as consisting of particles that were helium atoms, as well as the definition of protons and neutrons. An associate of the group, Frederick Soddy, introduced the term "isotope" to describe the different atomic varieties of the same element that had the same chemistry but different atomic weights.[6]

It was a short step from description and explanation to manipulation. Once the general nature of the atom became known, several workers set about the task of changing it artificially. The idea of bombarding atoms with protons to change the atomic structure was current during the 1920s. This bombardment was most effective if the protons could be accelerated to high energy levels, leading to the development of several schemes to increase the efficiency of the "atom smashers." One of the more successful efforts was by Ernest O. Lawrence and M. Stanley Livingston of the University of California at Berkeley. Their system, based on the precept of accelerating ions around a curved track using magnets, resulted in the production of several cyclotrons, or particle accelerators, during the 1930s.

After about 1932, several research groups experimented with bombarding elemental targets with alpha particles, protons, positrons (positively charged electrons), and neutrons. The result was a prolific industry in the production of new isotopes, previously unseen varieties of many common elements. Among the most active groups were those in Paris (Irene Curie and Frederick Joliot), in Rome (directed by Enrico Fermi), and in Berlin (Otto Hahn, Lisa Meitner, and Fritz Strassmann). The Rome group systematically explored the periodic table and found that the heavy elements captured and retained neutrons most readily while emitting a beta particle. As a result, the element moved one step up in the periodic table. The discovery was significant because it meant that transmutation could occur not only down the table with the loss of energy as discovered earlier, but it could also occur up the table with the addition of energy.[7]

The Berlin group worked with the heaviest elements, and found that they could create an entire new family of elements not previously known. They bombarded uranium with neutrons and created several transuranic elements (elements higher than uranium in the periodic table). The chemical mixture resulting from the experiments was so complex, however, that they were unable to sort out the various components. In 1935, Hans Bethe, R. F. Backer, and M. Stanley Livingston undertook a massive review and summary of the research to that point. They developed the theory of "fusion" to explain the creation of the new elements wherein the nuclei of various atoms fused together to form the new element. In 1938, the Paris and Berlin groups explained some of their new products as the result of "fission" whereby the nuclei divided or split to create two new daughter products.[8]

The processes of fusion and fission released huge quantities of energy, and researchers began to consider the military implications of their work. By the late 1930s, a global war of proportions not previously contemplated began to seem inevitable. The possibility of controlling the energy in fusion and fission processes became a strategic consideration. The power of weapons manufactured to take advantage of the energy became even more awesome to contemplate when the possibility of chain reaction appeared in 1939. As fission might cause a uranium atom to release a neutron, that neutron might trigger fission in another nearby uranium atom, making the explosive release of energy self sustaining. Leo Szilard, an associate of Fermi, along with Albert Einstein, petitioned President Roosevelt to support exploration of the new developments in nuclear physics for military applications. They were concerned that German research might produce similar weapons capable of destroying American cities. Roosevelt approved, and in 1940 Fermi (now at Columbia University) received military funds to continue his work attempting to generate a chain reaction. After two years of work and a move to the University of Chicago, Fermi and his group successfully generated a chain reaction on December 2, 1942.[9]

Fissionable materials therefore suddenly became very important in the early 1940s because they would be the fundamental substance of an atomic weapon. Uranium-235 is fissionable, but found in only tiny amounts in deposits where it is associated with the much more abundant uranium-238. Separation of the two isotopes is difficult and requires large quantities of ore which were in short supply. Alternative fissionable materials were therefore highly desirable, and transuranic elements offered possible substitutes for weapons materials. In 1940, Philip Abelson and Edwin McMillan of the University of California at Berkeley conceived of elements 93 (eventually named neptunium) and 94 (eventually named plutonium) as the beginning of a series of transuranic elements in the periodic table similar to the rare earths. They obtained evidence that element 93 emitted beta particles and therefore that it must transmute into element 94 Louis Turner of Princeton University deduced that element 94 must have a fissionable isotope and that this isotope could be created by adding neutrons to uranium-238.[10]

Element 94 was the special interest of Glenn T. Seaborg of the University of California at Berkeley. In 1939, chagrined at missing the discovery of fission, he focused his energy on exploration of elements 93 and 94, especially on the production and isolation of element 94. During the summer and fall of 1940, he, Edward McMillan, and Arthur Nahl experimented with neutron bombardment of uranium. They produced what appeared to be an isotope of a new element with an atomic number of 94. On February 23, 1941, he and his team of chemists isolated element 94 combined with thorium, but they could not yet produce it in pure form. On March 28, 1941, he demonstrated that plutonium 239 was fissionable. The chemical isolation of plutonium was a formidable task that required the development of special tools for handling microscopic quantities of material. It was not until August 20, 1942 that Seaborg's group successfully precipitated a pure particle of plutonium. Generated from more than a kilogram of uranium, the plutonium was a microscopic particle of less than a microgram, but from that date, plutonium was a physical reality rather than a hypothetical concept.[11] On September 10, 1942, B. B. Cunningham and L. B. Lerner of the Metallurgical Laboratory, University of Chicago, isolated and weighed the first visible quantity of plutonium 2.77 micrograms.[12]

Seaborg named element 94 plutonium after the planet Pluto, discovered in 1930. Martin Kaproth had followed similar logic in 1789 when he named uranium after the then newly discovered planet of Uranus. Edwin McMillan suggested that given the trend, element 93 should therefore be neptunium after the planet Neptune. Seaborg chose Pu as the chemical symbol for the new element rather than Pl, partly to avoid confusion with platinum (Pt), but also partly on a whim to create attention. He thought the element would be nasty to deal with, so he derived the symbol from P.U., a slang term for putrid or smelly.[13] The new element 94 therefore came to carry the name of the ancient Greek god Pluto, a ruler of the underworld, a god of the earth's fertility, and the god of the dead.

2.2 Plutonium and Los Alamos

Once defined by science, plutonium became a primary object of engineering and industrial activity. The industrial structure needed to build an atomic bomb had begun to develop before the isolation of plutonium. In April 1941 at the direction of President Roosevelt, Vannevar Bush, Director of the Carnegie Institution of Washington, created a special section (S-1) of the Office of Scientific Research and Development. James B. Conant, President of Harvard University, became his deputy in charge of the theoretical and industrial aspects of bomb development. Arthur H. Compton, a University of Chicago physicist was the major managing committee leader. Within a year, laboratories at several institutions across the nation were connected into an interlocking network with each unit addressing a limited part of the problem.[14]

The acquisition of restricted industrial materials and plants during the Second World War, however, made a civilian production effort impossible. It was clear to Bush and Conant that the military would have to be directly involved, and it was at their behest that the U.S. Army became a working partner in the bomb project. The Army established a special office in New York for the project in August 1942, labeling it the Manhattan Engineer District and appointing General Leslie R. Groves as its commanding officer. Groves quickly orchestrated the construction of an industrial effort larger and more complex than any previously attempted.[15]

The major installations in the Manhattan Project were at Oak Ridge, Tennessee, Hanford, Washington, and Los Alamos. Oak Ridge was the site of four major industrial plants. Y-12 to generate uranium 235 by electromagnetic processes, Y-25 to generate uranium 235 by gaseous diffusion, S-50 to augment the first two by thermal diffusion, and the Clinton Laboratories to conduct research on locally generated plutonium. By late 1942 it became clear to project managers that the Clinton Laboratories could serve only experimental and pilot purposes because there was not enough space available at the site to construct plutonium production facilities.[16]

Groves selected Hanford, Washington as the site for the huge plutonium production plants. Begun in January, 1943, the facilities on the 500,000 acre site included three water cooled reactors and four separation plants. Construction was complete and production of plutonium began in September, 1944. Hanford became the primary source of plutonium, and except for small experimental quantities, it produced all the American made plutonium that eventually reached the Northern Rio Grande system in New Mexico.

The culminating activity of the Manhattan Project was the refinement of the plutonium and the construction of weapons. By early 1942, the far flung laboratory and industrial elements of the project had become so diverse and used such a wide variety of equipment and techniques, that Conant and Groves decided a final research design and assembly facility should be included in the system. In December, 1942, they formally appointed J. Robert Oppenheimer of the University of California at Berkeley to oversee the operation of this final aspect of the project, although he had already been essentially acting in that capacity. Oppenheimer suggested to Groves that the site of the final laboratory in the system be in northern New Mexico, an area he knew from earlier vacation visits. They finally settled on the Los Alamos Ranch School, a boy's boarding school on the Pajarito Plateau northwest of Santa Fe (Figure 2.2). The location had some housing already available, was easily acquired by the government, had large uninhabited spaces, and could be made militarily secure. Condemnation proceedings began in November, 1942; in February, 1943, the school closed, the Manhattan Project arrived, and Los Alamos Scientific Laboratory became a reality.[17]

Although Oppenheimer and Groves originally anticipated that the site would house about 30 scientists, the complexities and problems of design and bomb construction using plutonium were so great that the laboratory quickly expanded. By 1945 Los Alamos had become a city of 5,000 inhabitants supported by dozens of buildings and laboratories (Figures 2.3 and 2.4). Building D in Technical Area 1 (TA-1) housed much of the plutonium handling.[18] The first plutonium delivery to Los Alamos was a small experimental quantity (probably less than a milligram) from the Clinton Laboratories at Oak Ridge in February 1944.[19] The first shipment of small quantities of plutonium from Hanford arrived at Los Alamos on February 2, 1945.[20] Large quantities of uranium-235 and plutonium-239 arrived at Los Alamos in early summer, 1945, and made up the cores of the first nuclear weapons: plutonium for the experimental Trinity blast east of Socorro, New Mexico, on July 16, and for the Nagasaki bomb on August 9. The Hiroshima bomb, also manufactured at Los Alamos, on August 6 was a weapon fueled by uranium. The significance of this history of plutonium shipments is that there was no plutonium at Los Alamos until mid 1944, and it was not present in large quantities until mid 1945. Significant releases of plutonium from the laboratory into the surrounding environment are therefore unlikely to have occurred until mid- to late 1945.

During and after the Second World War two factors drove the management of plutonium at Los Alamos to produce atomic weapons. First was the perceived need to develop the ultimate weapon before an adversary could do so, and to win the war.[21] Many scientists at the laboratory were refugees from countries conquered earlier in the war, and their most common after dinner toast was "Death to Tyrants." Their sense of political and scientific history imparted uncommon devotion to their work. The second driving force was an inertia inherent in the process.[22] After devoting their lives to the project, they could not stop before its completion, even after the surrender of their primary enemy, Germany. After being engaged in the work to build the first bomb for four years, the process was larger than any individual or one group of individuals, and extensions of the original project continued after the war despite divisions of opinion about how to control the weapons and their materials. During the early days of the Cold War, the Soviet Union became the major international competitor with the United States. The result was further experimentation with plutonium at Los Alamos with

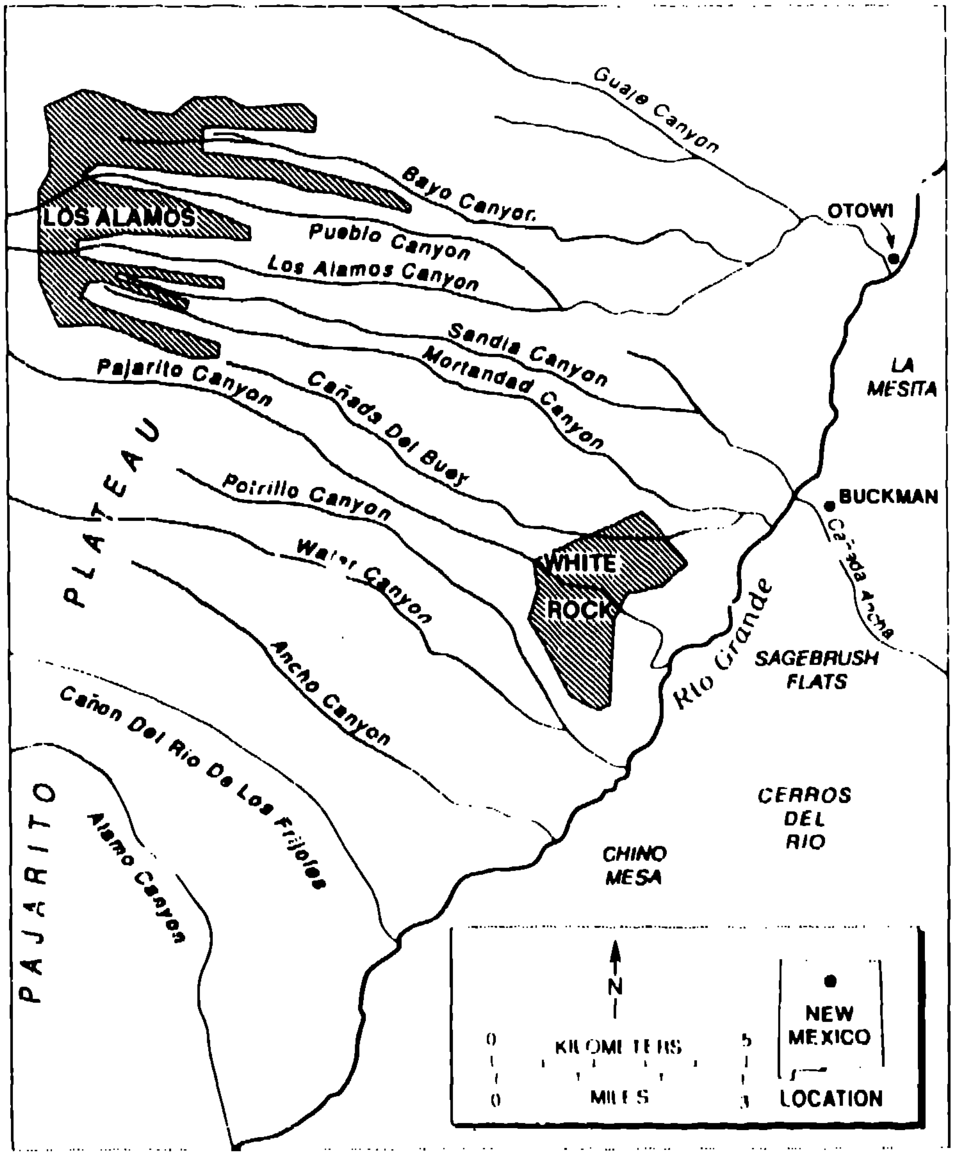
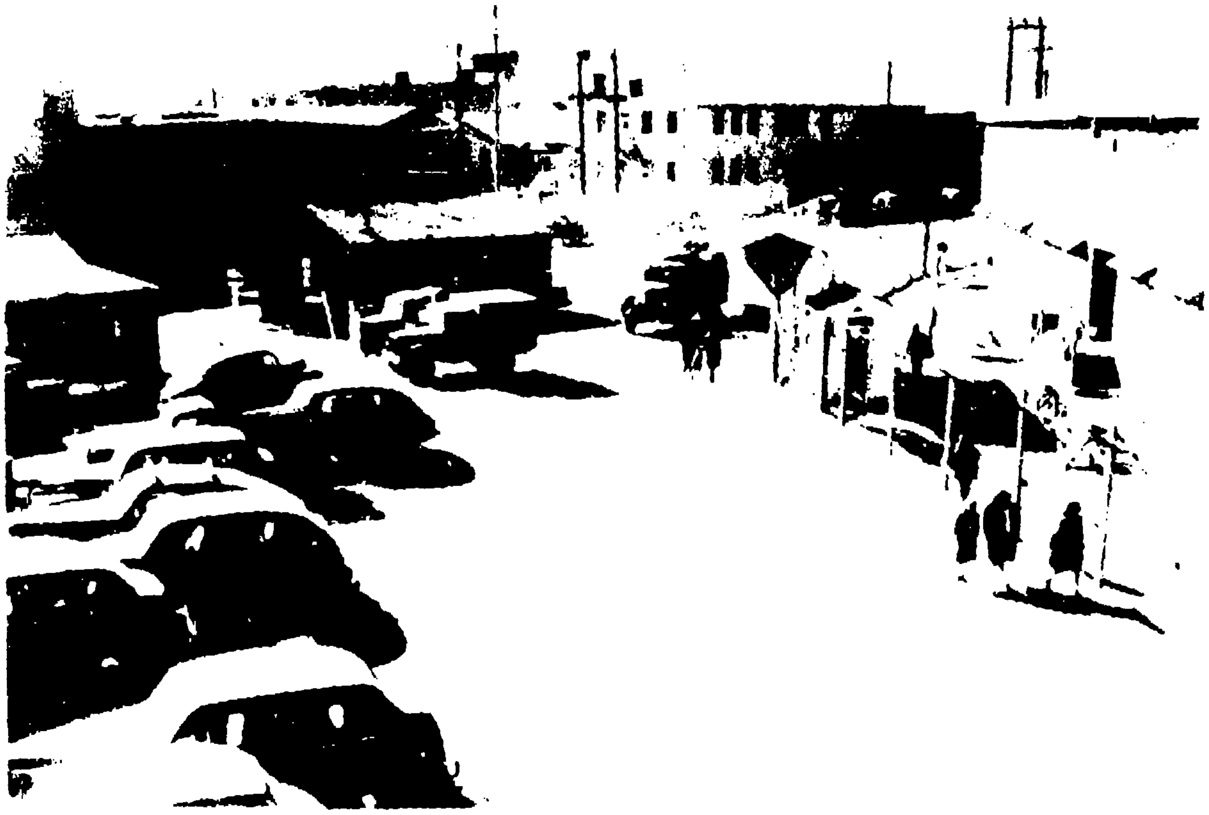


Figure 2.2 General location of Los Alamos, New Mexico.



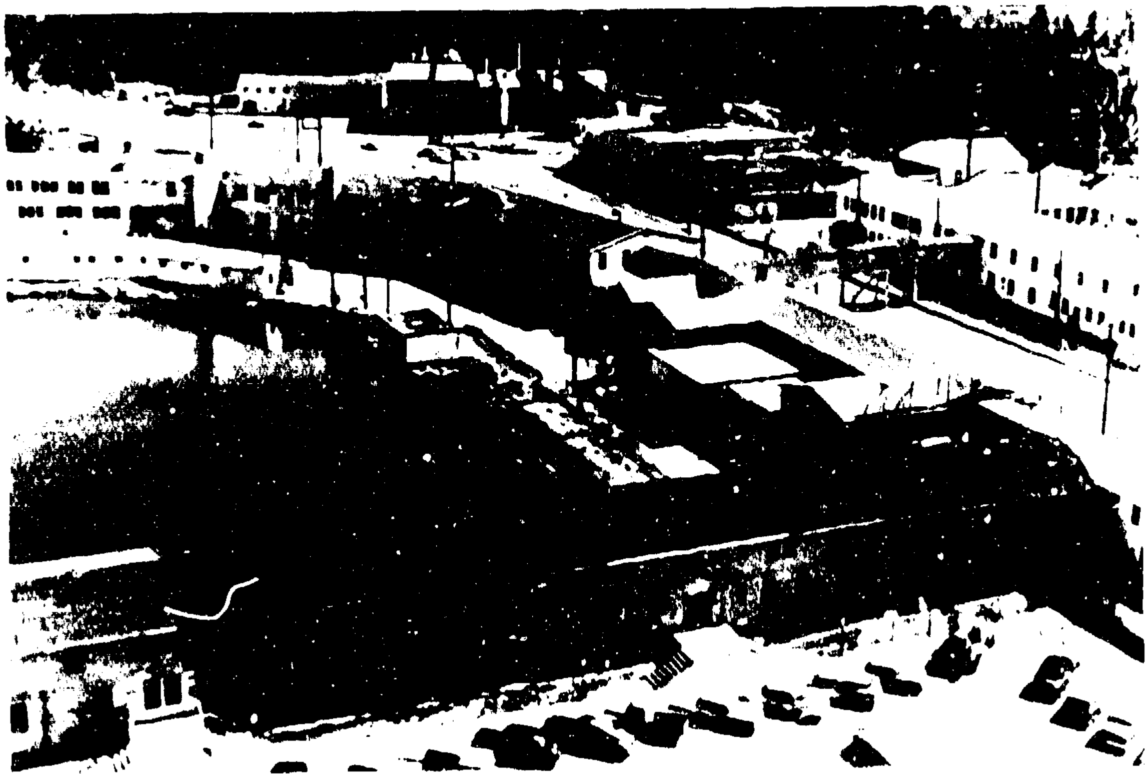


Figure 2.4 The Main Technological Area (TA 1) at Los Alamos in 1955 with its extensive development and permanent buildings. Ashley Pond is at the left.

continued attending releases of plutonium to the environment

These considerations are important explanations in understanding why the potential pollution hazard of plutonium received less attention in the 1940s than it does in the 1990s. In the midst of a global war followed by global competition between the remaining super powers, environmental quality was a minor issue. It is only in recent years, especially since 1970, that American society has embraced environmental quality as a national goal.[23] Even early in its development, researchers recognized the hazardous nature of plutonium, and in the design of laboratories and industrial plants. Groves was greatly concerned about worker safety. At the time, however, there was no scientific expertise to deal with radiation and toxic hazards from the material.

To address this lack of knowledge, Compton established a health division at the Metallurgical Laboratory at the University of Chicago in July 1942. From then on, biophysicists, physicians, and biologists began to explore the implications of plutonium and radiation for human health. Many of the early developments in the health physics dimensions of plutonium were at Los Alamos. Joseph Kennedy, director of the Chemistry and Metallurgy Division, and Dr. Louis Hempelmann, laboratory medical director, worked to develop methods for detecting plutonium in human tissues and to devise ways to prevent plutonium poisoning.[24] Hempelmann designed safety rules for handling plutonium at the laboratory that were similar to rules previously established for the radium processing industry.[25]

During the Second World War and the early days of the Cold War, work to understand the dynamics of plutonium in the natural environment was several years in the future. The term "radioecology" did not appear in the scientific literature until 1956.[26] Reports by British researchers in 1941 and by Los Alamos chemist George Kistiakowsky in 1944 mentioned potential environmental contamination by fallout, but the issue was not taken seriously until efforts by physical chemists Joseph Hirschfelder and John Magee at Los Alamos in April, 1945.[26] By the time of the Trinity Blast, considerable efforts were made to assess the intensity and distribution of fallout from nuclear detonations. The problem was too complex for solution at the time, as was the issue of waste disposal from experiments and bomb manufacturing. General Groves adequately summarized the perspective of the project participants in the 1940s and 1950s regarding environmental pollution by plutonium: "We had always thought that it would be possible by intensive research to eliminate much of this radioactive problem in the future."[28]

From 1945 to 1949, health officials at Los Alamos made periodic surveys of the radiological characteristics of water and sediment in the Los Alamos system. The results of these investigations appeared in internal laboratory reports that were classified until the late 1950s. From 1949 to 1971 the Water Resources Division of the U.S. Geological Survey investigated the effects of plutonium releases from the laboratory, with the results appearing occasionally in publications of the survey (Water-Supply Papers, Professional Papers, and the general scientific literature). After 1970, laboratory staff in the Environmental Studies Group and the Environmental Surveillance Group undertook a series of investigations, in many cases reporting the results in the general scientific literature. Significant data and conclusions appeared in annual "surveillance reports," laboratory publications that were publically available but not widely distributed. Alan Stoker and his associates collated most of the important data and published a summary of the work that had been accomplished from 1945 to 1975.[29]

Despite more than four decades of research and General Groves' optimistic view of a future when the problem would be "solved," a clear understanding of the dynamics of plutonium in the environment remains elusive. Although physicists and engineers were able to surmount the problems of nuclear fission and bomb-building, environmental scientists have yet to completely unravel the fate of plutonium in the environment. The explanation for the difference between the expected and actual outcomes relates to money and complexity. The amount of money invested in environmental research is miniscule in comparison to the amount invested in weapons development. Also, the natural environment exhibits a complexity far greater than the relatively simplistic conditions of the physical or chemical laboratory. Environmental measurements are difficult and inaccurate compared to laboratory efforts, many variables are often unassessed, and control cases are difficult to identify.

2.3 Nature of Plutonium

The plutonium that was the focal point of the Los Alamos industrial activity and that now is an environmental pollutant is a metallic element formed by neutron capture in uranium-238 (Figure 2.5). Although 14 isotopes of plutonium are known, only four occur in quantities great enough to be of concern as contaminants: plutonium-241 (half life of 13.2 years), plutonium 240 (6580 years), plutonium 239 (24,400 years), and plutonium-238 (86.4 years). Of the four, plutonium-239,240 are the most common isotopes found in the natural environment, being about 21 times more common in sediment than plutonium-238. Plutonium-241 is an emitter of beta radiation, while the other three are alpha emitters during their decay. As plutonium decays to more stable isotopes and elements, it passes through a series of predictable stages, eventually becoming stable as lead 207 (Figure 2.6).

Plutonium can be separated chemically from its precursor uranium 238 in nearly pure form, but its chemical characteristics and behavior are complex. In aqueous systems, for example, it can exist in four oxidation states simultaneously.[30] The most common, stable plutonium compound at earth environment temperatures and pH ranges is plutonium dioxide (Figure 2.7). Most plutonium in the natural environment is likely to be of this form, although it also occurs in six allotropic metal forms. Plutonium in natural sedimentary environments as a metal or as plutonium dioxide is relatively insoluble. This insolubility explains why in terrestrial ecosystems more than 99 percent of the plutonium occurs in soils and sediments. It is not chemically mobile enough to easily pass through organic membranes into plant roots. Concentrations in plants are usually 0.001 to 0.000001 times the concentration in underlying soils and sediments, and concentrations usually decline by a mean factor of 0.0001 through each of the transitions from soil to plant to animal systems.[31]

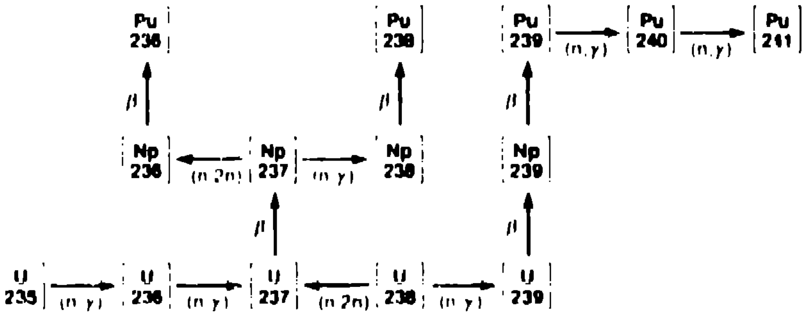


Figure 2.5 Formation scheme for plutonium (redrawn from Watters *et al.*, 1983, p. 89).

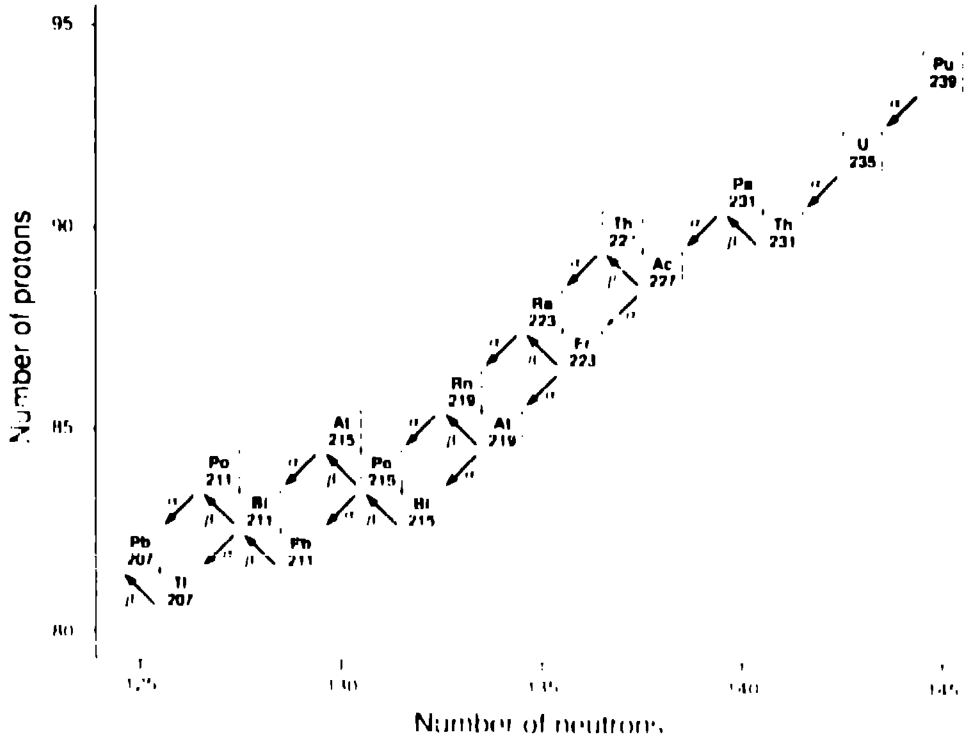


Figure 2.6 Decay series for plutonium (redrawn from Dennis, 1984, p. 462).

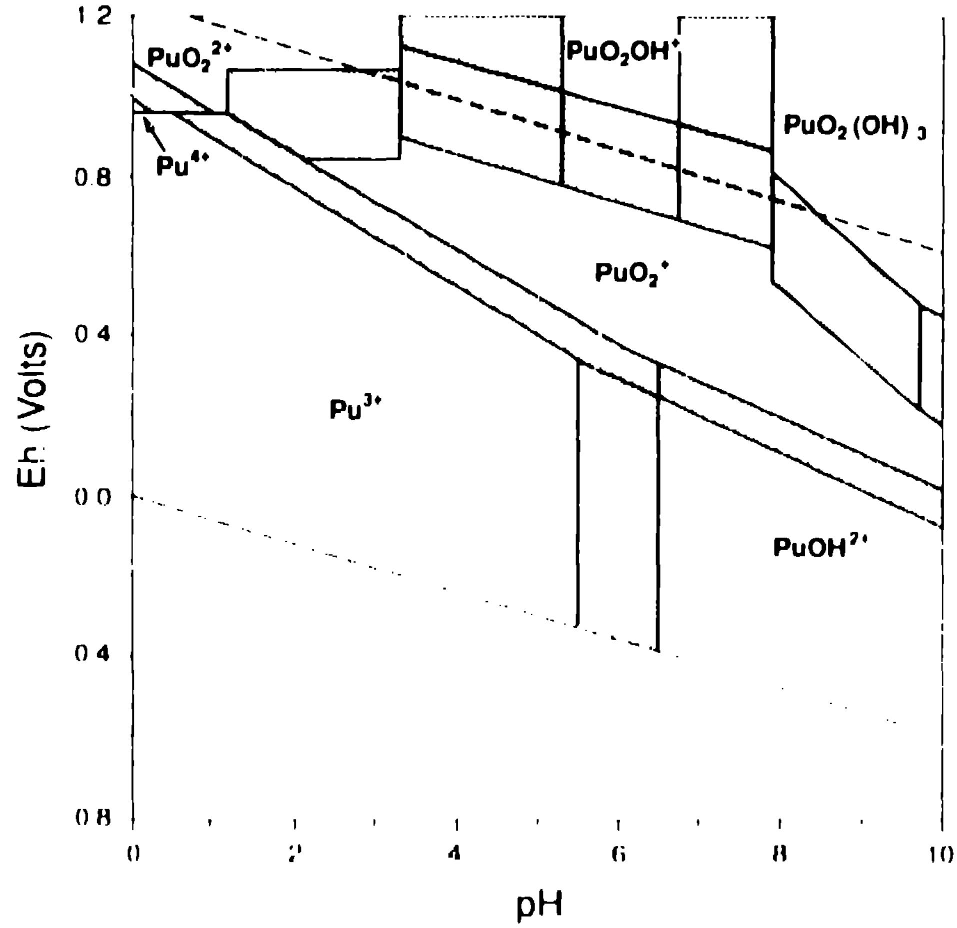


Figure 2.7 Equilibrium diagram for plutonium (Watters *et al.*, 1983, p. 93).

The human health hazard from plutonium is its radiotoxicity. Because the most common forms of the element are alpha emitters, radiation from decaying plutonium does not readily pass through physical barriers, including the human skin. However, if particles containing plutonium are inhaled or ingested and become internally lodged in the human body, the persistent emission of alpha radiation leads to cell destruction and development of cancers. Like most actinides, internally mobile plutonium is often deposited in bone tissue, where its residence time in humans is greater than a century.[32] This concentration process is nonuniform, so that more plutonium occurs in some parts of the skeleton than others.[33] Plutonium ingested in animal systems often concentrates in the liver, while that inhaled concentrates in the lungs, in each case leading to the development of cancers. Small amounts of plutonium taken into animal systems are absorbed under normal conditions: about 0.0001 of that ingested is absorbed by the intestinal tract.[34] Larger amounts enter typical animal systems through air ways: about 0.05 percent of that inhaled enters the blood stream and about 0.15 percent enters the lymphatic system.[35] For these reasons, plutonium-contaminated sediments that might become airborne and then inhaled are probably the most important consideration from the standpoint of human contamination.

The degree of chemical toxicity of plutonium for humans is relatively well known, probably because "perhaps no single element has ever been so intensively studied".[36] Plutonium is hazardous to human health, but arsenic and some biological toxins are probably more poisonous.[37] Among radioactive isotopes, cesium 137 and strontium 90 are more hazardous because they are more common and/or more mobile in the earth surface environment.[38] There are no records of physical damage to humans through exposure to plutonium. The potential for poisoning and radioactivity damage to humans is great enough, however, to warrant careful monitoring, measurement, and assessment of concentrations. A responsible program to protect human health includes an accurate evaluation of the location and magnitudes of plutonium in those environments used by the general population.

2.4 Measurement and Safe Limits

The amount of plutonium in samples of environmental materials is most often measured as a concentration, a certain amount of plutonium per unit mass for sediment (per unit volume for air, and per unit liquid measure for water). For non-radioactive metal isotopes, the units are usually milligrams per kilogram or micrograms per kilogram (mg/kg or μg/kg, that is, parts per million or parts per billion), but for radioactive isotopes in sediments, the units are atomic disintegrations per minute per unit mass.[39] In the United States the most common unit for the rate of atomic disintegrations is a Curie, which is equal to about 37 billion atomic disintegrations per minute (that is, about 37 billion atoms disintegrating by giving up a unit of radiation per minute). The standard for determining a Curie is the number of atomic disintegrations per minute experienced by one gram of pure radium. Plutonium occurs in the natural environment in such small quantities that a Curie is too large to use as a convenient measure, so fractions of a Curie are the usual unit of measure. Common measures are pico Curie (pCi, 1×10^{-12} Ci) and femto Curie (fCi, 1×10^{-15})

(Appendix A). One pico-Curie is equal to about 2.2 atomic disintegrations per minute.

General amounts of radioactive isotopes as measured in Curies include the mega-Curies produced by a nuclear detonation. Kilo-Curies represent the amount used in medical treatments for tumor reduction. Micro-Curie amounts serve as tracers in environmental systems research. Because of the worldwide nature of nuclear fallout, most people have pico-Curie amounts of radioactive isotopes in their tissues. One pico-Curie per gram of plutonium in sediment represents much less than one part per billion of the metal in the natural material and would not be detectable by ordinary physical or chemical methods.[40]

The pico-Curie per gram is an odd combination of metric and nonmetric units, but it is used in this work because the original data and most of the publications cited used the measure. The International System of Units measure of atomic decay is the Becquerel (Bq) which is equal to one disintegration per second. The standard measure of concentration in environmental materials is therefore Bequerels per gram, and one pico-Curie per gram equals 0.0367 Bequerels per gram. Neither the Curie nor the Bequerel defines the identity of the isotope creating the decay emissions, a problem that is only resolved by analysis of the number of kinds of radiation produced during the decay.[41]

Laboratory methods assess plutonium concentrations in environmental samples by counting the number of atomic disintegrations per minute and then comparing that value with the mass of material involved. The laboratory environment and instruments create some emissions of their own which are counted in the process, so that a standardized number of emissions representing the background must be subtracted from the total number of emissions counted. The resulting value represents the number of emissions presumably derived from the sample. Because the background is inconsistent from one time to the next, the correction factor is the mean of many attempts to measure the background values. The reported values for the number of emissions from a sample is a number equaling the measured emissions minus a mean value representing a statistical distribution of values for the background. For some samples, if the actual background at the time of sample analysis happens to be exceptionally low and far below the mean value used for correction, a negative number may be reported for the sample. Some negative numbers of this type appear in the following pages. For analytic purposes, they are carried forward in further calculations to preserve the integrity of the statistical distributions that created them. Practically, they indicate that plutonium in the sample was either absent or present in quantities too low for detection.

The primary health hazard from environmental plutonium is related to radiation, so that determination of safe limits for plutonium concentrations in environmental materials is predicated on evaluating the radiation hazard if the material is ingested. The U.S. Department of Energy uses concentration guidelines for water and air that are concentrations above "background" levels because the purpose of the guidelines is to assess the safety of occupational environments.[42] For water the standard is 0.000005 micro-Curies per milliliter or 5,000 pico-Curies per liter. For air it is six times ten to the minus-14 micro-Curies per milli-liter, 60,000 atto-Curies per cubic meter, or 0.06 pico-Curies per cubic meter.

No agencies in the United States have plutonium standards for sediment quality. This oversight is especially important for the heavy metals that are radioactive isotopes, because most research shows that almost all of the metals in the natural environment occur in association with sediments or soils. An example of such standard is in the Netherlands, where governmental guidelines for sediment quality include evaluation of copper and zinc: 100-500 ppm copper and 500-3,000 ppm zinc require further evaluation, and greater than 500 ppm copper or 3,000 ppm zinc indicate the need for removal and disposal (Leenaers, 1989). The development of sediment quality standards for metals including plutonium the United States would undoubtedly require considerable bureaucratic effort, but the legal, monitoring, surveillance, and scientific rewards would be substantial

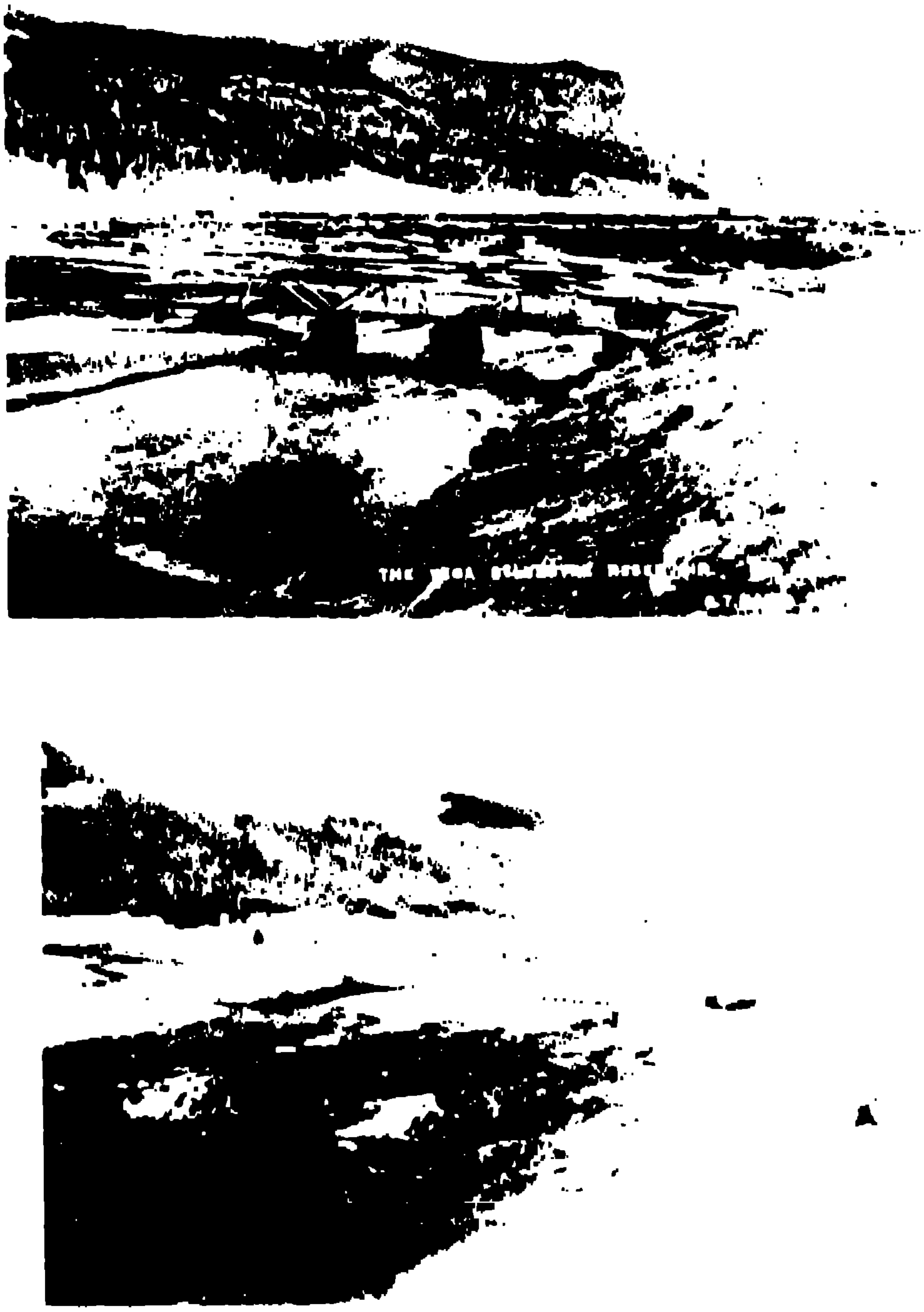


Figure 3.1. The Rio Grande near Creede, Colorado, is typical of the streams in the upper basin in the area immediately west of the San Luis Valley. The reach has significant amounts of stored sediment and probably stores [illegible] from [illegible] in mountain watersheds. The general character of the reach has not changed in nearly 90 years, despite the construction of the Rio Grande Reservoir upstream. Above, looking west along the stream at the site of a proposed [illegible] in 1911 [illegible] Photo [illegible] Denver Public Library, Western History [illegible] (W. L. Graf Photo [illegible]).

PART 2. THE NORTHERN RIO GRANDE FLUVIAL SYSTEM

CHAPTER 3. THE DRAINAGE BASIN

3.1 Drainage Network

In northern New Mexico, environmental plutonium bound to sedimentary particles experiences its greatest mobility in river systems, particularly the Rio Grande. The purpose of this chapter is therefore to outline the physical characteristics of the drainage basin into which Los Alamos operations have released plutonium. The following pages review those characteristics of the basin which most strongly influence the movement of sediment and its associated plutonium: landforms, geology and soils, climate, and vegetation.

The portion of the Northern Rio Grande emphasized in this work consists of the watershed upstream from the U.S. Geological Survey stream gage on the Rio Grande at San Marcial,[1] at the headwaters of Elephant Butte Reservoir. The drainage network within this 71,700 sq km area is the primary mechanism for surface transport and storage of plutonium. The Rio Grande begins as a trickle of meltwater from a semi-permanent snow bank at Stoney Pass in the San Juan Mountains in southwestern Colorado. Steep mountain tributaries are the primary sources of water, joining the main stem as it trends southeastward to the San Luis valley and the Alamosa, Colorado, area (Figure 3.2). Additional mountain waters from the Rio Conejos, which drains the southern San Juan Mountains in southern Colorado, join the main stream as it flows southward into New Mexico.

The northern Sangre de Cristo Mountains in Colorado generate surface runoff, but relatively little reaches the main river. About 7,500 sq km of the San Luis Valley constitute a closed basin, with no direct surface contributions to the Rio Grande. The Sangre de Cristo Mountains contribute only about 10% as much water as the San Juan Mountains.[2] The Rio Chama, which drains the New Mexico San Juan Mountains, joins the Rio Grande near Española; its combined 37,000 sq km area drains to the main river at the upstream end of the present study area. Of the two major basins above Española (and thus above Los Alamos), the upper Rio Grande above Española produces more water, while the Rio Chama produces more sediment.

The Rio Grande watershed almost doubles its drainage area between Otowi (a short distance downstream from Española) Bridge and San Marcial (Figure 3.3), but all the large basins added to the system within this reach are on the west bank. The Jemez River, draining the Jemez Mountains, is small compared to the Rio Chama and Upper Rio Grande components. The Rio Puerco drains a large area, but it is mostly plateau rather than mountain terrain so that it adds much sediment but little water. The Rio Salado also drains non-mountainous terrain and is primarily a sediment producer.

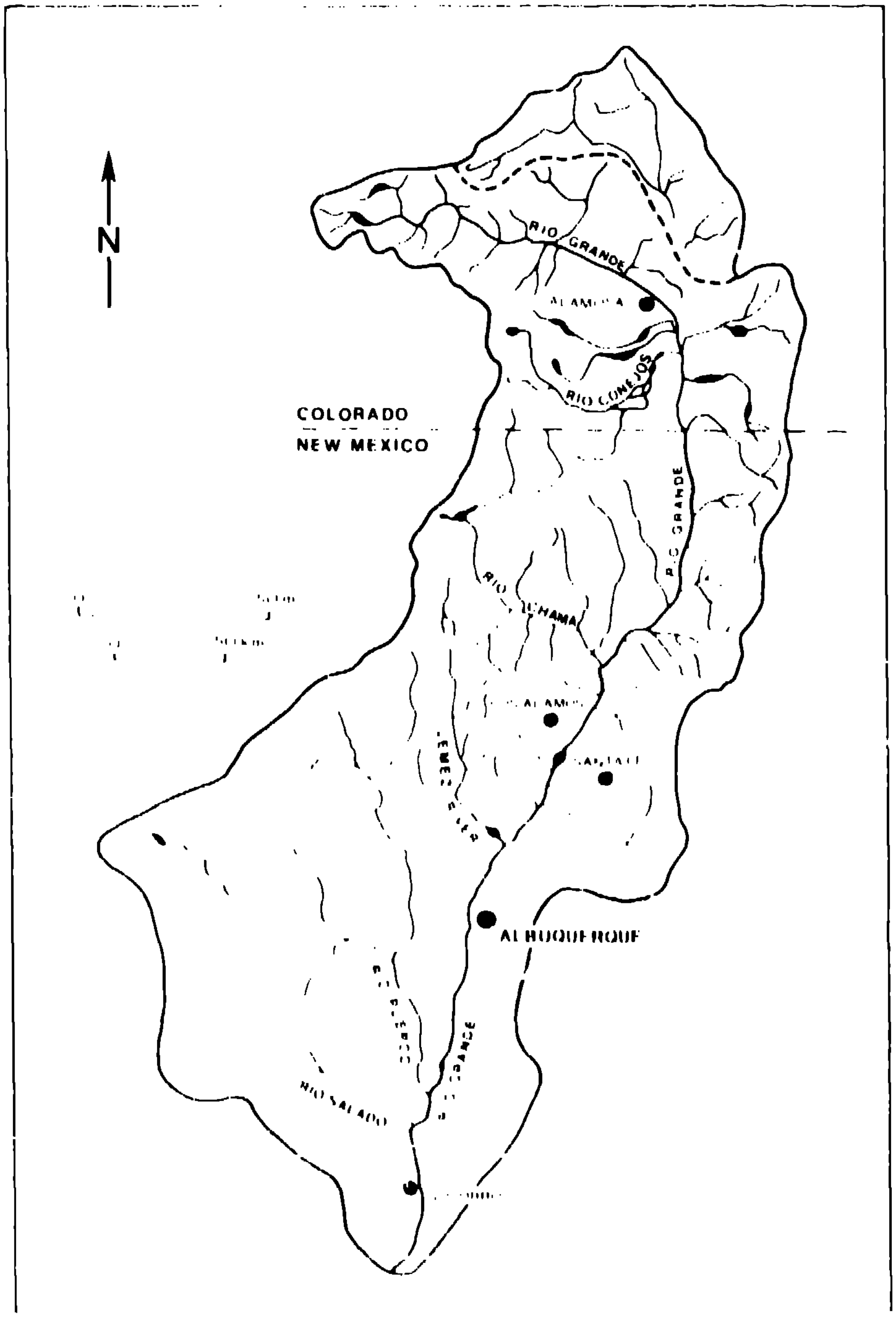


Figure 3.2 General drainage basin map of the Northern Rio Grande.

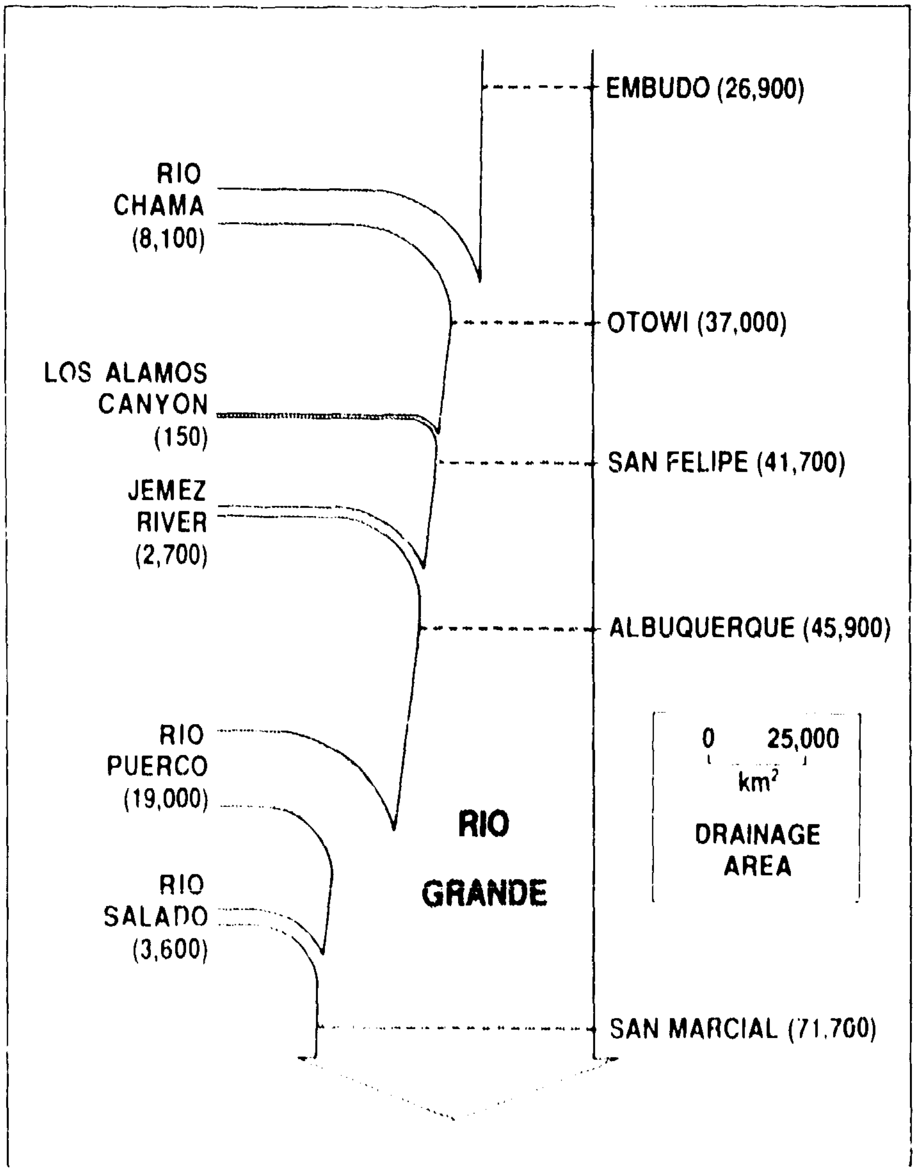


Figure 3.3 Drainage basin map of the Northern Rio Grande represented as a flow diagram with the width of the arrow representing the drainage area upstream or within tributary basins. Parenthetical drainage areas are given in km^2.

3.2 General Geomorphology

An appreciation of the landscape through which this channel network flows is important for understanding the transportation and storage of plutonium, because steep slopes shed their debris and associated fallout contaminants more rapidly than moderately sloping terrain. Topographic variation is also significant because high elevations with their greater amounts of rainfall are likely to receive more fallout.[3] Altitudes in the northern Rio Grande range from about 1,400 m on the river at San Marcial to about 4,360 m on Blanca Peak in the Sangre de Cristo Mountains. The northern Rio Grande basin includes portions of the Southern Rocky Mountains, the Colorado Plateau, and the Basin and Range Province (Figure 3.4).

The components of the Southern Rocky Mountains included in the basin are the San Juan, Sangre de Cristo, and Jemez Mountains as well as the San Luis Valley.[4] The San Juan Mountains dominate the northwestern part of the Basin. The range is the first mountain mass exceeding 3,000 m in altitude downwind from the Nevada Test Site. It is therefore a logical locale for deposition of fallout plutonium that might be in greater concentrations than the latitudinal or global average because of the possible additions from activities at the Test Site directly upwind. The mountains have steep, glaciated slopes with thin soils,[5] so that erosion of fallout is likely. Recent sampling of Rio Grande Reservoir, located in the high-altitude portion of the San Juan Mountains revealed elevated levels of plutonium-238 and plutonium-239,240,[6] reflecting these conditions.

The Sangre de Cristo Mountains are even higher than the San Juan Mountains, but their location downwind with respect to the prevailing westerly winds makes them drier. They are also likely to contribute some fallout plutonium to the Rio Grande system, but no direct measurements are available. The Jemez Mountains are a relatively small unit west of the Rio Grande. Essentially a massive caldera complex, they give rise to the Jemez River and several smaller streams, but within the regional context the mountains produce water, sediment, and probable radionuclide output in quantities much smaller than the other mountains.

The topographic highs of the mountains are complemented by the topographic lows of several major valleys in the drainage basin of the Northern Rio Grande. The San Luis Valley is a deep structural basin about 160 km by 80 km and filled to depths of several thousand meters with alluvium derived from the surrounding mountains. The valley includes broad alluvial plains, isolated volcanic cones and mesas such as the San Luis Hills, and the alluvial fan of the Rio Grande as it exits the San Juan Mountains.[7] The valley is important from the perspective of mass transport in the Rio Grande system because it is a zone of especially low stream gradients.[8] Deposition of sediment and associated contaminants is common in the valley, producing meandering channels and extensive zones of channel and flood-plain deposits.[9] Under present conditions, it is likely that the majority of sediments and contaminants eroded from the surrounding mountains move no further south than the San Luis Valley.

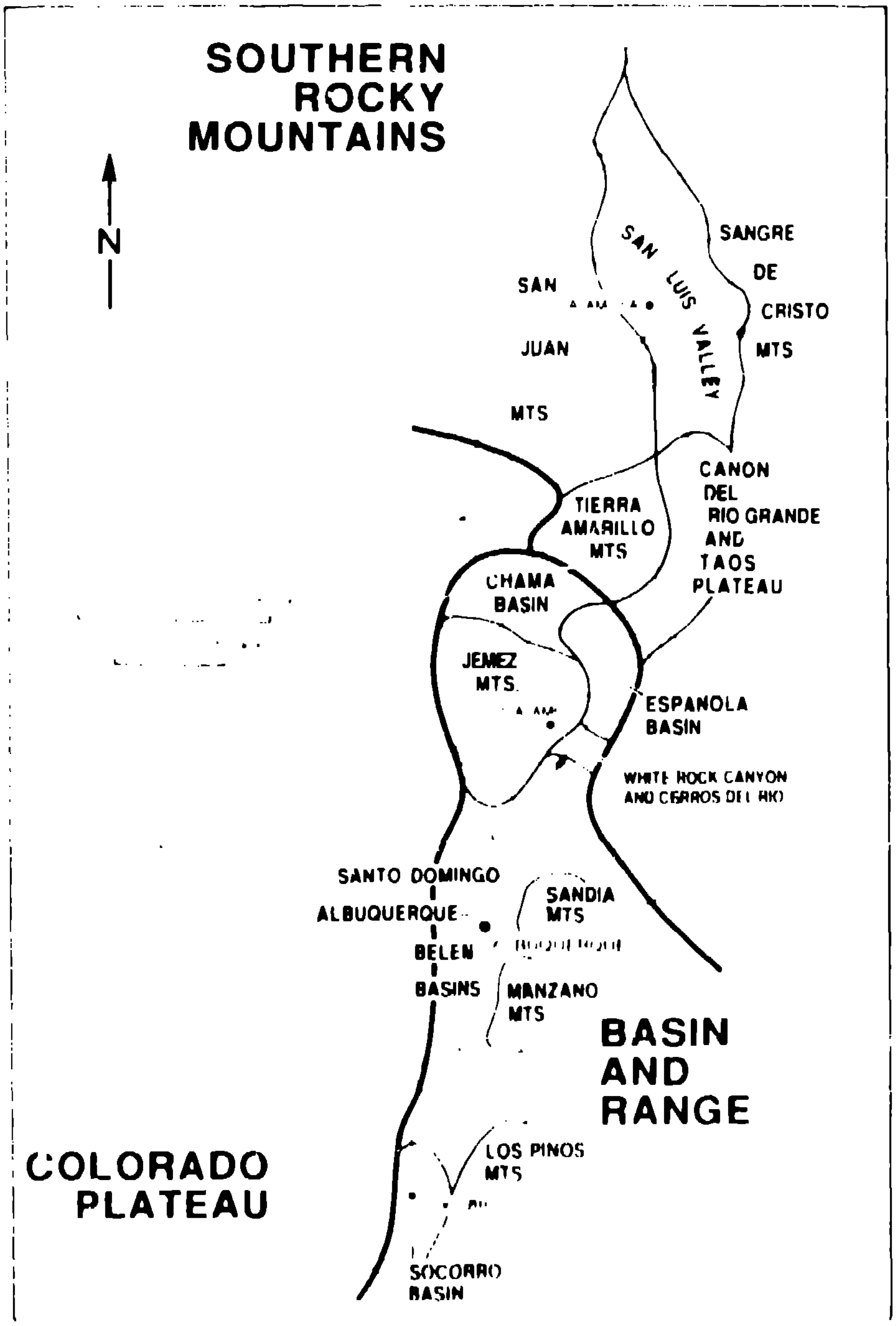


Figure 3.4 Landform divisions of the basin of the Northern Rio Grande

The Cañon del Rio Grande, a deep gorge etched into volcanic rock at the southern end of the San Luis Valley, marks the passage of the river into the Basin and Range Province. Further downstream, the Española Basin provides a broad alluvial valley for the course of the river, but volcanic rock associated with the Jemez Mountains and the Pajarito Plateau (the location of Los Alamos) confines the river to the narrow White Rock Canyon. Thereafter, the Rio Grande flows southward through a series of structural basins, with fault-block mountains on the east and west sides. Erosion of the fault zones produces abrupt boundaries between steep mountain slopes and gently inclined pediments leading down to the flood plain on the valley floor. Between White Rock Canyon and San Marcial the flood plain varies between 5 and 12 km in width.[10]

3.3 Geology and Sediments

A general review of the geologic materials underlying the northern Rio Grande system provides a foundation for understanding plutonium transport because of the strong association between radionuclides and sediment. Weathering of the bedrock and erosion of the resulting soils are primary pathways for movement of the contaminants. The distribution of highly erodible outcrops is a direct control on the geographic characteristics of the sediment and contaminant budget (Figure 3.5). The following general review provides a geologic overview and references significant publications that serve as entry points to a vast and detailed literature.

In the Rio Grande headwaters, the San Juan Mountains represent an immense pile of Tertiary volcanic rocks that present formations of variable erodibility at the surface.[11] For general locations of the this and other geomorphic areas discussed below, see Figure 3.2. Structurally, the mountains are a dome dissected by glacial and fluvial erosion. In detail, however, they consist of an array of basalt, latite, rhyolite flows, collapse calderas, ash flows, breccia, and reworked volcanic tuff that formed during a series of eruptions, probably during the early Tertiary.[12] Considerable erosion altered the surfaces of these deposits. Subsequently, during the Oligocene, Miocene, and Pliocene, new eruptions created intrusions of quartz latite, rhyolite, and some basalt into the older rock.[13] The later eruptions apparently emplaced many of the mineral deposits that fueled gold and silver mining activities in the area. Recent erosion of this vast array of rock types produces sediment of variable particle size. The basalt flows generate boulders that streams fail to transport long distances. The ash flows produce fine particles through rapid erosion of steep slopes. They may be a major source of fallout plutonium in the Rio Grande Reservoir, because some ash occurs in the higher portions of the watershed above the reservoir, combining high erodibility with likely infusions of fallout.

The Sangre de Cristo Mountains are a fault block range made up of a core of Precambrian gneiss with deformed Permian and Pennsylvanian sedimentary rocks and some Tertiary volcanics on its eastern side.[14] On the west, the portion that drains to the northern Rio Grande, sharply defined faults divide the resistant core from the neighboring San Luis Valley.[15] Although slopes are steep in this area, the crystalline rock is relatively resistant to erosion, and sediment bound radionuclides are probably

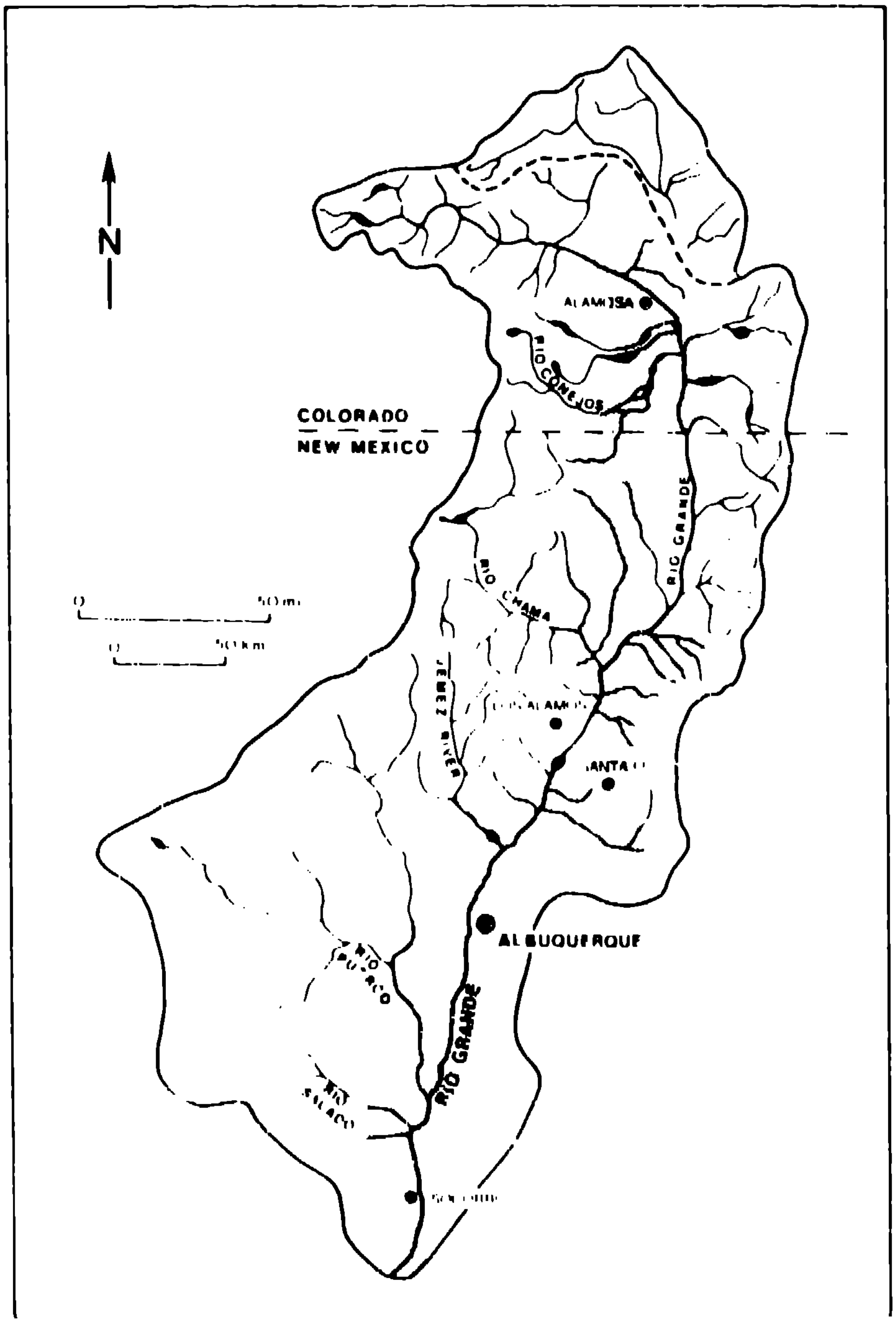


Figure 3.5 Distribution of highly erodible surface rocks in the basin of the Northern Rio Grande.

not as common here as in the San Juan Mountains.

On a geologic time scale, erosion of the San Juan and Sangre de Cristo Mountains has produced huge quantities of debris that fill the intervening San Luis Valley (structurally, the Alamosa Basin) to a depth of up to 9,000 meters.[16] The sediments filling the basin are interbedded gravels, sands, and clays, some resulting from deposition in Tertiary lake beds.[17] Present-day processes continue the general trend toward deposition: the Rio Grande does not incise the basin's sediments more than a meter, and the modern river aggrades continuously throughout its course in San Luis Valley.[18] Erosion of materials stored in the basin is unlikely, and the area is a sink for sediment and fallout plutonium.

The Cañon del Rio Grande, immediately south of the San Luis Valley, has geologic materials radically different from the valley. The canyon is a defile eroded by the Rio Grande into the Taos Plateau, a complex sheet of sediments and volcanic materials that extends from the San Juan and Tierra Amarilla Mountains on the west to the Sangre de Cristo Mountains on the east.[19] The Quaternary basalts and interbedded sedimentary units tilt gently toward the east and the Rio Grande, while alluvial fans and coalesced fans slope westward toward the river.[20] The stratigraphy of the area indicates tectonic instability characterized by warping and faulting throughout the Tertiary, accompanied by repeated drainage interruption and fan building.[21] The basalts shed large blocks into the canyon of the river, while the sedimentary beds lend instability to the side slopes, but the geologic conditions are not conducive to large-scale contributions of sediment to the river.

Some radionuclides may enter the main river in the Taos Plateau and Cañon del Rio Grande reach because uranium deposits occur naturally in some of the volcanic rocks of the area. Mining activities for uranium have been limited, but the element occurs in natural association with other minerals that occur in economically viable concentrations, especially in the Red River valley area.[22] Erosion of mine tailings or of natural country rock may introduce some uranium into the Rio Grande, but it is probably in extremely small quantities and no plutonium is involved.

The Española Basin, one of several basins along the course of river through the Rio Grande Rift Zone in New Mexico, is a shallow structural depression at least partly bounded by faults and is located immediately downstream from the Cañon del Rio Grande and the Taos Plateau.[23] Because the confluence of the Rio Grande and its principle tributary, the Rio Chama is within the Española Basin, it is the site of deposition for large amounts of poorly consolidated sands and gravels with interbedded lenses of finer materials. It is the first reach downstream from the San Luis Valley that contains significant quantities of Quaternary alluvium along the channel.[24] The Santa Fe Group and particularly the Tesuque Formation are geologic units that crop out over large areas of the basin and that provide easily eroded materials for fluvial transport.[25] These geologic formations form the buff and yellow colored hills so often depicted by local artists in paintings. General erosion of the formations has produced a landscape dominated by ramp like pediments extending at a number of levels from the course of the river to the foot slopes of the mountains.[26] Local erosion of these materials has produced badlands and emptied large quantities of fine-grained debris into the Rio Grande.[27] The Española Basin therefore represents the entry point for a significant portion of the sediment load of the northern Rio Grande downstream from the San Luis Valley. Although prospectors have found some uranium in the Santa Fe Group in the basin, amounts have been so small that they are not economical to mine.[28] Natural erosion probably adds some uranium to the Rio Grande from this source, but there is probably little fallout plutonium because of the low amounts of precipitation in the area.

The Rio Chama drains a particularly erodible part of the Española Basin, and thus contributes more sediment to the downstream areas than the upper Rio Grande. These erodible materials are parts of the Santa Fe Group that extend from the area of the confluence with the Rio Grande upstream to the vicinity of Abiquiu.[29] As is the case elsewhere in the Española Basin, badland terrain is common on the Sante Fe Group near Abiquiu,[30] and it was a common subject of many of Georgia O'Keefe's best-known landscape paintings. The Rio Chama enters the Abiquiu area after draining the southern San Juan Mountains and flowing through the Chama Basin, a broad shallow depression at the eastern edge of the Colorado Plateau.[31] The rocks in the Chama Basin are dominantly sandstones and shales,[32] but erosion rates are moderate, and sediment production is less than in the areas downstream from Abiquiu. Fallout plutonium eroded from the San Juan Mountains probably does not reach the lower river, because of intervening large reservoirs and dams. Uranium occurs naturally in several locations in the Rio Chama drainage (particularly in the Morrison Formation and Dakota Sandstone), so that erosion may introduce some radioactivity into the stream system. There are no known large or highly concentrated deposits.[33]

South of the Española Basin, the Rio Grande flows in White Rock Canyon, a 300 m deep gorge between the Pajarito Plateau on the west and the Cerros del Rio on the east. The Cerros del Rio, a westward extension of the Santa Fe Plateau, is an elevated basalt platform that is exceptionally resistant to erosion.[34] Although generally little sediment enters the river from the east side throughout the canyon, an exception is Cañada del Ancho, a stream draining exposed Santa Fe Group slopes of arkosic sands in the Buckman area, about 5 km downstream from Otowi Bridge.

The significance of the reach near Otowi in terms of plutonium is that it includes the entry point of sediment and radionuclides from Los Alamos Canyon which drains the only industrial source of plutonium in the northern Rio Grande. Los Alamos National Laboratory, is located on the Pajarito Plateau, a broad, dissected apron of Bandelier Tuff on the west side of White Rock Canyon.[35] Erosion by streams has etched deep canyons into the relatively smooth surfaces sloping from the Jemez caldera downward toward the Rio Grande and Rio Chama. Most of the erosion has occurred during three periods of the Pleistocene,[36] so that the resulting landforms have relatively unstable sideslopes. Erosion of all members of the Bandelier Tuff unit except a welded tuff member of limited extent produces mostly sand to gravel sized particles for transport in the region's river system. Contaminants released into these materials are therefore associated with sediment that is unlike the silt sized particles with which fallout plutonium is associated.

South of White Rock Canyon lies a structural low in the Rio Grande Rift Zone consisting of three interconnected basins: the Santo Domingo, Albuquerque, and Belen Basins. They provide a relatively broad, interconnected valley for the river and its deposits. In the Santo Domingo Basin, the erodible Santa Fe Group again crops out near the river.[37] Erosion of the unit injects large quantities of sediment into the main valley where some remains as channel and flood-plain deposits. An upper mid-Pleistocene pediment, known locally as the Oriz Geomorphic Surface, grades toward the Rio Grande at about 150 m above river level.[38] Numerous arroyos excavate the surface and conduct sediment to the modern channel and flood plain. Natural uranium occurs in sandstone of the Galisteo Formation in the Hagan Basin area of Sandoval County, east of the Rio Grande and south of Galisteo Creek.[39] The deposit was of ore quality, so that natural erosion may have contributed some radionuclides to deposits downstream in the Rio Grande. Plutonium is not involved.

The Albuquerque-Belen Basin contains fluvial sediments 6,000 m in depth.[40] Sediment eroded from this material in tributary arroyos, mostly from dissected Quaternary terraces, contributes to the load of the main stream and produces aggradation in the channel and on flood plains. Though the literature includes a variety of labels for them, the geologic formations that crop out in the basin are similar to the Santa Fe Group in age, particle size, and mobility.[41] The result is the infusion of large amounts of sand and silt into the Rio Grande system from nearby elevated terraces. The Jemez River derives most of its water from the Jemez Mountains and most of its sediment from poorly consolidated Tertiary materials south of the mountains including the Santa Fe Group.[42] It is a major component of the sediment system near the junction of the Santo Domingo and Albuquerque Basins.

At the southern end of the Belen Basin, the Rio Puerco and Rio Salado join the Rio Grande from the west. The two tributaries drain several hundred square kilometers of Colorado Plateau terrain consisting of erodible sandstones and shales, so that the two streams carry high sediment loads. The Rio Puerco, for example, commonly has 400,000 ppm sediment in floods, with a maximum record of 680,000 ppm; 75 per cent of the load is sand.[43] Most of the materials in the Rio Puerco are fine grained: fine sand, silt, and clay.[44] The tributaries derive additional sediment from erosion of the Santa Fe Group formations commonly found in the southwestern portion of the Albuquerque-Belen Basin.[45] In addition to plutonium related to global fallout, the Rio Puerco also transports in its sediments some natural uranium from mining activities in the Grants area.[46]

Between the southern end of the Santo Domingo-Albuquerque-Belen Basin and Elephant Butte Reservoir, the Rio Grande flows through two relatively narrow troughs, the Socorro and San Marcial Basins. Volcanic rocks in the forms of cinder cones, basalt flows, and tuffs are common along the margins of the Rio Grande Valley.[47] Their erosion contributes little to the sediment and contaminant loads of the river.

3.4 Climate

The climate of the northern Rio Grande varies greatly with elevation, ranging from warm dry deserts in the south to alpine climates in the San Juan Mountains. Climate is important in understanding the dynamics of plutonium in the Northern Rio Grande because precipitation delivers fallout to the surface and provides the mass and energy driving the kinetics of the river systems. Within the watershed of the northern Rio Grande above Elephant Butte Reservoir, precipitation ranges from an annual minimum of less than 400 mm near Socorro to a maximum of over 2000 mm on some of the peaks of the San Juan Mountains.[48] The precipitation has an unequal distribution, with the three areas of maximum values concentrated in the mountains: the San Juan range which has the highest values, the Sangre de Cristo Mountains, and the Jemez Mountains (Figure 3.6). This distribution of precipitation shows why water source areas for stream flow are severely restricted. Throughout its length in New Mexico, the Rio Grande receives little augmentation because precipitation inputs decrease from north to south.

Variation of precipitation is also highly seasonal, with most of the input in the mountains in the form of snow. The maximum annual recorded snowfall in the basin is at Wolf Creek Pass in the San Juan Mountains, and often exceeds 9 m.[49] In the northern portion of the basin, the meltwater from the winter snowpack provides the annual peak of runoff in late spring months. In the central portion of the basin, an additional, smaller peak often results from summer convective precipitation. In the southern extremities of the area, the wettest months are in late summer.

Temporal variation in precipitation also occurs on decade and century long time scales. While the annual precipitation record for Santa Fe shows no long term trend, the frequency of rainy days and the mean daily rainfall has varied systematically since records were first kept in the 1850s.[50] Rainfalls greater than 12.5 mm became progressively more frequent throughout the late 1800s, with the trend peaking during the 1920s. Since that time, despite large interannual variation, frequency of intense rainfalls has generally declined. During the same century long record, the mean daily rainfall declined during the late 1800s, reaching a minimum during the 1920s before beginning an increase later. Thus, during the late 1800s, rainfall occurred increasingly often, but in declining amounts during each event. In recent decades, there have been fewer precipitation events, but the ones that do occur have issued larger amounts of rainfall.

The implications of this variation for the transport of sediment and associated contaminants is unclear. It is possible that the arroyo cutting during the late 1800s and early 1900s was partly a response to high intensity, low frequency rainfalls.[51] If this hypothesis is correct, more recent trends may signal a return to the highly erosive conditions in arroyos seen a century ago. The behavior of the main river, however, probably responds indirectly to this control, because the erosion of tributary arroyos inundated the main channel with sediment, causing aggradation and the development of braided conditions, a phenomenon observed during and immediately after the last arroyo cutting episode in the late 1800s and early 1900s. The hydrologic behavior of

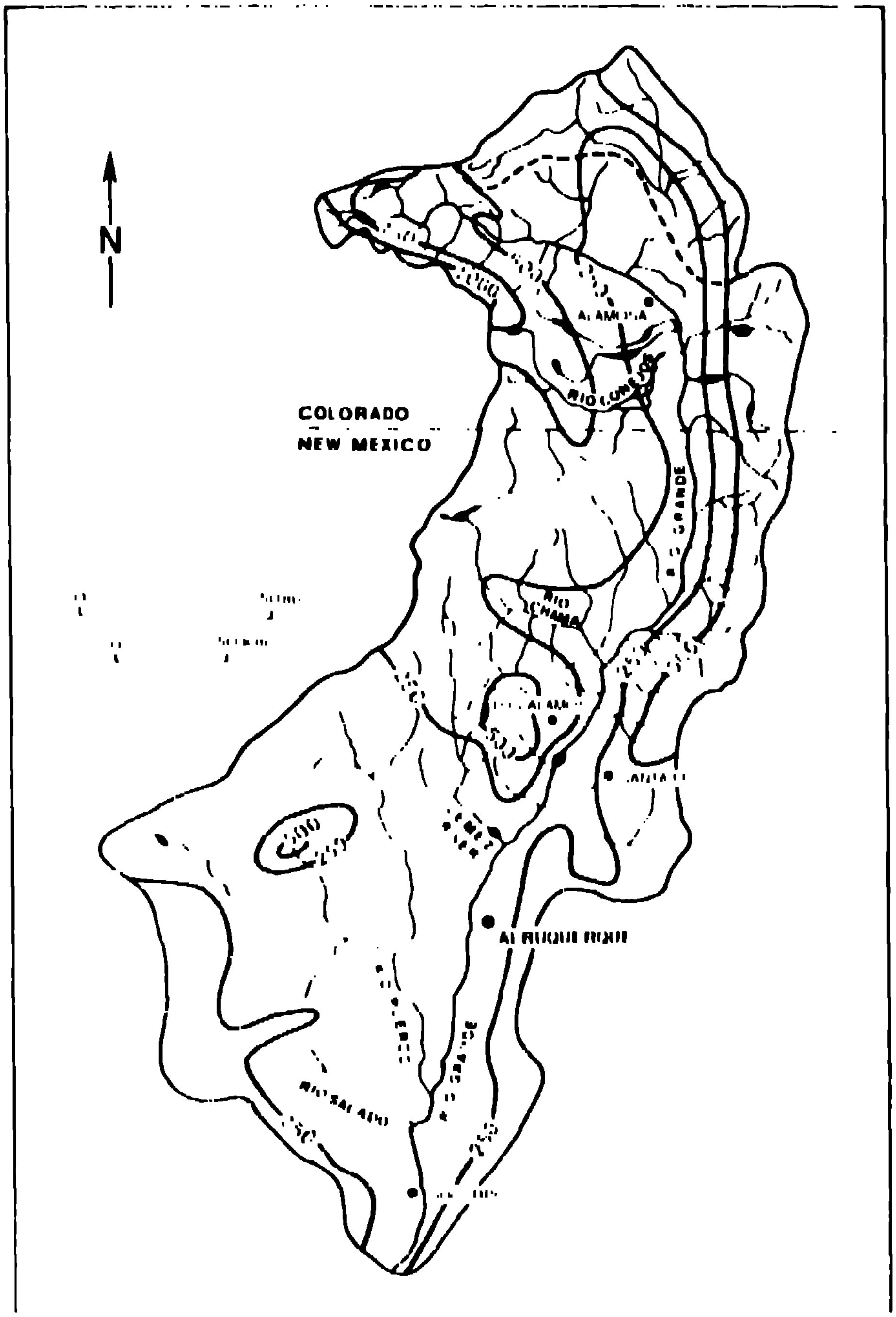


Figure 3.6 Annual precipitation (mm) in the basin of the Northern Rio Grande (modified from Williams, 1986, and Erickson and Smith, 1985).

the main stem of the Rio Grande is more closely tied to precipitation events in the mountain source areas, and their temporal variability is not clearly known.

3.5 Vegetation

Vegetation influences the dynamics of plutonium in the regional river systems because the nature of the plant cover influences the amount and timing of runoff. Vegetation also influences the amount of surface erosion and the production of sediment available for transport in the streams. The vegetation of the Northern Rio Grande Basin occurs in two distinct geographic distributions, upland and riparian. The distribution of upland vegetation of the basin reflects geologic, pedologic, precipitation, and geomorphic controls. Montane conifer forests grow in the well-watered highland areas of the San Juan, Sangre de Cristo, Jemez, and Cebolleta Mountains (Figure 3.7). At lower, drier elevations, the forests give way to Great Basin conifer woodland.[52] In the Northern Rio Grande Basin these woodlands consist mostly of pinyon pine (*Pinus edulis* Englem.) and juniper (*Juniperus scopulorum* Sarg.) that often occur as widely spaced trees with seasonally barren ground between the trees. The barren ground is susceptible to rapid erosion during infrequent severe storms.[53]

In those parts of the basin too arid to support even the pinyon pine and juniper, Great Basin grasslands occur. This vegetation community is particularly widespread in the southern half of the basin, and often occurs on the highly erodible Santa Fe Group. In the northern half of the area above Elephant Butte Reservoir, Great Basin Desert scrub communities cover dry areas with mixture of grass and low woody stemmed plants. At the southern extremities of the area, high annual temperatures and little rainfall produce semidesert grassland and Chihuahuan desert scrub, communities that provide little stability for erodible soils on terraces and pediments near the river. Riparian communities owe their characteristics to the water rich environments along streams and are substantially different from the surrounding upland vegetation. As with upland vegetation, riparian communities also vary with elevation in the Northern Rio Grande Basin.[54] Because riparian vegetation directly influences river processes it is discussed in several subsequent chapters in some detail.

The general environment of the Rio Grande above Elephant Butte Reservoir, therefore, is highly variable in terms of its landscape, geology, water, and vegetation. The geography of these features influences the contributions of fallout plutonium to the Rio Grande and controls the flow of water through the streams providing a transport mechanism for contaminants. The interactions of all these factors produce a definite characteristic behavior of water in the Northern Rio Grande system defining the regional hydrology, the subject of the next chapter.

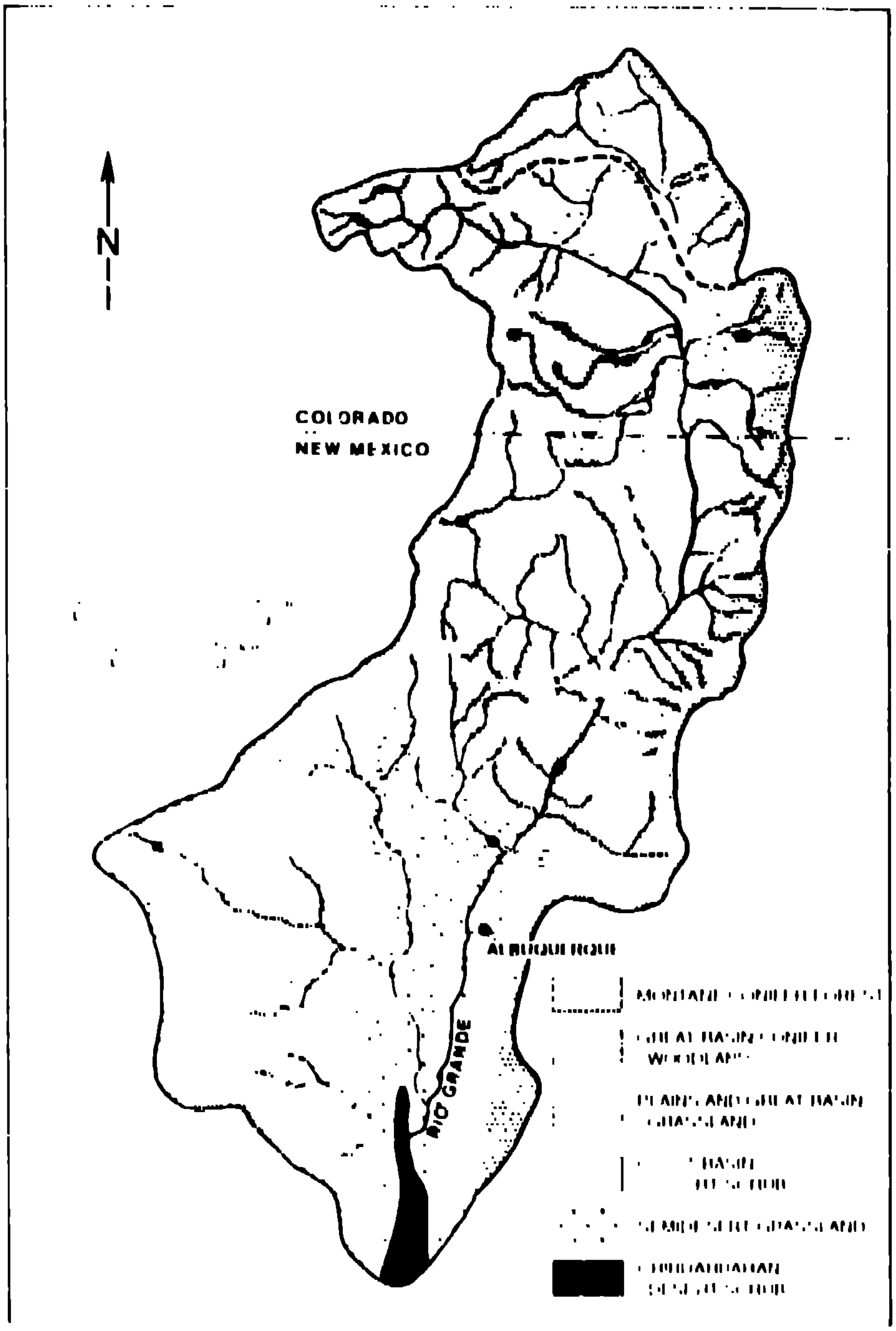


Figure 3.7 Upland vegetation in the basin of the Northern Rio Grande (modified from Brown *et al.*, 1980).

Figure 4.1 The U.S. Geological Survey [illegible] Embudo, New Mexico, was the first [illegible] station established [illegible] the first measurements made in 1889. The [illegible]

CHAPTER 4. REGIONAL HYDROLOGY

4.1 Sources of Data

Precipitation and elevation provide the energy that is the primary driving force behind river processes within the Northern Rio Grande Basin. The geographic variation in streamflow and the temporal characteristics of its magnitude and frequency explain how water, sediment, and contaminants such as plutonium move through the system. An accurate accounting of stream flow is therefore essential in the development of a basin-wide budget for water, sediment, and contaminants. Calculations for the mechanics of sediment transport (and the transport of associated contaminants) depend on measurements of streamflow from a variety of places within the system. The purposes of this chapter are to outline the nature of the basic data for streamflow in the basin, and then to define and explain the temporal and geographical variation in the system. The outcome of this effort is to establish a regional streamflow budget.

The U.S. Geological Survey has maintained an extensive network of stream gages for the Northern Rio Grande to measure water and sediment discharges. The river is one of the most extensively instrumented in world, and has higher quality data than any other arid-semiarid drainage basin of similar size. Interest in adjudication of water rights and distribution of the resource led to the establishment of the first long-term stream gage in the United States at Embudo, New Mexico in 1885 (Figure 4.1).[1] The gage is the longest-running measurement site in the country. Construction and maintenance of reservoirs later led to an interest in sediment transport rates, and from the late 1940s to the present, some gages have produced sediment information in addition to water discharge data (Figure 4.2).

Scores of stream gages have operated within the basin at various places and times, but the construction of a regional budget for water and sediment depends upon a limited number of long running, high quality gages. Fourteen such sites span the basin from the San Juan Mountains to San Marcial (Figure 4.3, Table 4.1). Even these main gages have variable lengths of record, and not all provide sediment data. Nonetheless, taken as a group, these gages represent the best source of information about the surface water hydrology of the Northern Rio Grande.

Three closely related repositories store the data from the gages. First, the *U.S. Geological Survey Water Supply Paper* series provides a permanent paper based record for the information. Most major research libraries stock the series which includes some summaries in addition to the basic daily information. Second, the U.S. Geological Survey also maintains a computer based system for hydrologic data that includes all the water and sediment information. This system, WATSTORE, is relatively complete, but is difficult to use for those not in close and direct contact with the Survey. Finally, all the data in the first two sources are available in a personal computer based system, HYDRODATA, marketed by EarthInfo, Inc. of Boulder, Colorado. HYDRODATA stores all the information about the gaging sites and their the

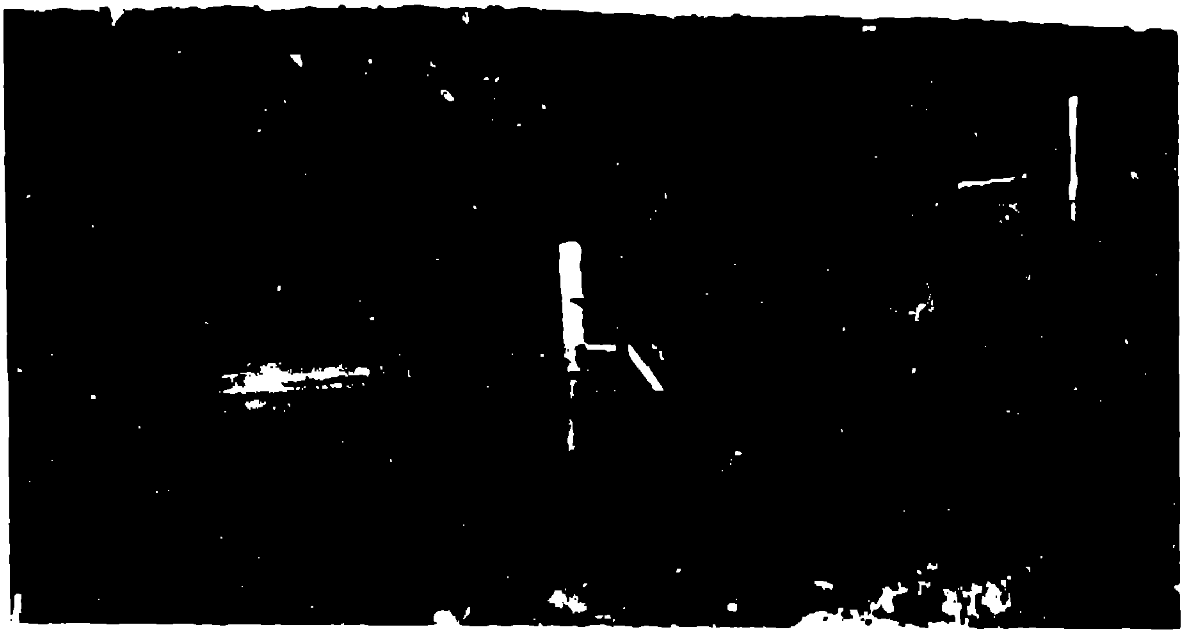


Figure 4.2 Stream gage on the Jemez River immediately below the Jemez Dam Site. The view shows the stilling well (vertical cylinder) for stage or depth of flow measurements and an overhead cableway for moving a current meter and sediment sampler across the channel (U.S. Geological Survey Photography and Field Records Library, Denver, G. P. Williams Photo #83).

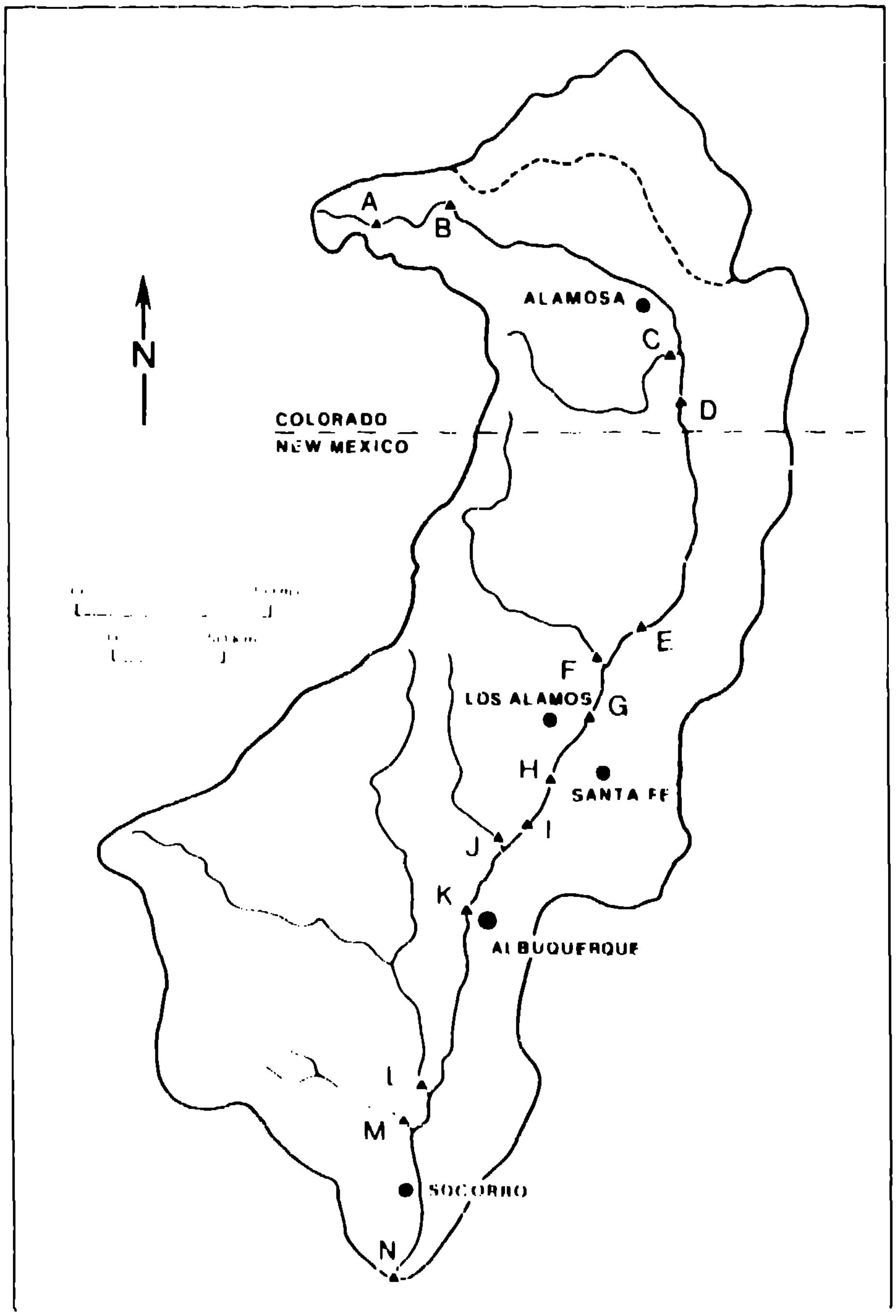


Figure 4.3 Locations of major stream-gaging sites in the basin of the Northern Rio Grande. See Table 4.1 for data.

TABLE 4.1 MAJOR STREAM GAGES IN THE NORTHERN RIO GRANDE SYSTEM

(LETTERS KEYED TO LOCATIONS ON FIGURE 4.1)

	Gage ID	Drainage Area (sq mi)	(sq km)	Water Data	Sediment Data
A	Rio Grande at Thirtymile Bridge near Creede, Colorado				
	2135	163	422	1923	none
B	Rio Grande at Wason, below Creede, Colorado				
	2170	705	1,826	1907 1954	none
C	Conejos River near Lasauses, Colorado				
	2490	887	2,297	1921	none
D	Rio Grande near Lobatos, Colorado				
	2515	7,700	19,940	1899	1969
E	Rio Grande at Embudo, New Mexico*				
	2795	10,400	26,930	1889	1970
F	Rio Chama near Chamita, New Mexico				
	2900	3,144	8,140	1912	1948
G	Rio Grande at Otowi Bridge near San Ildefonso, New Mexico				
	3130	14,300	37,037	1895	1947
H	Rio Grande at Cochiti, New Mexico				
	3145	14,600	37,810	1924 1970	none
I	Rio Grande at San Felipe, New Mexico				
	3190	16,100	41,700	1925	1975
J	Jemez River below Jemez Dam, New Mexico				
	3290	1,038	2,690	1936	1966
K	Rio Grande at Albuquerque, New Mexico				
	3300	17,740	45,950	1941	1969
L	Rio Puerco near Bernardo, New Mexico*				
	3530	7,350	19,040	1939	1947
M	Rio Salado near San Acacia, New Mexico				
	3540	1,380	3,570	1947	1947
N	Rio Grande at San Marcial*				
	3584	27,700	71,740	1895	1946

Note: * - combined data for two closely associated gaging sites.

data on optical disks that are readable using personal-computer hardware and software. The streamflow and sediment data in this book are from either the *Water-Supply Paper* Series or from HYDRODATA (Appendix B).

The gaging data provide three types of information useful for exploring the transport and storage of plutonium in the river system: annual water yield, the annual flood series, and annual sediment yield. For hydrologic purposes, the water year begins on October 1 and ends on September 30 the following year. This arrangement is convenient, because many mid-latitude streams, including the Rio Grande, experience an annual cycle of discharge that is at a minimum in early autumn. A date at the end of this season is therefore a useful starting and ending time for accounting purposes.

Annual water yield refers to the total amount of water that passes the gaging site in a given year. It is a measure of the total amount of water and therefore of the total energy available to perform work, including the transportation of sediment and contaminants. Likewise, annual sediment yield refers to the total of suspended sediment that passes the gaging site in a given year, and it is one measure of the work accomplished by the stream.

The annual flood series, also known as the annual maximum series, is the set of the peak discharges that have occurred in each of the years of the entire gaging record.[2] There is one value for each year, representing the single largest discharge recorded during that year. Floods are important in assessing the geomorphologic and sedimentologic work accomplished within a river system, because most major channel changes and a large percentage of the sediment (and thus contaminant) transport occur during flood periods. The amount of work, change, or transport is often directly related to the magnitude of the annual flood (Figure 4.4),[3] which is also a reliable indicator of the timing of major system adjustments. The magnitude of the annual flood is often strongly correlated with the annual sediment yield (Appendix B3).

4.2 Water Yield and Annual Floods

The records for the river at Otowi Bridge and at San Marcial describe the time series for water yield in the Northern Rio Grande. At Otowi Bridge the data reflect the total amount of water available for work each year between 1895 and 1985, with the exception of four years without data. Broad temporal trends in water yield show that the first two decades of the twentieth century were a time of maximum yield, but thereafter, a general decline is apparent (Figure 4.5). Two exceptionally high yield years occurred in the early 1940s. A minimum of yield occurred in the late 1950s, and between the late 1950s and the present there has been a steady increase.

The trends at Otowi Bridge at the upstream end of the study area are similar to trends at San Marcial at the downstream end (Figure 4.6). The differences between the two records are attributable to the hydrologic adjustments in streamflow between the two sites: irrigation withdrawals, flow loss through percolation into the bed, evaporation, additions from tributaries, and the closure of Cochiti Dam in

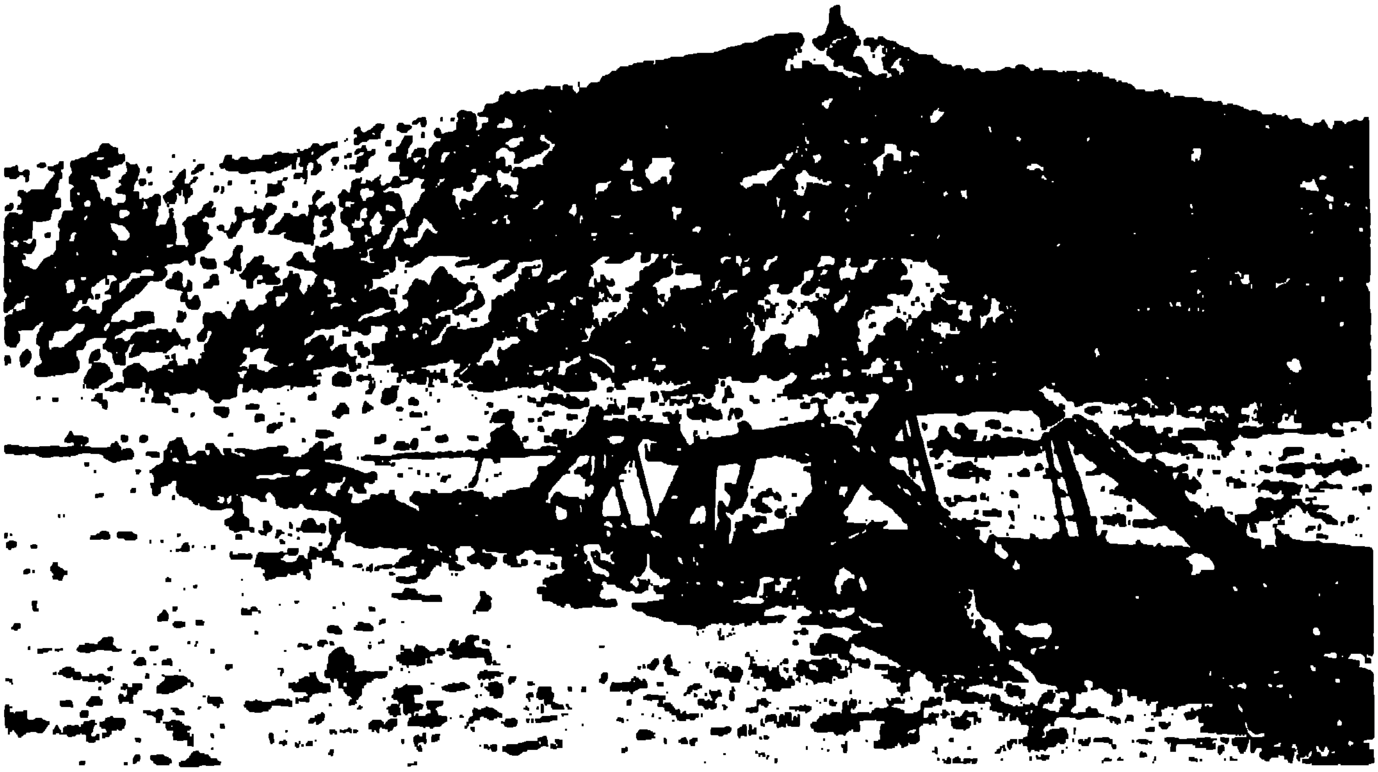


Figure 4.4 A flood on the Rio Grande destroys a bridge during the 1930s (Los Alamos Historical Society Photo #R3458C)

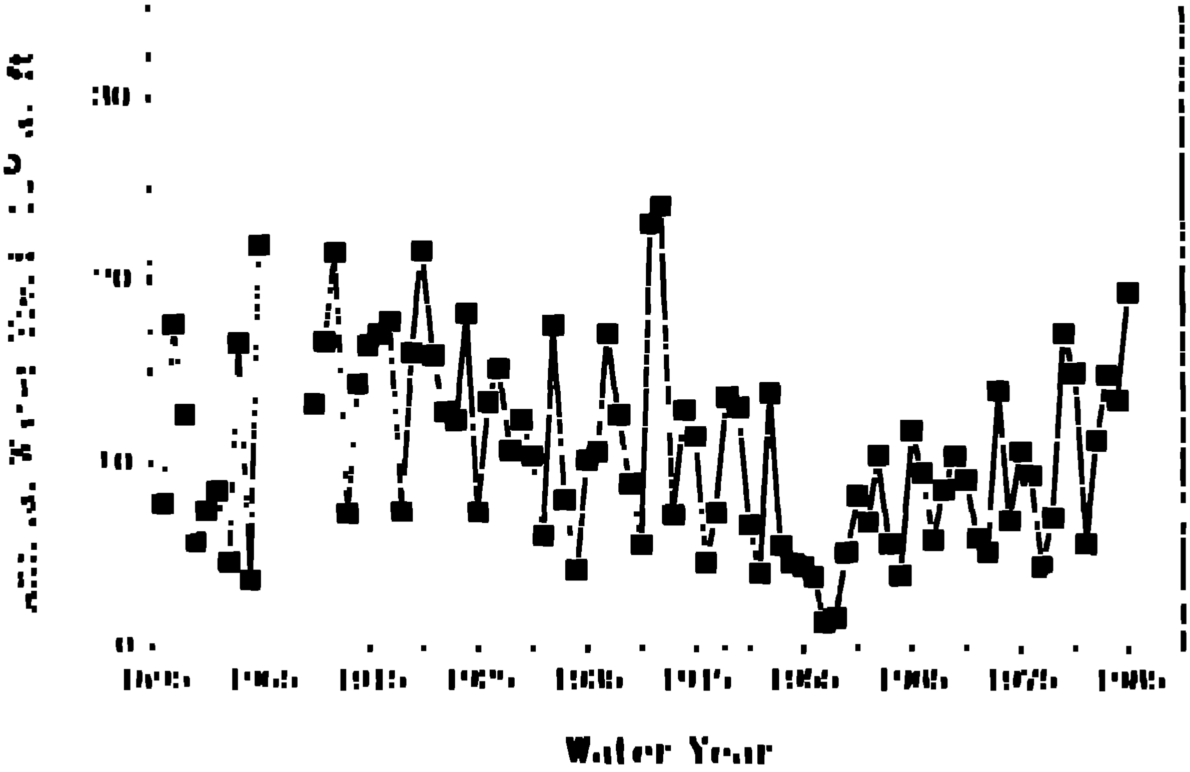


Figure 4 5 Annual water yield, Rio Grande at Otowi (U.S. Geological Survey data).

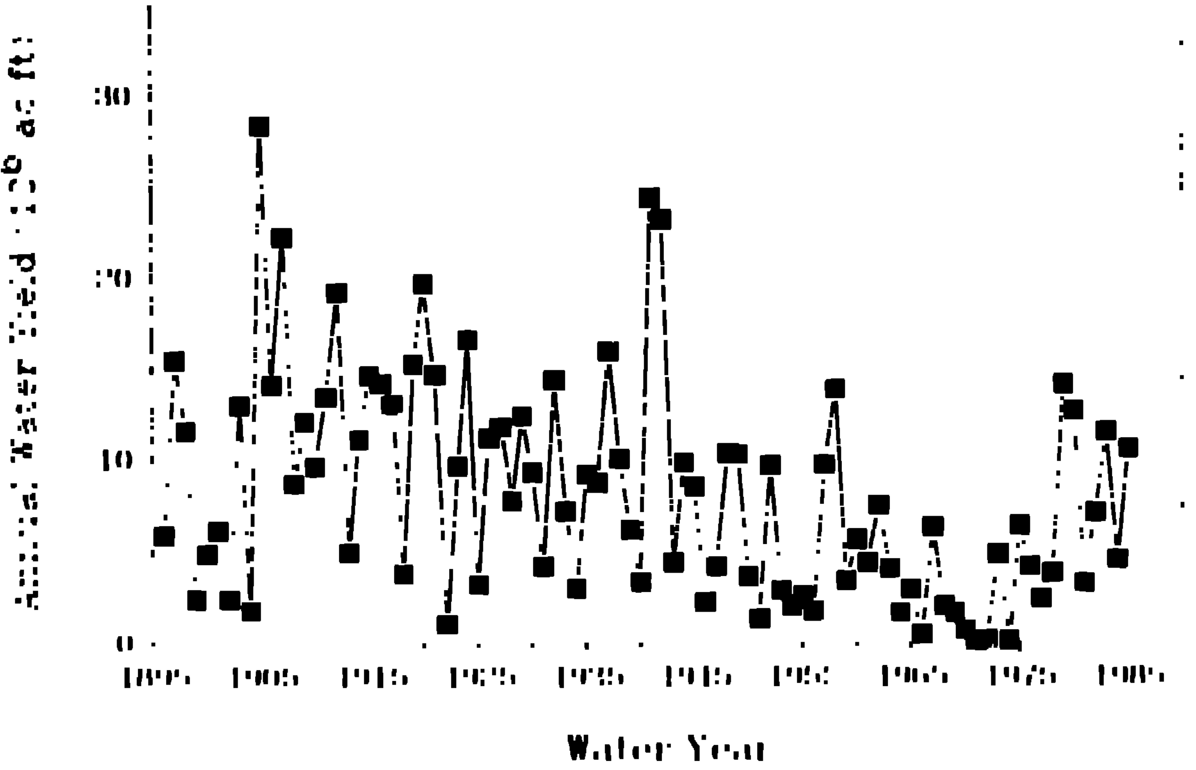


Figure 4.6 Annual water yield, Rio Grande at San Marcial (U.S. Geological Survey data).

1973, which impacted the flow at San Marcial but not at Otowi Bridge.

Temporal trends in annual flood peaks for Otowi are similar to the water yield trends (Figure 4.7), in part because a substantial percentage of the annual yield is associated with the spring snowmelt flood, a months-long event that usually includes the highest discharge in any given year. The most recent major flood was in 1941, a year of wide-spread flooding throughout the southwestern United States. Since that time, the annual flood peaks gradually declined until the 1980s, when a slight upward trend appeared. The annual flood series for San Marcial at the downstream end of the study area is similar to the Otowi Bridge record, except attenuation of the 1941 flood relegated it to secondary status relative to events in 1930 and 1937 (Figure 4.8).

Because flood flows generate high amounts of energy for sediment transport and river channel change, the temporal trends of the annual flood series are important in explaining the transport and storage of plutonium associated with river sediments. Before plutonium appeared in the Rio Grande system, the river functioned at a higher energy level than after plutonium was available. At Otowi, mean annual flood peak after 1944 was 66 percent lower than the mean values before that year; at San Marcial the mean annual flood during the post-1944 period was only 46 percent of the mean in the pre-1944 period. These drastic declines suggest that during the mid 1940s to the 1980s period, the system experienced a declining energy regime, and that processes during the time when plutonium was in the system were different from the processes in the system before the element was present. After the mid 1940s the channel was more stable and in general became progressively smaller.

The reasons for the temporal variation in water yield and flood peaks are obscure, but there are three commonly cited explanations. First, during period of water yield decline, federal and local governments erected numerous dams on upstream tributaries.[4] The reservoirs of these structures lose water through evaporation, decreasing downstream yield. The magnitude of such loss in water yield is not likely to be as large as the recorded decline, however, and the presence of the reservoirs did not prevent the increase in yield in the late record, so that reservoir construction is probably a minor influence. The influence of dams on flood peaks is more convincing: as more structures appeared, flood peaks clearly declined downstream.

Second, land management strategies may have influenced the water yield record. Overgrazing and extensive logging in the late 1800s and early 1900s may have accelerated runoff rates, and produced high water yields in rivers by removing vegetation from hillslopes. Later conservation measures may have reversed the trends.[5] Experiments on small western watersheds have demonstrated that increased grazing activity leads to higher water yields and larger floods.[6] There is no evidence, however, that these effects are cumulative in very large western river basins on the scale of the Rio Grande where the effects of climate are more pronounced.[7] Some research has suggested similar significant limitations for the land management explanation in eastern river basins.[8]

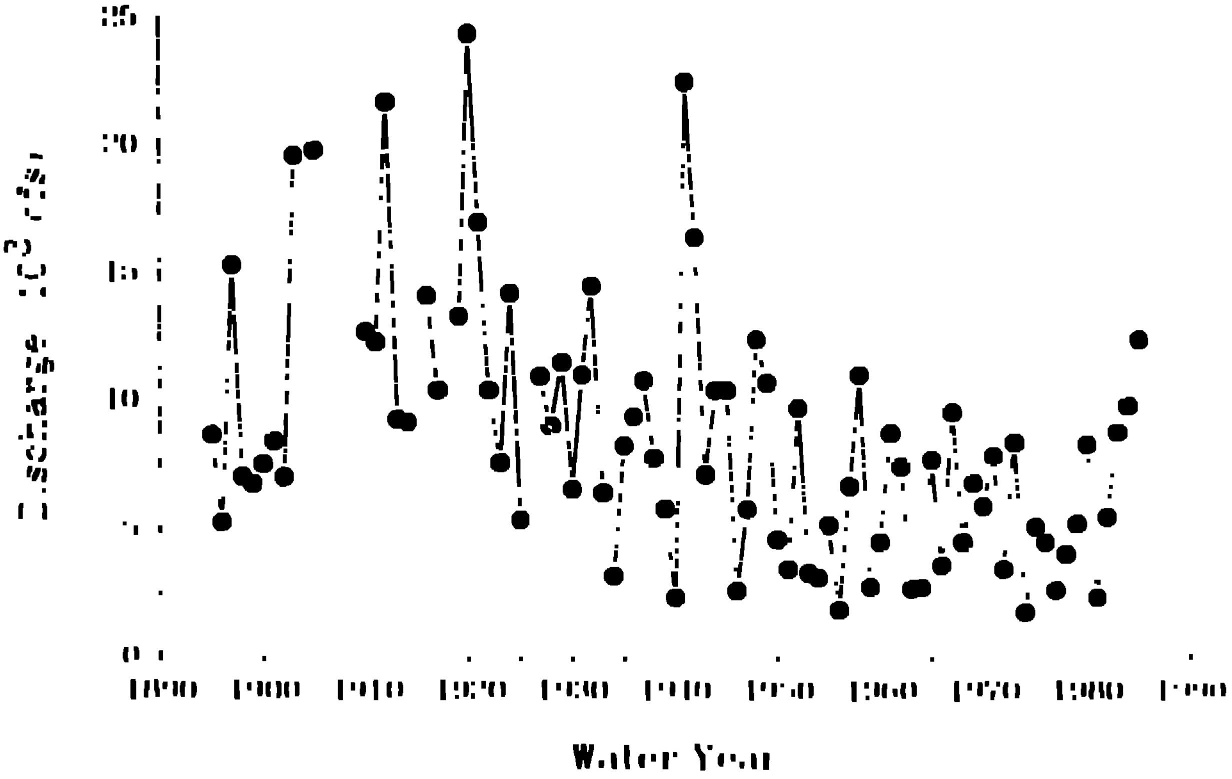


Figure 4.7 Annual maximum flood series, Rio Grande at Otowi (U.S. Geological Survey data)

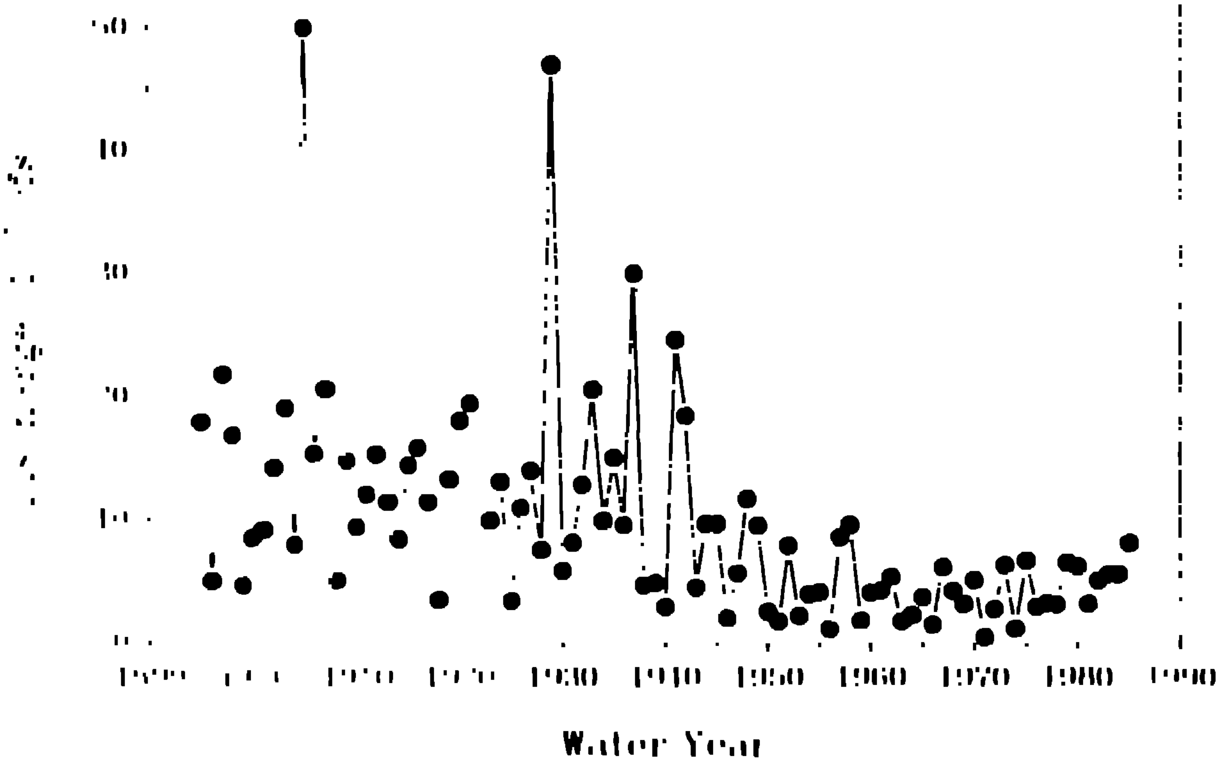


Figure 4.8 Annual flood series, Rio Grande at San Marcial (U.S. Geological Survey data).

In addition to water yield, flood peaks on tributaries also respond to land management in the Rio Grande basin,[9] but the connection between local land management and response in the main river is unproven. Historical records do reveal that some peaks in flow on the Rio Grande were related to logging activities in the nearby mountains in northern New Mexico. During the period 1909-1926, logging in the watersheds of the Rio Santa Barbara and Rio del Pueblo (tributaries of the Rio Grande north of Española) influenced the flow of the main river in the spring of each year.[10] During much of the year, timber cutters harvested logs from the mountain forests and stored them along the tributary streams. Temporary crib dams on the tributaries held the spring runoff until large volumes of water accumulated. The loggers then broke the dams to release the stored water, raising the discharges in the Rio Grande to levels that permitted their store of logs to float easily downstream. They floated the logs through the Rio Grande to an area near Cochiti Pueblo, where a tie boom across the river trapped them and made them available for nearby sawmills. The high flows generated by this mechanism contributed to the maintenance of the Northern Rio Grande as a wide, shallow, braided stream during the early twentieth century. After logging and with reforestation, the water contribution of tributary watersheds to the Rio Grande decreased and became less erratic.[11]

Finally, an important explanation for the water yield and flood peak variation is that they respond to climatic changes, especially the magnitude and frequency of atmospheric circulation patterns that deliver moisture to the basin from ocean sources.[12] Records of patterns over the western United States show considerable variation over the past century, with New Mexico precipitation showing marked declines and increases coincidental with the changes in water yield and flood peaks.[13] Since 1900, small watersheds in northern New Mexico have experienced declines in runoff, primarily because of decreased winter precipitation and snowpacks. Summer precipitation (falling as rain during dry soil periods that generate little runoff) has increased at the same time as the winter decrease, but an overall decline results from the inability of the summer additions to compensate for the loss of snowmelt.[14]

The general influence of climate may be assessed through the standard measures of precipitation and temperature, but because the two mutually influence the availability of water in the surface hydrologic system, a combined measure is more useful. The Palmer Hydrologic Drought Index is a daily metric combining temperature, precipitation, and a lag factor that can have a strong connection to river hydrology.[15] Figure 4.10 shows that there have been clearly defined trends throughout the twentieth century. Fluctuations in river responses such as water yield and flood peaks appear to closely reflect the change in the drought index, showing the strong connection between moisture conditions (and thus, the climatic conditions that cause them) with the large regional river system. A combination of all three major influences on river hydrology (dams, land management, and climate) is probably required for a detailed explanation of changes in twentieth century river flows in the Northern Rio Grande.

The implications of the water yield records for plutonium mobility in the Northern Rio Grande are that during the time period when plutonium was likely to be entering

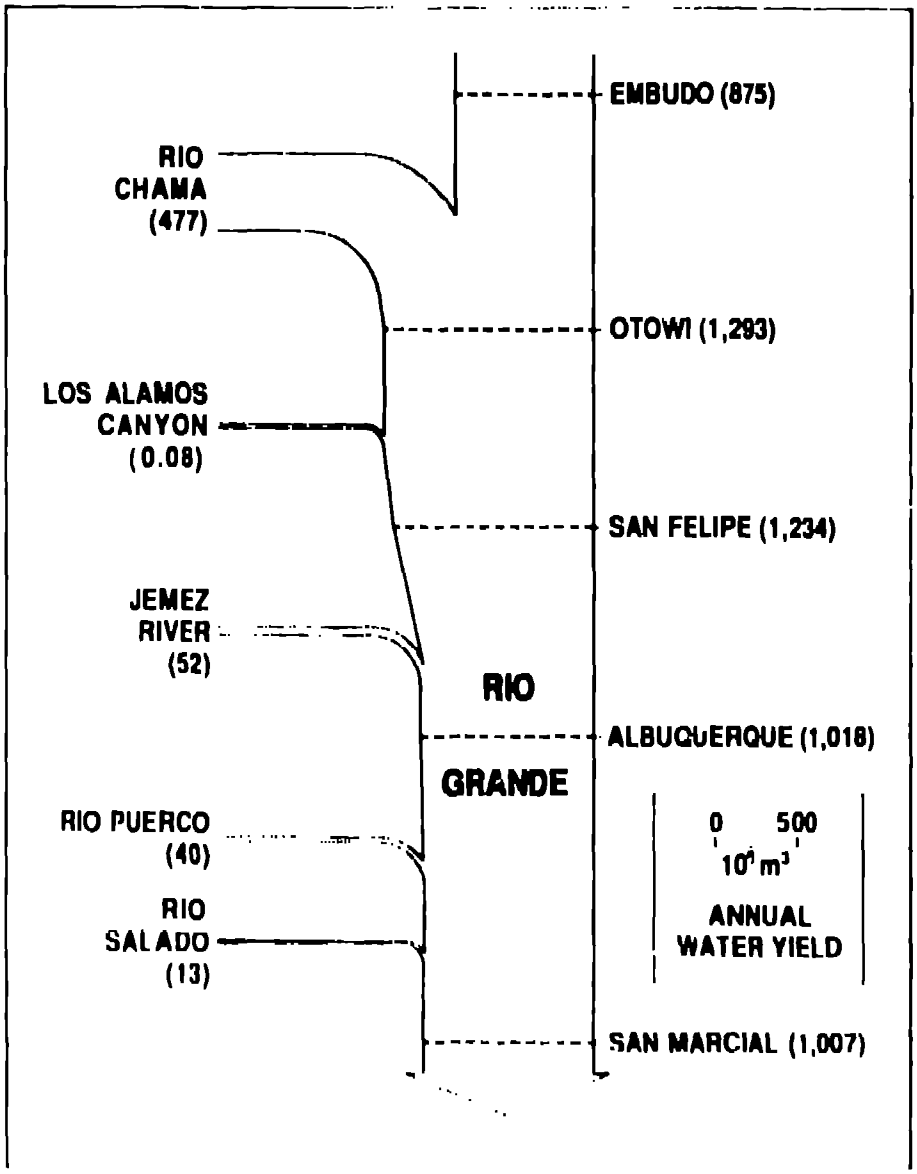


Figure 4.9 Flow diagram for annual water yield budget of the Northern Rio Grande.

the system in greatest quantities from fallout and laboratory releases (the late 1940s to the early 1960s), the amount of energy in the system likely to be available to transport the plutonium was at or near a minimum. Reversals of the trends in the 1980s suggests that remobilization of sediments and associated plutonium is a possibility

4.3 Regional Streamflows and Floods

The annual water yield and floods also vary geographically throughout the system. The spatial variation explains in part why transport or deposition occurs in particular places within the channel network. Although the drainage area consistently increases in the downstream direction through the study area (Figure 3.3), the annual water yield declines in the downstream direction (Figure 4.10). Within the study area, and probably within the entire Rio Grande Basin, the maximum annual water yield occurs at Otowi Bridge, where inflows from the upper Rio Grande at Embudo combine with the inflows from the Rio Chama. Downstream from Otowi, additions from tributaries are small, and the main channel loses water through evaporation, transpiration by riparian vegetation, irrigation withdrawals, and transmission losses through bed percolation. Between Otowi Bridge and San Marcial, annual water yield declines by about 23 percent.

The geographic significance of this decline is that although sediment and plutonium contributions to the main stream increase with increasing drainage area, the total amount of streamflow available to transport the materials becomes progressively less downstream. It may be that the stream does not use all its available transport capacity in the northern part of the system, so that it can accommodate the increased load, but the downstream decline in transport capacity is one reason to expect storage of sediments and plutonium within the system between Otowi and San Marcial.

The geography of annual flood peaks is not as simple as the water yield distribution. Annual floods on the upper Rio Grande at Embudo and on the Rio Chama combine to create a minor maximum at Otowi Bridge (Figure 4.11). The flood maximum declines in the downstream direction through Albuquerque, but floods from the Rio Puerco and Rio Salado create the regional (and probably the basin wide) main stem maximum at San Marcial[16] The Rio Puerco has annual floods that are similar in magnitude to the annual floods of the upper Rio Grande and Rio Chama, while those of the Rio Salado are similar to Rio Grande floods at San Marcial, all despite the relatively small sizes of the tributaries. The Rio Puerco and Rio Salado drain semiarid basins that lack the dense vegetation cover of the larger basins, leading to flash floods that are often larger than those on the main stem

Flood peaks represent a gross measure of the ability of streams to move sediments, so that these data indicate a broadly similar ability to entrain materials throughout the system The result is that during the mean annual flood, seemingly small tributaries can move as much material as is moved in the main channel Also, water yield and annual flood magnitude on the main stream are often not closely correlated with annual sediment transport because of the large out of phase contributions of the tributaries (Appendix B3) This arrangement implies that as

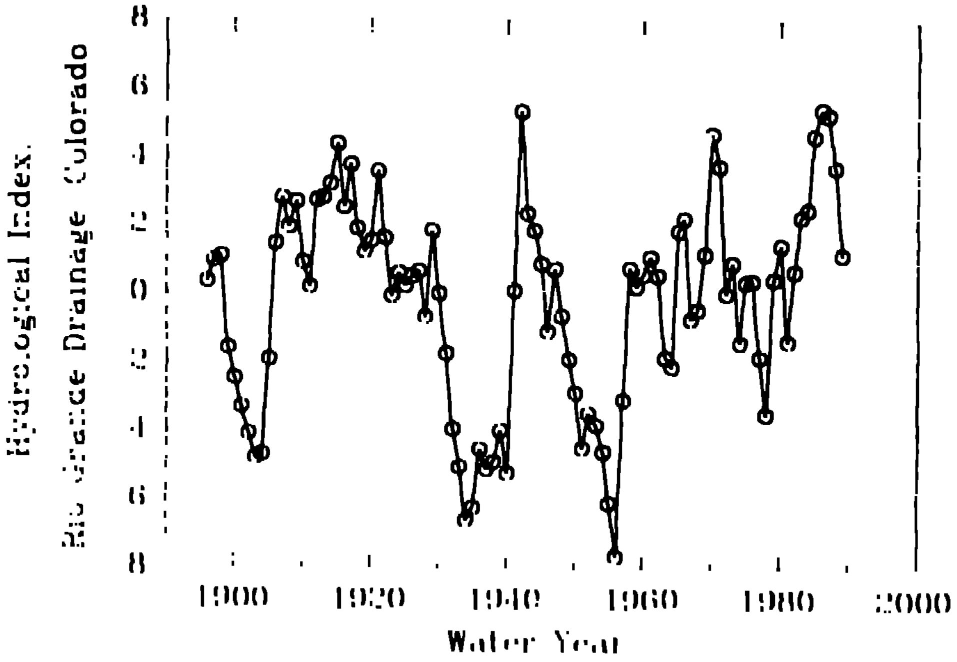


Figure 4.10 Annual mean values for the Palmer Hydrologic Drought Index for the water source areas of the Northern Rio Grande (National Climatic Data Center data).

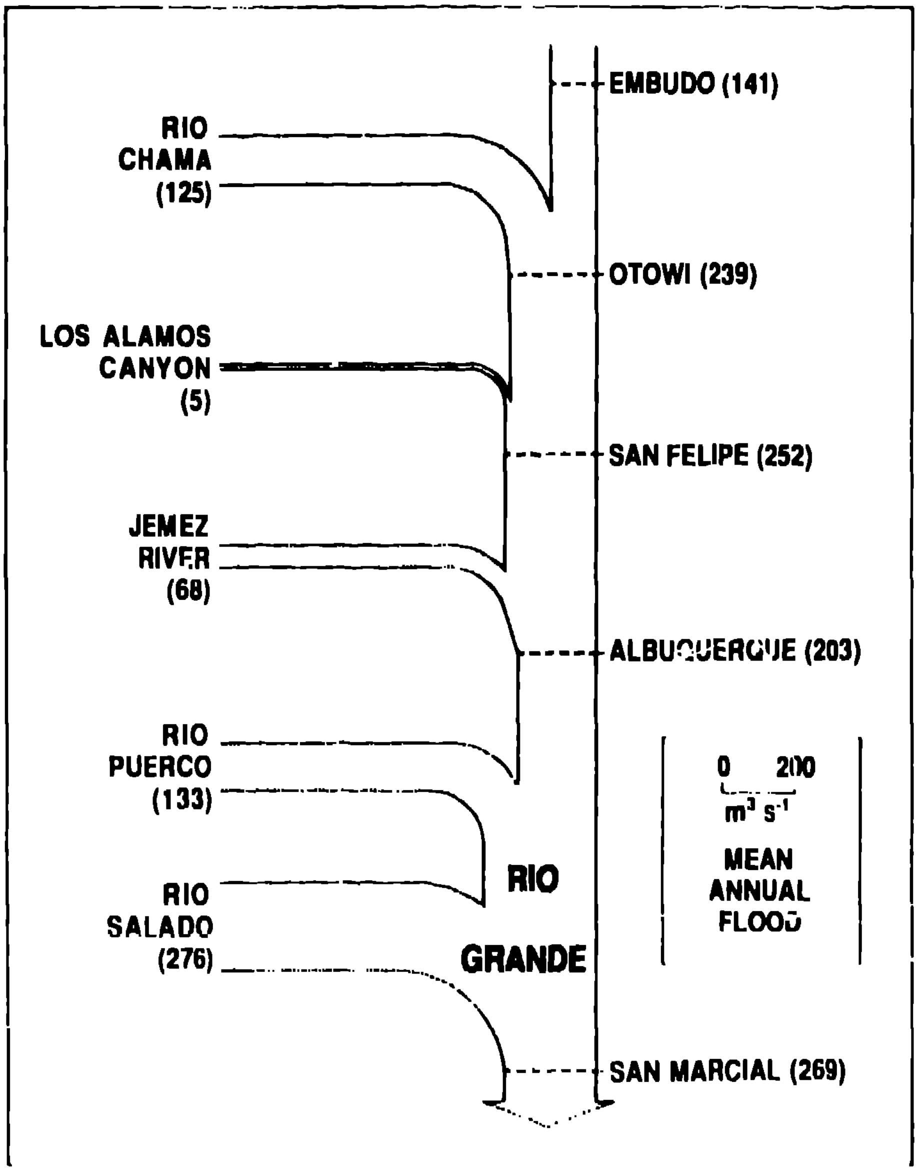
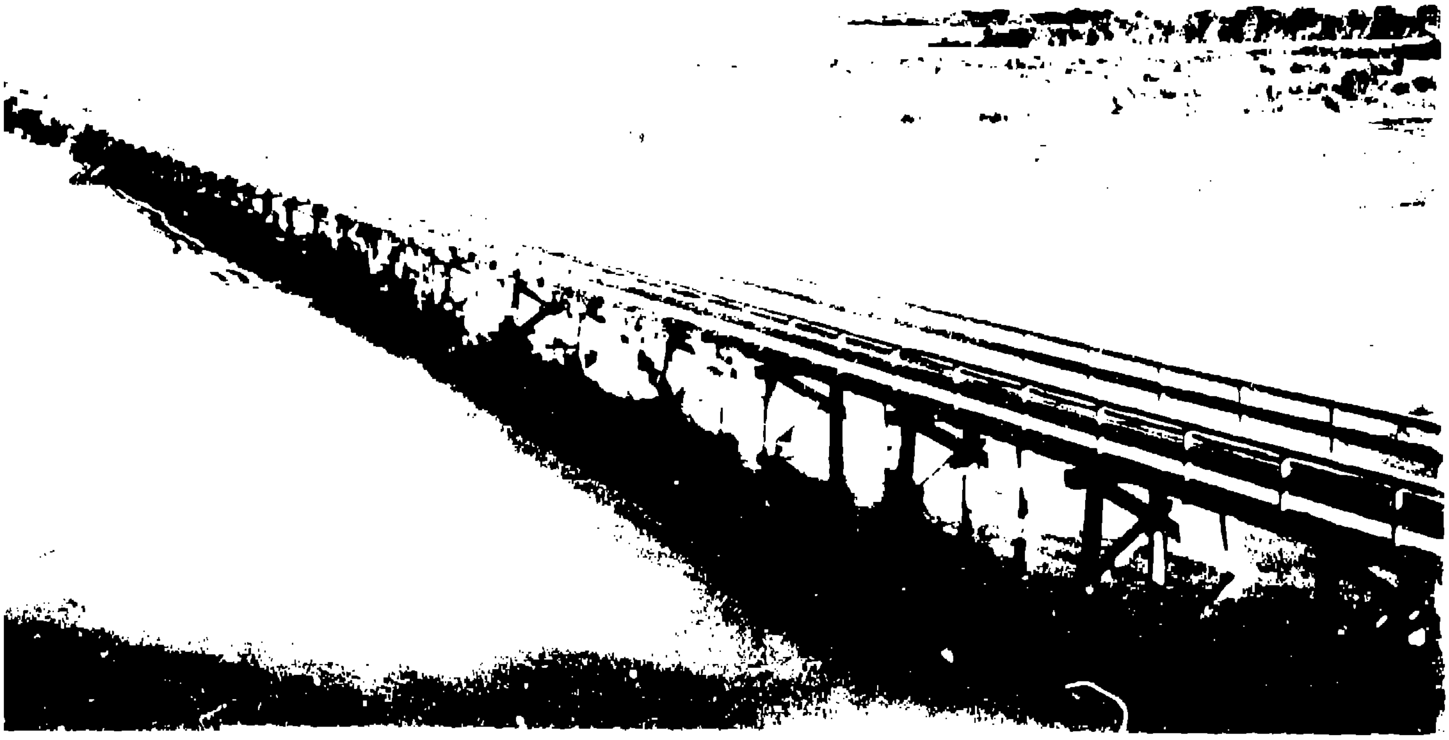


Figure 4.11 Flow diagram for the annual maximum flood series of the Northern Rio Grande.

plutonium from mountain fallout zones and from Los Alamos moves downstream, it is likely to be diluted from tributary materials carried in floods. The arrangement also implies that internal storage of sediment and its plutonium is likely, because in the lower basin larger amounts of sediment are not matched by corresponding larger amounts of flood water to provide transport energy. The next chapter explores the nature of the sediments.



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CHAPTER 5. FLUVIAL SEDIMENT

5.1 Types and Sources of Data

Although there are numerous aspects of sediment that might be considered in conjunction with questions related to plutonium transport and storage in rivers, particle size is the critical characteristic. Information on the size distribution of particles in sedimentary deposits connects plutonium, sediment, and river processes. The geography of plutonium depends on the affinity of the metal for fine particles and the uneven distribution of fine particles in the system. Some general data concerning the size characteristics of fluvial sediment in the Rio Grande system are available from published sources for a few locations, and particularly for the Los Alamos Canyon.[1] Recent, previously unpublished field and laboratory investigations provide additional detailed information for sedimentary environments associated with the river system (Figure 5.1). The following chapter reviews the characteristics of river sediments in the Northern Rio Grande and presents a regional sediment budget from historical and geographical perspectives.

Almost 200 sediment samples from deposits of various ages near the channels of the Rio Grande and tributaries provide a picture of the variability of sediment particle sizes. The method of analysis included three parts: sample collection, sieving, and electronic particle analysis. In the sample collection phase, collection sites represented identifiable sedimentary units or channel deposits. Technicians collected three samples from each site to provide an indication of local variability. Penetration of surfaces to depths of 5-90 cm with a standard cylindrical soil probe provided masses of about 120 g each for laboratory analysis. Investigators retained only the split of the sample that included those particles with diameters less than 2 mm (that is, sand size or smaller).

Laboratory procedures included sieving and electronic counting. Sieving divided each sample into masses consisting of those particles larger than 63 microns in diameter (the sand fraction) and those less than 63 microns (the silt and clay fraction). The weight of each fraction provided a standardized means of comparison among the samples for this study and with results reported by other researchers. Analysis of the silt and clay fraction using a Coulter electronic particle analysis system permitted detailed investigation of the frequency distribution of particles in this restricted range. The system analyzes tens of thousands of particles in a brief period of time by passing a laser beam through a container filled with water and sediment. A photo electric device detects the light passing through the mixture and computer processing of the resulting signal provides information on sizes, volumes, and surface areas of the particles.[2]

At a larger scale, the stream gaging network for the Northern Rio Grande includes several primary sites for the collection of bulk sediment data (Figure 4.2, Table 4.1). Although there are some measurements and estimates of sediment dynamics in the Rio Grande from the late 1800s and early 1900s, the most accurate and useful sediment data begin during the late 1940s at most locations. Even with some discontinuities, the regional data set is superior to information from most other systems in similar environments. The U.S. Geological Survey *Water-Supply Paper* series, the computer-based WATSTORE system, and the microcomputer optical disk system HYDRODATA contain all the relevant sediment records. Appendix B lists data used in the present research.

Two types of sediment are of importance in assessing contaminant transport and storage: suspended load and bedload. Rivers such as the Rio Grande transport fine sediments, those consisting of silt and clay (with particle diameter less than 63 microns), as suspended load.[3] Suspended materials move within the flowing water, giving it a turbid appearance. Because plutonium and other heavy metals preferentially adsorb onto the finest particles, fallout products are most likely to be associated with silt and clay in suspension. Bedload sediments are sand and gravel in the Rio Grande (sand with particle diameters between 63 microns and 2 mm, gravel greater than 2 mm). They bounce, roll, and creep along the bed at the base of the flow. At flood discharges, the larger amounts of energy available permit the transport of sand in suspension. Sand-sized particles are not as likely to contain concentrations of fallout products that are as high as the finer particles, but in many systems, the sand may be more abundant. When water spills out of the channel, it loses velocity and energy, and suspended materials settle out of the flow. Hence, the flood plains along the Rio Grande contain mixtures of sand, silt, and clay depending on the type of materials carried and the energy available to perform the hydraulic work of transport.

U.S. Geological Survey sediment records for the Rio Grande are almost exclusively for suspended sediments. Direct measurements for bedload are rare, so that estimations for the amount of material moving at the bed must be based on a known or suspected ratio between suspended load and bedload. The total load, the sum of the suspended and bedload portions, represents the total amount of sedimentary material moving through the system and available for contaminant transport.

5.2 Sediment Characteristics in the Rio Grande

In terms of particle size distributions, the sediment in the Northern Rio Grande system is highly variable because of the sorting processes inherent in the deposition of the material (Figure 5.2). Although the mean silt and clay (here referred to as "fine" material) content of all the samples collected in this study was 25 percent, significant variation appears when the samples are partitioned according to sedimentary environment (Table 5.1). Flood plain (38 percent silt and clay) and reservoir sediments (44 percent) along the Rio Grande contain the most fine materials. Tributary streams draining coarse grained geologic outcrops have the least amount of fine material: channel sediments of the Rio Salado have 7 percent fine materials and those in Los Alamos Canyon have 6 percent (Appendix C).

Areas of the flood plain near the Rio Grande channel also exhibit substantial variability in sediment characteristics. Planners often consider all the relatively flat

Figure 5.2 Boys from the Los Alamos Ranch School swimming in the Rio Grande near Otowi Bridge, circa 1935. The channel bar in the background is mostly cobbles and gravel in this view, but by the 1980s it was mostly sand, partly because of changes in river behavior and partly because of local gravel mining operations. (photo from Los Alamos Historical Society)

TABLE 5.1 SUMMARY OF PARTICLE SIZES, SEDIMENTARY DEPOSITS IN THE NORTHERN RIO GRANDE SYSTEM.

(DATA FOR PERCENT BY WEIGHT OF SILT AND CLAY)

River	Sedimentary Deposit	n	min.	max.	mean	st.dev.	sk.	kur.
Rio Grande	Active Channel	19	0.58	49.60	23.38	21.21	0.01	1.82
Rio Grande	Flood Plain	59	1.74	64.68	38.37	13.94	0.22	0.12
Rio Grande	Abandoned Single Channel	52	0.42	58.61	18.52	15.85	0.67	0.37
Rio Grande	Abandoned Braided Channel	21	1.25	61.00	24.25	20.07	0.34	1.41
Rio Grande	Bar	21	3.48	54.34	16.77	12.25	1.23	2.12
Los Alamos Canyon	Active Channel	13	0.00	16.89	5.83	5.15	0.77	0.14
Rio de Frijoles	Active Channel	1	7.45	7.45	7.45			
Cochiti Reservoir	Slack Water Deposit	4	41.00	49.85	44.89	3.77	0.29	1.18
Rio Puerco	Active Channel	3	26.59	29.59	[illegible]	1.76	0.38	1.50
Rio Salado	Active Channel	3	6.71	7.15	6.94	0.22	0.12	1.50
All Samples		196	0.00	64.68	25.00	18.34	0.25	1.14

Notes: n = number of samples

min - minimum value

max - maximum value

mean - average value

st.dev - standard deviation

sk - skewness of the frequency distribution of values

kur - kurtosis of the frequency distribution of values.

surfaces near the channel as "flood plain," but the various subcomponents of those surfaces have different geomorphic histories. Abandoned channels, for example, contain less than half the fine particles present in true geomorphic flood plain areas (Table 5 1). Within the silt size range alone (2.5-63 microns), different environments have different particle size distributions (Figure 5.3). Reservoir and suspended sediments not only contain more silt and clay than the other environments, their clay and silt occurs in the finer ranges of these size classes.

Fallout plutonium adsorbed onto silt and clay particles is therefore likely to have a specific geographic distribution in the near channel environment and to occur in higher concentrations in flood plain and reservoir sediments, with lower concentrations in abandoned channels. Because effluent released into Los Alamos Canyon entered the Rio Grande from a coarse-grained sedimentary system, it is likely to have a depositional geography different from the geography of fallout-related deposits. Mixing of sediments from Los Alamos Canyon with upstream materials in the Rio Grande presumably obscures the differences as distance increases downstream away from Los Alamos.

The suspended sediment in the Rio Grande consists of about 50 percent silt and clay as indicated by U.S. Geological Survey gaging records. Samples collected in the present study support this generalization, because the slack water sediments from Cochiti Reservoir (near the Cañon de Rio de Frijoles, Bandelier National Monument) which essentially represent materials settled from suspension in the main river have 45 percent fines. Bedload for the Rio Grande is more coarse, with about 25 percent fines. In the reach below Cochiti Dam, bed materials have become more coarse after the closure of the dam in 1973, a change observed in most channels below large dams.[4] Because the dam results in the release of water without its pre-dam sediment load, erosion of the channel below the dam causes the evacuation of finer materials, leaving the coarser, heavier particles as an armored layer.[5] The closure of Cochiti Dam caused the median diameter of course particles (those materials with particles diameters greater than 63 microns, all but the silt and clay) in the channel floor downstream from the dam to increase from 1 mm to as much as 5 mm.[6] Between 1973 and 1980, the "clear water" flows from the dam had winnowed the smaller particles from the bed for a distance of about 32 km downstream from the structure (to a location a short distance upstream from the Jemez River). Post-1980 processes may have extended this armoring effect further downstream, but studies in other rivers show that there is a definite limit to the distance of the impact,[7] and in other cases the impact has not extended much beyond a few tens of km.[8]

The small tributaries of the Rio Grande in northern New Mexico transport sediment loads consisting of particle sizes larger than the main stream. In the Rio Puerco, samples collected for the present study show that the silt and clay content is only about 29 percent, a finding in agreement with previous investigations.[9] In some cases, the tributaries drain geologic formations that weather into coarse debris, such as that generated by the rocks of the Jemez Mountains. The Los Alamos Canyon system contains very little silt and clay in either the channel or the flood plain (Table 5 1). The mean silt-clay content of 13 samples in the present study from Los Alamos Canyon

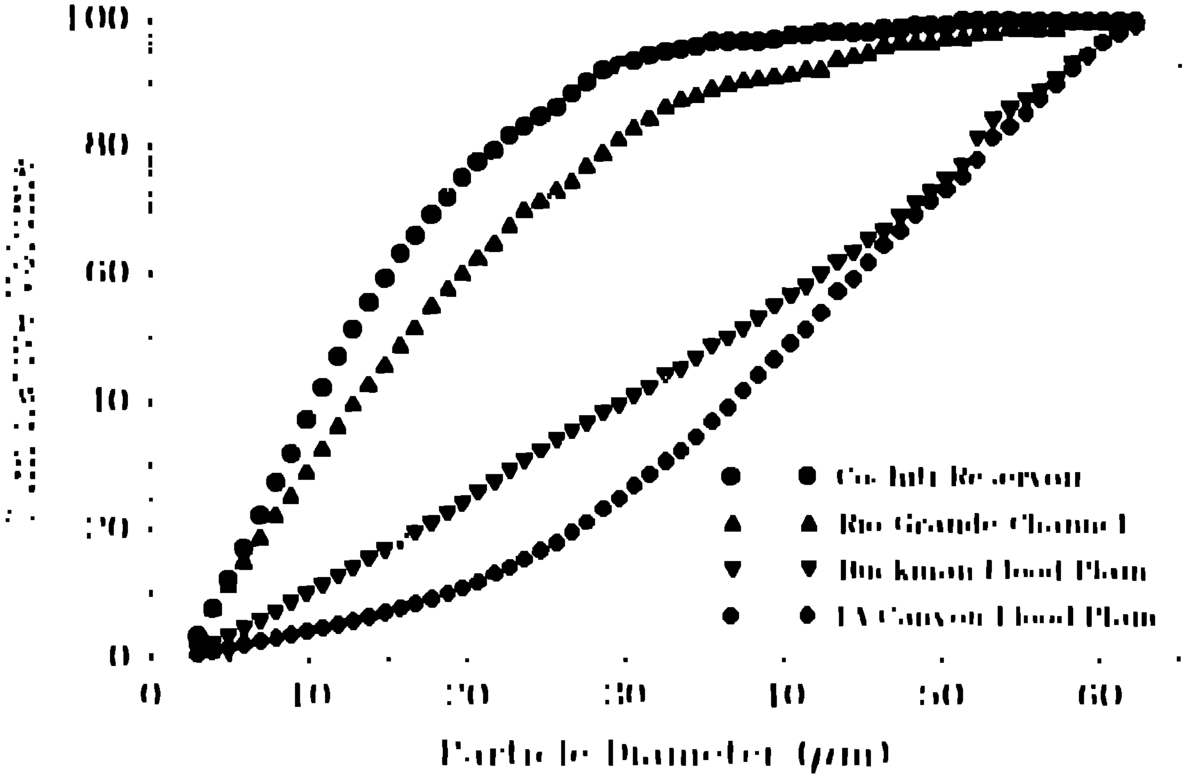


Figure 5.3 Detailed particle size distributions for representative depositional environments in the Northern Rio Grande near Los Alamos.

near Otowi was about 6 percent, a value generally similar to those reported by other researchers (Table 5.2).[10]

5.3 Regional Sediment Budgets

The records of sediment transport at various gaging sites permit the construction of regional budgets for the movement of suspended and bed sediments in the Northern Rio Grande. Because the records are of various length throughout the region, the resulting budgets are approximations based on average values, but they provide a general framework within which the likely transport of plutonium may be considered. The suspended load data from direct measurement indicate that, taken as a whole, the gaging period was one of some internal storage in the system (Figure 5.4). Summary diagrams illustrate this discussion of sediment budgets, while Appendix B contains the basic numerical data from the budget calculations. The amount of sediment contributed to the northern part of the system is that from the Rio Grande at Embudo, from the Rio Chama, and from minor tributaries. The total was more than 2.4 million Mg per year, yet only 1.7 million Mg per year passed Albuquerque. The remaining 0.7 million Mg per year remained between Otowi and Albuquerque as flood plain sediments and materials in abandoned channels and as lake sediments in Cochiti Reservoir.

Despite its relatively small size (Figure 3.2) and small annual water yield (Figure 4.6), the Rio Puerco contributes more than twice the amount of sediment that the Rio Grande carries past Albuquerque. Under conditions between the late 1940s and the late 1980s, about half of the sediment from the Rio Puerco and the Rio Salado remains in near channel deposits upstream from the gage at San Marcial (Figure 5.4). Any plutonium associated with the sediments is likely to have a similar storage pattern.

The regional budget for bedload is less precise than the budget for suspended load, because, except for experimental activities, there are no direct measurements of the bedload sediment transport. Fluvial and hydraulic research suggests ratios between the two types of load for the various parts of the system, but the reliability of these ratios is unknown. The estimates of bedload are likely to be accurate to within an order of magnitude.[11] Given the amount of published research on the river, in the case of the Rio Grande the error is probably less than 50 percent. For the main stream, bedload is 14 percent of the total load,[12] a value that is useful for the Rio Chama and the Rio Grande at Otowi, Albuquerque, and San Marcial. There are no sediment data for the Rio Grande at Embudo, but it can be estimated as the difference between values recorded for the Rio Chama at Chamita and the Rio Grande at Otowi. The bedload for the Rio Puerco is 71 percent of the total load.[11] Bedload as 50 percent of the total load of Los Alamos Canyon, Jemez River, and Rio Salado is a reasonable assumption.

The regional bedload budget is somewhat different from the suspended budget because of the overwhelming impact of the Rio Puerco (Figure 5.5). The northern part of the system carries relatively little bedload, but the arid and semi arid watershed of the Rio Puerco generates large amounts of bedload materials, two thirds of which are

TABLE 5.2 SUMMARY OF PARTICLE SIZES IN SEDIMENT OF THE LOS ALAMOS CANYON SYSTEM, REPORTED BY STOKER ET AL. (1981, P. 126, 130, 133) (DATA FOR PERCENT BY WEIGHT OF SILT AND CLAY, RECALCULATED FOR COMPATIBILITY WITH DATA IN THE PRESENT WORK BY ELIMINATING MEASUREMENTS OF PARTICLES LARGER THAN SAND)

Location	n	mean	st dev
Acid Pueblo Canyon	7	[illegible].79	3.46
DP and Upper Los Alamos Canyon	6	[illegible].59	2.62
Lower Los Alamos Canyon	3	4.01	0.48

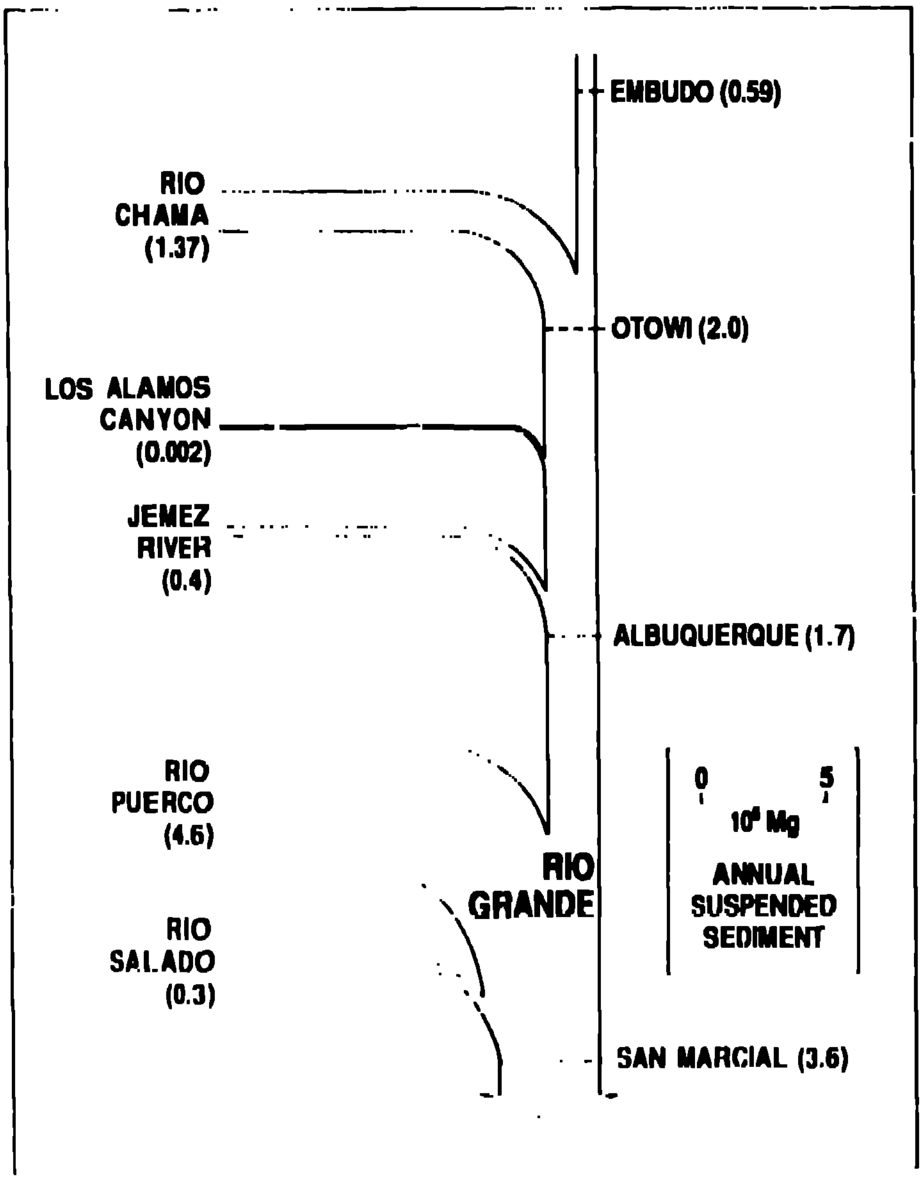


Figure 5.4 Flow diagram for the annual budget for suspended sediment in the Northern Rio Grande

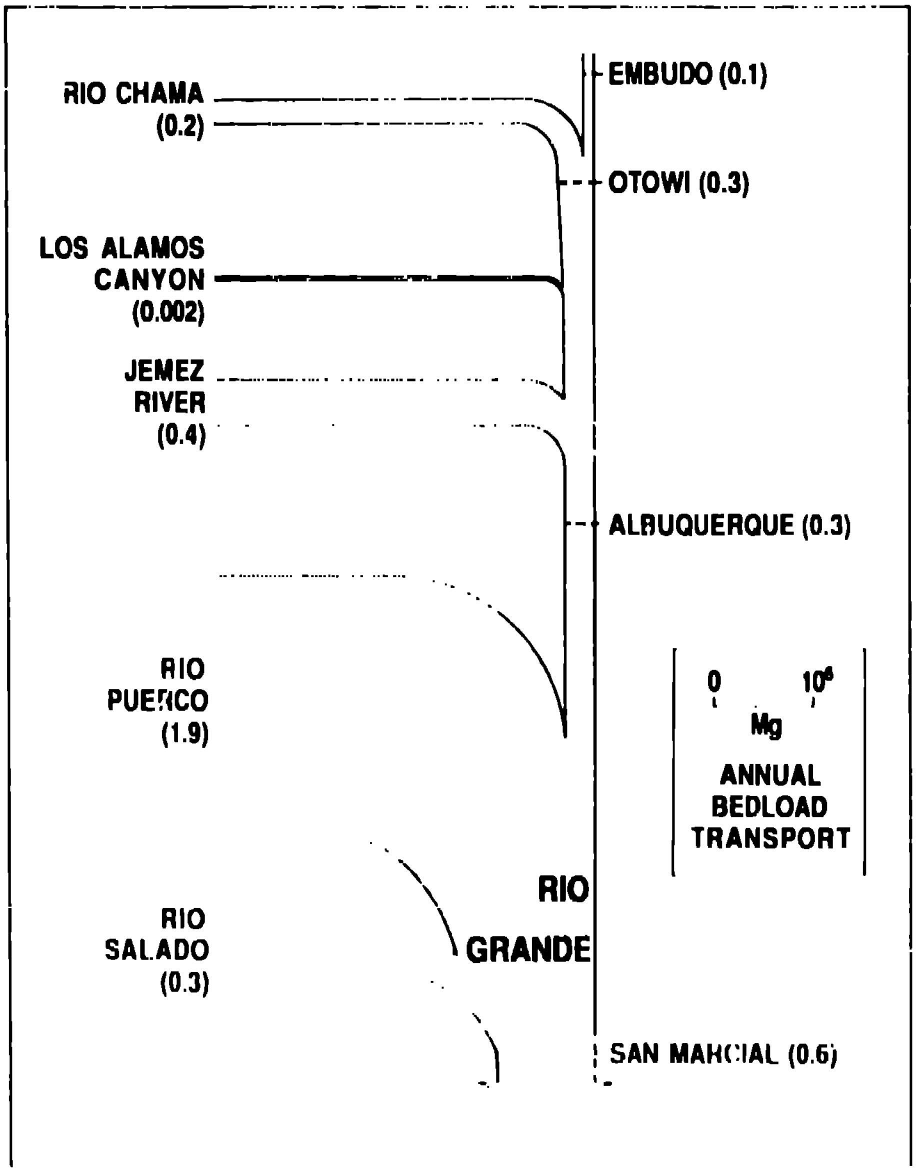


Figure 5.5 Flow diagram for the annual budget for bedload sediment in the Northern Rio Grande.

stored in the near-channel environment once they enter the Rio Grande. Plutonium associated with releases of effluent into the alluvium of Los Alamos Canyon is connected to a tiny portion of the regional bedload budget, and if those materials were to move as far south as the Rio Puerco, mixing with bedload sediments from the tributary would be likely to dilute the Los Alamos contribution to such a great degree that they would be unrecognizable.

5.4 Time Series for Sediment Transport

The general regional budgets for suspended and bedload sediments provide a geographic perspective on fluvial transport processes, but there is considerable interannual variation in the rates of movement as recorded in the gaging records. The record of suspended sediment yield of the Rio Grande at Otowi began after the major flood of 1941, which probably would appear in the record as the year with the largest sediment yield in recent decades. Since records began in 1947 at the location, the highest recorded yield occurred in 1958 (Figure 5.6), a regional flood year in which the Rio Grande as well as local tributaries experienced significant high discharges. Before 1958, there were two years when sediment yield was greater than any year after 1958: 1948 and 1952. After 1958, considerable variation occurred from year-to-year, with a slight downward trend in mean annual sediment yield.

At the lower end of the study area, on the Rio Grande at San Marcial, the record of sediment yield is different because of inputs from tributaries between Otowi and San Marcial, especially the Rio Puerco (Figure 5.7). The highest year of record is again 1958, but later in the record, tributary floods either contributed large amounts of sediment to the system or remobilized sediments previously stored along the channel. Releases of sediment free water from Cochiti Dam also contributed to increased erosion of the channel and near channel areas of the Rio Grande,[14] increasing the sediment yield of the river at San Marcial and Elephant Butte Reservoir.

Because of the plutonium releases by Los Alamos National Laboratory, the sediment yield of Los Alamos Canyon is of special interest in this study. Using data from an intermittent gaging record on the stream with precipitation records at nearby locations, previous researchers calculated the probable sediment yield from the canyon into the Rio Grande.[15] Figure 5.8 depicts their previously unpublished results, showing the record from 1943 to 1980. The stream is less consistent in its sediment yield than the main river, because the tributary is an intermittent stream, drains a smaller watershed, and lacks a large water source area at high elevation. The years of high sediment yield from Los Alamos Canyon (1944, 1951, 1952, 1957, and 1968) are out of phase with peaks on the main stream, because the Los Alamos stream responds to local events in the Jemez Mountains while the Rio Grande responds to larger scale climatological conditions in the San Juan Mountains (for example, compare Figures 5.8 and 5.6). Any plutonium associated with sediments in Los Alamos Canyon therefore entered the main system sporadically, experiencing more or less dilution by main stream sediment depending on the annual yield of the Rio Grande for the particular year.

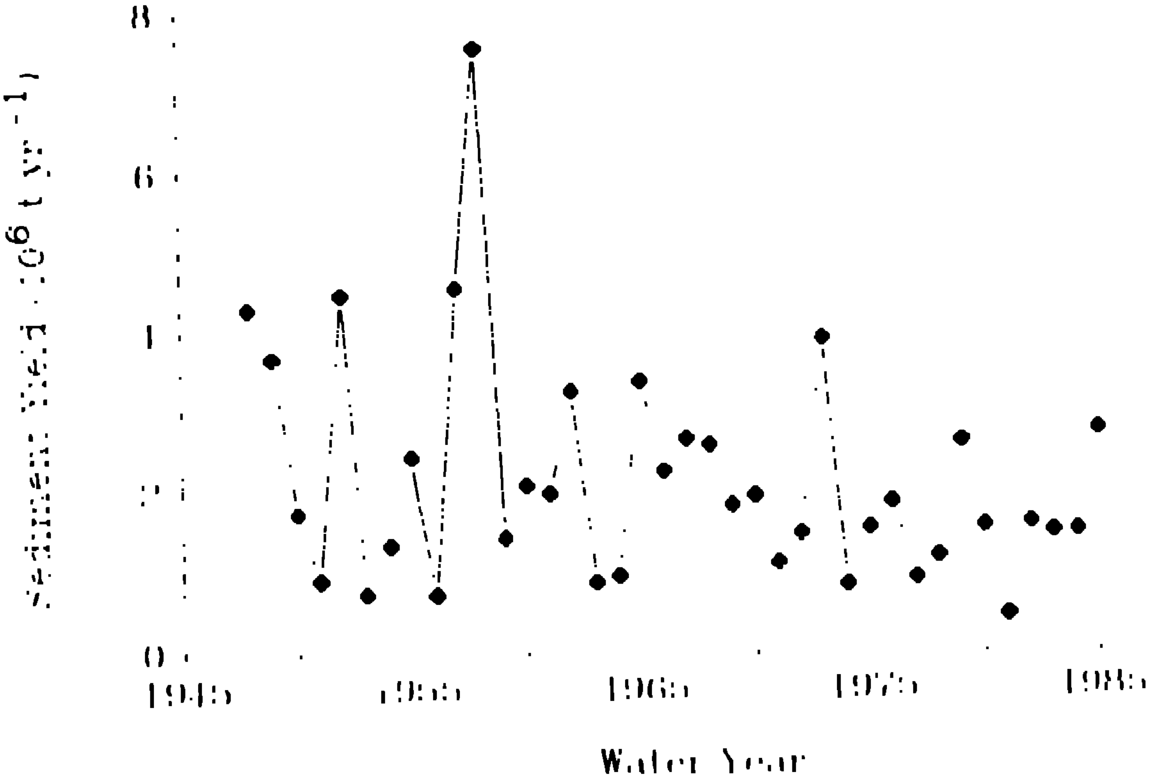


Figure 5.6 Annual suspended sediment discharge, Rio Grande at Otowi (U.S Geological Survey data).

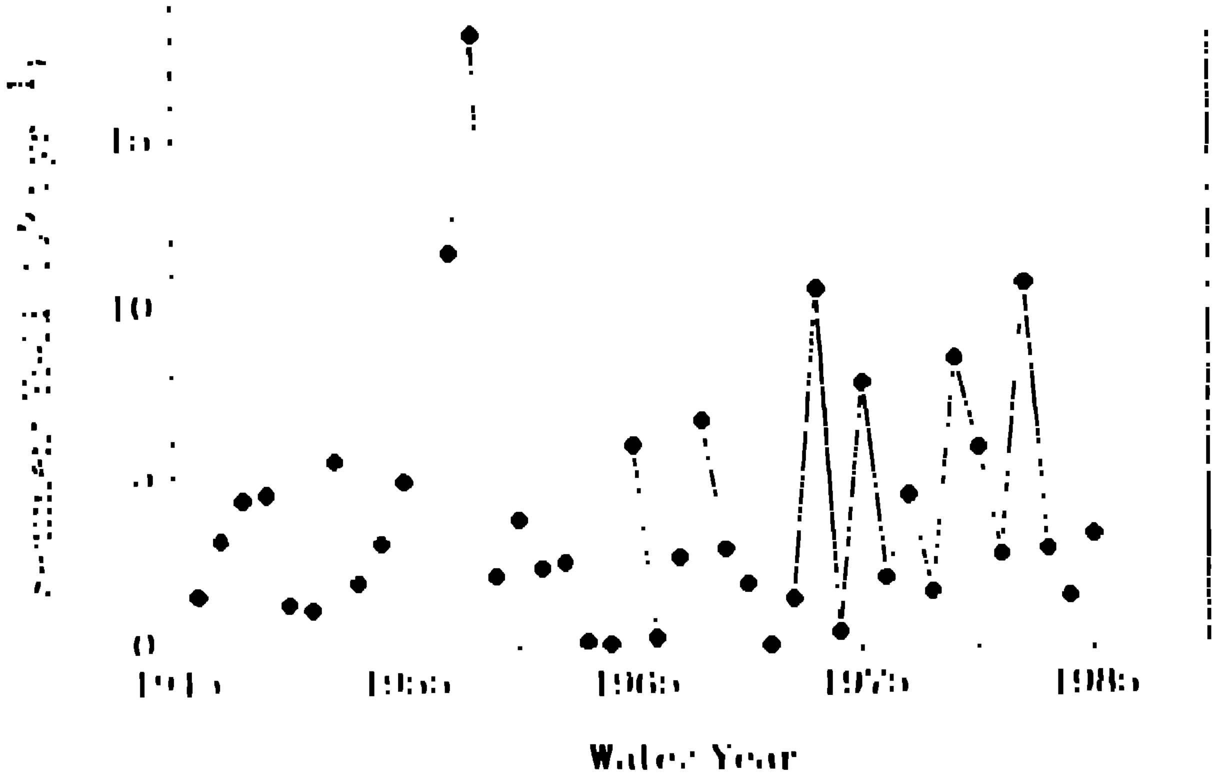


Figure 5.7 Annual suspended sediment discharge, Rio Grande at San Marcial (U.S. Geological Survey data).

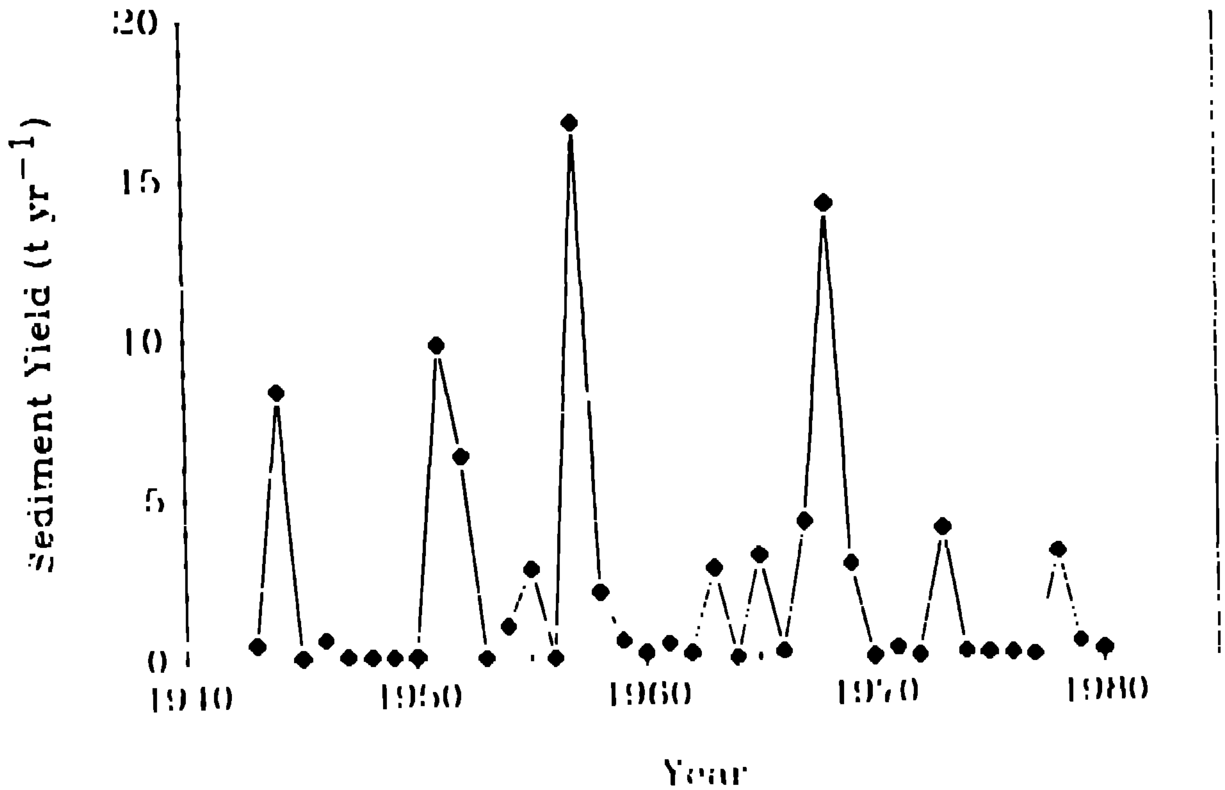


Figure 5.8 Annual sediment discharge from Los Alamos Canyon to the Rio Grande (data from L. J. Lane, Agricultural Research Service).

The storage component of the annual sediment budget warrants further attention, because it has important implications for understanding the dynamics of plutonium in the system. The stored sediments and the plutonium that is attached to them have a particular geographical distribution within the system, and amounts of annual storage have varied considerably over time. The distribution of gaging sites on the Rio Grande permits the definition of four accounting areas within the larger general study reach from Otowi to San Marcial. The reaches of the Rio Grande and the gages that define them are

1. Otowi to Jemez River, gages at Otowi Bridge and on the Jemez River;

2. Jemez River to Albuquerque, gages at Otowi Bridge and Albuquerque on the Rio Grande and on the Jemez River;

3. Albuquerque to the Rio Puerco, gages at Albuquerque and on the Rio Puerco;

4. Rio Puerco to San Marcial, gages at Albuquerque and San Marcial on the Rio Grande and on the Rio Puerco.

The 1948-1985 record of total sediment (suspended load plus bedload) stored in the system as calculated from the gaging data for these reaches shows that the system has neither stored sediment continuously throughout the period of record, nor stored it evenly throughout the length of the river. In the two reaches above Albuquerque, storage or losses have been relatively small, with storage dominating the system from the late 1950s to late 1960s and then again in the late 1970s (Figure 5.9). Losses were prominent in the late 1940s and early 1970s. Thus, the years of major sediment yield from Los Alamos Canyon (probably including plutonium) coincided with a period of system storage. These variations may be related to flood events, especially in the late 1950s, when flows spilled out of defined channels and deposited much material on flood plains. The closure of Cochiti Dam in 1973 resulted in increased erosion by clear-water releases from the dam, producing the observed sediment losses above Albuquerque. These losses did not occur in the record for the Otowi-Jemez River reach, which includes only a limited portion of the channel impacted by the erosion below Cochiti. The dam affected all of the Jemez River-Albuquerque reach, so that its record shows the erosion effects.

The two reaches below Albuquerque had more variable storage records than those upstream (Figure 5.10). The 1953 flood resulted in significant erosion and loss of stored sediment, and floods on tributaries affected other years. Channel "improvements" (levees and channelization by artificial works) may have restricted flow and caused some erosion during the post 1960 period between Albuquerque and the Rio Puerco. The massive influxes of sediment during flood years on the Rio Puerco cause extreme variability in the record for the Rio Puerco-San Marcial reach. Unlike the reach immediately upstream, its record is one of nearly continuous storage.

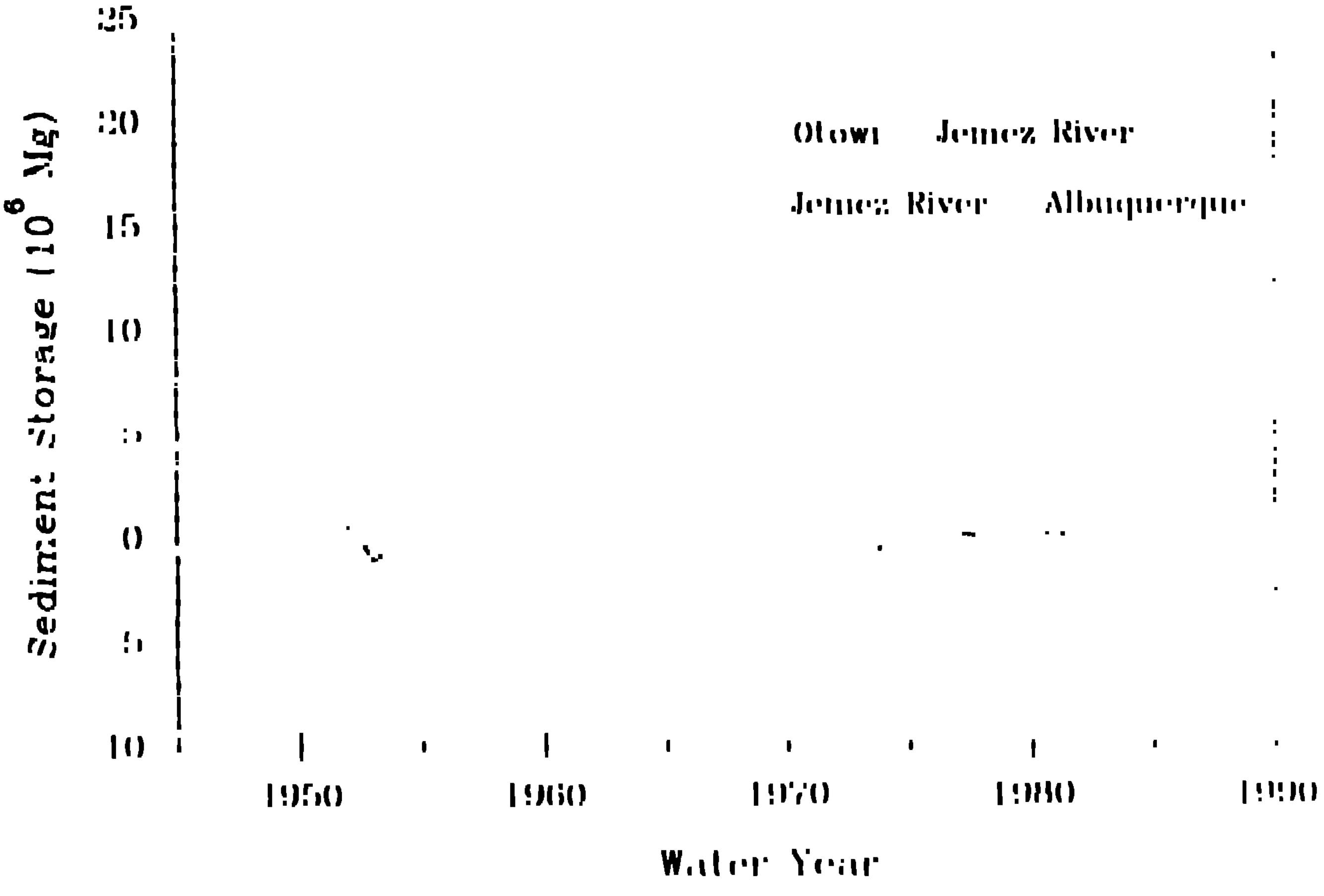


Figure 5.9 Total annual sediment storage along the Rio Grande, Otowi to Albuquerque.

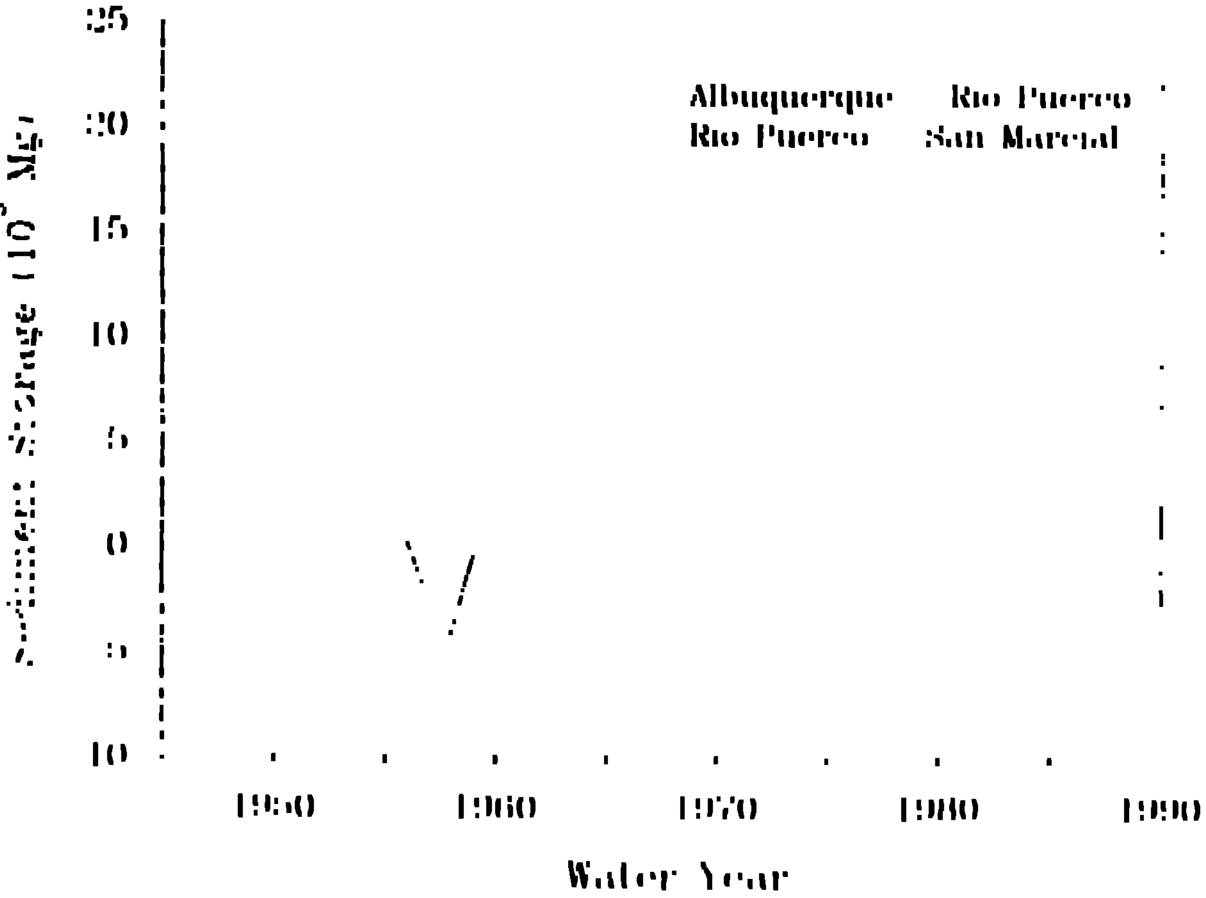


Figure 5.10 Total annual sediment storage along the Rio Grande, Albuquerque to San Marcial.

5.5 Annual Variation in the Regional Sediment Budget

A total system view of the suspended sediment is a useful summary of the temporal changes that have affected the regional sediment budget. Because suspended load and bedload are related to each other, the trends for suspended sediment are indicators of change in the entire sediment system. The suspended sediment trends are also more reliable because they represent measurements rather than calculated values based on assumed ratios as is the case for bedload. In a simplistic view, the total input for the study reach is the sum of inputs from the Rio Grande at Otowi and the Rio Puerco. While this simplification ignores inputs from other tributaries, they are relatively small (Figure 5.4). The total output from the system is the suspended sediment yield of the Rio Grande at San Marcial. Further simplification of the picture is possible by smoothing the annual data by using a tenth-order polynomial to describe the time series of annual input and output (Figure 5.11).

The generalized approach shown in Figure 5.11 illustrates several important points about the temporal variation of the sediment transport system in the Northern Rio Grande from 1948 to 1985. Throughout the period, the sediment flux in the Rio Grande at Otowi has gradually declined, largely because of declining amounts of water passing through the river to provide a mechanism for transport. As outlined in a previous chapter, this decline in water is the product of several factors, including human influences and climatological changes. Because it is in a different climatological and vegetation zone, the Rio Puerco first increased and then decreased its huge sediment contributions. Late in the record, the Rio Puerco began to increase its inputs again. The sediment output from the Northern Rio Grande system at San Marcial has fluctuated somewhat throughout the record by reflecting trends in the Rio Puerco, but changes have been less dramatic than those in the tributary.

The generalized sediment budget also shows that between 1948 and 1975 much more sediment entered the system than left it. Internal storage of sediment by deposition on flood plains accounts for the difference. This well defined storage period coincides with the time period when maximum amounts of plutonium were likely to have entered the system from fallout and from Los Alamos Canyon. It is highly probable that much of the plutonium remains in internal storage in various deposits associated with the depositional period. For a relatively brief period after 1975 more sediment left the system than entered it, indicating evacuation of sediments stored in internal flood plains. These remobilized sediments, containing varying amounts of plutonium depending on their ages, were probably transported by the relatively clear water discharges from Cochiti Dam, closed in late 1973. The sediments moved passed San Marcial to their new deposition site, the pool of Elephant Butte Reservoir a short distance downstream from San Marcial. The general trends shown in Figure 5.11 suggest that by the 1980s this evacuation process had ended. The reach by reach budget (Figures 5.9, 5.10) suggests that the 1975-1985 erosion removed only a small amount of the total mass of sediments stored after 1945.

The interactions of the landscape, climatic, and sediment systems that resulted

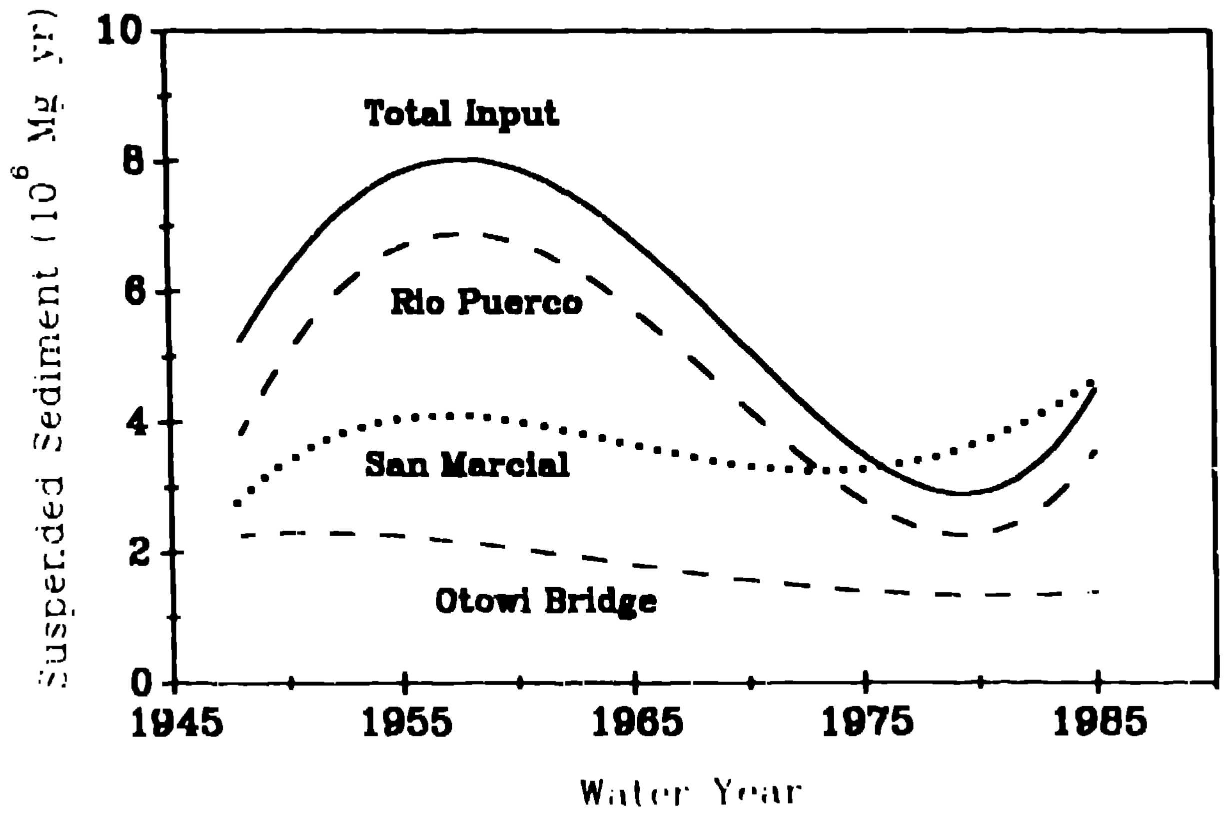
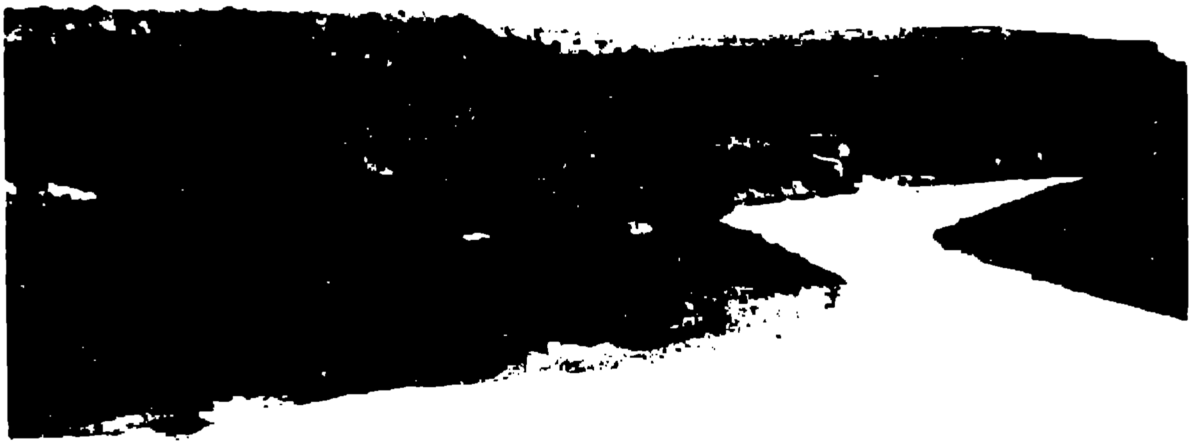
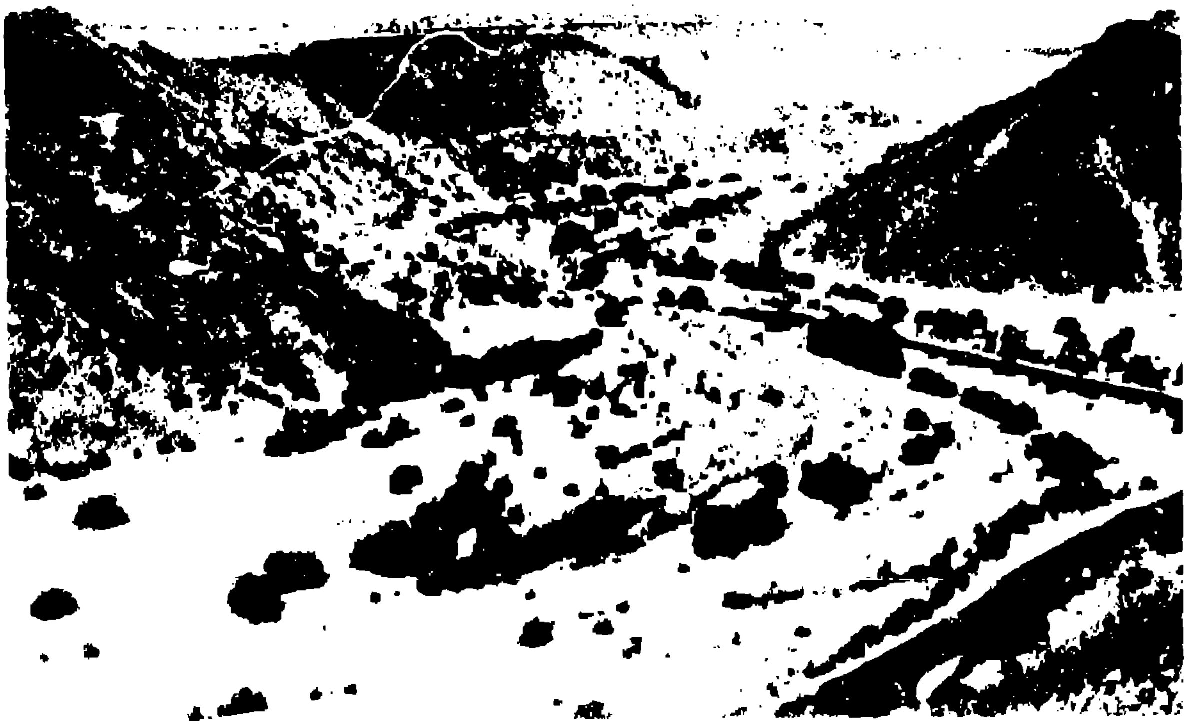


Figure 5.11 System-wide annual sediment budget for the Northern Rio Grande, smoothed with tenth-order polynomials.

in the storage of large quantities of sediment along the active channel of the Rio Grande created a suite of landforms associated with the river. The next chapter focuses on these landforms, particularly the channels and flood plains, as keys to understanding the arrangement of plutonium possibly contained within their sediments.





CHAPTER 6. FLUVIAL GEOMORPHOLOGY

6.1 Sources of Data

The fluvial processes that move and store sediment in the Northern Rio Grande operate within a system of landforms consisting of the river channel and its associated flood plain. As the amounts of water and sediment change over time and from place to place, and as the magnitude and frequency of floods change, the channel and near-channel landforms adjust to accommodate the new hydraulic conditions (Figure 6.1). The channel often changes its size, shape, pattern, or location in response to hydraulic controls, and in so doing it creates a suite of flood plain features that include abandoned channels, terraces, active and inactive flood plains, and a variety of bars inside and outside the present active channel.[1] Explanation of the fate of plutonium in this environment requires a clear understanding of the chronology and mechanism of river channel change, because sediment with associated contaminants compose the various landforms. In the case of plutonium in the Northern Rio Grande, it is necessary to identify, map, and assign dates to the near-channel landforms and their sediments to establish linkages with materials that entered the system during particular years when contamination was most likely. The regional sediment budget shows that the river has stored large amounts of sediment between Otowi and San Marcial; analysis of the fluvial geomorphology of the system can identify the locations and dates of the stored material.

Topographic maps and aerial photography provide basic location information for fluvial landforms. Topographic maps published by the U.S. Geological Survey depict the river and its environs at 1:24,000 scale and serve as base maps for plotting data and locating specific landforms or deposits. Appendix F provides a complete list of the topographic quadrangles that show the river from Española to San Marcial.

Aerial photographs provide basic mapping information on the location and extent of landforms and deposits at a variety of times for the reach between Espanola and San Marcial. Through photogrammetric techniques the photos yield quantitative data, particularly for area and distance measures. Most reaches of the river appear in aerial photographs at least once in each 10 year period from the late 1930s to the present. Since the middle 1940s most reaches were photographed from the air every three years at least. Sources of aerial photography include the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Geological Survey, U.S. Department of Agriculture, U.S. National Archives, U.S. Bureau of Indian Affairs, Los Alamos National Laboratory, New Mexico Highway Department, New Mexico State Land Department, county and city planning agencies, telephone and electrical utilities, and private aerial photographic and engineering firms. In the present study, a representative selection of aerial photography from a limited number of sources provided information on river channel change (Appendix G contains specific addresses for sources).

In some cases, historic ground photography supplemented the aerial photographic record of channel changes. These historical photos are more sporadic in their temporal and geographic coverage than their aerial counterparts, but they provided qualitative information and useful perspectives as well as reinforcing interpretations. Sources of historical photos of the Northern Rio Grande include the Colorado Historical Society, Denver Public Library, U.S. Geological Survey (Denver), Los Alamos Historical Society, Albuquerque Public Library, University of New Mexico Library, and the New Mexico State Archives (Appendix H contains specific addresses for sources). The present study used only photos of areas of special interest rather than collecting all available images.

6.2 Channel Change, 1940s-1980s

The temporal changes in water yield, flood series, and sediment yield that have occurred in the Northern Rio Grande between the 1940s and the 1980s have led to a predictable series of changes in the channel and its surroundings. Decreasing amounts of water have produced a progressively smaller channel throughout most of the river from Española to San Marcial. The shrinkage of the channel has resulted in increased flood plain areas and the abandonment of some minor subchannels. The decline in the magnitude of the annual floods has contributed to this conversion from large to small channels. The internal storage of large quantities of sediment has contributed to the expanded flood plain areas and has filled some of the abandoned channels.

The overall character of the Rio Grande changed during the 1940s-1980s period (Figure 6.2). Prior to the early 1940s, the channel was broad and shallow with numerous bars and subchannels, a classic case of a braided stream produced by high sediment loads, erodible banks, highly variable discharge, and high amounts of stream power.[2] As declining water yields, sediment yields, and flood magnitudes forced the development of a smaller channel, the braided characteristic gradually disappeared, so that by the 1980s the river consisted of a single thread.

The change from braided to single-thread pattern has occurred on most major streams in the western United States, including the Platte in Nebraska[3] and the San Juan in Colorado and Utah.[4] The shrinking trend is often directly related to closure of dams,[5] and in some limited parts of the Rio Grande, specifically in the reach of the Jemez River downstream from Jemez Dam, the connection is obvious. The tendency toward single-thread channels must also derive from region-wide hydroclimatic influences because the Rio Grande above Cochiti Dam also has contracted, and many other streams without major dams exhibit the same changes: the Fremont River in Utah,[6] the Paria River in Utah and Arizona,[7] the Little Colorado River in Arizona,[8] and the upper Gila River in New Mexico and Arizona.[9] In the Rio Grande, engineering works have exaggerated the change and made it more lasting by imposing artificially designed pilot channels and levees on the system.

As the Rio Grande channel has decreased in width, it has also been locationally unstable, moving from one position to another across the valley floor in those reaches where it is unconfined by rock outcrops or levees. During the 1940s-1980s period, the main channel of the Rio Grande changed horizontal position by as much as a

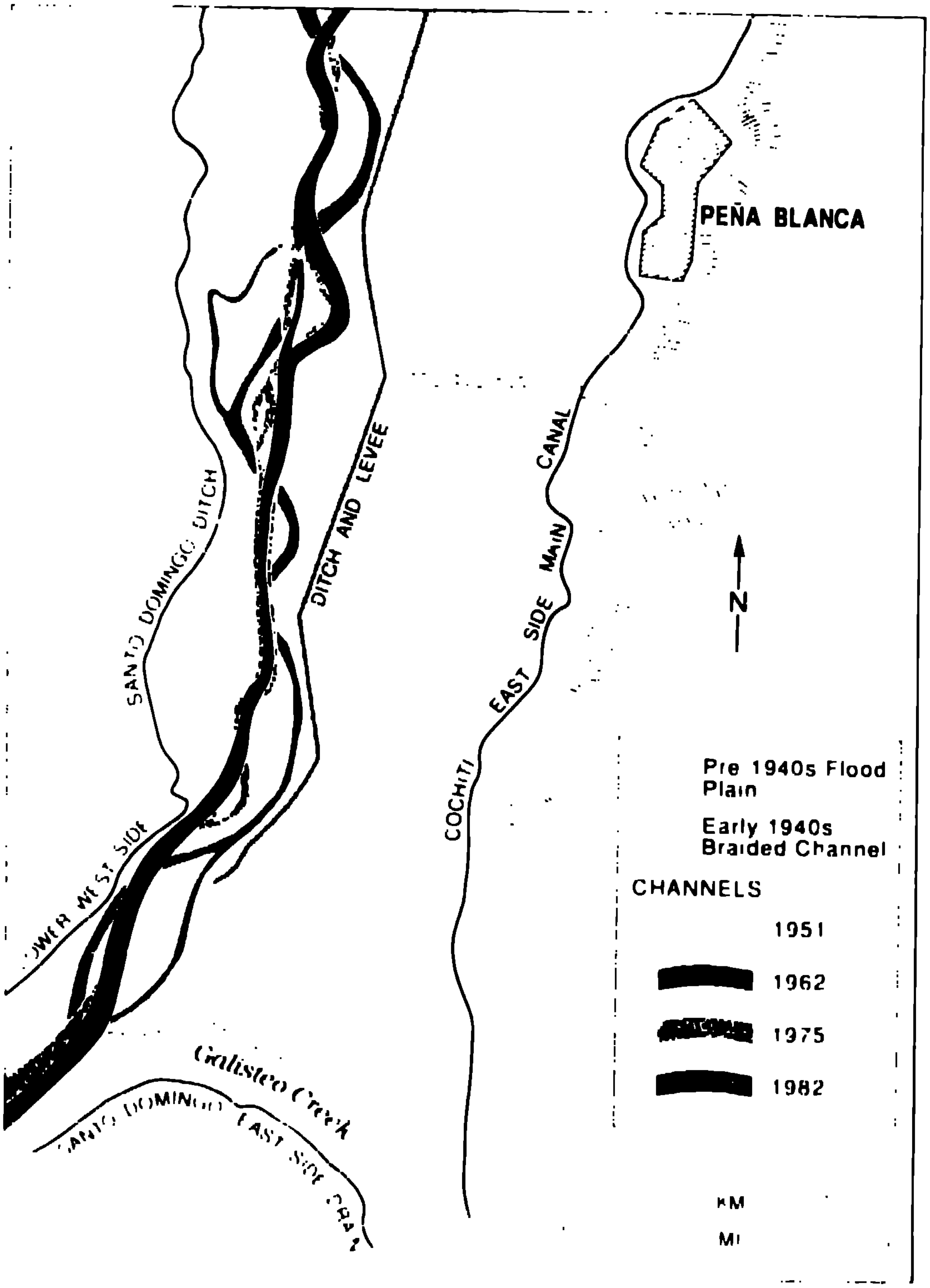


Figure 6.2 Channel location and pattern changes as deduced from aerial photography, Rio Grande near Peña Blanca, from the late 1930s to 1982

kilometer. The changes occurred during floods when sediment plugged old courses and flows spilled over poorly consolidated banks to cut new courses. This migration is also common on dryland rivers, and the rate of change on the Rio Grande has been similar to that seen in other streams in the western United States.[10]

6.3 Near-Channel Landforms

Channel shrinkage, pattern change, and migration produce a characteristic series of landforms on the valley floor near the channel. Planners and engineers refer to this relatively flat area separated from the channel by banks in undisturbed environments as the flood plain.[11] From a geomorphological and sedimentological perspective, however, this area consists of a variety of forms and deposits with different origins and characteristics. A true geomorphological and sedimentological flood plain is an alluvial surface next to a channel, separated from the channel by banks, constructed of materials transported and deposited by the present hydrological regime of the river.[12] The sediments that make up the flood plain are usually finer than the bed sediments in the nearby channel, because when water spills out of the channel, its velocity decreases and it deposits some of its fine suspended load. Small scale features sometimes include extensive ripple patterns or occasional splays of gravels where flows exited the channel.

The near-channel areas of a changing river like the Rio Grande also include abandoned courses etched into the surfaces of the flood plain. Abandoned braided channels have sandy and gravelly beds, with linear depressions separated by ridges that reflect the original subchannels and bars. The bars often rise to levels similar to the level of the flood plain on either side of the abandoned channel area. Abandoned single-thread channels form linear depressions through flood plains and may have more coarse material than that on the flood plains, representing the bedload once carried in the channel. Many abandoned single thread channels have had a more complex history, however, because after they were abandoned, flood flows temporarily occupied them with slack water that deposited fine suspended sediment. If the abandoned channel is not completely filled with sediment, it retains its depression characteristics and is a noticeable interruption of the planar flood-plain surface. If the abandoned channel is completely filled with slack water sediments, its surface may be coincidental with the surrounding flood plain, and indirect evidence such as vegetation may be the only obvious indicator of its presence. Excavation reveals sedimentological variation that confirms the location of channel and its filling.

Flood bars provide positive relief above some flood plains. As flood waters spill out of channels and over flood plains, turbulence in the lee of obstacles such as trees, buildings, bridge piers, or other structures produces localized accumulations of debris and sediment. Usually such features are less than a meter high and several meters long, but if they occur in great numbers as in a thicket or in artificial sediment traps, their total accumulation can be substantial.

Near-channel areas also include some deposits not directly related to processes in the main stream--deposits from tributary channels that interfinger with flood-plain and related materials near the valley margin. In some cases, tributary deposits cover the flood-plain materials in the form of alluvial fans extending from the mouths of tributaries in the valley side, across the flood plain, and terminating at the active channel of the main river.

In the Rio Grande between Española and San Marcial, the near-channel environment includes all of these forms, but in many cases human activities have modified them. The construction of levees (reviewed in detail in the following chapter) has eliminated flows from many geomorphic flood plains, and they no long receive infusions sediment. Construction activities have disrupted other forms or obliterated them completely. Within White Rock Canyon, the basalt and tuff walls constrict the valley floor so that flood plain features are generally absent except for isolated deposits in small pockets in the canyon walls.

6.4 Near-Channel Deposits

The surface expressions of the near-channel forms have connections to subsurface variation in terms of sediment characteristics (Figure 6.3), with the sediment in each form exhibiting distinctive structure and particle size distributions.[13] Flood-plain deposits have finely laminated structures consisting of thin horizontal sheets. Along the Northern Rio Grande, the sheets are usually a cm or less in thickness and consist of very fine sand, silt, or occasionally clay. Abandoned braided channels have materials that are relatively uniform in size, mostly sand and coarse sand in the Rio Grande, but prominent structures include cross-set beds developed by migrating dunes, bars, and sand waves when the channel was active.[14] Mid-channel bars sometimes appear in the deposits as gravel lenses. Abandoned single thread channels may appear in deposits as linear accumulations of massively bedded sand, or they may contain large amounts of silt and clay if they were filled by slack water deposits after their disconnection from the active channel system. Tributary deposits are almost always more coarse than materials from the main channel because the tributaries have steeper gradients and therefore generate more shear stress for transport of larger particles. The alluvial fan deposits tend to become more coarse in successively higher layers,[15] while deposits of the main river often become more fine in the upward direction.

The implication of these arrangements for plutonium movement and storage in the near-channel environment is that if sediment in the active channel carries plutonium adsorbed to its surfaces, if that sediment is deposited near the channel during a general storage period, and if the depositional forms and materials can be explained and mapped, then it is possible to deduce the ultimate distribution of the contaminant. Such knowledge can guide sampling and monitoring programs and can lead to definition of areas of likely concentration, especially given the affinity of plutonium for fine particles.

In the Rio Grande system, the differences among flood plains, abandoned channels, and bars are clear but subtle to the observer on the surface. Minor variations in elevation, surface irregularities, minor depressions or ridges, and small

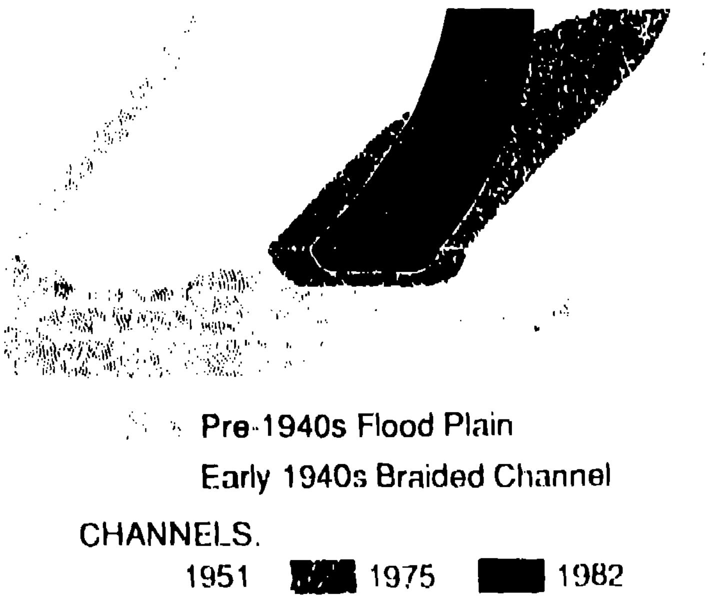


Figure 6.3 Cross-sectional sketch of a representative area along the Rio Grande near Peña Blanca as shown in Figure 6.2.

scarps, all less than 0.5 m high provide clues to the origin and type of landform and the nature of sediments likely to be found beneath the surface. The surface forms are not usually visible directly on aerial photography, but because the various forms connected to particular particle sizes and moisture conditions, vegetation communities visible in aerial photographs almost always reflect them.

6.5 Distribution of Flood Plains

The distribution of active channel and flood plains (both active and those now isolated from the channel by engineering works) along the Northern Rio Grande is variable from place to place. The distribution is important for understanding the distribution of potential storage sites for plutonium. A useful measure of the amount of flood plain area in a given limited reach of the river is the concept of unit area, the number of sq km of flood plain associated with each km of river channel length. In a particular reach, if the unit area of flood plain is 1.0 sq km/km, then for each km of channel lenth there is 1.0 sq km of flood-plain area. In this case, the flood plain might form strips 0.5 km wide on each side of the channel or a strip 1.0 wide on only one side. A similar approach defines the unit area of active channel, the area of active channel per unit length of the river.

Data from aerial photography (1982-1985) permitted assessment of the distribution flood-plain and channel area along the Rio Grande using the following method.

Step 1: Define the scale of each frame of photography by measuring the horizontal distance between two prominent objects that appear in the photograph and on a topographic map of scale 1:24,000. Convert the map measurement M to the actual real-world distance it represents (A):

$$A = 24{,}000\ M$$

Measure the distance between the same two objects in the photograph, and determine the scale of the photograph by comparing the photograph measurement (P) to the actual distance:

$$\text{Photo Scale} = P/A.$$

The scales of photographs in this analysis ranged from about 1:20,000 to about 1:80,000.

Step 2: Divide the length of the study river into convenient segments. The useful landmarks and geomorphic variation in the Rio Grande generate 42 segments ranging in length from 2 to 14 km, with a mean length of 6.8 km. Appendix D identifies the segments.

Step 3: Using a computerized digitizing system (Jandel SIGMA SCAN, Version 2.1), measure the length of each segment (L)

Step 4: Using the same system, measure the area of active channel (C).

Step 5: Using the same system, measure the area of flood plain (F).

Step 6: Calculate the unit area of channel (UAC) for each segment by

$$UAC = C/L,$$

and the unit area of flood plain (UAFP) by

$$UAFP = F/L.$$

Step 7: Plot the unit areas of channel and flood plain against the downstream distance of the center of each segment to produce a summary diagram.

The results of this procedure for the Rio Grande between Española and San Marcial show the exact distribution of channel and flood plain (Figure 6.4; detailed data in Appendix D). While tabular data describe the regional sediment budget in numerical terms, Figure 6.4 depicts the geography of the storage term in the total sediment budget for the main river system. Kilometer 0 is the Old Española Highway Bridge, and kilometer 313 is the Southern Pacific Railroad Bridge near San Marcial. The unit area of flood plain changes radically from one segment of the river to another, mostly in response to available space on the valley floor and contributions of tributaries. Peaks in the distribution represent segments of the Rio Grande where the flood plain is exceptionally broad and where large amounts of sediment are stored. The first prominent peak is at about km 78, the confluence of the main stream with Galisteo Creek. Other areas of extensive flood plain are downstream from the confluence with the Jemez River (km 97), downstream from the confluence with the Rio Puerco, and wide valley areas near San Antonio (km 285) and near San Marcial (km 300).

The active channel area is much less variable than the flood-plain area. Bedrock exposures constrict the channel severely in a few places, such as at km 91, upstream from the confluence with the Jemez River. The only segments where the channel is wider than the flood plain are those in White Rock Canyon, where the channel occupies most of the available space on the valley floor. The waters of Cochiti Reservoir drown the segments from km 50 to km 66

6.6 Depth of Deposition, 1948-1985

Given from the regional sediment budget the approximate amount of total load deposited with the Northern Rio Grande from Otowi to San Marcial 1948 1985 and the area over which that deposition occurred, it is possible to estimate the depth of the deposition on flood plain surfaces for the 1948-1985 period. The sediment transport data from gaging stations is by weight, necessitating conversion to volume using an

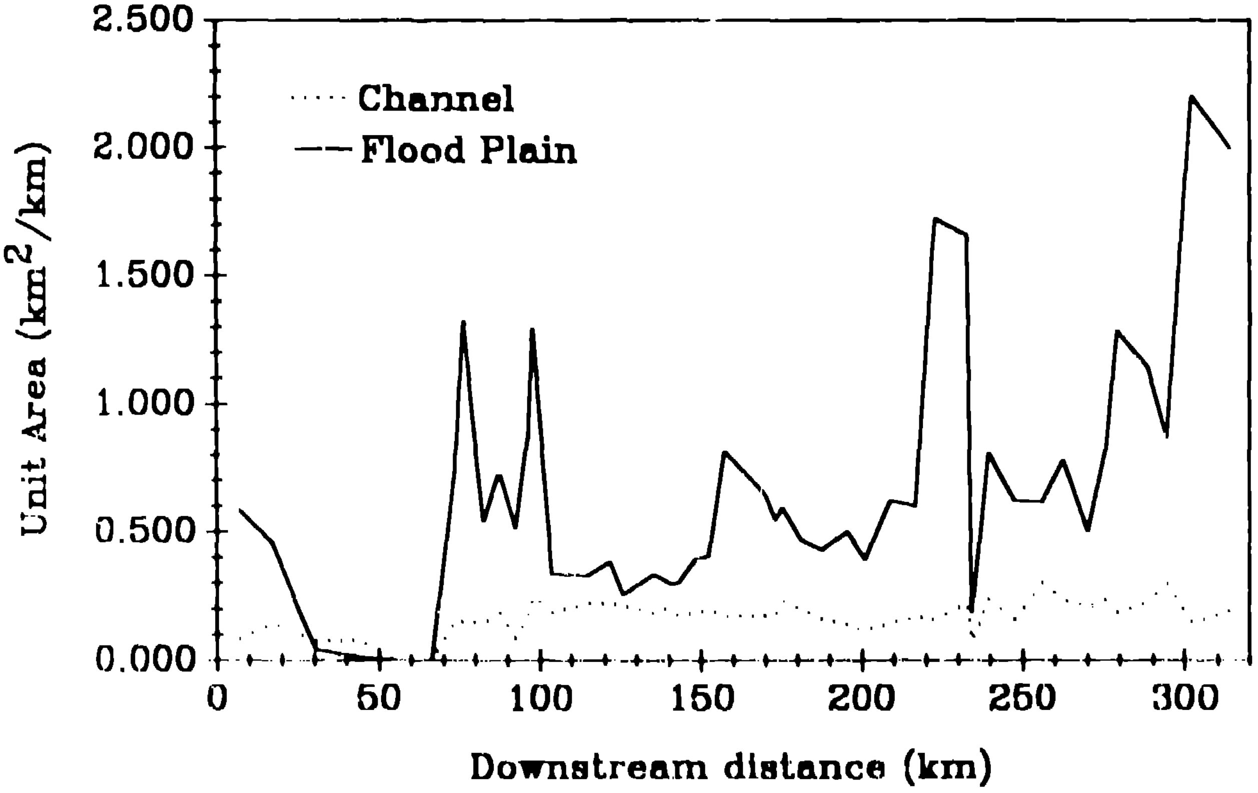


Figure 6.4 Downstream distribution of active channel and flood-plain areas along the Rio Grande from Española to San Marcial (313 km) as measured from aerial photography taken in the period 1981 1985.

estimation of bulk density for deposits. For flood plain and related deposits, the following calculations used a bulk density of 1.6 Mg/cu m and data reviewed in Appendices B (for sediment masses) and D (for areas of deposition).

Step 1: Convert the total sediment stored as measured by its weight (W in Mg) to the total storage measured as volume (V in cu m):

$$V = W/1.6.$$

Step 2: Partition the area data for potential storage areas into reaches that match reaches defined by the gaging data for sediment and define the total available storage area within each reach.

Step 3: Determine the mean depth of storage (D in m) within each reach by dividing the volume (V in cu m) of storage by its area (A sq m):

$$D = V/A.$$

These calculations assume an equal distribution of deposition over the available area, so that they produce only mean values. Field observations indicate that the depth of deposition varies from place to place, but not by more than a factor of about 2. The reach-by-reach summary (Table 6.1) shows that in the Otowi-Jemez River and Albuquerque-Puerco River reaches there was negative deposition, that is, a net loss of stored sediment through erosion. In the Otowi-Jemez River reach, White Rock Canyon has little storage and erosion after the closure of Cochiti Dam insured the negative value. In the Albuquerque-Puerco River reach, channelization and levee construction that restricted the channel and enhanced erosion. The Jemez River-Albuquerque and Puerco River-San Marcial reaches had net gains in storage, resulting in an increase in the elevations of the surfaces of their flood plains and channels

In those areas where net deposition occurred between 1948 and 1985, the mean depth ranged from 0.19 to 0.82 m. The overall average from the entire river from Otowi to San Marcial was 0.53 m. Assuming the local variability to be within a factor of 2, the expected range of depths is therefore about 0.1 to 1.6 m. Detailed surveys of selected cross sections between Cochiti Dam and Isleta Diversion Dam south of Albuquerque confirm those estimates.[10] The importance of these estimates for the analysis of plutonium storage is that almost all plutonium in the system must have entered the main stream during this period of record. It is therefore associated only with the sediment stored during the same period, and that sediment occurs in deposits that average less than 1.6 m deep. Given the tendency of plutonium not to migrate vertically within soil profiles, it is likely that the contaminant stored in flood plains along the river is within about 1.6 m of the surface. Local distribution of the materials may be strongly influenced by engineering works, the subject of the next chapter.

TABLE G.1 SUMMARY OF CALCULATIONS FOR MEAN DEPTH OF DEPOSITION OF STORED SEDIMENT.

	Otowi - Jemez River	Jemez River - Albuquerque	Albuquerque - Rio Puerco	R. Puerco - San Marcial
Weight of Stored Sediment (tons)	2,725,773	12,919,299	20,653,569	220,331,627
Weight of Stored Sediment (Mg)	2,472,821	11,720,388	18,736,917	199,884,852
Volume of Deposition (cu m	1,545,513	7,325,243	11,710,573	124,928,033
Area of Deposition (sq m)	29,395,800	38,166,500	58,133,400	151,235,700
Depth of Stored Sediment (m)	0.0526	0.1919	0.2014	0.8260
Annual Rate of Sedimentation (cm/yr)	0.1422	0.5186	0.5441	2.2324

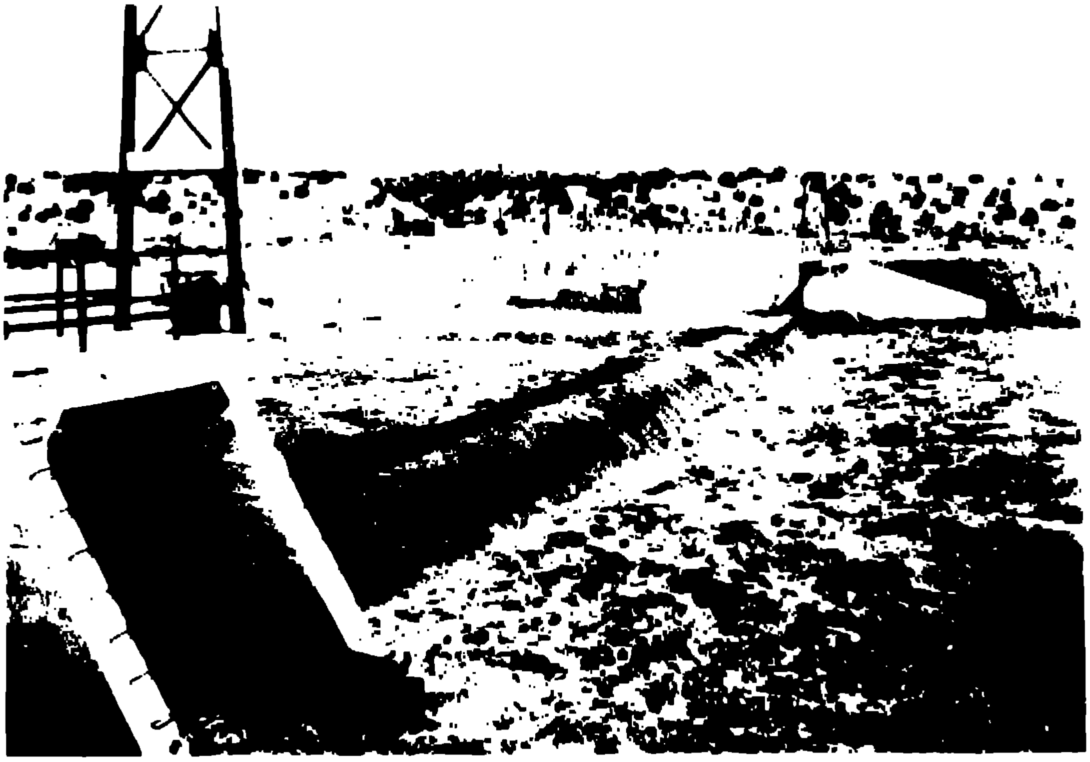


Figure 7.1 Engineering works near Cochiti Pueblo have produced profound changes to the Rio Grande. Above, looking east across the crest of Cochiti Diversion Dam about 1935 (Unknown photographer, Museum of New Mexico Photo 59142). Below, looking west across the site of the dam in the upper photograph in 1992. The small diversion work is submerged below the reservoir impounded by Cochiti Dam, the large flood control structure along the left side of the view (W. L. Graf Photo 105-13).

CHAPTER 7. ENGINEERING WORKS

7.1 Historical Background

The hydrologic, sedimentologic, and geomorphic processes of the Northern Rio Grande as outlined in the previous chapters do not operate under natural, undisturbed conditions. Numerous engineering structures and activities have modified the processes and forms (Figure 7.1), so that an explanation of the movement and storage of contaminants in the system requires an understanding of the channelization and dam construction in the region. Channelization works are usually directed toward controlling the horizontal position of the channel, keeping it aligned in an economically advantageous arrangement, and maintaining a clear path for flood waters to prevent overbank spillage. The imposition of an artificial, stable channel on a naturally unstable system is rarely completely successful, but even with partial success, the newly defined system is a radical departure from the natural one.[1] Modified channels usually conduct flood flows at higher velocities than natural channels, so that they may transmit more sediment in the channel. Low flows, however, may deposit sediment in the engineered channel, reducing its efficiency and raising its bed. Abandonment of previously active minor channels or braided sections provides new areas of colonization for riparian vegetation, which may enhance sedimentation when flows exceed capacity of the designed channel. The construction of dams obviously disrupts river processes in the reservoir area, but indirect impacts extend throughout the river system because of newly instituted controls on flood flows, normal low flows, and sediment discharges.[2]

The first engineering structures on the Rio Grande probably appeared about 1200 A.D. With the collapse of irrigation societies in the Salt and Gila River Valleys in Arizona and in tributaries of the San Juan River in Colorado and New Mexico, migrants moved into the Rio Grande Valley.[3] By the time of the Spanish incursions in the middle and late 1500s, the native population had developed extensive irrigation systems along the entire Northern Rio Grande to support numerous pueblos.[4] Diversion works on the main stream probably consisted of brush and boulder structures that directed flow into canal entrances through the low banks. The structures probably washed away with each spring flood.

Spanish and Mexican immigrants arrived in the 1500s and later produced more extensive canal systems on flood plains and terraces near the river, with an extensive legal system for water management.[5] Still, the impacts on the main river channel were probably limited. Hispanic settlers and later Anglo-Americans who arrived in greater numbers after 1848 did little to improve upon the Pueblo dwellers' efforts to control the main river until the late 1800s when diversion structures became more numerous and elaborate. Irrigated acreage expanded until about 1880.

After about 1880, irrigated acreage declined in the Northern Rio Grande because of drainage problems in the fields and because the river was aggrading.[6] The aggradation resulted from at least two causes, changing hydroclimatic conditions and erosion of tributaries. The late 1800s was a time of increasingly intense rainfalls as previously discussed, and general erosion of the landscape surrounding the river increased. Land use in tributary watersheds also probably contributed to gully and arroyo development, increased hillslope erosion, and general increases of sediment to the main stream which was unable to transport all of the new load.[7]

As part of an 1890s regional assessment of the possibilities of water resource development throughout the American West, Congress and the executive branch of the federal government began to consider larger and more permanent diversion works for the Northern Rio Grande.[8] Problems associated with controlling the river, establishing useful diversions, and draining the fields led to the establishment of Middle Rio Grande Conservancy District in 1925. Within 10 years, the district, with considerable federal assistance, had completed diversion dams at Cochiti, Angostura, Isleta, and San Acacia as well as 290 km of riverside drains and 260 km of interior drains.[9] The drain projects included linear heaps of dredge spoil that separated the drains from the river as it was aligned during the 1930s. The area between the levees that included the active channel was a "floodway." Later engineering works followed the same alignment. Therefore, significant parts of the drainage system and main channel as they exist in the late twentieth century owe their geometry to a river channel alignment that was naturally established more than 50 years ago.

As part of the general economic rehabilitation efforts of the New Deal in the administration of President Franklin D. Roosevelt, several federal and local agencies conducted investigations of the Rio Grande during the late 1930s. The U.S. Department of Agriculture evaluated the consumptive uses of streamflow along the main river and collated the available flow, consumption, and crop data.[10] These data supported and complemented the activities of the National Resources Committee, an interagency group at the cabinet level tasked with regional resource planning for the Rio Grande, including a division of its waters among competing states.[11] The committee report included detailed maps of the river and near-channel environment that are so detailed they extend the record of aerial-photographic quality images back to the mid-1930s (Figure 7.2). Although the 1930s investigations provided data and recommendations for extensive engineering and control structures, the advent of World War II diverted national funds to other uses.

During the war years, the original Middle Rio Grande Project structures failed to control the problem of excess sediment, and the main stream continued to aggrade. Channel instability, exaggerated by the aggradation, continued, especially during floods. In the Albuquerque area, a flow of 25,400 cfs in 1941 and 24,200 cfs in 1942 caused 27 breaks in the poorly constructed levees.[12] In conjunction with the Flood Control Act of 1948, the Corps of Engineers and Bureau of Reclamation surveyed the river's management problems and began attempts to stabilize the channel and reduce inflow of sediment.[13] By 1962, the agencies had rehabilitated the drain system, strengthened levees, built conveyance and pilot channels, cleared vegetation, and installed sediment traps.[14] Cochiti Dam on the Rio Grande and several other dams on tributaries provided additional flood and sediment control by the 1970s. These structures now function as part of the river system, and they partly control the fate of plutonium in the system.

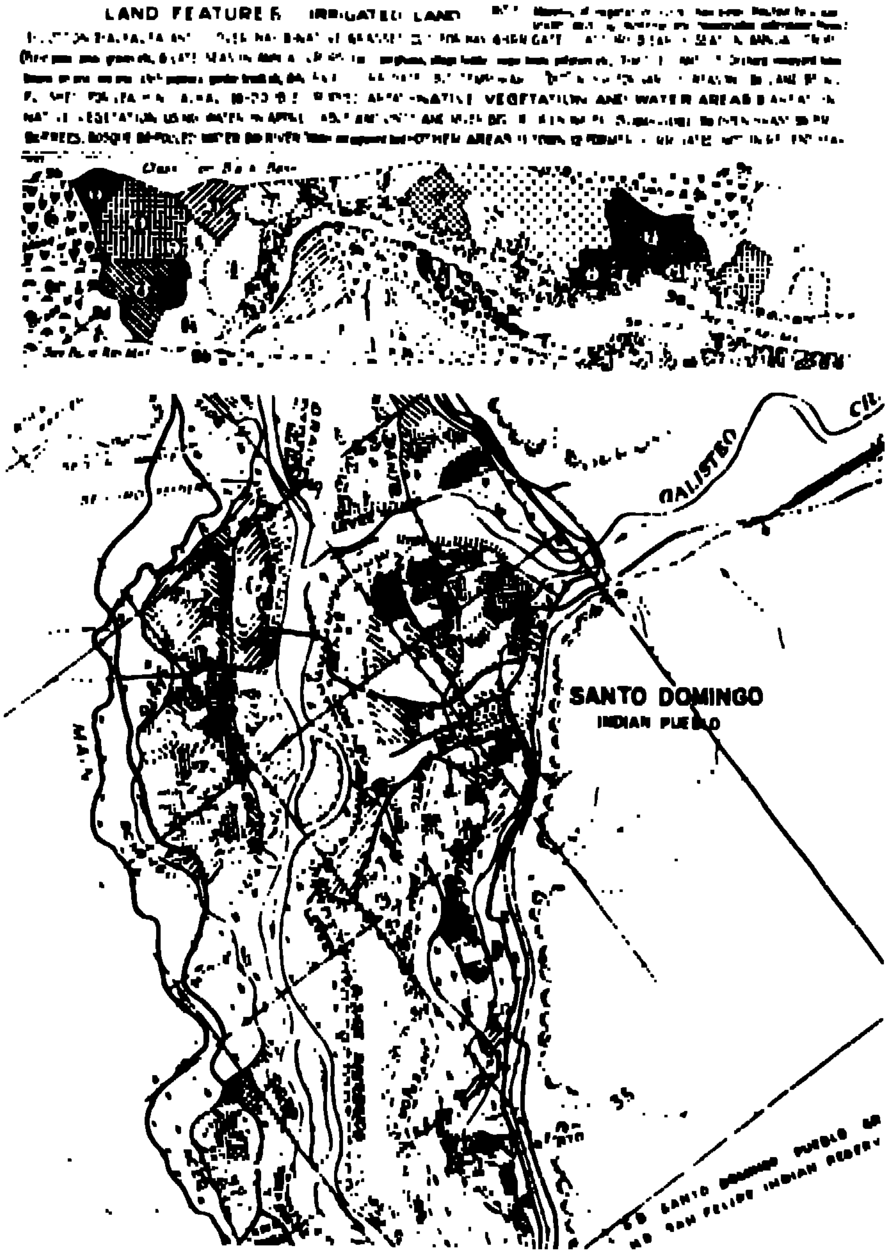


Figure 7.2 An example of the detailed mapping of the river and riparian zone of the Northern Rio Grande by planners during the New Deal era of the mid 1930s, showing the intricate detail of the effort (from National Resources Committee, 1938)

7.2 Channelization Works

The purposes of channelization works are to control the channel location and to prevent flooding outside the channel area by employing levees, conveyance channels, pilot channels, and vegetation clearing. Construction of sediment traps stabilizes channel margins. Levees in the Northern Rio Grande system are of two types: spoil heaps and designed levees. Spoil heaps are accumulations of sediment dredged from canals and drains. Placement of the heaps between the river and the canal or drain affords some protection to the ditch, but the heaps are not designed to any specifications. Vegetation stabilizes their slopes, and they often carry unpaved roads on their upper surfaces. They are easily eroded if channel migration forces flood flows against their outer banks. Engineered levees meet design criteria for size and resistance to erosion, and they are sometimes protected by riprap, waste rock less susceptible to erosion than soil material.

Conveyance channels conduct low flows of the river in designed, confined channels that are stable. Relatively steep gradients insure the continued movement of sediment through the conveyance channel. During flood periods, the natural channel conducts flow as well. Pilot channels are artificially aligned portions of the original, natural channel. The pilot version is usually straighter than the natural version, in an attempt to reduce channel migration that results from meandering and bank erosion.

Vegetation and sediment management along the Northern Rio Grande may increase the stability of pilot channels and levees. If riparian vegetation grows between the levees and the channel, destruction of the levee is less likely, because if water spills out of the channel, the vegetation introduces considerable hydraulic roughness to the flow, reducing its velocity and increasing the probability of sedimentation. Artificial clearing of vegetation in other parts of the system may enhance the locational stability of the channel. If vegetation does not grow within the pilot channel or in the natural channel, flood waters are more likely to flow by these routes than they are to carve new courses. Clearing projects therefore focus on maintaining a vegetation-free floodway in the most desired alignment.

Finally, structures introduced to the channel and flood plain area between the levees may artificially stimulate sedimentation, providing protection for the levees and stability for the channel.[15] The U.S. Army Corps of Engineers attempted to use pile jetties to protect levees in 1944, but without success. The jetties caused turbulence in flood flows that scoured the channel bed and removed the jetties. Between 1953 and 1962 the Corps installed jetty fields made of Kellner "jacks."[16] Developed for small Kansas streams and first used by the Santa Fe Railroad in the Rio Grande system in 1936, these jetties consisted of jacks made of connected lengths of steel rail and a lattice work of wire. Cables connected the individual jacks to each other and to anchoring posts outside the active channel area. The jacks create enough turbulence in flows to cause sedimentation, but at high discharges their porosity and flexibility decreases scour. Since the early 1950s, river management agencies have placed jack fields in those areas where the development of new channel is undesirable, leaving the preferred channel areas free of jacks. Field reconnaissance shows that by the late

1980s the jacks had accumulated 0.1-1.0 m of sediment and were the sites of dense riparian vegetation.

Throughout the Northern Rio Grande, the application of these measures varies from one segment of river to another. Between Española and Cochiti, engineering structures are rare, the mining of sand and gravel has afffected channel conditions in some reaches (Figure 7.3). Between Cochiti and the southern edge of Albuquerque, designed levees restrict the floodway on both sides. Inside each levee is a zone of dense vegetation, and jack fields are common but relatively small. South of Albuquerque, channel clearing and large jack fields supplement channelization efforts, while in the vicinity of Bernardo a conveyance channel removes all the flow of the river during low discharge periods. A pilot channel appears in several reaches south of Albuquerque. All the major channelization works that presently affect the river have dates of completion between 1950 and 1962 (Figure 7.4).

The success of these efforts is problematic. While the jack fields have successfully stimulated moderate sedimentation, declining flood flows during the later period of record suggest that sedimentation might have occurred in any case. Vegetation maintenance for the protection of levees has produced dense riparian forests in some areas, but clearing of pilot channels has been expensive and in some cases ineffective. In the Albuquerque area, for example, the original floodway design was for conductance of discharges up to 42,000 cfs, but present conditions of channel filling and vegetation growth probably restrict capacity to less than 25,000 cfs, and elsewhere the original design capacities were 20,000 cfs, but are now only 10,000 cfs[17] The sediment (with its adsorbed contaminants) that is stored in these reaches is part of the explanation of the regional plutonium budget.

7.3 Dams

North of Truth or Consequences the Rio Grande basin contains thousands of minor retention works for erosion control and stock water development. Thirteen large structures directly affect the flow of the river and its sedimentary load (Figure 7 5; Table 7 1) The large structures are products of three distinct eras of dam construction an agricultural development period in the 1910s and 1920s, the Middle Rio Grande Conservancy District period (1925 1936), and the Middle Rio Grande Project years after 1948

In the northern part of the basin, agricultural development in the San Luis Valley Colorado, stimulated the construction of several dams in the 1910s Although individuals and corporations established large numbers of artesian wells in the valley, water from the river also contributed to a land investment boom early in the century[18] Valley based water districts constructed dams in the San Juan and Sangre de Cristo Mountains to store excess spring runoff for release during the summer dry period By 1925 six dams in mountain locations influenced the upper river's hydrology by reducing the spring flood peak and extending low flows at higher discharges into summer months. Later construction added a seventh structure

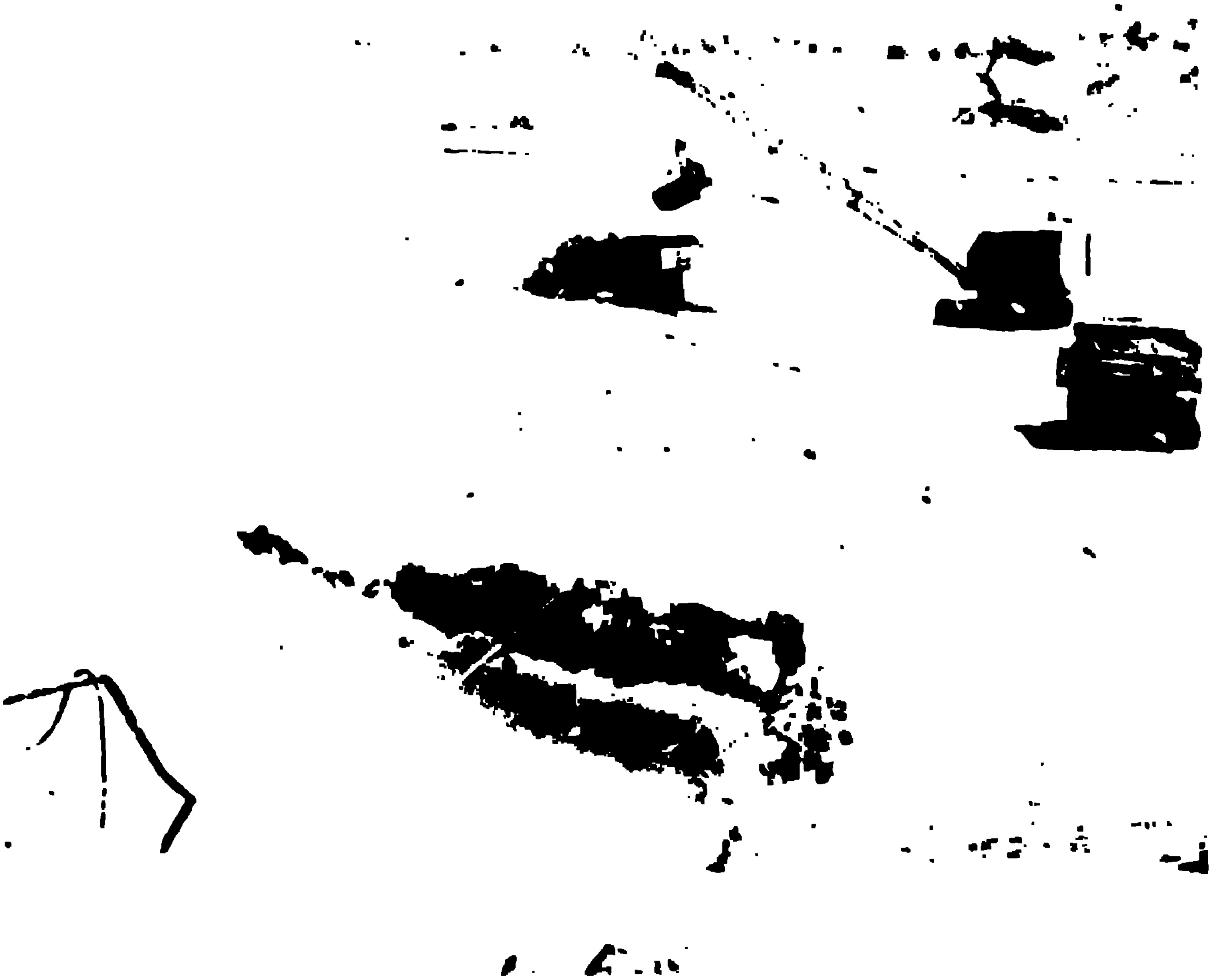


Figure 7.3 Sand and gravel mining in the Rio Grande near Otowi Bridge introduces significant changes in channel geometry circa [illegible] (Los Alamos Historical Society Photo #[illegible])

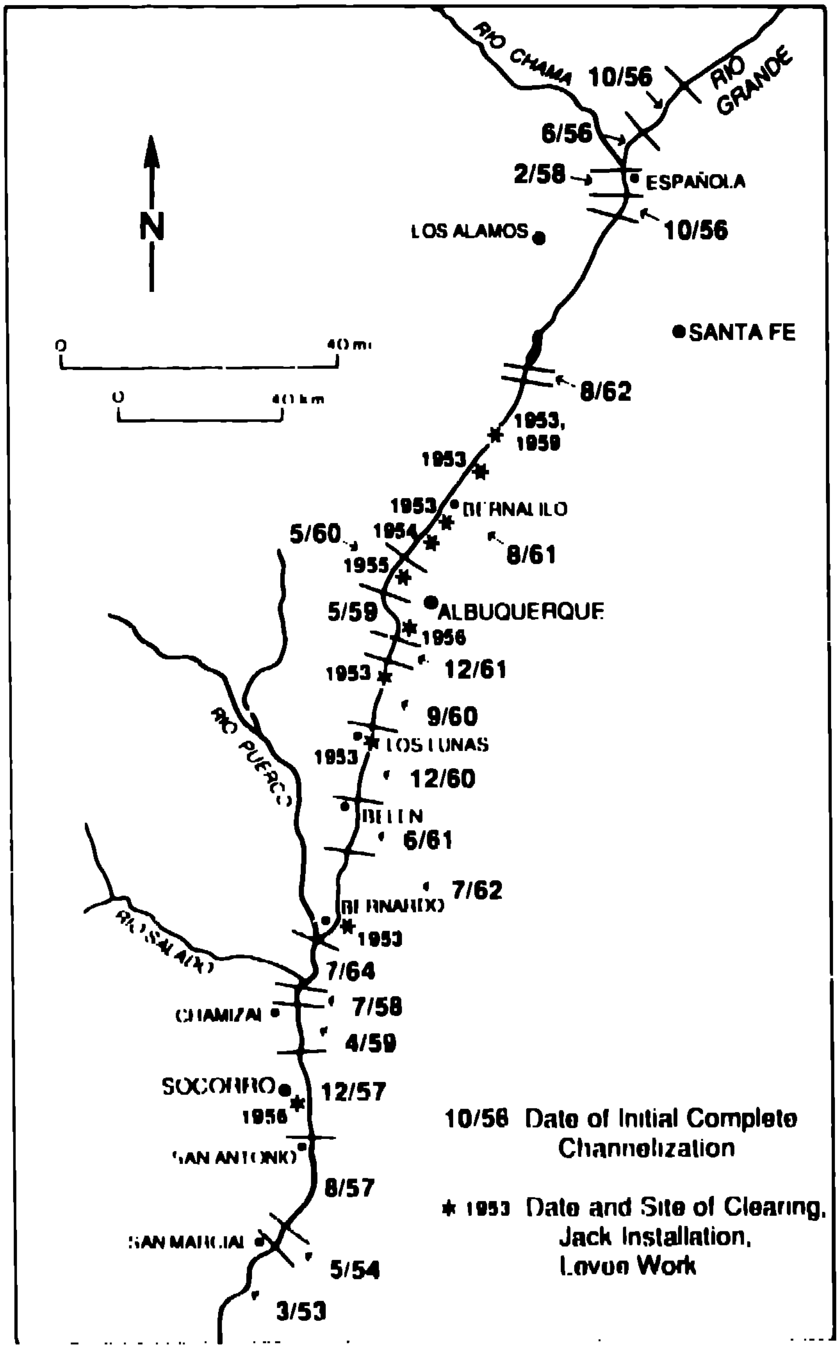


Figure 7.4 Completion dates for channel engineering works along the Northern Rio Grande in the post-1948 era.

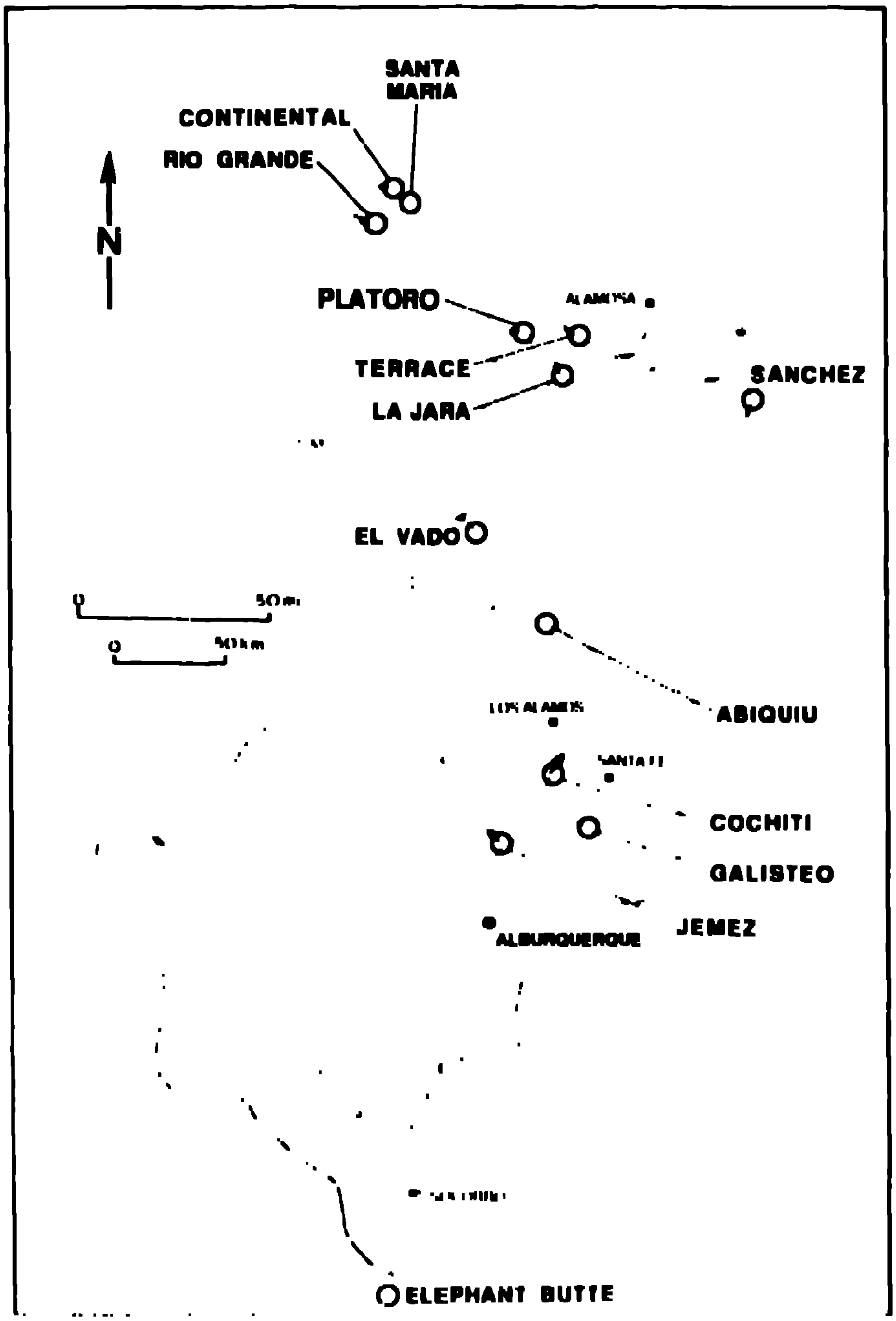


Figure 7.5 Locations of major dams in the Northern Rio Grande basin.

TABLE 7.1 MAJOR DAMS IN THE NORTHERN RIO GRANDE SYSTEM

Date	Dam	Stream	Capacity (ac ft)	Capacity (cu m)
1910	La Jara	La Jara Creek	14,100	17,189,000
1911	Sanchez	Culebra Creek	104,000	127,214,000
1912	Terrace	Alamosa Creek	17,700	21,651,000
1913	Rio Grande	Rio Grande	51,500	63,000,000
1913	Santa Maria	Gooseberry Creek	42,000	51,375,000
1916	Elephant Butte	Rio Grande	2,155,000	2,636,000,000
1928	Continental	North Clear Creek	26,700	32,679,000
1935	El Vado	Rio Chama	198,700	243,000,000
1951	Platoro	Conejos River	60,000	73,392,000
1952	Jemez	Jemez River	113,000	139,250,000
1963	Abiquiu	Rio Chama	1,221,000	1,493,000,000
1970	Galisteo	Galisteo Creek	90,600	110,770,000
1973	Cochiti	Rio Grande	607,100	742,567,000

Notes. Data from International Commission on High Dams (1979) and Mermel (1958). Dates for initial closure, several structures subsequently modified

During this early period, attempts to control the flow of the river in central New Mexico resulted in the construction of Elephant Butte Dam, completed in 1916. Elephant Butte Reservoir, the downstream terminus of the present study area, is a storage pool for gradual release of water to irrigation lands in southern New Mexico and the El Paso, Texas area. The U.S. Reclamation Service (later to change its name to Bureau of Reclamation) also built the dam to meet international treaty obligations for water delivery to Mexico.[19]

The Middle Rio Grande Conservancy District produced several diversion structures during its initial period of activity, 1925-1936. The project built low structures designed to divert flow of the main river efficiently into the headgates of extensive canal systems at Cochiti, Angostura, and Isleta. Local interests had constructed a diversion work at San Acacia in 1920, so that taken as a group, these four structures constituted a firm basis for irrigation withdrawals. El Vado Dam on the Rio Chama provided further control of the spring melt flood in the main stream. In the late 1950s the Bureau of Reclamation and the conservancy district agreed to an arrangement whereby the bureau assumed management control and maintenance of the structures.[20]

After World War II, the Middle Rio Grande Project, a joint venture of the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation, stimulated the construction of additional large structures, principally for flood and sediment control. Because of the high-value urban investments in the Albuquerque area, the benefits of these new structures emphasized flood protection for the city and sediment retention to prevent channel aggradation through the metropolitan area. Jemez, Abiquiu, and Galisteo Dams on large tributary streams perform sediment control functions as well as preventing catastrophic summer flash floods.

Cochiti Dam, closed in December, 1973 on the main stream, is the primary flood control structure for the Albuquerque area. Built near the site of the old Cochiti Diversion Dam, the new structure has a permanent pool that fluctuates drastically in response to annual inflows. Normal storage in the early years of the reservoir's history was about 55,000 ac ft, but in the spring of 1979 high runoff from the upper basin left 189,000 ac ft in the pool.[21] During the mid-1980s, a series of floods brought the reservoir close to its capacity of slightly over 600,000 ac ft. The reservoir also stores huge quantities of sediment that otherwise would be deposited on flood plains and in channel areas south of Cochiti.[22]

7.4 Implications for Plutonium Mobility

The extensive engineering works in the Rio Grande system alter the natural behavior of the river and influence the mobility of plutonium by changing the sediment transport processes. Because most of the plutonium in the system is attached to sediment, the fate of sediment is also the fate of the radionuclides. Engineering works partly control the location of deposition, and they therefore also partly control the sites for plutonium storage in the system.

Channelization works that focus the discharge into predetermined alignments generally have higher velocity than the original natural flows, creating an environment for enhanced sediment transport in a limited part of the valley and channel cross section. Fine sediment that is likely to have the highest concentration of plutonium is rarely deposited under such conditions. The course of the river through much of Albuquerque has channels of this type. However, adjacent to the channel are sediment-trapping areas with dense riparian vegetation and jack fields where sediment of all sizes accumulates. Through the Albuquerque area these depositional zones are relatively narrow, but elsewhere the accumulation areas occupy substantial portions of the valley cross section between the levees. Width of this accumulation zone may be more than a km, providing primary storage space for plutonium-bearing deposits that are almost always associated with riparian forest. Detailed mapping of these zones and precise dating of the implantation of the deposits can therefore inform on the likely distribution of plutonium in local areas along the river.

Dams have a major impact on the mobility of sediment and attached plutonium in the Rio Grande. With the exception of Platoro Dam on the Conejos River, all the mountain reservoirs were in place before plutonium entered the drainage system. Fallout plutonium eroded from mountain slopes is likely to be stored within the mountain reservoirs, and the only fallout plutonium entering the lower reaches of the river (south of the Colorado-New Mexico boundary) comes from those slopes downstream from the mountain reservoirs. The possible impact of this arrangement on the regional plutonium budget is unclear, because the reservoirs contain water, sediment, and plutonium from the alpine zones where input of fallout is likely to be greatest. The sediments of Rio Grande Reservoir contain relatively high amounts of plutonium as a reflection of this process.[23] Alternatively, the mountain drainage areas downstream from the dam sites are larger than those upstream from the dams and their pools. Without further research, the specific plutonium contributions of these areas are unclear.

Dams and reservoirs on tributaries of the Rio Grande that are not in the high mountains trap sediments from landscapes that probably do not receive as much fallout as the alpine zones. Occasional sampling of the materials stored in Abiquiu, El Vado, and Platoro Reservoirs show plutonium concentrations lower than those in Rio Grande Reservoir (Environmental Surveillance Group, 1987-1989).[24] The total amount of plutonium stored in the low elevation tributary reservoirs may eventually exceed the amount stored in the alpine reservoirs, however, because the tributary pools drain landscapes that produce more sediment.

Cochiti Reservoir is especially significant for the analysis of plutonium mobility because of its size and location. Its capability to store almost all the sediment that enters the lake make Cochiti Reservoir the ultimate storage site for almost all river sediment generated in the basin north of Cochiti. The location of the dam on the main stem of the Rio Grande downstream from Los Alamos National Laboratory insures that the sediments of the reservoir store plutonium from both fallout and laboratory sources. Before December 1973 the plutonium in river sediment could be stored across thousands of square kilometers of flood plains and could be diluted by tributary sediments from streams south of Cochiti, including the Galisteo Creek, Jemez River, been deposited in the restricted reservoir basin behind the dam, and concentrations of the metal, though variable, have recently appeared to be in the same range as those in Rio Grande Reservoir.

Figure 8.1 Variation in vegetation cover in a sand dune area immediately upstream from the San Acacia Diversion [illegible] changes in plant communities of the Rio Grande Basin. Above looking [illegible] with the small pond behind San Acacia [illegible] the middle distance showing [illegible]

CHAPTER 8. RIPARIAN VEGETATION

8.1 Riparian Vegetation Communities

The interaction among water, sediment, landforms, and human environmental manipulation on the Northern Rio Grande have produced a distinctive assemblage of plants in the riparian (or near-channel) community. Fluvial landforms and the sediment that composes them are often not immediately visible in field investigations because of the dense cover of riparian vegetation. In aerial photography, the primary source of data for historical river channel change and sedimentation, riparian vegetation is often the only aspect of the near-channel environment that is susceptable to interpretation and mapping. Vegetation also provides information on the date of emplacement of the sediments upon which it grows, information useful in tracking contaminants introduced into the system during known time periods. Vegetation communities therefore provide useful keys to understanding the distribution of near-channel sediments and the contaminants they contain. The following chapter provides a brief review of the origin and changes in riparian vegetation of the study area, including an overview of its connections with geomorphic systems.

Almost all major rivers in the American Southwest have undergone considerable geomorphic and vegetation change since the early 1800s when channel margins were the sites of bogs, lakes, abandoned meanders (sloughs), and marshes (Figure 8.1).[1] Most major rivers had broad, sandy channels with braided configurations and meandering low flow channels.[2] Even small tributaries had marshy areas created by beaver activities.[3] The riparian vegetation originally evolved in association with frequent extensive flooding (White, 1979; Rupp, 1982).[4] Removal of the beaver, gully and arroyo development, land management schemes, climatic change, and the construction of dams changed the streams into single thread or compound channels with reduced overbank flooding.

The Rio Grande's recent history is typical of the larger region except for the extensive recent engineering works that restrict the active channel and flood plains. There are few detailed descriptions of the channel and riparian vegetation before major human impacts, but most general comments from first hand observers indicate that the Northern Rio Grande was broad and shallow, with meandering subchannels frequently altered by flooding.[5] After channel migration, cottonwood, willow, and cattail colonized newly exposed alluvial surfaces.[6] Early in the twentieth century, cottonwood groves near the river rarely developed trees more than about 10 m high before renewed channel change destroyed them.[7] As elsewhere in the Southwest, a high water table existed close to the river, creating marshy conditions and lakes, irrigation contributed to this natural condition until the Middle Rio Grande Conservancy District engineering work in the late 1920s and 1930s. Prior to the engineering work, lakes, marshes, wet meadows, and a mixed woodland (including cottonwood and willow trees) fringed the river, but after the construction, the lakes, marshes, and wet meadows disappeared. Willows, once a common tree form everywhere in the riparian environment,[8] also disappeared except for small scattered shrubs.

The absence of large floods since 1941, the Middle Rio Grande Project beginning in 1948, and the closure of flood control dams in the 1960s and 1970s completed the changes in the vegetation system.[9] Spring floods were smaller than previously, moderate flows extended longer in the summer season, and the channel location became much more stable. As a result, cottonwood trees have developed into large forms 20-30 m high, and they no longer regenerate through flood damage. Instead, human disturbance by construction and fire lead to new growth in the riparian forest. The Kellner jack fields, erected on abandoned braided channels and flood plains, became the sites for rapid colonization by cottonwood, willow, tamarisk, and russian olive.

Tamarisk (also known as salt cedar, *Tamarix chinensis* Lour.) and russian olive (*Eleagnus angustifolia* Lour.), especially useful in mapping river forms and deposits, are exotic species that may be gradually replacing the native species. Tamarisk, a native tree or shrub in the Mediterranean region, was part of an international seed exchange program and appeared in Southern California nurseries as an ornamental plant in 1852.[10] By 1900 the plant had escaped cultivation and grew along sand bars and channel margins of the major rivers in the Sonoran Desert.[11] It spread throughout the Southwest between 1900 and 1940; it was a domestic ornamental plant in Albuquerque early in the twentieth century, but became widely naturalized throughout the valley by about 1935 (Thompson, 1958; Robinson, 1965).[12] The plant's prodigious production of airborne seeds, long germination period, and rapid growth allowed it to compete favorably with native trees in colonizing newly stabilized sandy or silty surfaces (Potter, 1975; Everitt, 1980).[13]

Farmers probably introduced russian olive to Albuquerque between 1900 and 1915, and by 1935 it too had become common in the Rio Grande riparian communities.[14] Like tamarisk, russian olive colonizes newly exposed river deposits where it grows well in shade and invades existing woodlands.[15] By the late 1980s, russian olive commonly occurred in linear groves along the margin of the channel, but individual trees appeared in cottonwood areas. It also appeared as new growth in many channel areas that were artificially cleared of vegetation as a flood control effort.

Along the Northern Rio Grande of the late 1980s, there were eight primary community types.[16] Cottonwood (*Populus fremontii* S. Wats.; *Populus fremontii* var. *wislizenii* [Torr.] S. Wats.; and *Populus angustifolia* James) dominates three of the most common riparian communities. In the cottonwood/coyote willow community, coyote willow (*Salix exigua* var. *nevadensis* [Wats.] Schneid.) is the most abundant understory plant, but tamarisk, russian olive, and seepwillow (*Baccharis salicina*) are also common. Grasses and forbs complete the ground cover.

The cottonwood/russian olive community has an understory consisting almost exclusively of russian olive or, in the area between Española and Albuquerque, of New Mexico olive (*Forestiera noemexicana*) without herbaceous growth. The cottonwood/juniper community also lacks significant herbaceous growth, and instead of olive, the dominant understory plant is one seed juniper (*Juniperus monosperma*). Russian olive communities, wherein the olive trees dominate in narrow strips along the main river channel, include a few seedlings of other trees. Tamarisk communities occur most commonly in the southern portions of the area, where the tamarisk plants grow to the exclusion of other tree species.

Three non-arborial communities also occupy the riparian environment of the Northern Rio Grande in New Mexico. Cattail marsh communities with cattails (*Typha latifolia*) and bulrush (*Scirpus acutus*) grow in some recently abandoned channel areas or in low, waterlogged portions of the flood plain. Two additional community types are related directly to the river. Sandbar communities have mostly barren, sandy surfaces, but occasionally support sparse grass, annuals, and various seedlings that do not survive flooding. The river channel is occasionally dry, and may briefly support some grasses.

Compared with upland vegetation, riparian communities are relatively unstable,[17] responding to changes in the river landscape on an annual basis. The importance of these various vegetation communities to the present investigation is that each community is associated with a particular type of river landform or sediment. The tamarisk communities, for example, colonize abandoned river channels, so that a map of that particular community is effectively a map of abandoned channels and sedimentary fillings. Mapping vegetation is often more efficient than mapping the landforms and sediments directly, because the vegetation is clearly defined on aerial photography. Definition of the age of the vegetation, either through photographic evidence or by direct physical evidence provides a minimum age for the deposition of sediments and associated contaminants.

8.2 Vegetation/Geomorphology Connection

The distribution of riparian vegetation communities is closely tied to the distribution of near-channel landforms through historical associations, influence of fluvial processes, the variation in sediment characteristics, and the availability of ground water. The river channel creates and abandons portions of the landscape that then become seed beds where colonization by vegetation reflects the temporal changes in the river's course (Figure 8.2). Forms created by the river before the advent of tamarisk and russian olive, for example, are less likely to be dominated by those species than forms created later when their seeds were available for colonization. In the Northern Rio Grande system, the areas most densely populated by tamarisk are those areas made available for seedling development during and after the 1950s when tamarisk had successfully established itself in the region.

In addition to the temporal factor, river landforms and processes also directly influence vegetation communities. Cottonwood often grew along the margins of single-thread channels before the invasion of tamarisk and russian olive. When the river course changed, abandoning some single-thread channels, the cottonwoods remained along the alignments of the previously active water courses, resulting in lines of trees across flood plains covered with other vegetation types (Figure 8.3). Vegetation communities respond to flood processes as well, so that flood plains frequently inundated by fast flowing water are likely to have flood-resistant plant types

Figure 8.2 Forms and riparian vegetation on the Rio Grande flood plain near Santo Domingo Pueblo, showing a minor abandoned channel across the foreground covered with grass and sedges, with tamarisk and cottonwood trees in the background along what was once the bank (W. L. Graf Photo 76-24).

Figure 8.3 An abandoned channel lined by cottonwood trees in the Rio Grande flood plain near Santo Domingo Pueblo (W. L. Graf Photo 76-21)

such as tamarisk or willow rather than relatively brittle hardwoods such as elm or cottonwood.

Fluvial form and process changes have direct connections to the particle sizes of the resulting deposits, providing another link with vegetation communities. Willow, for example, favors fine-grained soils, and so is most likely to grow on flood plains rather than on coarse bar deposits. There are limits to this particle size and vegetation connection, however, because some species, including tamarisk, grow aggressively in soils dominated by particles ranging from silt to course gravel.

Availability of ground water is a major determinant for the distribution of many riparian species that are phreatophytes, plants that have extensive tap root systems that allow them to obtain water directly from the zone below the water table.[18] In most areas near the channel of the Northern Rio Grande, the water table is within a few meters of the surface, and minor variations in depth to ground water may influence the nature of the vegetation communities on the surface. In those places where ground water is forced close to the surface by obstructions, phreatophytes may gain a competitive advantage over other species. Near San Marcial, for example, a basalt flow constricts the river channel and the groundwater flow, forcing it close to the surface. Tamarisk, an aggressive phreatophyte, grows so densely there that it excludes almost all other species.

An ecological sampling scheme reveals the general nature of the geomorphology and vegetation connection. The following procedure provided a census of tree-forms 2 m or greater in height from 32 sample plots scattered throughout the Northern Rio Grande.

Step 1. Select a starting point for the plot in a representative landform- sediment area such as a flood plain, bar, or abandoned channel.

Step 2. From the starting point, define a straight sample line in a random direction for a distance of 100 m.

Step 3. Define as the sample area the rectangle outlined by the area 1 m on both sides of the sample line, resulting in an area 100 × 2 m.

Step 4. Identify and tally all woody stemmed plants 2 m or greater in height within the sample area.

Of the 1,985 trees identified on the 32 plots, 66 percent were tamarisk, 10 percent willow, 9 percent cottonwood, and 8 percent russian olive. The remaining 7% were saltbush (*Atriplex canescens*), Rocky Mountain maple (*Acer glabrum* Torr.), American elm (all juvenile, *Ulmus americana* L.), red mulberry (*Morus rubra* L.), and sagebrush (*Artemisia tridentata*).

Data from each plot including soil samples and identification of the fluvial landform permit a test of the associations among the four most abundant species, sediment particle size, and landform (Table 8.1). The tree densities on the sample plots ranged from about 3,300 per sq km (an open stand of cottonwoods) to about 560,000 per sq km (a dense thicket of tamarisk). A review of the data shows that tamarisk is so common that it occupies all forms and soil types when considering the entire study reach of the river. At the scale of individual reaches, however, tamarisk is a significant discriminator of forms and sediment, with its distribution closely associated with abandoned channels, for example. Russian olive occurs almost exclusively in association with active channels, and rarely elsewhere except on abandoned bars that recently were next to active channels. Cottonwood is a flood-plain species, with highest densities occurring along abandoned single-thread channels. Willow grows on flood plains and in abandoned single-thread channels where fine-grained materials are common.

When viewed as communities, the four dominant species provide unique signatures for the various depositional environments along the Northern Rio Grande (Figure 8.4). Although tamarisk is the most common species in each environment, large amounts of Russian olive identify active channel areas and bars Flood plains have a mixture of species similar to the mixture growing on abandoned single-thread channels, though the latter have more cottonwoods. Abandoned braided channels lack the willow found on flood plains and abandoned single-thread channels. When supported by field checks, these associations establish connections between vegetation visible in aerial photography and the less visible underlying landforms with their sediment The result is a rapid and efficient method of mapping large areas in the search for likely sites for deposition of plutonium.

8.3 Dating Deposits With Vegetation

Once identified, landforms and bodies of sediment that might contain plutonium must have a specific date of origination to permit assessment of their potential as plutonium storage sites. Because plutonium entered the river system only after 1944, identifying the mapped deposits with post 1944 dates is the method for connecting the deposits to potential plutonium loading. In the present study, information from aerial photography and tree ring ages provided dates for the deposits

Since 1935, aerial photographic coverage of the Northern Rio Grande has been frequent enough to permit the assignment of a specific date of origination to most sedimentary bodies and landforms created during that time Because the major channel changes occur during large floods, the year of most likely change is usually obvious even if the period between photographic coverage for a particular area is three or four years In a few cases, ground photographs or documentary evidence further narrows the range of possible dates for the landform and sediment body in question

TABLE 8.1 VEGETATION DATA FROM SAMPLE PLOTS, NORTHERN RIO GRANDE.

Reach	Map Unit	Landform	% Tama-risk	% Cotton Wood	% Russian Olive	% Willow	Total Count per km²
Otowi	1B	Active channel edge	3	75	16	0	53333.44
Otowi	2B	Aband flood plain	0	18	82	0	110000.20
Buckman	2B	Aband slough	84	0	11	0	150000.30
Buckman	2B	Aband slough	94	0	4	0	140000.20
Buckman	3B	Aband flood plain	98	0	2	0	363334.00
Peña Blanca	4A	Aband channel	0	100	0	0	3333.34
Peña Blanca	4B	Aband flood plain	74	26	0	0	45000.08
Peña Blanca	5A	Older aband channel	0	71	0	0	11666.69
Coronado	2A	Aband channel	0	43	7	45	70000.14
Coronado	3B	Aband braid channel	77	4	15	4	43333.42
Coronado	3A	Older aband channel	4	17	2	77	88333.51
Los Griegos	2A	Aband channel	66	3	1	24	145000.20
Los Griegos	2B	Aband flood plain	0	60	0	0	25000.05
Los Griegos	3A	Older aband channel	51	11	11	26	88333.51
Los Lunas	2B	Aband channel	11	5	1	74	218333.70
Los Lunas	3A	Aband braid channel	50	42	8	0	40000.07
Los Lunas	3A	Aband braid channel	60	33	7	0	25000.05
San Geronimo	1A	Active channel edge	7	0	93	0	90000.17
San Geronimo	2A	Aband channel	85	15	0	0	130000.20
San Geronimo	2A	Aband channel	100	0	0	0	6666.68
San Geronimo	2B	Aband flood plain	100	0	0	0	33333.36
San Geronimo	2B	Aband flood plain	98	0	2	0	71666.80
Chamizal	1B	Active flood plain	93	0	0	2	70000.14
Chamizal	2A	Aband braid channel	20	27	0	0	25000.05
Chamizal	2B	Aband flood plain	89	5	0	5	133333.50
Chamizal	2B	Aband flood plain	76	19	0	5	20000.14
Chamizal	2B	Aband flood plain	76	24	0	0	15000.07
San Marcial	1A	Active channel edge	96	4	0	0	198333.70
San Marcial	2A	Aband channel	81	0	0	19	26666.72
San Marcial	2B	Aband flood plain	5	0	0	0	175000.30
San Marcial	3A	Older aband channel	63	32	2	4	95000.19
San Marcial	3C	Older aband bar	100	0	0	0	560001.10

Notes Reaches and observation units keyed to geomorphic maps in Chapters 12, 13, and 14

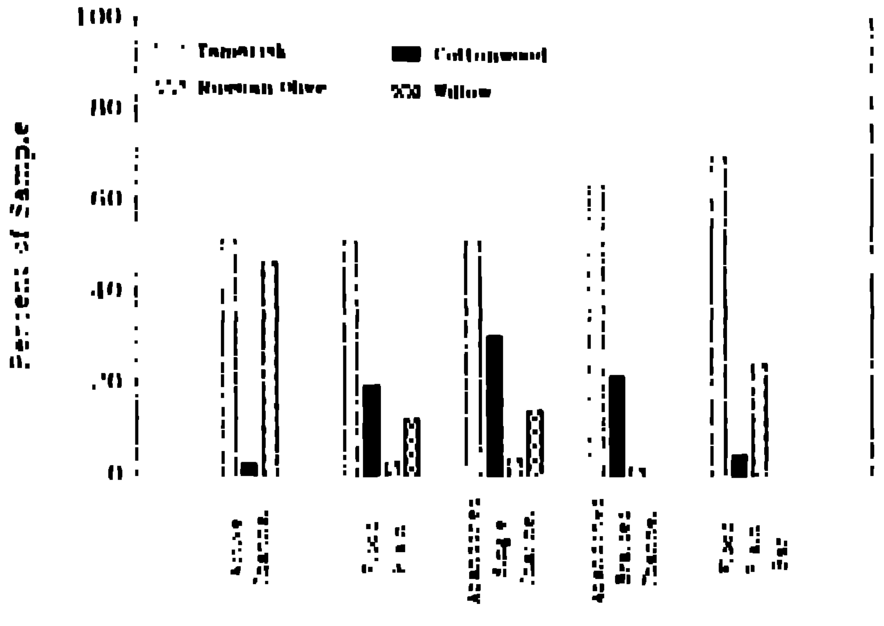


Figure 8.4 The statistical association between composition of riparian vegetation and the underlying sediment/landform complex.

For those few features remaining in question and for small areas examined in the field, the vegetation itself provides a minimum age for the landform and sedimentary body upon which the vegetation grows. After creation, either through deposition or abandonment by flowing water, newly exposed surfaces provide seed beds for tree growth. Direct observation of the Northern Rio Grande shows that tamarisk, willow, and Russian olive begin growth in new areas within one year, and cottonwood seedlings develop within two or three. Except for willow, each species records the age of individual plants by developing annual growth rings, usually one ring per year.[19] When exposed with a Swedish increment borer, a drill that extracts a cylindrical sample of the tree in cross section 1.5 m above the ground, the ring count indicates the age of the tree. Samples from several trees on the same form provide a minimum age for the sediment.

Tamarisk, russian olive, and cottonwood yielded useful ring sequences for dating purposes. Cottonwood was most consistent and provided the most easily interpreted rings, and most tree-based dates in this study were from this species. Use of the Swedish increment borer is time-consuming, especially when several samples provide the most reliable date. Large trees also required greater amounts of time for drilling. A more efficient approach was to measure the trunk circumference 1.5 m above the ground and to relate the circumference to age. Figure 8.5 shows the connection between circumference and ring age for 60 test cottonwood trees. The association was especially close for those trees less than 50 years old, the age of primary interest in the present study. After this initial calibration effort, the circumference measurement and the statistical relationship shown in Figure 8.5 provided estimates of the ages of cottonwood trees on the Northern Rio Grande flood plains.

8.4 Vegetation as a Radionuclide Reservoir

The importance of riparian vegetation in the analysis of the plutonium budget is as an indicator of the location and age of bodies of sediment that contain the contaminant. The vegetation itself is probably not a significant reservoir of plutonium in comparison to the amount stored in sediment. Although plutonium occurs in plants with greatest quantities in roots,[20] the total amount associated with biosystems is relatively limited and does not approach toxic proportions.[21] As with other heavy metals, the amount of plutonium found in soil and sediment is 10,000 to 100,000,000 times greater than the amount found in associated plants.[22] It is therefore reasonable to disregard riparian vegetation as a significant component of the regional plutonium budget.

The rings in riparian trees may, however, contain useful information about plutonium in shallow ground water. Many cottonwood trees near the active channel of the Rio Grande in the Albuquerque area have rings for the years 1965 and 1973 with distinctive red coloration. Only those trees close to the channel have these easily recognized rings that may contain an unknown material drawn from the water during their development. The years 1965 and 1973 had annual floods significantly larger than other years during the 1959-1978 period, but the reason for the coloration is not clear. Evaluation of individual rings for the their chemical or radionuclide content might reveal a time series of contaminant concentrations in shallow ground water in those trees close to the channel. Such an investigation is beyond the scope of the present work.

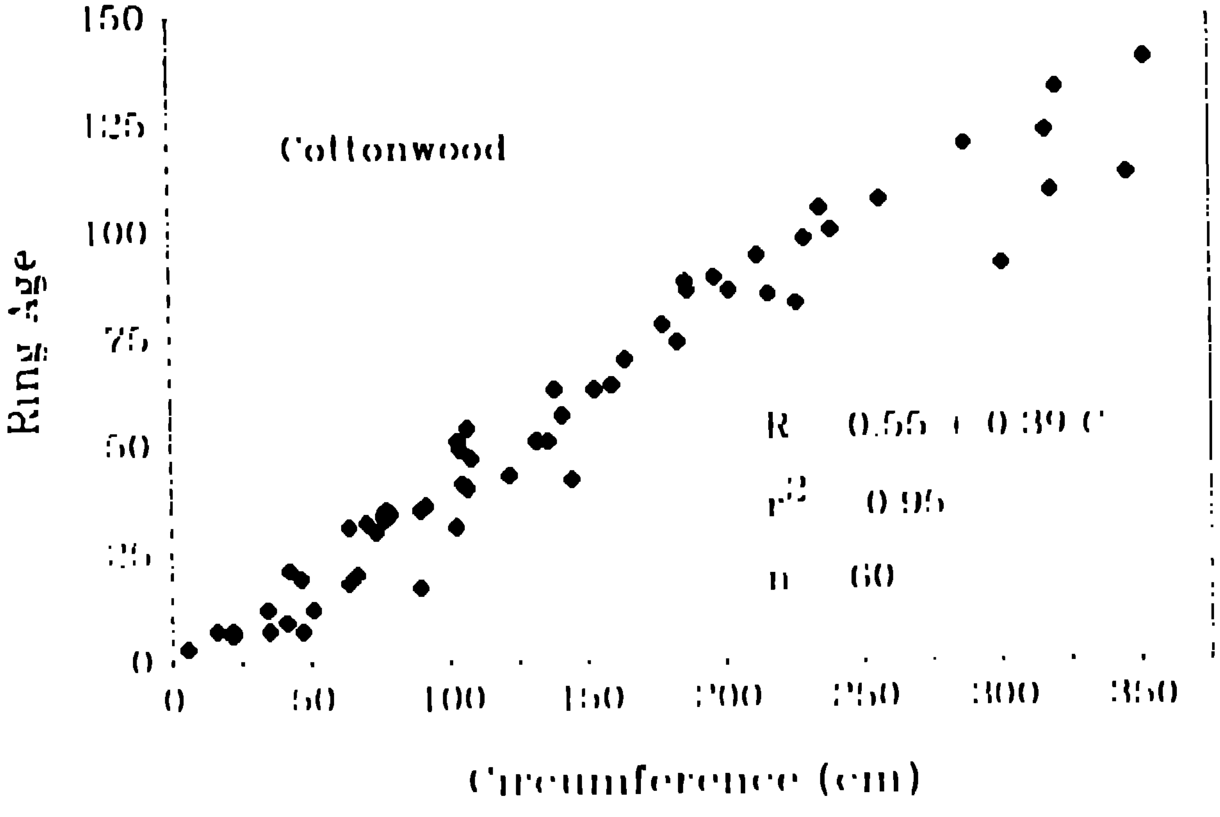


Figure 8.5 The association between trunk diameter and ring age for cottonwood trees along the Northern Rio Grande.

In summary, then, vegetation in and of itself is not the object of the present work, but rather it supplies a vital link in assigned dates of deposition to various accumulations of sediment. More importantly, vegetation boundaries are useful in defining the boundaries of the bodies of sedimentary materials with similar ages of deposition. In combination with the river's geomorphology, vegetation is therefore a key in unraveling the fate of plutonium in the system, the subject of the following chapters.

PART 3. THE PLUTONIUM SYSTEM OF THE NORTHERN RIO GRANDE

CHAPTER 9. SOURCES OF PLUTONIUM IN THE RIO GRANDE

9.1 Inputs From Fallout

The water, sediment, landform, and vegetation systems of the Northern Rio Grande provide the environmental framework within which plutonium moves and is stored. Plutonium enters the Northern Rio Grande from two sources: atmospheric fallout and releases from operations of Los Alamos National Laboratory that enter the main by transport through Los Alamos Canyon (Figure 9.1). The following chapter outlines the nature and timing of plutonium loading in the river's sediment system as a means of identifying those years when sedimentation is likely to have accumulated deposits with the highest concentrations of plutonium.

Most of the plutonium in atmospheric fallout is from the testing of nuclear weapons. Five nations have detonated a total of 484 nuclear devices in the atmosphere--466 with known dates.[1] These explosions have injected plutonium into the general atmospheric circulation, resulting in a global distribution of fallout as the material returns to the surface. There are three types of fallout: local, tropospheric, and stratospheric.[2] Local or early fallout occurs within a day of the detonation, and consists of particles 100 200 microns in diameter (fine sand) transported in the lower atmosphere and deposited within several hundred kilometers of the site of the explosion.

Finer particles travel greater distances and disperse over greater areas. Tropospheric fallout occurs within a month of the detonation, and consists of particles less than 100 microns in diameter (mostly silt sized) transported in the lower atmosphere. The global atmospheric circulation transports tropospheric fallout around the world in a band about 30 degrees latitude wide, centered on the site of the explosion. Most of the tropospheric fallout delivers plutonium to the earth's surface in precipitation events, with only about 10 percent occurring as dryfall.[3]

Stratospheric fallout requires several years to return to the surface and consists of particles less than 10 microns in diameter (mostly clay sized) that the explosion has injected above the tropopause into the stratosphere. At these high altitudes (greater than 10,000 m), global atmospheric circulation distributes the material throughout the hemisphere of the originating detonation. Only in unusual circumstances when the direct injection exceeds 21,000 m in altitude does the circulation system transport the materials across the equator.

The Northern Rio Grande watershed has probably received inputs of all three types of fallout. Early fallout from detonations at the Nevada Test Site may have reached the San Juan Mountains, and tropospheric fallout certainly did because the Rio Grande lies in the center of the latitudinal belt containing the test site. Stratospheric fallout has been greatest in the northern hemisphere where the majority of atmospheric detonations occurred, so that the Rio Grande has also received inputs from this source. The majority of detonations at the Nevada Test Site were at times when the prevailing wind was from a westerly direction,[4] and the San Juan Mountains are the first major mountain range exceeding 3,000 m in elevation downwind from the test site. The paths of debris clouds often crossed the axis of the Northern Rio Grande,[5] so that it is likely that the river system now contains plutonium from the test site.

In addition to weapons testing, sources of atmospheric fallout of plutonium include atmospheric disintegration of satellites fueled by plutonium and weapons accidents. Several satellites have fallen from decayed earth orbits and released their plutonium in the upper atmosphere, including the SNAP-9A navigation satellite lost in 1964.[6] Most plutonium from satellite debris is likely to be in the form of tropospheric and stratospheric fallout with hemisphere-wide distribution and latitudinal bands of higher concentrations. Weapons accidents such as crashes of aircraft carrying nuclear weapons have released plutonium in restricted local environments, but because they were not in the western United States they are not likely to have affected the Northern Rio Grande.

The total amount of fallout over the entire earth surface is about 24 kCi of plutonium-238 (16 kCi of which is from SNAP-9), 154 kCi of plutonium-239, and 209 kCi of plutonium-240.[7] At a global scale, the distribution of this fallout is uneven. Plutonium fallout from all sources is at a minimum (less than 0.005 mCi per sq km for plutonium 238 and 0.01 mCi per sq km for plutonium-239,240) in the 10 degrees of latitude surrounding the South Pole.[8] The maximum is in the band between 40 and 50 degrees North: 0.079 mCi per sq km for plutonium-238 and 2.2 mCi per sq km for plutonium-239,240. In the latitudinal band containing the Northern Rio Grande, fallout has been 0.042 mCi per sq km for plutonium-238 and 1.8 mCi per sq km for plutonium 239,240.

Atmospheric detonations that have contributed fallout plutonium to the surface have occurred irregularly since 1945. Figure 9.2 shows the time series of all known detonations, except 18 tests in the former Soviet Union between 1949 and 1958 for which there are no exactly known dates.[9] The amount of material injected into the atmosphere by each individual test depended on the altitude of the burst, ground conditions beneath the burst, local weather conditions, and the nature of the exploded device, but the overall trends indicate the probable general plutonium loading of the atmosphere and resulting fallout.

The importance of the fallout time series is that inputs to the Northern Rio Grande surfaces were greatest during the late 1950s and 1960s. The years of maximum number of detonations were 1958 with 96 and 1962 with 81. A moratorium on atmospheric testing resulted in no detonations during 1959 and most of 1960. The Partial Test Ban Treaty became effective August 5, 1963, and thereafter the United States, the Soviet Union, and the United Kingdom confined testing to underground sites. A composite time series for plutonium fallout from those tests does not appear in the general literature. However, the plutonium fallout probably followed a trend similar to the time series for strontium 90 which was also produced by the

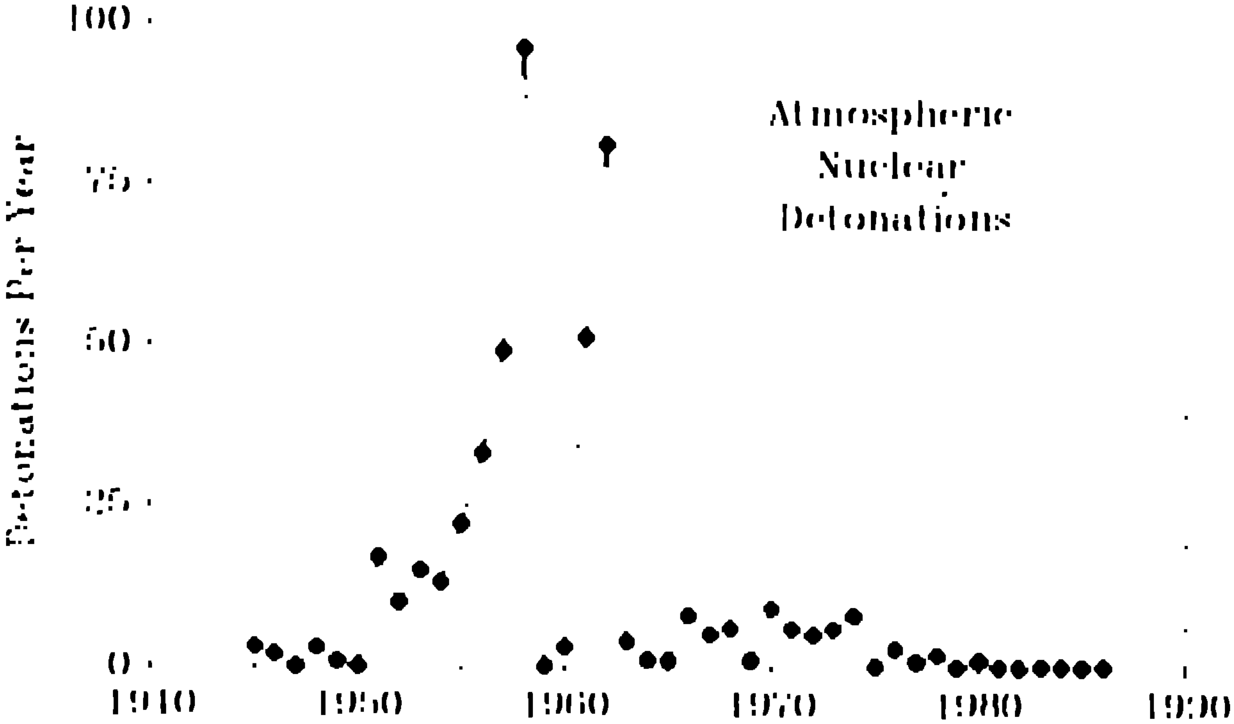


Figure 9.2 Annual number of atmospheric nuclear detonations (data from Stockhom International Peace Research Institute, 1987).

detonations.[10] Strontium-90 loadings in surface materials increased significantly from the early 1950s to 1961, and then rapidly from 1962 to 1965 in response to the numerous tests in the early 1960s (Figure 9.3). Assuming that plutonium followed a similar trend, the peak rates of fallout input to the Rio Grande landscape probably were between 1954 and 1967.

Once fallout plutonium reaches the surface, it quickly binds with soil materials and becomes part of the soil erosion and sediment transport system. "The movement of these...materials determines the fate of the radioactivity."[11] In a broadly based study using agricultural models, George Foster and Thomas Hakonson estimated the amount of the fallout plutonium that was likely to be eroded from earth surfaces and contributed to river systems.[12] Taking into account climatic variations, differences in land management, and vegetation cover, they attempted to account for variability in plutonium mobility from one region to another. They estimated that about 0.02 percent of the total plutonium inventory in soils was delivered to streams each year in the eastern United States. The delivery rate was about 0.04 percent per year for the Northwest, 0.05 percent for the agricultural Midwest, and 0.08 for the sparsely vegetated Southwest. If the average fallout deposition on landscapes had been 1.0 mCi per sq km, the resulting concentration of plutonium in river sediments would range from about 0.01 in the Midwest to about 0.04 in Southwestern rivers.

Foster and Hakonson's calculations provide a useful general picture of fallout plutonium in the Rio Grande system. Their calculated "enrichment ratio" for the system, defined as the ratio between the amount of plutonium in soils and the amount in river sediment, showed that concentrations in river sediments were about 2.76 times the concentration in soils--close to the national average (Table 9.1). The value of their "concentration index" for the Rio Grande, a measure of the concentration of plutonium on sediments in fluvial transport, was much above the national average. Given the estimation of a plutonium-238,239,240 combined fallout burden for the latitudinal belt including the Northern Rio Grande of 1.842 mCi/sq km,[13] Foster and Hakonson's method predicts about 0.0737 pCi/gm total plutonium in river sediments. This value is the same order of magnitude as values reported for reservoir sediments in the system.

Foster and Hakonson's analysis contained a theme central to the present research. They estimated that, in the Rio Grande system, more than 99 percent of sediment eroded from the landscape remains in the river system over a 20 year period, and that because the fallout plutonium is almost all attached to that sediment, more than 99 percent of the fallout also remains in the system. The empirical data in the present work indicates that the figure is probably 98 percent. These high rates of storage provide two important conclusions regarding plutonium in the Northern Rio Grande:

1. The distribution of the stored sediment and plutonium is highly variable geographically, with concentrations likely to occur in some places but not others. The purpose of the present work is to define this geography

2. The fate of plutonium released by Los Alamos National Laboratory into the system

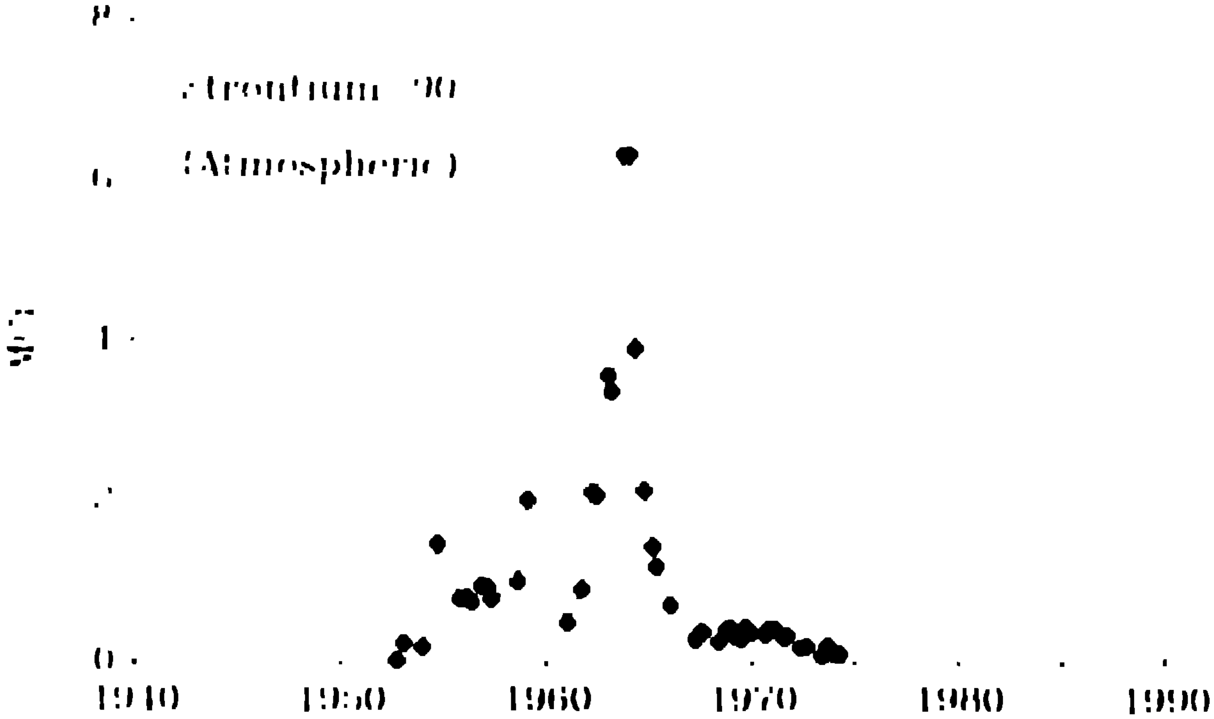


Figure 9 3 Annual atmospheric loading of strontium 90 from nuclear weapons testing (data from Glasstone and Dolan, 1977)

TABLE 9.1 PLUTONIUM AND SEDIMENT PROCESSES IN LARGE BASINS

River Basin	Average Erosion Rate (kg/sq m/yr)	Percent Sediment Stored	Enrichment Ratio	Concentration Index (sq m/kg)	Percent Plutonium Eroded in 20 Years
Hudson	0.36	97.5	2.76	0.0125	0.271
Savannah	0.36	99.5	2.83	0.0070	0.151
Miami	0.83	97.0	2.74	0.0090	0.459
Ohio	0.68	94.5	2.49	0.0116	0.605
Tennessee	0.71	94.0	2.50	0.0111	0.574
Upper Mississippi	1.07	97.9	2.57	0.0064	0.438
Missouri	0.71	85.3	2.43	0.0044	0.461
Total Upper Mississippi	0.82	90.4	2.48	0.0040	0.488
Arkansas	0.67	98.0	2.71	0.0114	0.486
Lower Mississippi	0.85	92.7	2.33	0.0049	0.357
Total Mississippi	0.79	92.2	2.51	0.0094	0.476
Rio Grande	0.72	99.3	2.76	0.0135	0.570
Columbia	0.32	98.2	2.70	0.0141	0.263
Mean	0.70	95.2	2.60	0.0092	0.433

Note Data and calculations based on data from Foster and Hakonson (1984) must be the same as the fate of the fallout plutonium. Therefore, almost all of the plutonium from the laboratory is, like the fallout, still in the system, mostly in river deposits.

The estimates by Foster and Hakonson necessarily contained significant simplifying assumptions.[14] Although they recognized that plutonium concentrations in non- agricultural soils declined exponentially with depth, for purposes of calculation they assumed uniform concentrations with depth. Thus, estimations of annual releases of fallout plutonium to streams were the same for each year in their calculations. In reality, plutonium losses to streams are probably relatively high immediately after the fallout occurs, and relatively low in later years. Fallout cesium (and almost certainly the associated fallout plutonium) losses from soil to river sediments was 50 percent greater in the year after fallout than in subsequent years.[15]

The time series for atmospheric nuclear detonations and the estimated delivery of fallout plutonium to streams from the landscape provide insight into the variability of plutonium in deposits. Because fallout loading of plutonium in the Northern Rio Grande occurred at a maximum rate during the 1960s, sediment deposited along the river during that period are likely to contain the greatest amounts of plutonium. Because loss from soils to river sediments was greatest in the years immediately after the fallout occurred, plutonium inputs to the river system from fallout peaked before the 1970s. Sediments deposited during the 1960s may therefore reasonably be expected to contain higher amounts of plutonium from fallout than deposits from other periods. Because almost all the sediments in the Northern Rio Grande during this time period were either stored on flood plains or in reservoirs, most of the fallout plutonium is still in the system.

9.2 Inputs from Los Alamos

Most plutonium reaching the Northern Rio Grande from research and development activities at Los Alamos entered the environment between 1945 and 1950. The first major technical facility constructed at Los Alamos for the Manhattan Project was the "Main Technical Area," known to users as "TA 1." Constructed near Ashley Pond at the old boys ranch buildings, TA 1 housed a general laboratory for process chemistry that generated relatively large quantities of liquid wastes containing strontium, cesium, uranium, plutonium, americium, and tritium (Figures 2.3 and 2.4). Acid sewers, consisting mostly of buried pipes, with some lengths above ground, carried the untreated liquid across the mesa top at Los Alamos through a main line that ended on the north edge of Acid Canyon (Figure 9.4 and 9.5). Acid Canyon is north of Los Alamos; a short distance downstream it joins Pueblo Canyon. Photographs of the pipe taken in 1947 show that it ended with an open outlet, with liquid spilling over the rock face of the canyon and eventually flowing into alluvial sediment on the canyon floor (Figure 9.6).[16] Water and materials have moved through Acid and Pueblo Canyons to Los Alamos Canyon which leads to the Rio Grande (Figures 9.7 a, b, c, d, and e).

The laboratory, in conjunction with the U.S. Public Health Service, constructed a

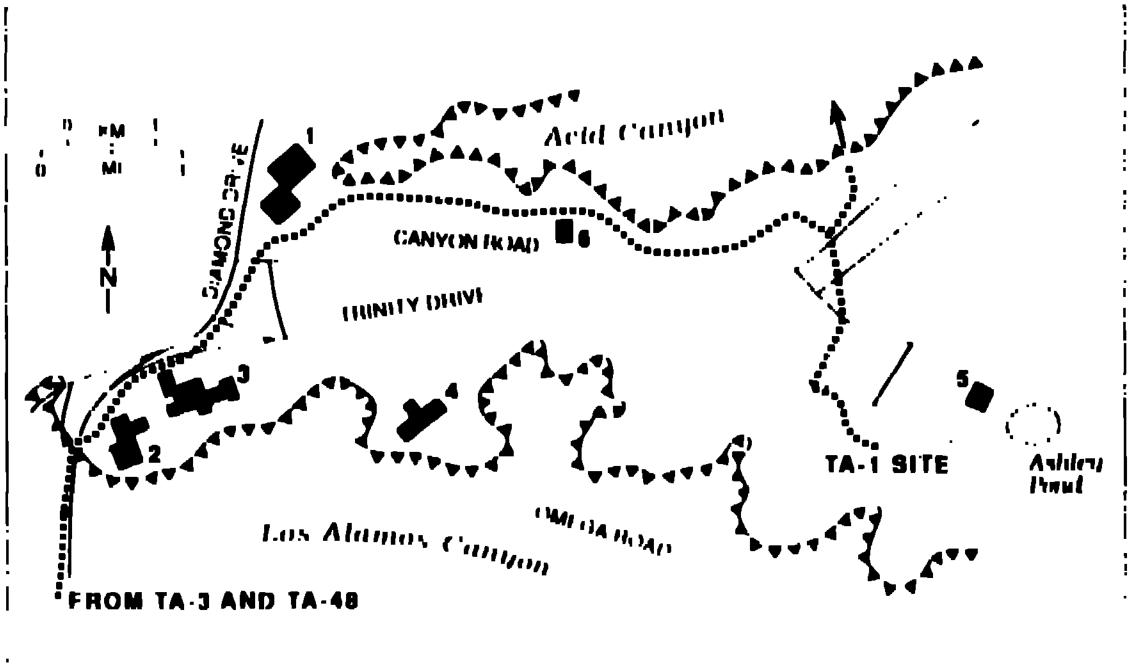


Figure 9.4 Sketch map of acid sewer lines on Los Alamos Mesa during the mid- and late 1940s (redrawn from Stoker *et al.*, 1981)

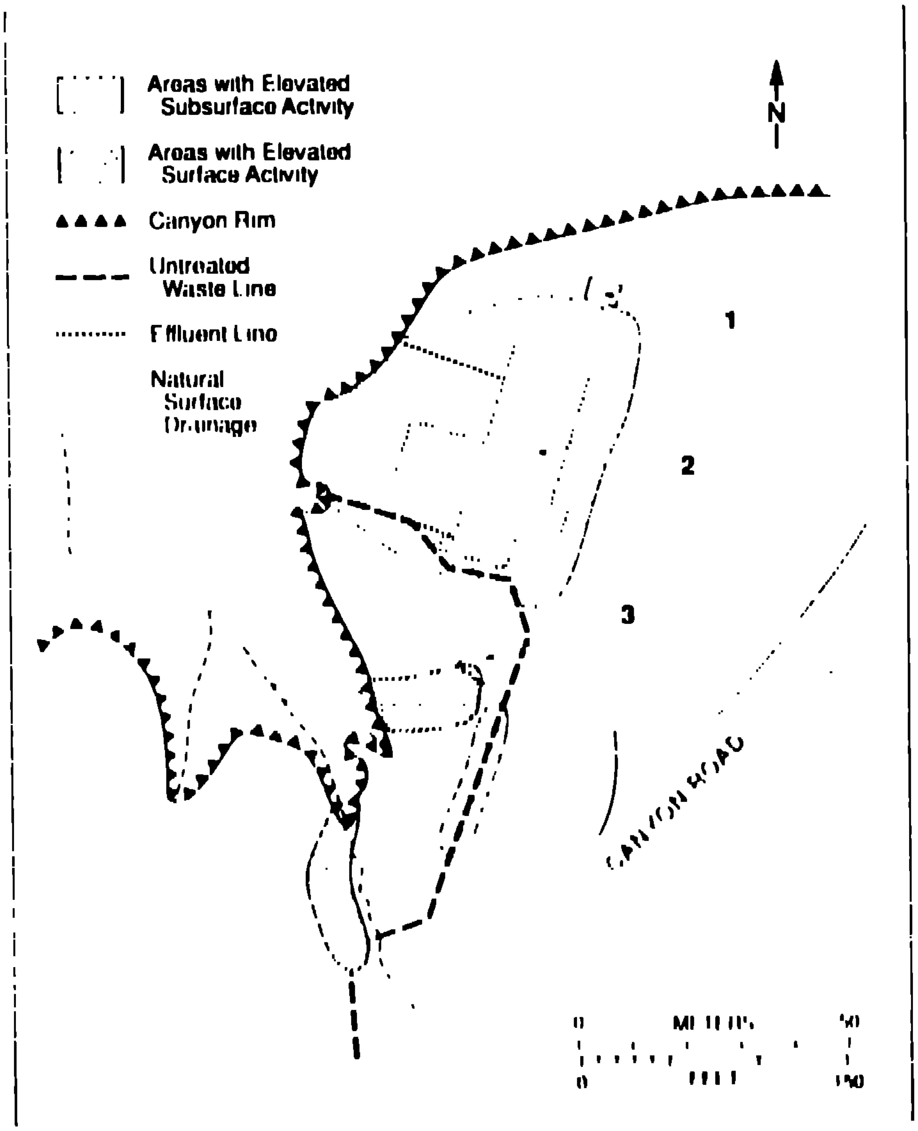


Figure 9.5 Sketch map of the Acid Canyon area, an enlargement of the area at the plutonium release site indicated by an arrow in the upper right corner on Figure 9.4 (redrawn from Stoker *et al.*, 1981). The general location of this area is shown by a circle on the topographic map in Figure 9.7b

Figure 9.6. **Untreated liquid waste exiting Acid Sewer No. 1 into Acid Canyon in 1947.** Location shown as the termination point of the heavy dashed line at the cliff's edge in Figure 9.5 (Los Alamos National Laboratory Photo, Document LAMS 516)

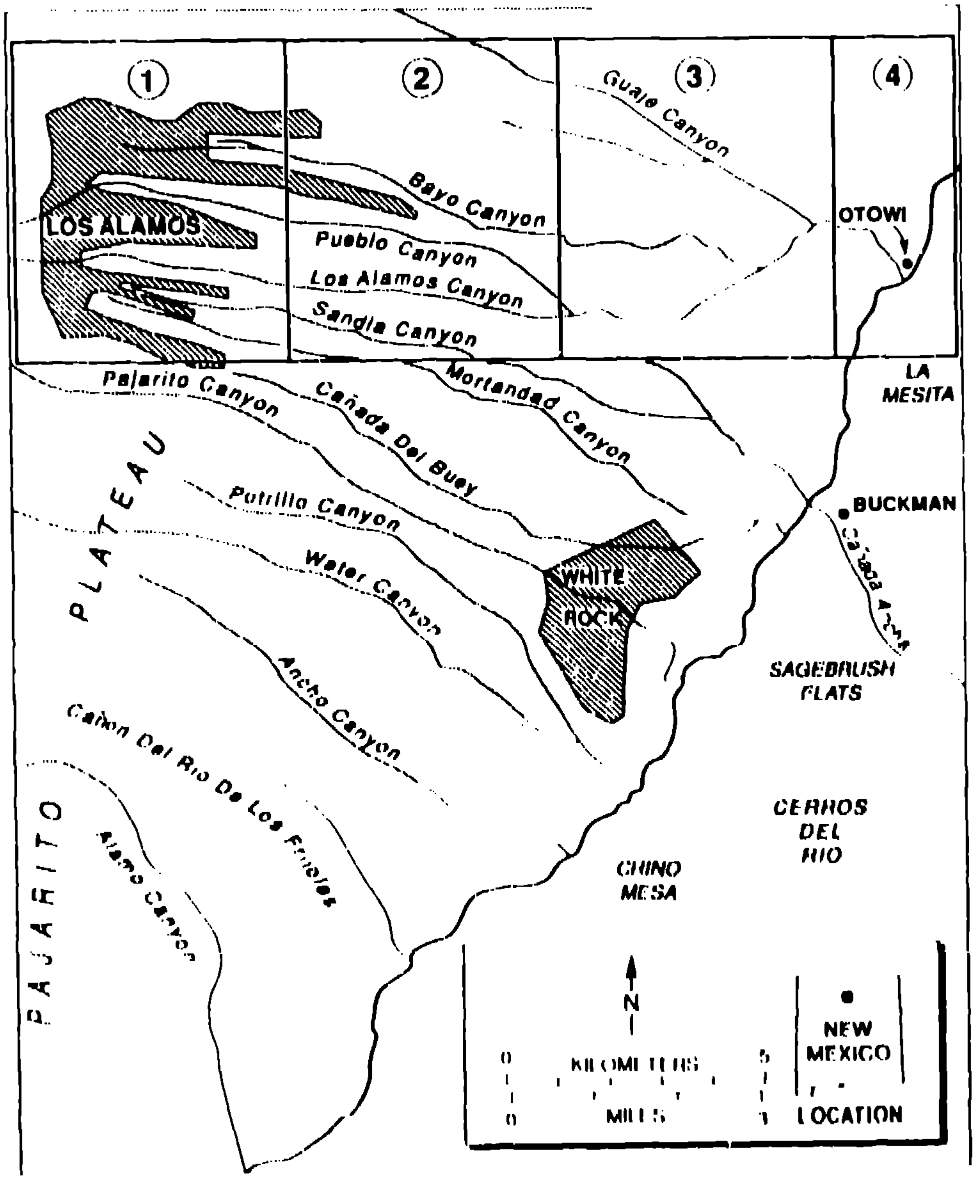


Figure 9.7a Locations of topographic maps showing the Los Alamos Canyon system. The numbered sections on this location map correspond to the detail maps: 1) Figure 9.7b; 2) Figure 9.7c; 3) Figure 9.7d, and 4) Figure 9.7e.

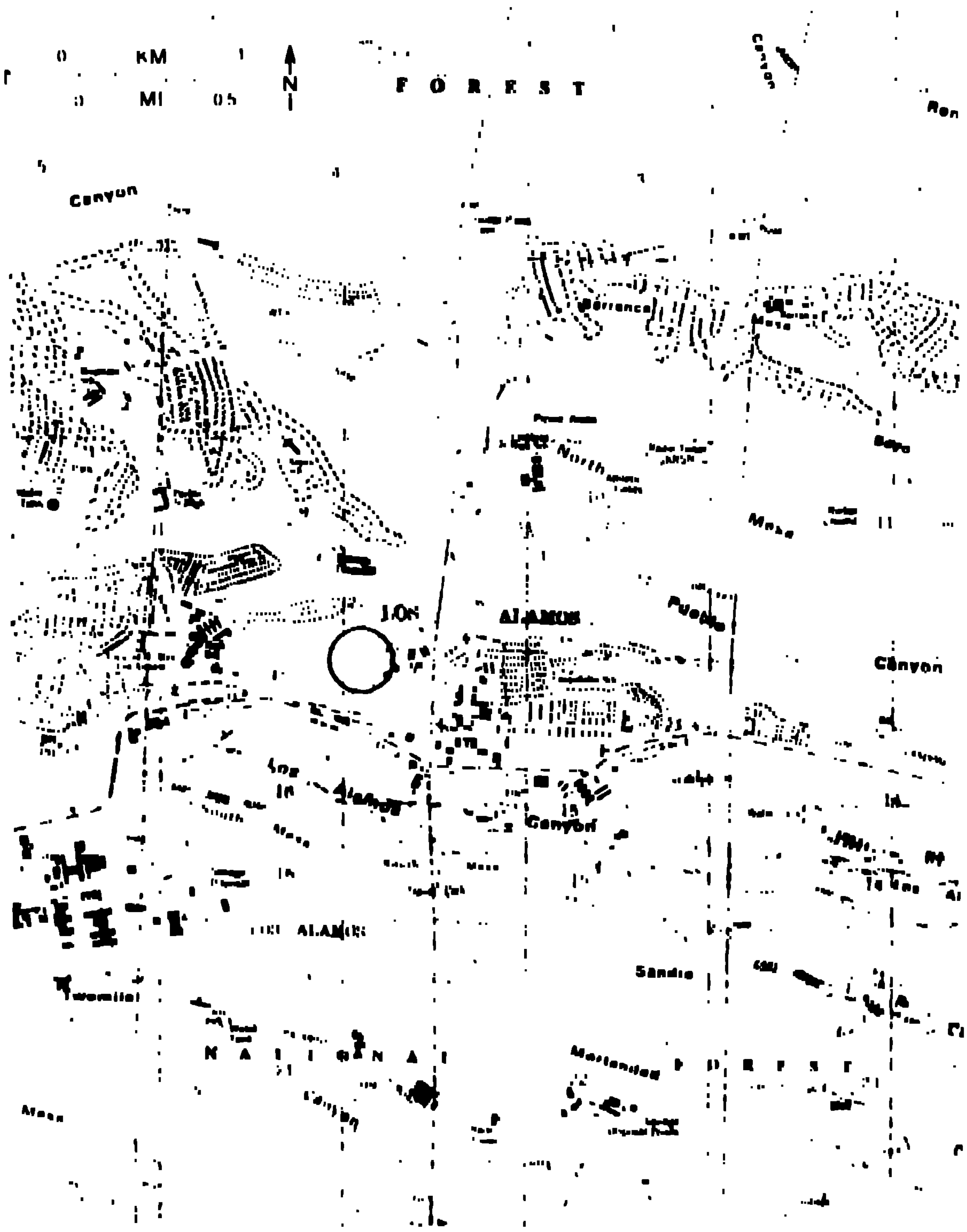


Figure 9.7b Topographic map of the Los Alamos area (section of U.S. Geological Survey quadrangle)

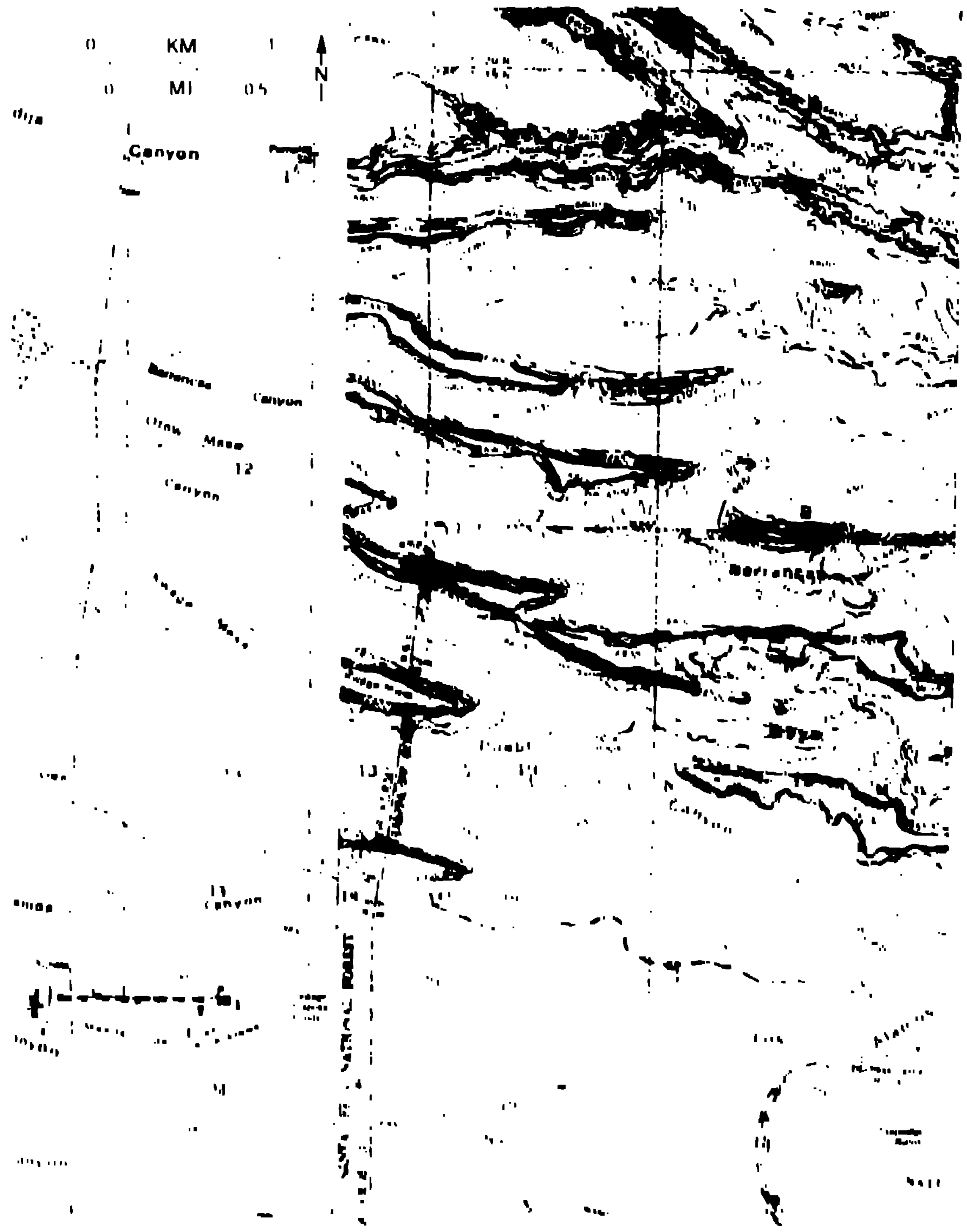


Figure 9.7c: Topographic map of the eastern edge of the Los Alamos area (section of U.S. Geological Survey quadrangle)

Figure 9.7d. Topographic map of the Totavi area (section of U.S. Geological Survey quadrangle

Figure 9.7a Topographic map of the Otowi area (section of U.S. Geological Survey quadrangle)

waste treatment plant in 1951 (labeled TA-45), and thereafter liquid that emptied into Acid Canyon contained relatively few radionuclides (Figure 9.8). Some variation in the radionuclide content of effluent occurred because new facilities began contributing to the materials being processed. In 1953 a new facility south of Los Alamos Canyon, TA-3 which included the Chemistry and Metallurgical Research building, sent liquid wastes to the treatment plant. Also in 1953 the Health Research Laboratory (TA-43) began providing wastes for processing. In 1958 a new radiochemistry facility added more materials for treatment. Wastes from these sources contained highly variable amounts of radionuclides, and not all of the material required processing to remove contaminants before release.

In 1963 a new treatment plant (TA-50) south of Los Alamos Canyon began accepting wastes from the research facilities south of the canyon (TA-3 and TA-48). Its releases contain so few radionuclides that they are not an issue in the regional river system. In 1964 the original laboratory facilities at TA-1 and the original waste treatment facility (TA-45) ceased operations, and there were no further releases of effluent into Acid Canyon north of Los Alamos. One additional facility on the main Los Alamos mesa, a plutonium processing plant (TA-21), released treated wastes into DP Canyon, a small tributary to Los Alamos Canyon, between 1952 and the early 1980s. These releases contained less plutonium than those from the waste treatment plant that emptied into Acid-Pueblo Canyon, but the materials became included in the alluvium in the canyon floor.

Decontamination and decommissioning of the original waste treatment plant (TA-45) and its acid sewers that emptied over the cliff face began in 1966.[17] Workers demolished the buildings, collected the debris, dismantled the pipelines, excavated soils in the vicinity of the structures and under the pipeline route, removed the rock from the cliff face, and buried the materials in the solid waste disposal area at Los Alamos. They also removed some alluvium from the floor of Acid Canyon and buried it at the disposal site.

The amounts of plutonium introduced into the alluvium on canyon floors in the Los Alamos Canyon system (which includes Acid Pueblo and DP Canyons) by laboratory operations are not precisely known, because the effluent was not continuously assessed for radionuclide contents. For Acid and Pueblo Canyons, there are two published estimates of the total plutonium releases in the period between 1943 and 1950 when there was no monitoring or treatment. First, Stoker and his associates estimated the total for the 1943-1950 period as 150 mCi.[18] Second, Lane and his co-workers used data from the plutonium concentrations in the canyon alluvium as published by Stoker and estimated that 150 mCi as input was too low to explain the amount measured in the sediments.[19] Lane calculated from the empirical data gathered in the late 1970s that the total amount of plutonium in the canyon was 300-900 mCi. Because that amount represents the remains after removal of some material by natural erosion, there would have been more in the canyon originally. Based on this line of analysis, Lane estimated that the 1943-19[illegible] releases could have been as high as 3,000 mCi.[20] For comparison, the amount of radioactive material released in the Three Mile Island, Pennsylvania, incident was about 30 mCi, and the

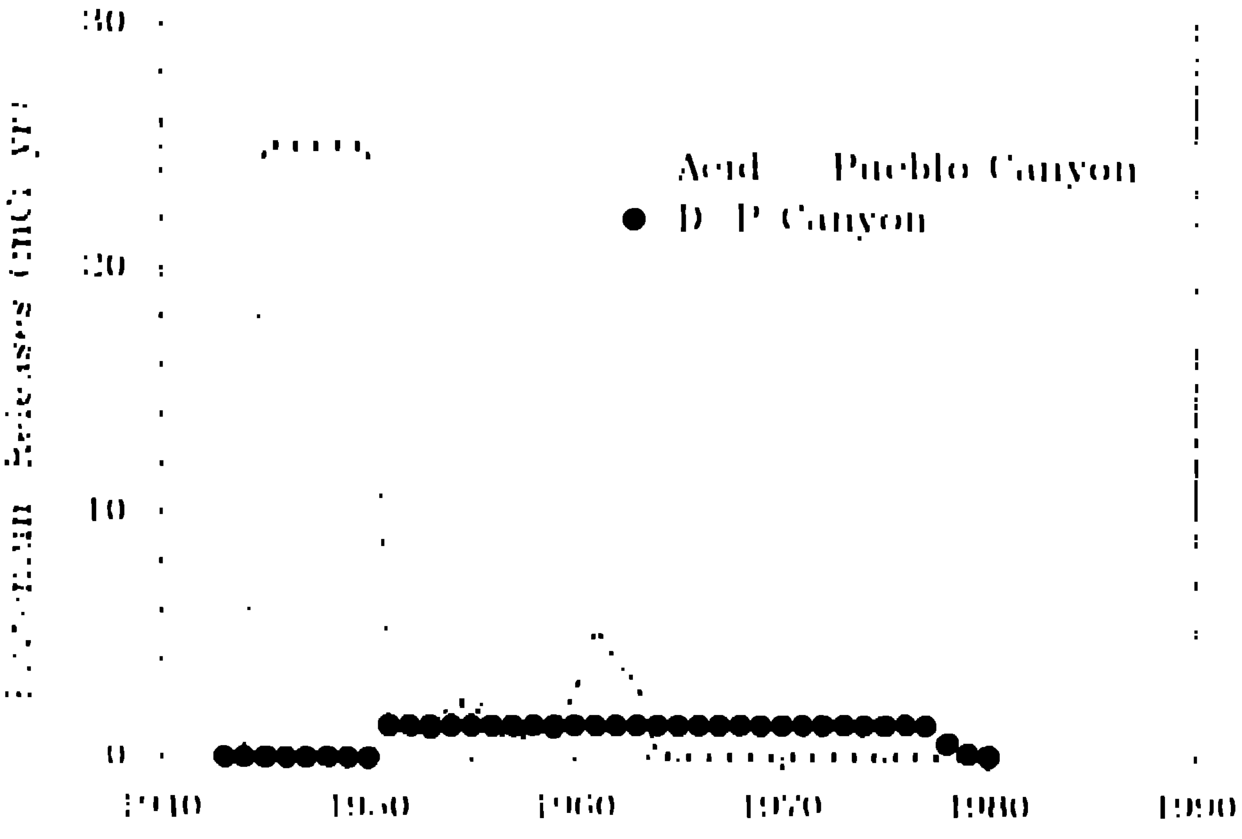


Figure 9.8 Annual plutonium releases into alluvium in the upper tributaries of Los Alamos Canyon (data from Stoker *et al.*, 1981)

amount of plutonium remaining at the Nevada Test Site, even after clean-up efforts, is about 200,000 mCi.[21]

The variability in the estimates for the Los Alamos releases make a general time series for the release of plutonium into Acid-Pueblo Canyon impossible for the 1943-1950 period. However, some refinement of the estimates of the timing of the releases is possible. Lane and his associates estimated that the minimum estimate of 150 mCi was distributed over the period 1943-1950 at an average rate of 18.75 mCi per year in the absence of better information.[22] However, historical accounts of plutonium delivery to Los Alamos (see Chapter 2) show that significant quantities did not arrive at the site until mid-1945. Therefore, the 150 mCi minimum estimate was probably distributed over the 1945-1950 period, with an average rate of 25 mCi per year. If the empirical data used by Lane are correct, the rate could have been three to 30 times higher than this minimum value.

After treatment and monitoring began in 1951, releases were very low, and also well defined. A similar estimation period followed by lower but better known values characterizes the record of releases for DP-Upper Los Alamos Canyon. Because the mean values are spread over several years, time series of releases for both canyons have periods without trends. Magnitudes are probably best represented as minimum values, but with the reservation that substantial errors are possible. The general trends for releases over several decades show that the pre-1951 period is the one of greatest importance for plutonium loading of the system (Figure 9.8, Table 9 2). After that time period, natural erosion, transportation, and depositional processes moved the contaminated sediments downstream toward the Rio Grande, and new loadings were relatively small.

The transfer of the contaminated sediments from Los Alamos Canyon into the Rio Grande through natural stream processes in the tributary canyons was an inconsistent process Stream flow in the canyons is sporadic, without flows during some years. In other years snow melt created spring discharges, and summer thunderstorms produced flash floods. As a result, the canyon system discharged plutonium bearing sediments into the Rio Grande several times, with the quantity related to the amount of water available for transporting the materials In work estimating contaminant transport through the Los Alamos Canyon system, Lane and his associates calculated that runoff would transport the entire plutonium inventory in the canyon system to the Rio Grande sometime before 2000[23] The exact timing would depend on the assumed original loading and the utility of their assumptions about magnitude and frequency of runoff events. They calibrated their model using reconstructed records of runoff events between 1943 and 1980, and estimated the amount of plutonium reaching the Rio Grande by combining sediment transport rates, magnitude and frequency of water discharges, and plutonium concentration data

Previously unpublished data and calculations used in Lane's conclusions show that during the 1943 1980 period, there were many years when no plutonium entered the main stream[24] During four years, plutonium discharge was at a maximum 1951, 1952, 1957, and 1968 (Figure 9.9) During these four years, floods in Los Alamos

TABLE 9.2 PLUTONIUM RELEASES INTO CANYON SEDIMENTS AT LOS ALAMOS (mCi/yr)

Year	Acid-Pueblo Canyon	DP Canyon	Comments
1943	0	0	Operations begin, no treatment or monitoring
1944	0	0	
1945	25.0	0	Delivery of large quantities of plutonium begins
1946	25.0	0	
1947	25.0	0	
1948	25.0	0	
1949	25.0	0	
1950	25.0	0	
1951	1.3	1.27	Treatment at TA 45, monitoring for Acid Pueblo Canyon
1952	1.1	1.27	
1953	1.2	1.27	Waste from TA 3 and TA 43 added to system
1954	2.2	1.27	
1955	2.2	1.27	
1956	1.1	1.27	
1957	0.9	1.27	
1958	0.9	1.27	
1959	1.2	1.27	
1960	2.6	1.27	
1961	5.4	1.27	
1962	4.9	1.27	
1963	4	1.27	Treatment begins at TA 50
1964	0.94	1.27	
1965	0	1.27	
1966	0	1.27	TA 45 Dismantled
1967	0	1.27	
1968	0	1.27	
1969	0	1.27	
1970	0	1.27	
1971	0	1.27	
1972	0	1.27	
1973	0	1.27	
1974	0	1.27	
1975	0	1.27	
1976	0	1.27	
1977	0	1.27	
1978	0	0.54	
1979	[illegible]	0.14	
1980	[illegible]	0.41	

Note: Data from [illegible] et al. ([illegible]) and Lane et al. (1985), 1945-1950 modified (see text). Data for 1945-1950 period for Acid Pueblo Canyon and 1951-1977 for DP Canyon are average values.

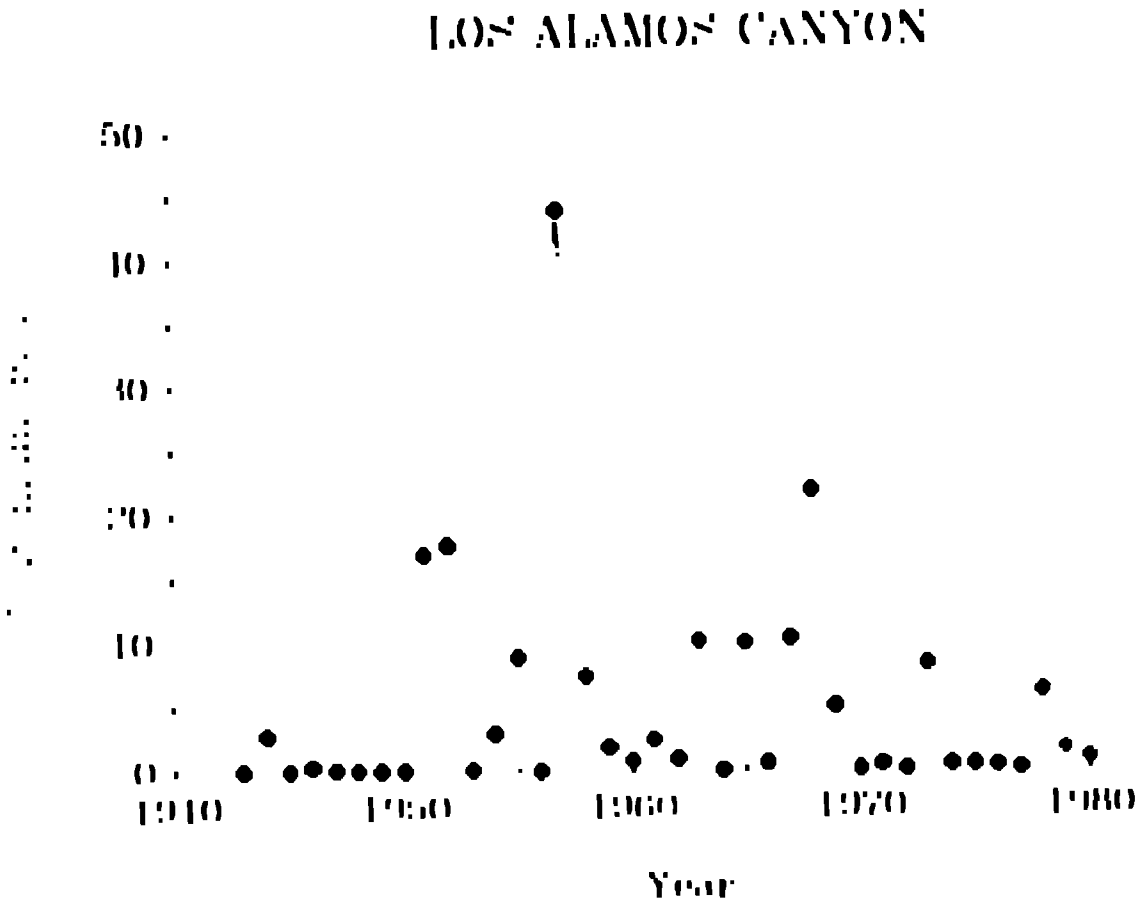


Figure 9.9 Estimated annual plutonium discharges from Los Alamos Canyon to the Rio Grande (data provided by L. J. Lane, Agricultural Research Service, Tucson, Arizona).

Canyon carried sediment and plutonium to the confluence with the Rio Grande, where the materials became involved in general transport processes in the main stream. In many cases, the flood peaks on the tributary stream did not coincide with the annual peak discharge in the main stream, so that sediments from the tributary moved only a short distance downstream in the Rio Grande. They were often deposited at the mouth of Los Alamos Canyon, along the north bank within a few hundred meters of the mouth, or on bars and in sloughs within a few km downstream along the Rio Grande.

9.3 Remobilization from Storage

This limited range of transport for the initial injection of sediments from Los Alamos Canyon is likely, because the materials from the tributary are coarse-grained, and likely to be mostly bedload in the energy environment of the Rio Grande, except during major floods. Silt and clay particles, with their higher concentrations of plutonium, make up a small amount of the sediment load from the tributary. These lesser amounts of fines would have remained in suspension in the Rio Grande, which would have transported them at least as far south as Peña Blanca. After the closure of Cochiti Dam in 1973, infusions of suspended sediment would have become reservoir deposits, and virtually none would have passed Cochiti Dam.

The actual amounts of suspended load and bedload injected by natural processes in Los Alamos Canyon into the Rio Grande are poorly known. The calculations in the present study assume that bedload carries the significant plutonium in the system, based on the importance attached to coarse particles by sedimentary studies in the canyon.[25] Measurements at gauging sites along Los Alamos Canyon have produced too few data to reach firm conclusions about the subdivisions of the sediment load. The sparse data from sixteen observations show that within Los Alamos Canyon where plutonium input has occurred, bed sediments accounted for an average of about 70 percent of the total sediment load (with a standard deviation of 21 percent, and a range of 24 to 95 percent).[26] At the confluence of the canyon with the Rio Grande, bedload moving in Los Alamos Canyon is only about 40 percent of the load (with a standard deviation of 21 percent, and a range of 11 to 66 percent). Some important materials in the system are therefore probably stored in overbank areas along lower reaches of the canyon. The fines are probably as important in transporting the Los Alamos derived plutonium into the Rio Grande as the bedload, but further research is required to define the relationships accurately. The best present estimate is that plutonium discharges from the tributary into the Rio Grande are about 3 percent by solution, 57 percent by suspended sediments, and 40 percent by bedload.[27]

Sediments in Los Alamos Canyon impregnated with plutonium move down the canyon system in a stepwise fashion, with each step taken as a few meters, to a few kilometers, during each flood event. Each flood stores the sediments as channel or flood plain deposits, and each subsequent flood remobilizes them until they reach the Rio Grande. Hypothetically, the same temporary storage and remobilization processes also occur in the main stream, but because the channel has consistently become smaller and more stable, storage consumes much of the material and relatively little becomes mobile again, at least on a time scale of several decades. After 1973, remobilized contaminated sediments came to rest in Cochiti Reservoir, so that continued monitoring of the reservoir is critical to an effective surveillance program

In summary, there are two sources of plutonium in the Rio Grande sediment system, and the maximum input from both sources occurred during roughly the same time period. Fallout plutonium from atmospheric testing of nuclear weapons and from satellite debris was at maximum in the 1960s, and erosion processes moved a substantial percentage of that fallout from slopes to stream channels during the same period. Contributions from the fallout on the landscape continue at a reduced level. Plutonium from releases at Los Alamos were at maximums from the late 1940s to the early 1950s, but sediment transport processes in Los Alamos Canyon that injected peak amounts of the plutonium into the Rio Grande occurred in 1951, 1952, 1957, and 1968. Sediments deposited in the Rio Grande immediately downstream from Otowi during the 1950-1970 period are therefore most likely to contain the highest amounts of plutonium in storage.

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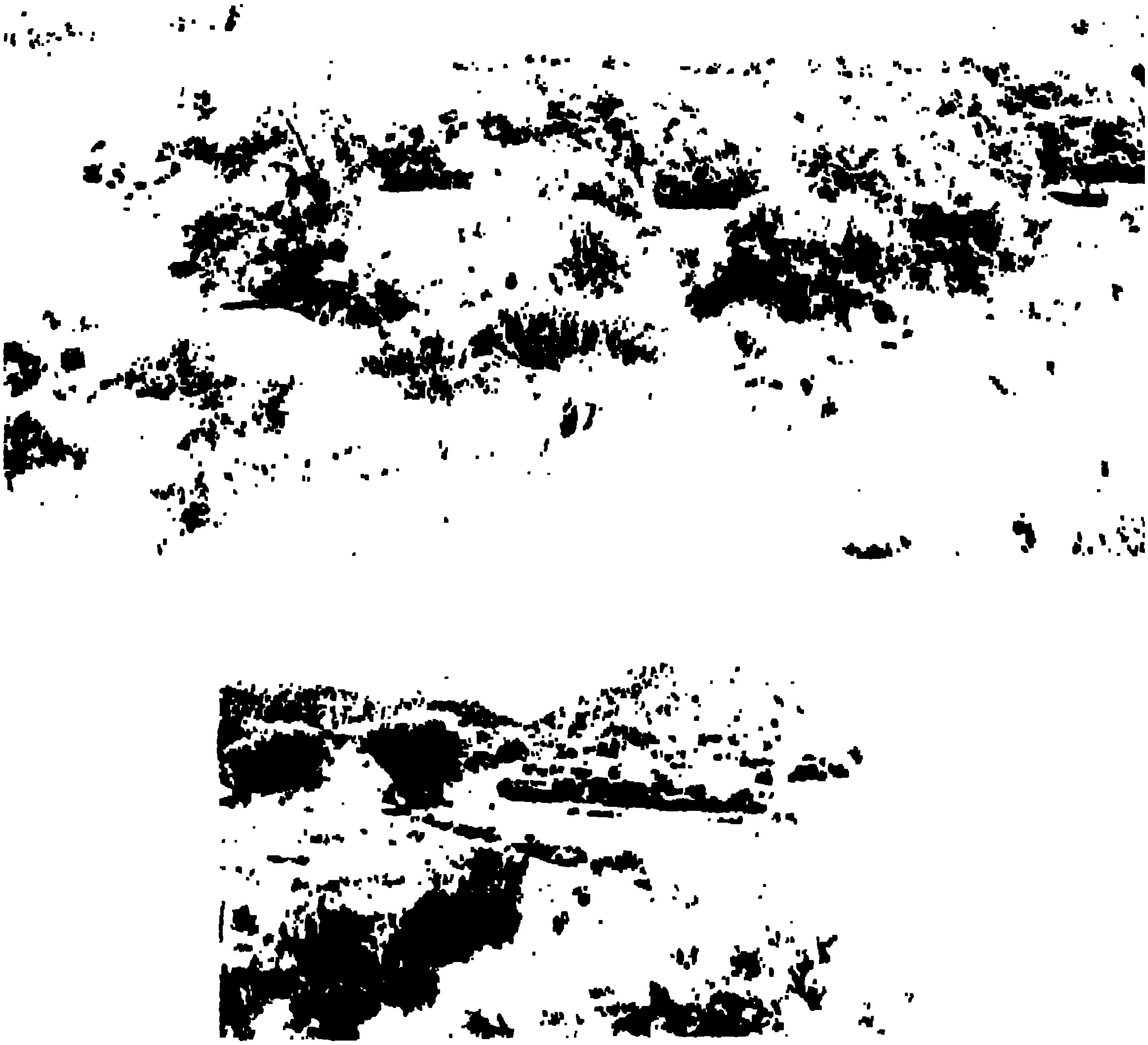

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CHAPTER 10. WATER, SEDIMENT, AND PLUTONIUM

10.1 Plutonium in River Water

Plutonium occurs in the natural environment of the Northern Rio Grande in the atmosphere, water, biologic systems, and surface materials. During the period when plutonium has been present, these systems and materials have undergone some general environmental changes affecting their distribution (Figure 10.1). The present work concentrates on sediments because they are the portion of the total system that contains 99% of plutonium in static environments,[1] including the environment of the southwestern United States.[2] In dynamic systems such as rivers, the movement of materials complicates general static impressions. For example, concentrations in water may be very low, but the amount of water passing through the system is large, so that the quantity may make up for the low concentrations in considering the entire flux. Therefore, a complete view of the plutonium in sediments depends on a context that accounts for the amount in river water. Decades long sampling of river water and sediment in the Northern Rio Grande combined with the exceptional data for water and sediment discharges in the system provide a unique opportunity to explore these relationships in a system hundreds of square kilometers in extent. The following chapter provides information on plutonium in river water, sediments in transit, and sediments deposited along and stored along the channel, as well as placing the various mean values of plutonium concentrations found at Los Alamos in a regional context. The review includes plutonium in the regional environments around Los Alamos including the compartments of river water, active sediments, flood plain deposits, and reservoir deposits. A final section in this chapter briefly explores plutonium concentrations in the sediments of Los Alamos Canyon (Figure 10.2).

Los Alamos National Laboratory has collected systematic and detailed regional river samples of river water for plutonium analyses for more than 20 years and published the results in its annual environmental surveillance reports. There are six major regional sites for which high quality, published data are available 1977-1988, with summaries of grouped data published for earlier years. Published values for 1974-1988 are measured plutonium concentrations, while in prior years published values appear as "less than" a given concentration. The sample sites on the Rio Grande are at Embudo, Otowi, Cochiti, and Bernalillo (Figure 10.3). Additional sites are on the Rio Chama and Jemez River.

The grand mean concentration for plutonium 238 in river water from the six major regional sites (excluding streams draining the immediate Los Alamos National Laboratory area which is treated separately) for 166 samples taken in the 1974-1988 period is nearly zero while the mean concentration for plutonium 239,240 is 0.0041 pCi/l (picoCuries per liter), a value close the minimum level of detection. Table 10.1 provides measures of the plutonium data while Appendix 1 contains the original data. There are no apparent temporal trends in plutonium concentrations in river water for the 1977-1988 period (when the published data represent individual sample sites rather than averages across all sites) either in the grand mean values or in the values for individual sample sites. The highest individual values, 0.010 pCi/l for

Figure 10.2. The outlet of untreated contaminated water and sediment into Los Alamos Canyon from the Los Alamos National Laboratory laundry in 1947. Note the sediment laden water entering from the left side (Los Alamos National Laboratory Photo, Document LAMS 516)

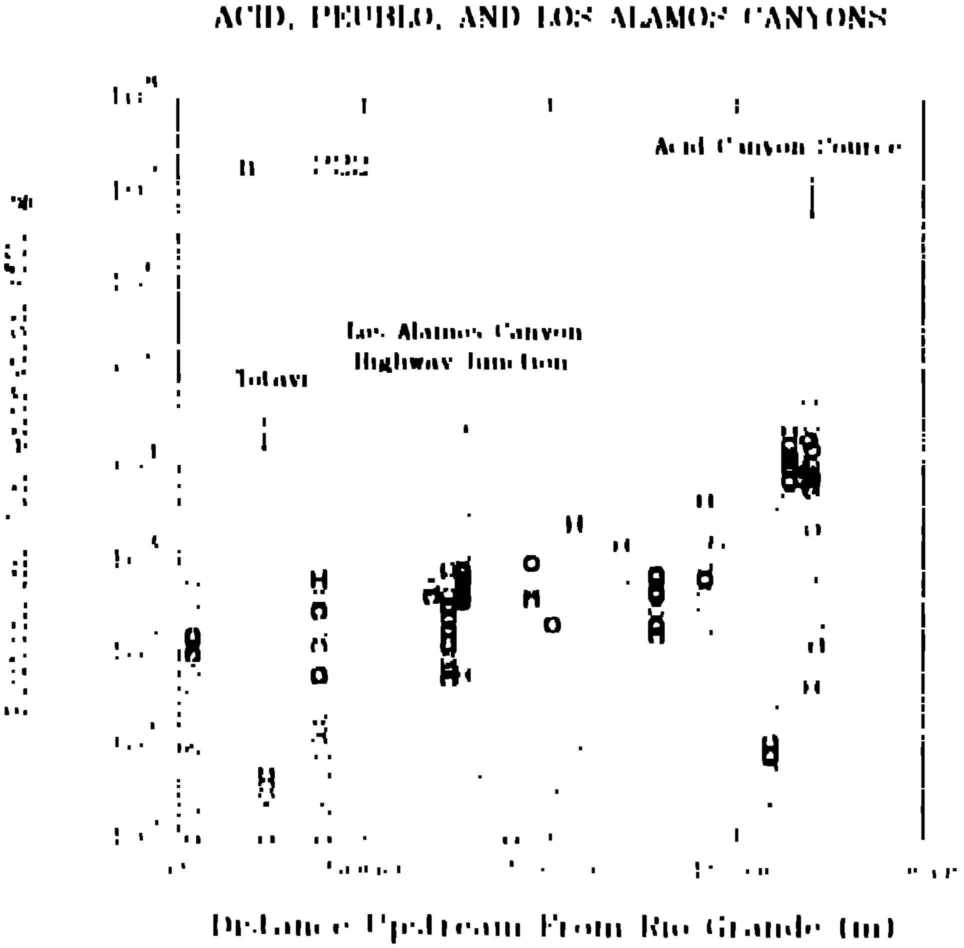

Figure 10.3 The along-stream distribution of plutonium in Acid, Pueblo, and Los Alamos Canyons. See Figure 9.7 for locations (data from Los Alamos National Laboratory).

TABLE 10.1 SUMMARY OF PLUTONIUM CONCENTRATION DATA FOR REGIONAL FLUVIAL SYSTEMS

Samples	Units	Plutonium 238			Plutonium 239,240		
		Mean	St Dev	Observ	Mean	St Dev	Observ
River Water	pCi/l	0.0078	0.0521	106	0.0050	0.0246	106
Tributary Water	pCi/l	0.0053	0.0191	73	0.0090	0.0178	73
Bedload Sediment	pCi/g	0.0002	0.0003	113	0.0048	0.0086	113
Flood Plain Sediment	pCi/g	0.0009	0.0012	8	0.0067	0.0070	8
Reservoir Sediment	pCi/g	0.0007	0.0007	60	0.0127	0.0073	60

Note: All data in table from samples collected 1977-1988 as reported in Los Alamos National Laboratory surveillance reports, except all flood plain data which was collected in 1989. See Appendix E for more detailed data for each sample type.

plutonium-238 and 0.130 pCi/l for plutonium 239,240, were from a sample collected from the Rio Grande at Embudo on August 7, 1984. There is no apparent explanation for the occurrence, although U.S. Geological Survey gaging records indicate that 1984 was the year of lowest annual water yield and lowest flood peak for the river at the sample site during the 1977-1988 period. The association between low flows and higher plutonium concentrations in water does not occur generally in the data.

There are no well-defined geographical patterns in the values for plutonium concentrations in river water in the Northern Rio Grande. The concentrations throughout the 1977-1988 period were consistently higher in the Rio Grande at Embudo and the Rio Chama at Chamita than at the other sites. According to a t-test of difference of means, the mean for the Rio Grande at Embudo is significantly higher than the mean for the Rio Grande at Otowi (at the 0.05 level). It is not immediately obvious why these relatively higher values do not continue in samples from sites downstream in the Rio Grande, but in any case all the values are small and close to levels of detection.

Los Alamos National Laboratory has also collected data on plutonium concentrations in the water of streams flowing from the Jemez Mountains and the Pajarito Plateau to the Rio Grande in the vicinity of Los Alamos. These local streams have concentrations of plutonium that are slightly higher than the main stream (Table 10.1, Appendix F2)), probably because of fallout on the higher mountain watersheds of the tributaries. These local streams include ones draining areas affected directly by laboratory operations, as well as ones draining unaffected areas.

Extensive sampling during the middle 1980s of water flowing in streams associated with laboratory operations (Los Alamos Canyon, Pajarito Canyon, Pueblo Canyon, and Water Canyon) showed that the streams carry no more plutonium in their water than other regional or local streams. The plutonium concentrations in the laboratory affected streams are statistically similar to the concentrations in unaffected streams.

10.2 Plutonium in River Sediments

Regional sampling for sediment in rivers for the Northern Rio Grande is also wide spread and of long duration compared to similar environments on a global scale. Los Alamos National Laboratory annually samples sediments from the Rio Chama at Chamita, the Jemez River at Jemez Pueblo, and the Rio Grande at Embudo, Otowi, Cochiti Reservoir, and Bernalillo (Figure 10.3). Additional, less regular sampling of sediments provides data for the Rio Grande at several points in White Rock Canyon between Otowi and Cochiti Reservoir. The laboratory's published environmental surveillance reports include these data as well as the results of occasional sampling in sediments of Rio Grande, Heron, El Vado, Abiquiu, and Cochiti reservoirs (for locations, see Figure 7.5).

The stream channels of the Northern Rio Grande transport sediment as bedload and suspended load. The more coarse bedload rests on the channel floor between flood flows, and is the material often sampled for plutonium concentrations and reported upon in Los Alamos National Laboratory surveillance reports as river "sediment." Investigators collected these materials near the channel margins as grab samples of sediment resting on the channel floor in the lee of cobbles or boulders.[3] Bedload sediment data for streams in the Northern Rio Grande for the 1974-1986 period have been previously published *en mass*.[4] Appendix E3 summarizes the plutonium concentrations for the Rio Chama at Chamita, the Jemez River at Jemez Pueblo, and sites along the Rio Grande at Embudo, Otowi, four sites within White Rock Canyon, Cochiti, and Bernalillo. The mean concentrations of plutonium-238 are near the minimum level of detection, while those of plutonium-239,240 are significantly higher (Table 10.1).

The data show that there are about three orders of magnitude more plutonium in bed sediments than in river water (note that the unit of measure for plutonium in sediments is pico-Curies per gram, while for liquids it is pico-Curies per liter, and that a liter of pure water has a mass of 1,000 grams). The values do not show temporal trends at any of the measurement sites. The bedload plutonium concentrations do not show a statistically significant geographic trend along the Rio Grande, though the concentrations at Otowi are the highest ones. The Otowi concentrations probably reflect combined inputs from fallout and from Los Alamos National Laboratory via Los Alamos Canyon. The contribution from the laboratory must be small in active bed sediments at the times of measurement, because the difference in mean concentrations between Otowi and Embudo (above Los Alamos Canyon, and reflecting only fallout contributions) are statistically insignificant. About 5 km downstream from the confluence with Los Alamos Canyon (at the confluence with Sandia Canyon, immediately below Buckman), plutonium concentrations in bed sediments return to levels so low that they are below the regional mean. Plutonium bearing bed sediments in the active channel may therefore be depositing between the two sites

For comparative purposes, plutonium concentrations in bedload sediments in areas directly affected by operations of Los Alamos National Laboratory are considerably higher than the regional values in Table 10.1. The maximum is probably found in the effluent area of Mortandad Canyon where the maximum plutonium 239,240 concentration in sediments in 1988 was 33.5 pCi/g. No values approaching this magnitude occur outside the laboratory boundaries.

Plutonium concentrations in the finer suspended sediments of regional streams are generally higher than those in the more coarse bedload because the of affinity of heavy metals for fine particles. The overall mean concentration of plutonium 239,240 in bedload sediments is 0.0086 pCi/g, while in reservoir sediments (derived from settled suspended sediment), the overall mean 0.0127 pCi/g, a useful figure for budget calculations. The mean from a few direct samples of suspended sediments in the Rio Grande at Otowi was 0.0316 pCi/g (reported in the surveillance report series of Los Alamos National Laboratory), but almost all the samples were from one year (1985) so that the figure is probably not representative. The reservoir data are probably more reliable as long term indicators. Suspended sediments from small streams directly affected by operations of Los Alamos National Laboratory and located within the laboratory boundaries have considerably higher concentrations sometimes ranging up to more than 20 pCi/g, but they are usually less than 2 pCi/g. These relatively high values do not occur outside the laboratory boundaries.

Almost all the plutonium detected in bedload and suspended sediments of the active channel of the main river is likely to be fallout-derived. The only time that plutonium from Los Alamos National Laboratory is likely to be in the active channel of the Rio Grande is during and immediately after discharges from the canyon channels draining the laboratory area. Because sampling of active sediments in the main stream rarely occurred during such events, the data describing active sediments are probably representative of the activity of the system without direct input from laboratory operations. Only reservoir and flood-plain deposits that integrate inputs over time are likely to contain plutonium from both sources.

Previous chapters showed that although there is a great deal of sediment moving through the Northern Rio Grande system, a great deal is also being stored, so that much of the plutonium in the system is also being stored. The storage process for plutonium has been highly variable through time because the inputs have been variable. The storage process is also geographically variable, but it focuses on flood plains and reservoirs.

Prior to the present project, there was no systematic sampling of flood- plain deposits and related materials such as abandoned channel areas, filled channels, and flood bars. The preliminary results of sampling of the deposits in the Buckman area indicate that the concentrations of plutonium in such materials is highly variable, reflecting the variation in plutonium concentrations at the various times of sedimentation (Table 10.1, Appendix F.4). For those deposits that were laid down in years when there were discharges from Los Alamos Canyon, plutonium concentrations are higher than those in the presently active channel. Because the channel of the Rio Grande is generally becoming smaller, straighter, and more stable, remobilization of this stored plutonium back into the active channel is minimal.

10.3 Plutonium in Reservoir Deposits

Unless it is deposited on flood plains or in abandoned channels, sediment moves through the streams of the Northern Rio Grande until it encounters a reservoir. As the stream flow encounters the still waters of the reservoir, its transport capacity declines nearly to zero and sediment is deposited on the reservoir floor.[5] The finest materials carry farthest into the middle and lower reaches of the reservoir.[6] Beyond the delta built by deposited bedload, reservoir sediments tend to be relatively fine compared with other deposits because the reservoir sediments mostly reflect the materials in suspension during channel transport.[7] Reservoir sediments from the upper reaches of Cochiti Lake, sampled in the present study near Frijoles Canyon, contained about 40-50 percent silt and clay, a figure that is a likely approximation of materials suspended in the channel portions of the Rio Grande above the lake.

Plutonium concentrations in reservoir sediments are variable from one reservoir to another in the Northern Rio Grande system (summarized in Table 10.1, data in Appendix E5). Concentrations are highest in Cochiti Reservoir which traps sediment containing contamination from fallout and Los Alamos National Laboratory. Concentrations in Cochiti Reservoir for plutonium 238 and 239,240 are significantly higher (at the 0.01 level in a t-test) than in Abiquiu Reservoir, the nearest reservoir upstream, indicating the possibility of significant additions from Los Alamos (Figure 7.5 shows locaitons). Plutonium concentrations in the Rio Grande Reservoir (in the mountainous headwaters of the river system) are similar to those in Cochiti Reservoir, but in Rio Grande Reservoir the only potential source is fallout on alpine slopes in the system's headwaters. Heron Reservoir, in the headwaters of the Rio Chama, has intermediate values, probably because its sediments derive from lower-elevation areas than the Rio Grande Reservoir. El Vado Reservoir, downstream from Heron Reservoir, does not receive sediments from the high landscapes above Heron, and its plutonium concentrations are therefore lower. Abiquiu Reservoir also has low values for the same reason.

Surveillance reports by Los Alamos National Laboratory explain that the plutonium concentrations in Cochiti Reservoir are the result of the fact that Cochiti has more fine sediment and more organic material than the other reservoirs. These explanations may be at least partly correct, but they are not demonstrated by particle size or organic content data. The particle size and organic material explanation also begs the question concerning the amounts of plutonium entering the reservoirs. If all reservoirs receive the same amount of plutonium, and if Cochiti collects more in sediment than the others, the fate of plutonium entering the others is unexplained. Water samples do not indicate that discharges from the other reservoirs contain more plutonium than the discharge from Cochiti. The best explanation is that Cochiti and Rio Grande reservoirs contain more plutonium than the others because more plutonium enters them as a result of their geographic locations: more plutonium in the Rio Grande Reservoir because it receives high inputs of fallout from surrounding mountain slopes, and more in Cochiti Reservoir because it receives inputs from Los Alamos.

This brief summary of plutonium in water and sediments demonstrates the importance of understanding the regional sediment budget in deducing the regional plutonium budget. Almost all the plutonium in the Northern Rio Grande system is associated with sediment. A comparison of the amount of plutonium in transit in the Rio Grande at Otowi shows the overriding significance of sediment bound plutonium in regional budgets and fluxes of the contaminant. The total annual movement of plutonium in river water at the site is,

$$F = Q * P$$

where F = the total flux of plutonium in water per year, Q = mean annual water yield from U.S. Geological Survey records, and P = mean plutonium concentration from Los Alamos National Laboratory surveillance reports. For the period 1977-1988, the total plutonium flux in water (combining plutonium 238, 239, and 240) at Otowi was

0.0199 mCi per year. A similar calculation for sediment (discussed in greater detail in the following section) shows that for the same period, the total plutonium flux in sediment was 29.4390 mCi, or three and a half orders of magnitude greater than in water.

10.4 Plutonium in Los Alamos Canyon Sediments

The sampling program of Los Alamos National Laboratory has collected over 400 stream sediment samples in Acid, Pueblo, DP, Los Alamos, Bayo, and Guaje Canyons at and near the laboratory. These samples, apparently collected as bedload materials, provide a useful assessment of the level of plutonium concentrations in stream sediments directly affected by the releases associated with the laboratory activities of the 1940s and early 1950s. The mean values that reflect this intensive sampling effort show the general degree of plutonium loading in sediments by the laboratory, while a detailed analysis of the data reveals the geographic variability of the concentrations within a few km of the source.

Bedload sediments from streams draining the eastern slopes of the Jemez Mountains and parts of the Pajarito Plateau unaffected by the laboratory activies have plutonium values (Table 10.2) that are somewhat higher than values in the lower elevation regional streams (Table 10.1). Apparently fallout contributions to the higher landscapes with their greater precipitation account for the difference.

Bedload sediments from streams directly affected by Los Alamos releases have the highest concentrations of pluotnium of any of the environments considered in this study. Mean concentrations in bedload sediments of Acid, Pueblo, DP, and Upper Los Alamos Canyon (above the confluence with Pueblo Canyon--see maps in Chapter 9 for general locations) are two and one half to three orders of magnitude higher than mean values for similar sediments in the regional river system (Table 10.2). In lower Los Alamos Canyon (downstream from the confluence with Pueblo Canyon), plutonium concentrations are only a fraction of the values in those areas directly affected by the Los Alamos National Laboratory releases, but they are still many times higher than values in the regional river system.

The mean values of plutonium concentrations in bedload sediments of the Los Alamos Canyon system are useful general indicators of contamination levels, but the mean values mask important temporal and geographical variation in the data. In many places, repetitive sampling over a period of decades has revealed substantial variation from year to year, with each site producing elevated values of plutonium concentrations as well as values approaching regional background levels (Figures 10.4 and 10.5). This temporal fluctuation is the product of sediment transport processes wherein some years see direct inputs to downstream sample sites from discharge events transporting contaminated sediments directly from release sites upstream. The result is relatively high concentrations of plutonium at the sample site. In other years, the release sites may have not experienced a significant discharge event, but other uncontaminated portions of the system may have been flooded, contributing relatively clean sediments to the downstream sample site, producing relatively low plutonium

TABLE 10.2 SUMMARY OF PLUTONIUM CONCENTRATION DATA FOR LOS ALAMOS CANYON SYSTEMS

Samples	Units	Plutonium 238			Plutonium 239,240		
		Mean	St. Dev	Observ.	Mean	St. Dev.	Observ
Background Streams[a]	pCi/g	0.00100	0.00140	44	0.00210	0.00210	44
Acid, Pueblo Canyons	pCi/g	0.03409	0.11876	132	3.10054	7.11496	132
DP, Upper Los Alamos Canyons	pCi/g	0.17077	0.65117	165	0.56541	1.17599	165
Lower Los Alamos Canyon	pCi/g	[illegible]	0.01277	49	0.19624	0.22290	49

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[a] Includes sites within the Los Alamos Canyon system not directly affected by laboratory activities: sites in Bayo and Guaje Canyons, at the highway bridge and reservoir sites in upper Los Alamos Canyon, and sites upstream from the points of plutonium releases in DP and Acid Can.

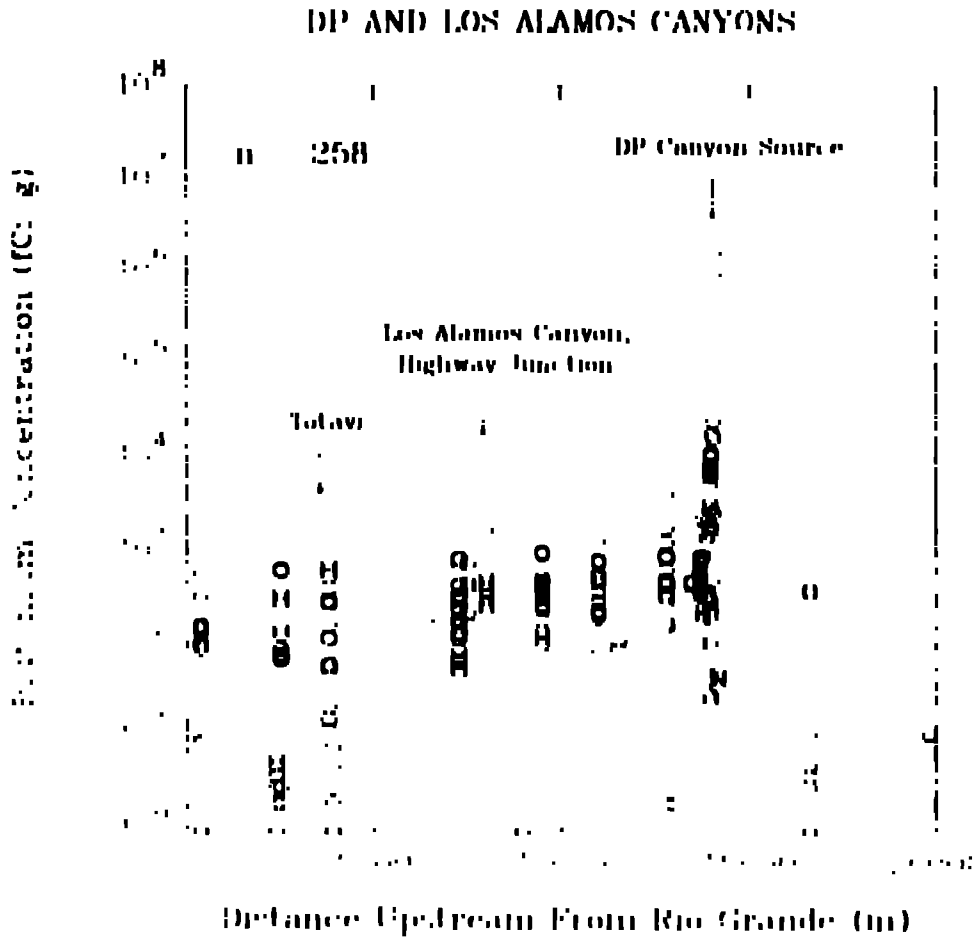


Figure 10.4 The along stream distribution of plutonium in DP and Los Alamos Canyons. See Figure 9.7 for locations (data from Los Alamos National Laboratory).

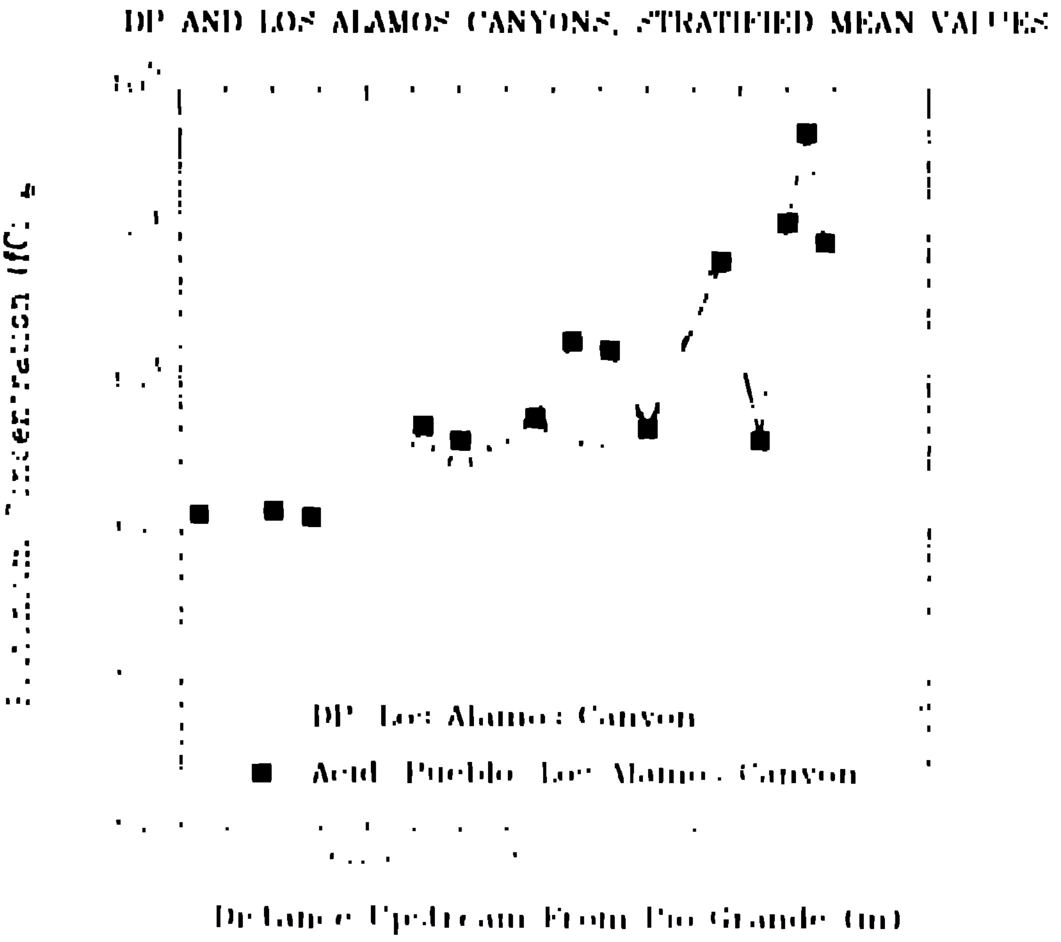


Figure 10.5 The along stream distribution of plutonium in Acid, Pueblo, and Los Alamos Canyons (squares and solid line) and in DP and Los Alamos Canyons (circles and dashed line) plotted as average values within individual 500 meter reaches. Reaches without samples are not plotted. See Figure 9.7 for locations (data from Los Alamos National Laboratory)

concentrations when sampled

As distance increases downstream away from the source of plutonium in Acid and DP Canyons, the mean values within limited reaches decline (Figure 10.5). Mixing of relatively uncontaminated sediment with polluted materials, deposition of contaminated materials in flood plains where it is not sampled as part of the bedload sediments, and dispersion resulting from streamflow processes contribute to a downstream decline in concentrations Figure 10.6 shows that the highest concentrations occur in Acid Canyon with general downstream decline to the junction with the Rio Grande Mean concentrations in the DP and Upper Los Alamos Canyon system are low in the upper most portions because these reaches are above the injections of plutonium from DP Canyon

The viewpoint of this chapter on plutonium concentrations in river water and sediments provides a backdrop against which it is possible to consider that movement of plutonium through the system This second, more complicated viewpoint occupies much of the remaining pages of this book The most important lesson of mean values is that while they provide valuable insight into the relative roles of various environmental compartments and geographical locations, the temporal and spatial variability of concentrations must temper any detailed views of the system The following chapter attempts to assess with a geographical perspective the annual movement of plutonium through the Northern Rio Grande

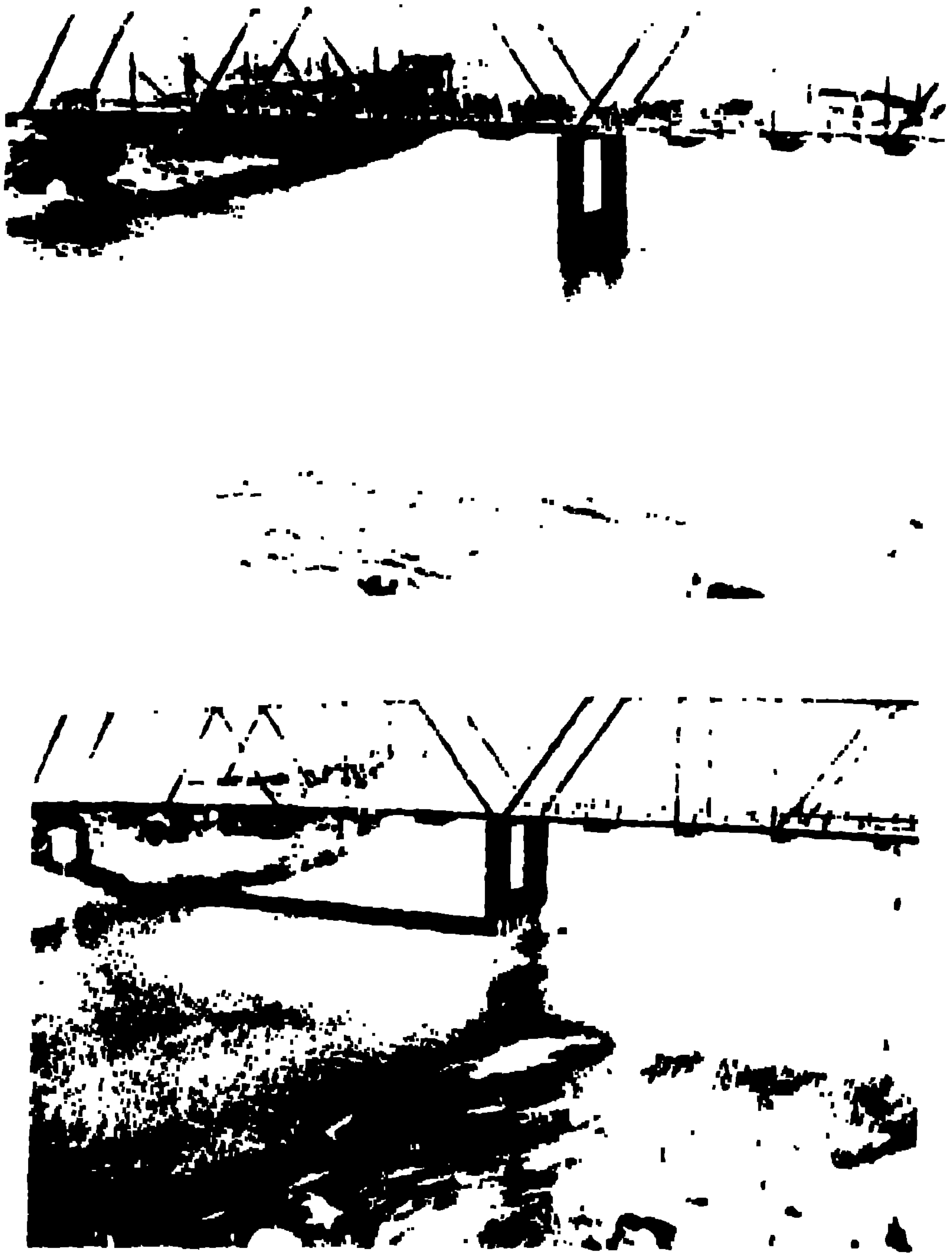


Figure 11.1. The State Line Bridge on the Rio Grande [illegible], between New Mexico and Colorado [illegible]

CHAPTER 11. ANNUAL PLUTONIUM BUDGET FOR THE RIO GRANDE

11.1 Sources of Data

A mean annual plutonium budget for the Northern Rio Grande provides an accounting of the amounts of plutonium moving into and out of various reaches of the river for a typical year. Such a budget is a basis for assessing the rates of plutonium transport and the location of storage along the river. The budget presented in the following pages is for bedload and suspended sediments. It does not include plutonium in water because water borne plutonium is such a small portion of the total in the system (as discussed in Chapter 10). The budget as calculated here requires data concerning sediment and plutonium concentrations in the sediment. The sediment discharge data that are available from U.S. Geological Survey gaging sites (see Chapter 5) define the overall framework for budget construction. A reasonably detailed picture is possible for the river system from the Rio Grande at Embudo and the Rio Chama at Chamita southward to the Rio Grande at San Marcial (see Figure 4.2 for locations) where the river empties into Elephant Butte Reservoir.

Data collected by Los Alamos National Laboratory and published in the annual surveillance reports by the laboratory's Environmental Studies Group and later by the Environmental Surveillance Group provide plutonium concentration data for bedload and suspended sediments. The calculations for each site in the present study used mean values of plutonium concentrations from all measurements at or near the site. Table 11.1 reviews the sources of plutonium concentration data for each of the sediment gaging sites in the regional budget calculations. Unfortunately, the sites for the collection of plutonium data were not always colocated with the gaging sites that produced the sediment discharge data (Table 11.1). Additionally, most of the plutonium concentration data are for bedload sediments because of the manner in which workers collected samples. In some cases, the best estimates of plutonium concentrations in suspended load for gaging sites are from concentrations found in sediments of the nearest reservoir upstream, because those sediments are likely to have been in suspension before their emplacement on reservoir floors. The assumption that the mean concentration is a useful representative value seems reasonable given that in those reaches with relatively large amounts of data, concentration values do not show temporal or geographic trends.

There are no direct plutonium concentration data for sediments in the Rio Puerco and Rio Salado. Budget calculations in this study assumed that data from Frijoles Canyon was also representative of sediments in the two southern tributaries, in the absence of more reliable estimates. The Frijoles drains a portion of the Jemez Mountains, and therefore might be expected to produce estimates of plutonium concentrations for the other two streams that are too high. This overestimation may be balanced by the fact that the Rio Salado and Rio Puerco have more erodible soils, that probably shed more of their burden of fallout plutonium than soils of the Frijoles system. Whatever shortcomings are imposed by the small number of samples, expensive chemical processing and analysis has always precluded acquisition of additional data.

TABLE 11 1 SOURCES OF MEAN VALUES FOR PLUTONIUM CONCENTRATIONS IN BUDGET CALCULATIONS

Site	Bedload	Suspended Load	Total Load
Rio Chama at Chamita	15 values, 1974 1986	5 values, Abiquiu Reservoir	Sum
Rio Grande at Embudo	16 values, 1974 1986	Difference between Chama and Otowi	Sum
Rio Grande at Otowi	16 values, 1974 1986	[illegible] values, 1981 1987	Sum
Los Alamos Canyon	Not used in calculations	Not used in calculations	L. J. Lane, unpublished
Jemez River below dam	15 values at Jemez Pueblo, 1974 1986	None	Sum
Rio Grande at Albuq	14 values at Bernalillo, 1974 1986	5 values, Cochiti Reservoir	Sum
Rio Puerco near Bern	3 values, Frijoles Canyon	[illegible] values, Frijoles Canyon	Sum
Rio Salado near S. Ac	3 values, Frijoles Canyon	[illegible] values, Frijoles Canyon	Sum
Rio Grande at S. Mar	14 values at Bernalillo, 1974 1986	5 values, Cochiti Reservoir	Sum

Note All data from Surveillance Reports of Los Alamos National Laboratory

Budget calculations used summary values for total plutonium transport in Los Alamos Canyon (rather than summing the bedload and suspended transport), because only the total values were available[1] In the case of the Rio Grande at Embudo, plutonium concentration data for the bedload sediments are available, but not for suspended sediments. Therefore, the total budget for the Rio Grande at Otowi minus the total budget for the Rio Chama at Chamita provided the estimate for the Rio Grande at Embudo

11.2 Methods of Calculation

The basic approach to calculating the plutonium budget in this work was to determine the mean annual flux (expressed as a rate of movement) of all plutonium (238, 239 and 240 isotopes) at each of nine sites in the Northern Rio Grande. The total mass of annual sediment discharge (bedload and suspended) times the plutonium concentration in each sediment type for plutonium 238 and plutonium 239,240 provided the data for total flux at each site. Algebraically,

$$\frac{\partial(Pu)}{\partial(t)} = C_b^{238}\frac{\partial(S_b)}{\partial(t)} + C_s^{238}\frac{\partial(S_s)}{\partial(t)} + C_b^{239,240}\frac{\partial(S_b)}{\partial(t)} + C_s^{239,240}\frac{\partial(S_s)}{\partial(t)}$$

where $\partial(Pu)/\partial(t)$ = total plutonium flux per unit time (Ci/yr)

C_b^{238} = mean concentration of plutonium 238 in bedload (Ci/Mg)

$\partial(S_b)/\partial(t)$ = mean bedload sediment discharge (Mg/yr)

C_s^{238} = mean concentration of plutonium 238 in suspended load (Ci/Mg)

$\partial(S_s)/\partial(t)$ = mean suspended sediment discharge (Mg/yr)

$C_b^{239,240}$ = mean bedload concentration plutonium 239,240 (Ci/Mg)

$C_s^{239,240}$ = mean concentration of plutonium 239,240 in suspended sediment (Ci/Mg)

Solution of the budget function for each of the sites in the river system given in Table 11.1 was possible for two scenarios: a general best-estimate budget and a specific budget for the time period 1970-1979. A general best-estimate or composite budget utilized mean sediment discharge values from the entire record at each of the sites. The length of these records and their dates of initiation and cessation varied from one site to another, so that the resulting general budget represents a statistical composite and does not reflect values for any particular year. On a several-decade basis, however, this budget is likely to be the most accurate given the nature of the available data.

A second set of budget calculations using the sediment discharge data for the 1970-1979 period is useful for comparison to the best estimate budget as an indication of variability and as a view of one representative time period. The decade of the 1970s was also particularly useful for sediment discharge data because it is the 10-year period for which the most data are available--only the Jemez River below Jemez Dam lacked data for the period, with all other stations providing data for the majority of years. In addition, the plutonium data included values from the middle and late 1970s, obviating the need to assume that mean values have not changed over the time period of analysis.

11.3 Magnitude of Error

The annual plutonium budgets for the Northern Rio Grande calculated in the present work are only first approximations. Although the calculations use the best available data from an environment that is data rich in comparison with most other areas, substantial errors may exist in the results. Sources of error include measurement, sampling, and estimation errors. Measurement errors occur when laboratory analysts measure plutonium concentrations in sediment and when field workers measure the sediment concentrations in river flows. Information published in annual surveillance report of Los Alamos National Laboratory indicate that one standard deviation for the measurements of plutonium concentrations in sediments is usually in the range of 0.0002 to 0.002 pCi/g for plutonium 238 and 0.0002 to 0.01 pCi/g for plutonium 239,240. The larger mean values are associated with larger standard deviations, and generally the mean and standard deviation are approximately equal.

Measurement errors for suspended sediment are relatively small compared to the measurement errors for plutonium. The reported mean values for suspended sediment include errors resulting from perturbations in the water flow caused by the sampling device and errors from weighing the samples. Measurement errors for suspended sediment are probably standard deviations equal to about 0.1 times the mean value.

Estimation errors for bedload are relatively large compared to other sources of errors. Direct bedload measurements are not available for the system except on a limited experimental basis, so that it is necessary to estimate them from limited amounts of research as outlined previously. Uncertainties associated with bedload data results in errors that are standard deviations equal to the means. The quality of data in the Northern Rio Grande is superior to that in most environments, so that a reasonable estimate is that the one standard deviation error is probably 0.5 times the mean value.

Sampling errors result from the method of using a small sample to represent a much larger population. Because the samples of sediment taken for plutonium analyses or for calculation of sediment discharge represent data from only a few years of a much larger and more variable population of years' data, sampling error must be considered in assessing the usefulness of the final estimates for the total annual plutonium budget. The statistical measure of this error is the "standard error," defined by the standard deviation divided by the square root of the sample size. For most of the stations in the present calculations, the standard error is less than 0.5 times the mean value. For the sediment discharges, the standard error is about 0.18 times the mean value for all the stations taken together. The sediment discharges for Los Alamos Canyon with a value of 0.28 times the mean and the Rio Salado with a value of 0.30 times the mean have high standard errors because of the variability of their processes and (in the case of the Rio Salado) a short record.

The sum of these errors indicates that the composite annual plutonium budget probably has a standard deviation of about half an order of magnitude. Error for the ten-year budget for 1970-1979 is probably somewhat smaller because the variability in the data for the restricted time period is less. The budgets produced from the presently available data cannot therefore be used to precisely predict the amounts of plutonium in a particular place at a particular time. They can show the geographic variation in regional transport and storage processes, and they can provide a context for the analysis of one particular source in relationship to all other sources.

11.4 Annual Plutonium Budgets

The composite annual plutonium budget represents a view of the system constructed with grand general mean values for plutonium concentrations and sediment discharges. It represents a picture made with the most stable mean values from the available data, and does not represent any one particular year. It is a useful general guide to the nature of the system from the mid 1940s to the mid 1980s. Figure 11.2 shows the composite annual budget in graphic form, with the width of the flow arrows related to the magnitude of plutonium movement. Table 11.2 reviews the basic plutonium data for the calculation and provides more detailed numbers for the budget.

The budget shows that for the general case fallout plutonium enters the Northern Rio Grande sediment system in relatively large amounts from the Rio Grande as it flows past Embudo and from the Rio Chama. The Rio Chama carries more sediment (as illustrated in Figures 5.4 and 5.5), but the Rio Grande carries more plutonium, because it occurs there in higher concentrations. Reservoirs on the Rio Chama trap most sediment and fallout plutonium from upper elevations in the watershed, so that sediments in the lower Rio Chama are derived from low elevation landscapes that received less fallout than the higher terrain that drains into the Rio Grande.

The Rio Puerco empties huge quantities of sediment into the Rio Grande system, but that sediment is likely to contain only low concentrations of fallout plutonium because of the relatively low elevation and the dry landscapes that the tributary drains. The resulting influx of plutonium is nonetheless large with respect to the amount entering from other tributaries, because so much sediment is involved in the Rio Puerco. The Jemez River and Rio Salado contribute mostly bedload materials which have low concentrations of plutonium, and so they contribute relatively small

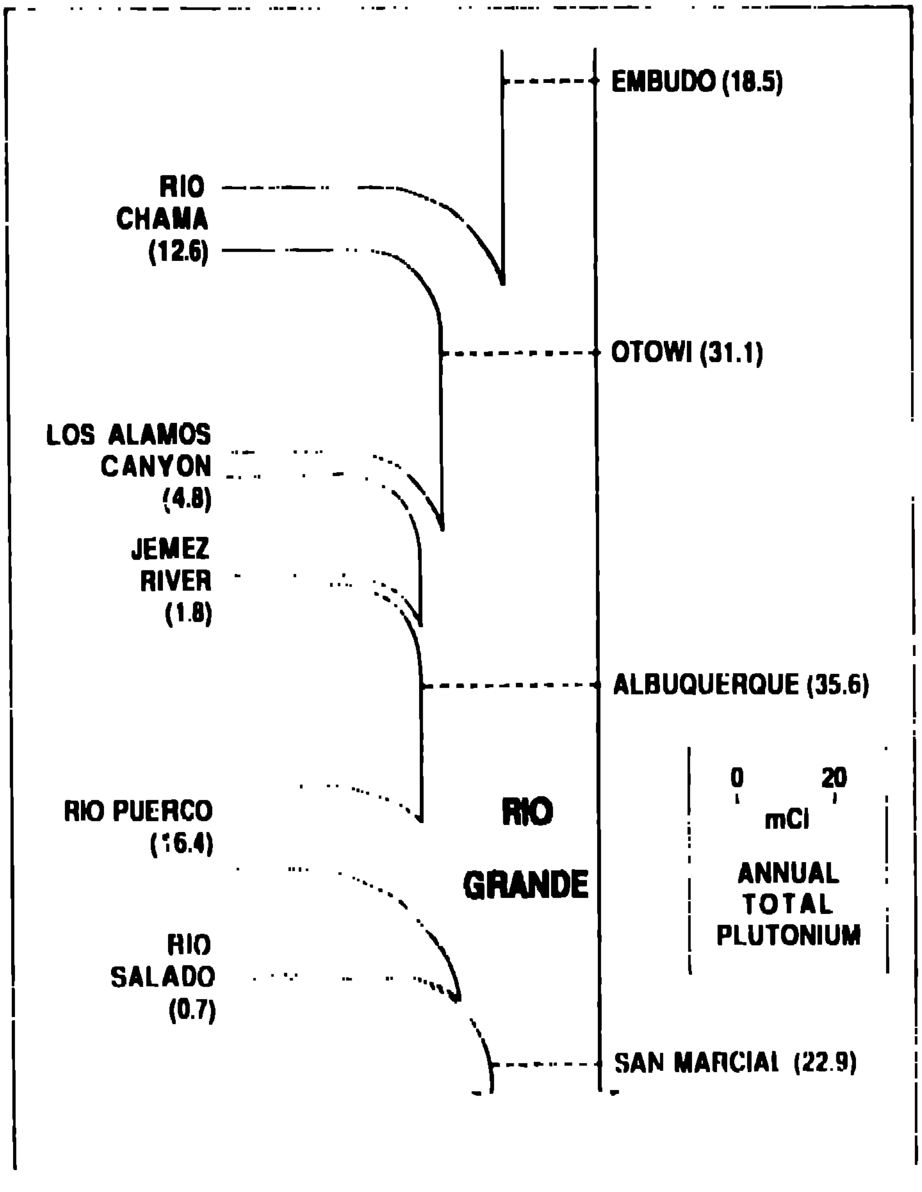


Figure II 2 Flow diagram showing the mean annual composite budget for total plutonium in the Northern Rio Grande

TABLE II 2 BUDGET CALCULATIONS FOR ANNUAL PLUTONIUM BUDGET

Site	In Bedload				In Suspended Load				Total Load		
	Pu 238		Pu 239,240		Pu 238		Pu 239,240		Pu 238	Pu 239 240	Total Pu
	Conc. (pCi/g)	Mass (mCi)	Conc. (pCi/g)	Mass (mCi)	Conc (pCi/g)	Mass (mCi)	Conc. (pCi/g)	Mass (mCi)	(mCi)	(mCi)	(mCi)
o Chama t Chamita	0.000133	0.029	0.001533	0.337	0.000506	0.686	0.008400	11.534	0.715	11.871	[illegible]
o Grande at Embudo									2.733	15.802	18.535
o Grande at Otowi	0.000357	0.112	0.005000	1.570	0.001700	3.336	0.013400	26.103	3.448	27.673	31.121
s Alamos Canyon											4.788
mez River	0.000467	0.204	0.00400	1.749					0.000	1.749	1.749
o Grande at Albuq	0.000000	0.000	0.005000	1.406	0.001100	1.932	0.018300	12.157	1.932	12.157	14.089
o Puerco near Bern	0.000000	0.000	0.002500	4.756	0.000000	0.000	0.002500	11.600	0.000	16.356	16.356
o Salado near S. A	0.000000	0.000	0.002500	0.321	0.000000	0.000	0.002500	0.321	0.000	0.647	0.647
o Grande at S. Mar	0.000357	0.206	0.003300	2.889	0.002500	1.290	0.017400	[illegible]	1.496	21.385	22.881

quantities of the element.

Los Alamos Canyon contributes tiny amounts of sediment to the total system, but because the concentrations of plutonium are higher in its sediment than in sediments elsewhere in the system, the influx from the tributary is proportionally larger than its sediment alone might suggest. The amount is still small in comparison with the amount coming down the Rio Grande. On a mean annual basis, the amount contributed by Los Alamos Canyon, mostly from the operations of Los Alamos National Laboratory, is about 15 percent of the amount contributed by fallout plutonium from the Upper Rio Grande and the Rio Chama. Thus, if the laboratory did not exist in the system, the amount of plutonium in flux and storage would be still be about 85 percent of the present total inventory in the vicinity of Otowi.

The composite budget indicates the general location of plutonium storage within the system. A minor amount, about 2.1 mCi per year, was stored along the river between Otowi and Albuquerque. After 1973, Cochiti Reservoir stored most of this amount, but before that year, storage was likely to have been more widespread. The system stored a major amount of plutonium about 29.8 mCi per year between Albuquerque and San Marcial on flood plains and in abandoned channels. Less than half of the plutonium that entered the Albuquerque to San Marcial reach exited the reach to Elephant Butte Reservoir. For the entire system, fluvial deposition stored more plutonium internally (about 32 mCi per year) than left the system and was stored in Elephant Butte Reservoir (about 23 mCi per year)

The downstream end of the Northern Rio Grande system for the purposes of this study is Elephant Butte Reservoir where the river deposits its sediment and associated plutonium. Very little of either passes Elephant Butte Dam to continue the journey down the Rio Grande. This arrangement explains the extremely low sediment and plutonium yields from the Rio Grande system indicated in the calculations of Foster and Hakonson.[1]

A comparison between the composite annual budget using all the available data (representing mostly the period 1948 1985 because of the nature of the sediment records) with the 1970 1979 mean annual budget shows the temporal variability of the annual plutonium budget (Table 11 3). During the 1970s, the Rio Chama annually contributed only about one third as much plutonium as it did annually during the longer period. The sediment discharge of the Rio Chama during the 1970s was relatively low because of the closure of Abiquiu Dam in 1963 and because of relatively low water yields and small annual floods. As a result, plutonium flux was also relatively low. Los Alamos Canyon also experienced reduced water discharges, because of climatic conditions, and therefore transported relatively small quantities of plutonium to the Rio Grande during the 1970s.

Processes on the main stream were the reverse of these tributary processes. Sediment discharges on the Rio Grande at Albuquerque and San Marcial were large because of channel adjustments resulting from the erosion downstream from Cochiti Dam (closed in 1973) and flash floods on smaller tributaries. Levee and pilot channel

TABLE 11.3 COMPARISON BETWEEN COMPOSITE BUDGET AND 1970-1979 ONLY BUDGET

Site	Composit Budget (mCi/yr)	1970-1979 (mCi/yr)
Rio Chama at Chamita	12.586	4.257
Rio Grande at Embudo	18.535	24.802
Rio Grande at Otowi	31.121	29.059
Los Alamos Canyon	4.800	1.702
Jemez River below Jemez Dam	1.749	No Data
Rio Grande at Albuquerque	34.094	50.546
Rio Puerco near Bernardo	16.356	14.169
Rio Salado near San Acacia	0.647	1.111
Rio Grande at San Marcial	22.881	79.968
TOTAL INPUTS	54.661	46.041
STORAGE (+) AND OUTPUT ( )		
Otowi Albuquerque	3.574	19.785
Albuquerque San Marcial	28.206	14.142
Total System	31.780	33.927

construction near San Marcial contributed additional inputs. The result was a 3.5-fold increase in plutonium flux on the Rio Grande at San Marcial.

Because internal erosion dominated the 1970-1979 processes, there was a net loss of plutonium stored within the river system during the decade, and more was flushed into Elephant Butte Reservoir than was stored along the channel. About 46 mCi of plutonium per year entered the river system, but 79 mCi per year exited to Elephant Butte Reservoir. This arrangement was not typical of the entire 1948-1985 period which was mostly a period of river deposition, but it illustrates the variability of the internal processes.

11.5 Relationship Between Laboratory and Fallout Contributions

The composite budget provides a useful framework for the assessment of the relative inputs of plutonium from fallout sources and from Los Alamos. The data in the composite budget are empirical and are specific to the Northern Rio Grande rather than general predictions based on assumptions about the latitudinal distribution of fallout. Despite limitations imposed by measurement, sampling, and estimation errors, the composite budget is likely to be more accurate than others previously published because it depends on local empirical data rather than general estimates from global approximations.

The best estimate of inputs to the system during the 1948-1985 period (Figure 11.2, Table 11.2) indicates that fallout sources introduced about 55 mCi of plutonium per year, while Los Alamos introduced through Los Alamos Canyon about 4.8 mCi per year. During the 1970-1979 period, fallout produced about 46 mCi per year and Los Alamos about 1.7 mCi per year. In any case, the contribution of Los Alamos to the annual plutonium flux in the entire Northern Rio Grande system (that is, the portion above Elephant Butte Reservoir) is relatively small, accounting for about 9 percent of the total. Fallout occurs in very small concentrations, but because relatively large amounts erode from the landscape and move through the river system, it accounts for more than 90 percent of all the plutonium in the river sediments. In the more restricted vicinity of Otowi (an area not including inputs from the Rio Puerco or Rio Salado), the inputs from Los Alamos accounted for about 15 percent of the plutonium in the composite annual budget and about 6 percent during the 1970s.

The significance of these annual fluxes is that large amounts of plutonium remain on the landscape of the general system and in Los Alamos Canyon. If the general estimate of Hanley and others is correct for the mean fallout of plutonium for the latitudinal belt of the Northern Rio Grande (1.8 mCi/sq km),[4] then a total of about 66,800 mCi have entered the landscape of the general basin above Otowi. Assuming a middle range estimate for the total plutonium loading of Los Alamos Canyon of 1,500 mCi,[5] the Los Alamos contribution to the total plutonium inventory of the basin upstream from the confluence of the Rio Grande and Los Alamos Canyon at Otowi is about 2.2 percent. The calculation used in this study suggests that the discharges of plutonium from Los Alamos Canyon have evacuated only about 10 percent of the total stored in the canyon, so that 90 percent of the amount released at Los Alamos is still in the tributary canyon. In the general basin above Otowi, erosion and fluvial transport have removed less than 2 percent of the fallout plutonium inventory. At present rates of flux as estimated in the composite annual budget, more than 2,100 years will be required to remove the fallout plutonium stored upstream from Otowi.

11.6 Particular Cases of Plutonium from Los Alamos

Plutonium from the fallout and from Los Alamos is not equally distributed in either time or in space. Fallout plutonium is mostly associated with fine-grained materials and suspended sediment, while the inputs from Los Alamos are mostly associated with coarse particles and bedload. These differences imply that in a restricted time period, fallout plutonium more readily moves over long distances in the river system, while plutonium from Los Alamos moves shorter distances. Also, fallout plutonium enters the system in a more gradual fashion, while the Los Alamos plutonium enters the main stream only sporadically as a result of infrequent flash floods in Los Alamos Canyon. During many years, no plutonium from Los Alamos enters the system. For these reasons, analysis of the contribution of Los Alamos requires a focus on bedload budget processes for the few selected years when contributions from Los Alamos Canyon were relatively large: 1951, 1952, 1957, and 1968.

Calculations for the bedload plutonium budget in the Northern Rio Grande near Los Alamos for particular years required sediment discharge data from U.S. Geological Survey gaging stations at Chamita on the Rio Chama, and Otowi on the Rio Grande, unpublished data on plutonium discharges from Los Alamos Canyon by L. J. Lane,[6] and plutonium concentration data published in surveillance reports by Los Alamos National Laboratory. There were two important assumptions in these calculations. The first assumption was that the plutonium from Los Alamos Canyon as calculated by Lane was mostly in bedload. This assumption seems reasonable because the original contamination was in coarse alluvium. Plutonium in transit in the late 1940s was in coarse materials along the stream channels as shown by photographs at the time,[7] and by subsequent findings that most of the contamination was associated with coarse particles.[8]

The second assumption was that the mean plutonium concentration data in bedload in the main stream was consistent over time. There are no identifiable trends in the concentration data collected at any of the stations in the data set, so that this assumption seems safe for the mid 1950s and thereafter when the amount of plutonium available from fallout was substantial. There was probably less than the estimated plutonium fallout in the system for the 1951 and 1952 calculations than this assumption implies, because there had been relatively few atmospheric tests at that time. Therefore, for 1951 and 1952, the amounts of fallout plutonium calculated as entering the system through the Rio Chama and Rio Grande are maximum estimates. The magnitudes of the numbers are relatively small in relationship to the contributions from Los Alamos, however, because the main stream carried small amounts of sediment and bedload during those two years. The errors are also probably small for budget considerations.

The annual budgets for plutonium in bedload for 1951, 1952, 1957, and 1968 for the Rio Grande in the vicinity of Los Alamos show the overwhelming importance of inputs from Los Alamos Canyon in bedload (Figure 11.3). The inputs from Los Alamos were clearly larger for these four years than the mean condition, but the inputs from fallout were also larger than average. The degree of increase for fallout contributions was not as great as for the more variable contributions from Los Alamos Canyon. The result was that the role of the Los Alamos contributions was exaggerated, and 71 percent (in 1952) to 86 percent (in 1957) of the bedload plutonium below Otowi was from Los Alamos.

For the four particular years of interest, water yield and annual floods on the Rio Grande were not especially large, so that flash flood sediments (coarse bedload particles) from Los Alamos Canyon entering the main river are not likely to have traveled far downstream. Evidence developed Chapter 12 shows that it is likely that these materials contributed to deposits immediately below the confluence of Los Alamos Canyon and the Rio Grande and to accumulations at Buckman, about 5 km downstream. The configuration of the Rio Grande downstream from Otowi during these four particular years was a channel constricted by the walls of White Rock Canyon, with wide portions suited for deposition only at Buckman, a few pockets in White Rock Canyon, and flood plains near Cochiti Pueblo and Peña Blanca. It seems unlikely that the sediments would have traveled further downstream than the Peña Blanca reach, but further research using hydraulic simulations could test this hypothesis.

Given these considerations, along with the fact that the general river system was aggrading (storing sediment) throughout the 1950s and 1960s, the 1951, 1952, 1957, and 1968, contributions of plutonium- bearing sediments from Los Alamos are likely to have formed deposits along the channel in flood-plain deposits, channel fills, and bars. It is possible to estimate the probable concentrations of plutonium in the deposits by combining the sediment discharge data for the Rio Grande developed in the present work with the data on plutonium inputs from Los Alamos Canyon developed by Lane and others.[9] Estimates given in Table 11.4 indicate that concentrations of total plutonium (-238, -239, and -240) in flood-plain and channel deposits are likely to be between about 0.01 and 0.1 pCi/g, values confirmed by analyses of samples recently taken from the deposits (Table 11.4). The deposits from different years may reasonably be expected to exhibit different concentrations, depending largely on the magnitude of inputs from Los Alamos Canyon.

Bedload sediments moving through the Rio Grande during the 1970s and 1980s in the vicinity of Otowi had mean plutonium concentrations of about 0.01 pCi/g, a value at the lower end of the range of predicted values for the deposits. Concentration values are an order of magnitude higher in the flood plain deposits near Buckman, probably representing levels in bedload sediments in the past, but they are not high enough to be hazardous. The United States does not have standards for sediment quality with regard to plutonium, but experience on the Puerco River in northwest New Mexico (not to be confused with the Rio Puerco, a tributary of the Rio Grande) provides a value for comparison. The Environmental Protection Agency

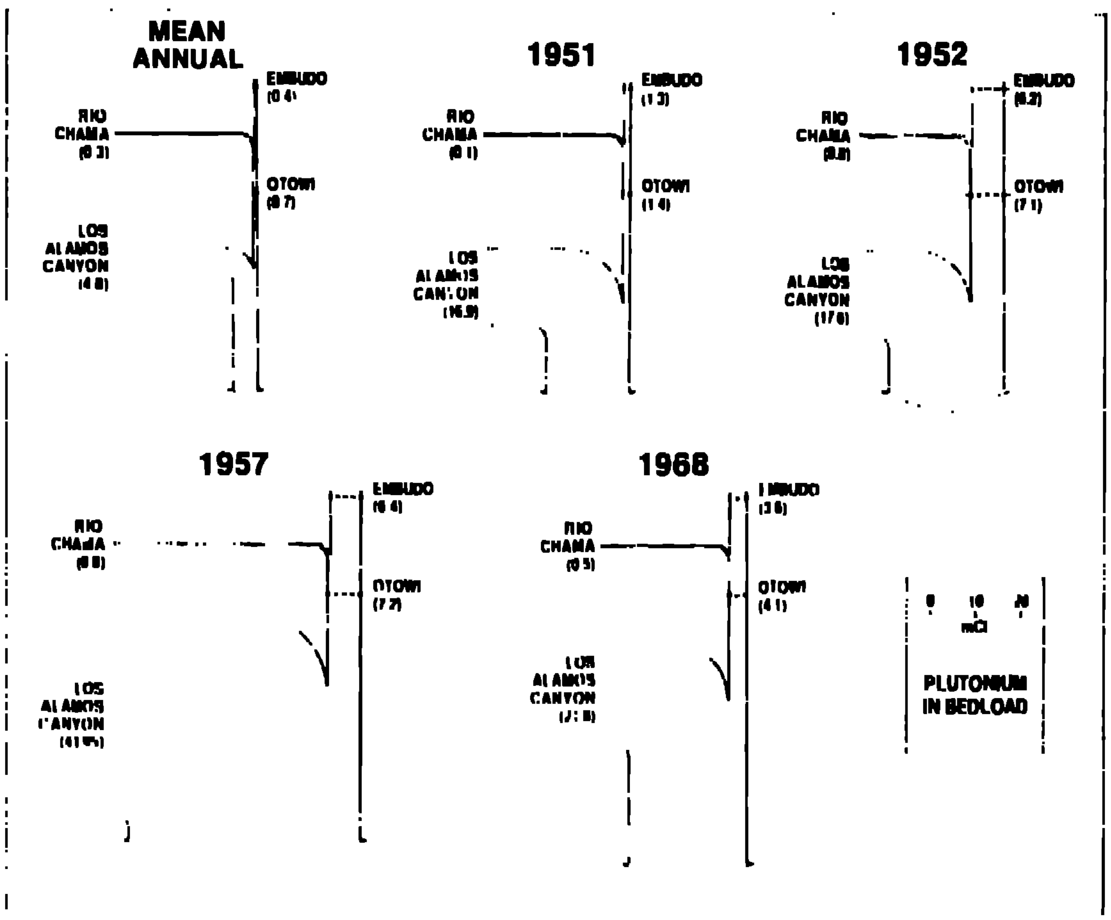


Figure 11.3 Flow diagrams showing the annual movement of total plutonium in bedload sediments in the Northern Rio Grande in the vicinity of Los Alamos.

TABLE 11.4 ESTIMATED PLUTONIUM CONCENTRATIONS IN BEDLOAD DEPOSITS FOR SPECIFIC YEARS

	Bedload			Plutonium			
Year	Otowi (Mg)	Los Alamos (Mg)	Combined Total (Mg)	Otowi (mCi)	Los Alamos (mCi)	Combined Total (mCi)	Concentration (pCi/g)
1951	130,744	8,077	138,821	1.42	16.90	18.32	0.13197
1952	649,323	5,730	655,053	7.06	17.61	24.67	0.03766
1957	661,508	14,942	676,450	7.19	43.95	51.14	0.07560
1968	373,576	12,809	386,385	4.06	21.82	25.88	0.06698
Total Mean	2,163,396	2,241	2,165,637	1.57	4.79	6.36	0.00293
Active Bedload, 1974 1986 (Purtymun, 1987)							0.01056

recommended a safe maximum limit of 30 pCi/g for thorium-230 after an accidental spill of contaminated sediments into the Puerco River.[10] This limit is three to four orders of magnitude greater than values associated with any data for plutonium in the Rio Grande system outside the boundaries of Los Alamos National Laboratory. Contributions from the laboratory are therefore probably not hazardous given our present understanding of the element, but the contributions are in recognizable amounts.

In summary, the development of a regional plutonium budget for the Northern Rio Grande produces the following generalizations:

1. Plutonium enters the system from fallout and from Los Alamos.
2. In the best estimate of processes for the 1948-1985 period, about half the plutonium that entered the system was stored along the river. The remainder moved into storage in Elephant Butte Reservoir.
3. In the total budget, fallout accounts for more than 90 percent of the plutonium in the system and Los Alamos accounts for slightly less than 10 percent.
4. The contribution of Los Alamos is mostly in bedload sediments where for four particular years the contribution is dominant.
5. Most of the Los Alamos contributions remain in storage along the river between Otowi and Peña Blanca--since 1973 their downstream progress has ended in Cochiti Reservoir.

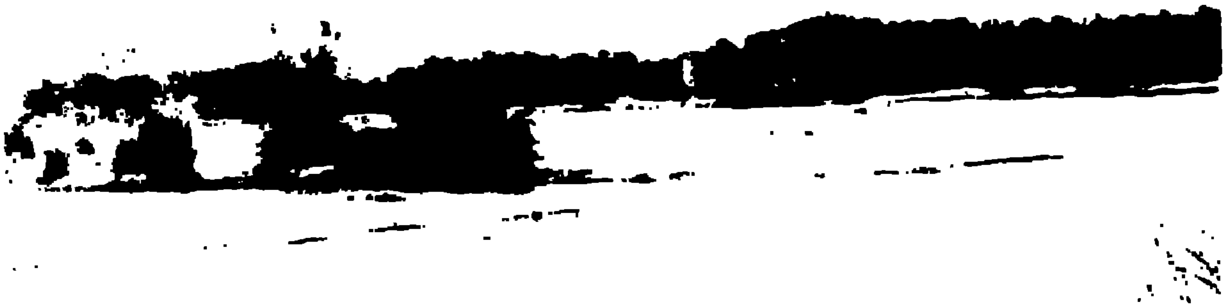


Figure 12.1. Considerable changes have occurred in the channel of the Rio Grande between Otowi Bridge and Black Mesa near San Ildefonso Pueblo. Above, looking north upstream in 1957 showing numerous, unstable sandbars, and a braided channel (F. Broeske Photo 120125, Museum of New Mexico). Below, 1981 view in the same direction but from a slightly higher perspective, showing a single, more narrow, and more stable channel than in the early view (W. L. Graf Photo 104.1.1).

PART 4. SEDIMENT AND PLUTONIUM STORAGE

CHAPTER 12. SEDIMENT AND PLUTONIUM STORAGE, SANTA CLARA TO COCHITI

12.1 Representative Reaches

The foregoing chapters demonstrated that large amounts of sediment and much of the plutonium entering the Northern Rio Grande have been stored along the river channel. A composite budget analysis defines the quantities of materials involved annually, but, except in very broad terms, it does not describe where the materials are stored. It is a matter of scale: the budget indicates the overall quantities of sediment and plutonium stored in the system, but does not reveal at a local scale where one might search for the materials. The following chapters show that the storage process has particular geographic characteristics, and that, in representative reaches, it is possible to map those deposits that were deposited during the years of maximum inputs of plutonium to the system. These critical deposits are likely to contain more plutonium than similar deposits of other years. In this way, the evidence of environmental change along the river provides a guide for determining the fate of plutonium in the system (Figure 12.1).

A sampling program for the assessment of plutonium storage along the Northern Rio Grande depends on the development of the connections among vegetation communities, fluvial landforms, sedimentary deposits, and plutonium contents. While it is not possible within the confines of the present project to completely map and interpret the entire 313 km length of river from Española to San Marcial, limited reaches can serve as representatives of larger portions of the whole. Eleven representative reaches, each about three to six km long, provide information on the entire study area because each representative reach exemplifies the conditions that obtain over a much larger portion of the total length of the river. Selection of the representative reaches began with a review of the entire river by aerial photography and then directly in the field. The river divides itself into sections based on the geomorphologic conditions as modified by engineering works. Each representative reach illustrates conditions within one larger section. For example, the Frijoles representative reach is similar to other relatively short reaches throughout White Rock Canyon. The eleven representative reaches with the geographic coordinates of their approximate center points are as follows (see Figure 12.2 for general locations shown with corresponding numbers).

1. **Santa Clara** (35° 54' N, 106° 06' W). Located between Española and a channel constriction caused by basalt flows, Rio Grande flows through a broad valley unaffected by dam construction at Cochiti and unaffected by processes in Los Alamos Canyon, a control reach for comparison with those further downstream.
2. **Otowi Bridge** (35° 52', N 106° 08' W). Reach immediately upstream from Otowi Bridge and the confluence of Los Alamos Canyon with the Rio Grande, the origin of contaminants from Los Alamos in the Northern Rio Grande system.

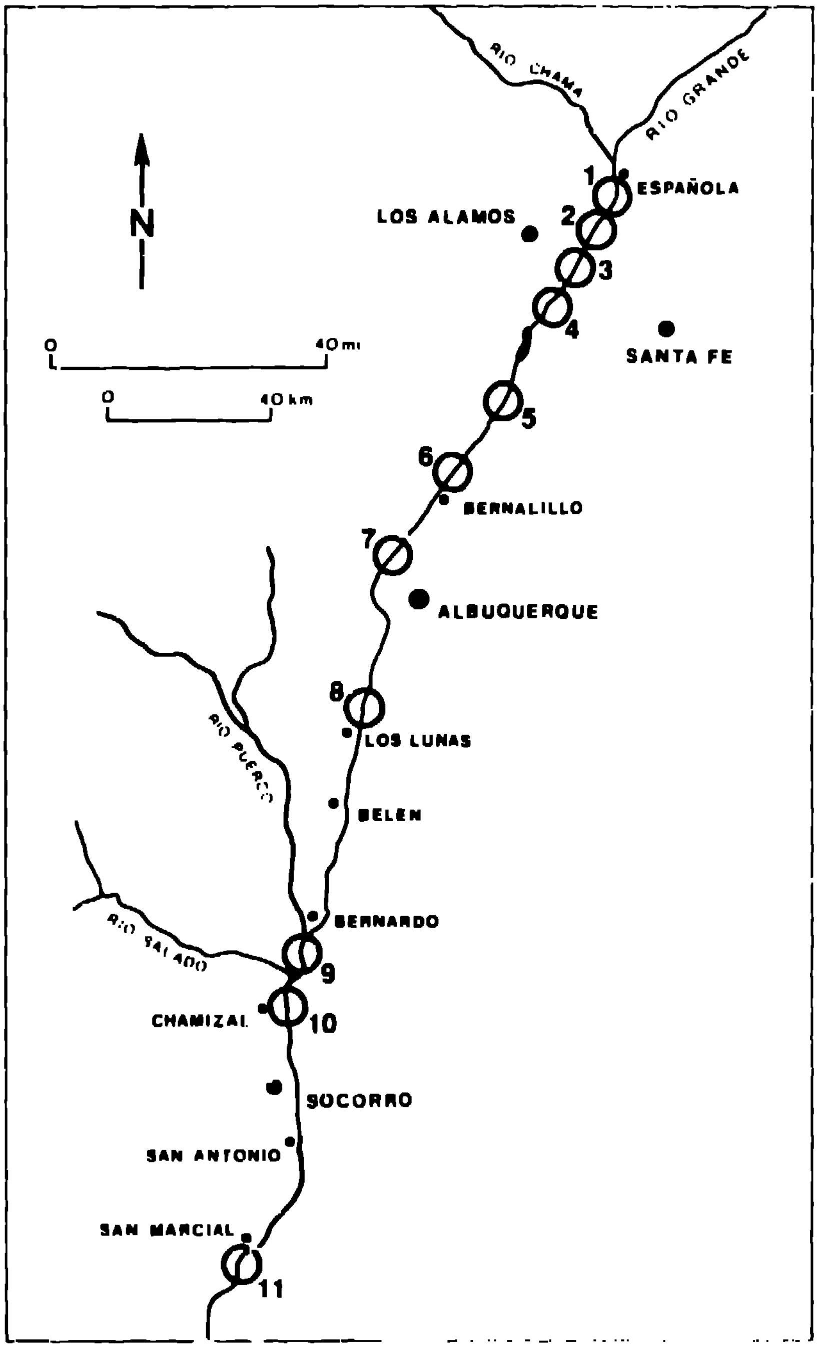


Figure 12.2 Locations of representive reaches along the Northern Rio Grande. See text for descriptions keyed to numbers on the map: 1, Santa Clara; 2, Otowi; 3, Buckman; 4, Frijoles; 5, Peña Blanca; 6, Coronado; 7, Los Griegos; 8, Los Lunas; 9, San Geronimo; 10, Chamizal; 11, San Marcial.

3. **Buckman** (35° 50' N, 106° 09' W). Deposition area in White Rock Canyon about two kilometers downstream from Otowi, a representative canyon site where some sediment storage occurs.

4. **Frijoles Canyon** (35° 45 N, 106° 15' W). Headwaters area of Cochiti Reservoir, at the edge of Bandelier National Monument, a representative canyon site where little sediment storage occurs except for reservoir backwater deposition.

5. **Peña Blanca** (35° 35' N, 106° 20' W). Reach from near Peña Blanca to Gallisteo Creek, representative of unstable reaches downstream from Cochiti Dam in a broad alluvial valley without extensive urban development.

6. **Coronado** (35° 20' N, 106° 32' W). North of Bernalillo at Ranchito, representing a partly confined channel with a levee on one side and strong tributary influences from the Jemez River and smaller streams.

7. **Los Griegos** (35° 17' N, 106° 36' W). In north Albuquerque at the Alameda Bridge, a channel confined by levees on both sides in an urban area typical of reaches in the Albuquerque area.

8. **Los Lunas** (34° 48' N, 106° 43' W). At the New Mexico Highway Route 49 Bridge, confined channel with a narrow space between the levees and an abandoned meander.

9. **San Geronimo** (34° 22' N, 106° 50' W). About ten kilometers south of Bernardo, a complex backswamp zone with the influence of an along- channel railroad embankment, downstream from the confluence with the Rio Puerco and its massive sediment load.

10. **Chamizal** (34° 14' N, 106° 55' W). Downstream from the confluence with the Rio Salado and San Acacia Diversion Dam, a wide channel area with a pilot channel and a settling basin, in an agricultural area.

11. **San Marcial** (33° 45' N, 106° 53' W). In Bosque del Apache, near Black Mesa in the backwater and delta area of Elephant Butte Reservoir with dense phreatophytes.

The purpose of examining limited, specific reaches was to identify sites for sample collection, evaluate the nature of river channel change, and to aid in the development of plutonium monitoring and surveillance programs. All these objectives must take into account the geographic and temporal variability of the fluvial environment where the plutonium is likely to be in transit or stored. Sampling for plutonium has occurred in deposits along the first three reaches, while investigation of the plutonium in deposits of the other reaches awaits further research. Plutonium concentrations in active bed sediments have been assessed in several reaches, but because the time of the sampling did not coincide with any of the critical years, these data show relatively low concentrations reflecting only small amounts of fallout plutonium in transit.

The base maps used for illustrations in the following pages are sections of U.S. Geological Survey topographic quadrangles (see Appendix F for a complete list). Often, the original topographic map shows conditions during the 1970s or early 1980s (depending on the date of aerial photography which provided the initial mapping information), but because of channel instability and construction activities, some details of the landscape had changed by the late 1980s. The locations of mid-channel sand bars and channel-side bars on the maps was correct for the year of the photography on which the maps were based, but by the late 1980s, bar configurations and locations were often different from the forms depicted by the maps.

The vegetation maps are sections from a major ecological survey completed for the U.S. Army Corps of Engineers.[1] The basic data for the vegetation communities came from aerial photographic interpretation and field surveys by Hink and Ohmart, and from further confirmatory field checks in the present project. The U.S. Geological Survey topographic outlines served as base maps for the data on vegetation communities. The maps use abbreviations for vegetation communities and community structure types as defined in the original ecological survey and summarized in Table 12.1.[2]

The vegetation maps and numerous coverages of aerial photographs from a variety of dates provided basic clues to create the geomorphologic and sedimentologic maps that also used the U.S. Geological Survey topographic outlines as base maps. Extensive field investigations, mapping, and sampling supplemented the vegetation maps in generating the final interpretations of the geomorphology and sedimentology. The geomorphology and sedimentology maps represent conditions in the 1986-1990 period.

12.2 Santa Clara Reach

The Santa Clara reach represents the Northern Rio Grande in an area not affected by the closure of Cochiti Dam and not impacted by potential inputs of plutonium from Los Alamos. The Santa Clara reach extends approximately 6 km downstream from the vicinity of the Santa Clara Pueblo to the vicinity of Black Mesa (Figures 12.3 and 12.4). The river flows through a broad alluvial valley that is up to 2 km wide and that is similar to valleys further south. During the 1920s and 1930s, the river in the Santa Clara reach was a braided channel with unstable margins and a wide, shallow, sandy channel. Places where the flow was concentrated had larger particles in the cobble size range. Maps made from 1930s aerial photographs show a braided channel several times wider than the 1990s channel.[1] A 1930s photograph showing boys from the Los Alamos Boys School swimming in the river near Black Mesa shows a flood bar of cobbles along one side of an otherwise sandy channel. The 1941 flood coursed through a broad, shallow channel, but thereafter low flows occupied a series of multiple threads across what once was a wider braided channel. The small single threads were gradually abandoned, either through slight

TABLE 12.1 VEGETATION COMMUNITY AND COMMUNITY STRUCTURE TYPES USED FOR MAPPING REPRESENTATIVE REACHES

Map Symbol	Explanation
VEGETATION COMMUNITY TYPE	
C	Cottonwood (*Populus fremontii* var. *wislinzenii*)
RO	Russian olive (*Elaeagnus angustifolia*)
SC	Salt cedar (tamarisk, *Tamarix chinesis*)
CW	Coyote willow (*Salix exigus*)
TW	Tree willow (*Salix goodingii*, *Salix Amygdaloides*)
SE	Siberian elm (*ulmus pumila*)
NMO	New Mexico Olive (*Foresteria neomexicana*)
I	Indigo bush (*Amopha fruticosa*)
SW	Seepwillow (*Baccharis salicina*)
J	Juniper (*Juniperus monosperma*)
Wb	Wolfberry (*Lycium andersonii*)
Rb	Rabbit brush (*Chrysothamnus nauseosus*)
COMMUNITY STRUCTURE TYPE	
1	Vegetation in all foliage layers, mature trees up to 20 m high, mixed age forest stands
2	Vegetation mostly in the canopy layer, mature trees up to 20 m high, sparse and patchy understory
3	Vegetation mostly in a dense layer below 10 m, intermediate age trees, with some growth extenting above 30 m
4	Open stands of intermediate age trees, most vegetation between 10 and 15 m height, widely spaced shrubs
5	Vegetation increases in density approaching ground level, most below 20 m, thich layer of grasses and annuals
6	Low and sparse herbaceous or shrub vegetation, most foliage below 2 m

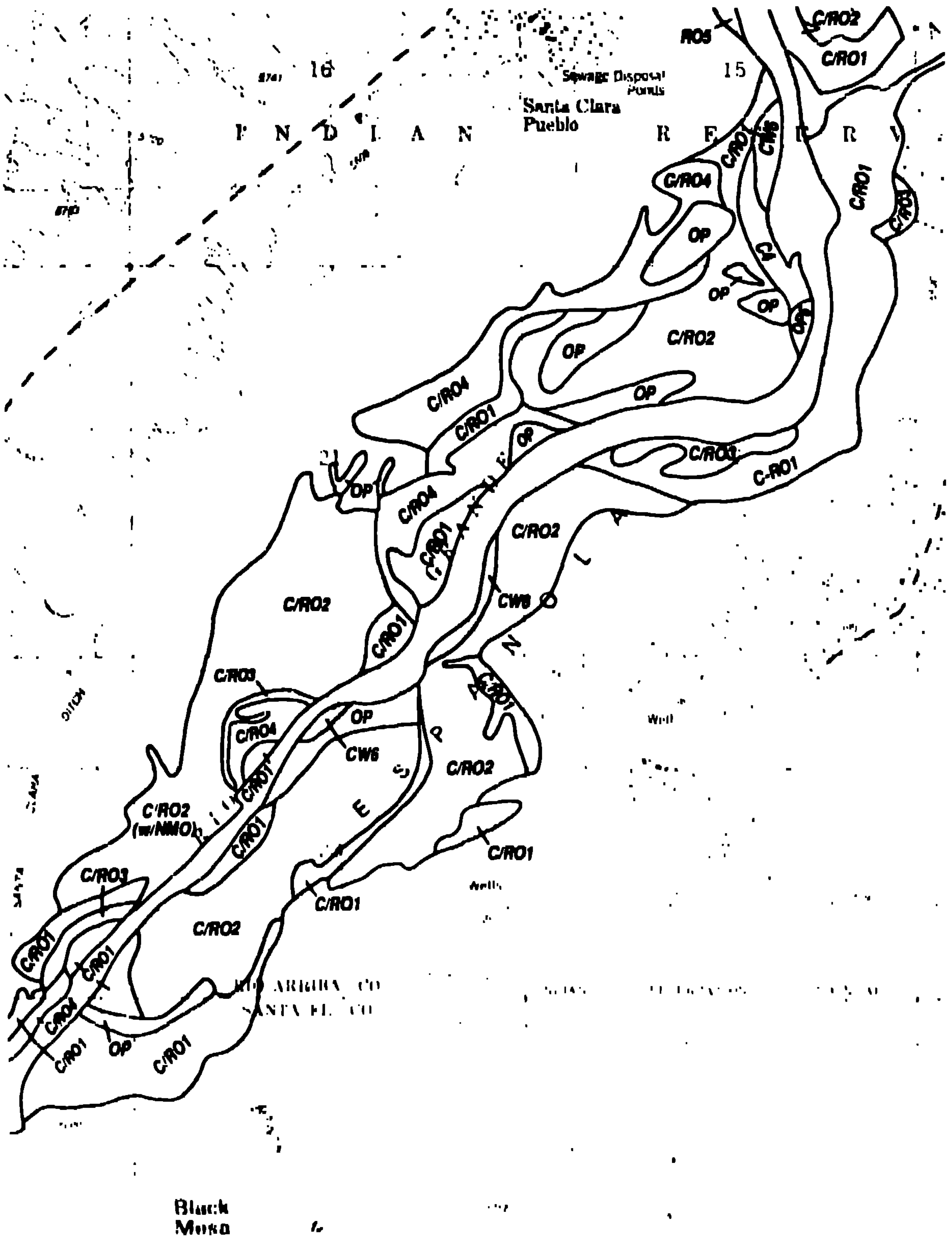


Figure 12.3 Riparian vegetation communities along the Santa Clara representative reach. See number 1 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

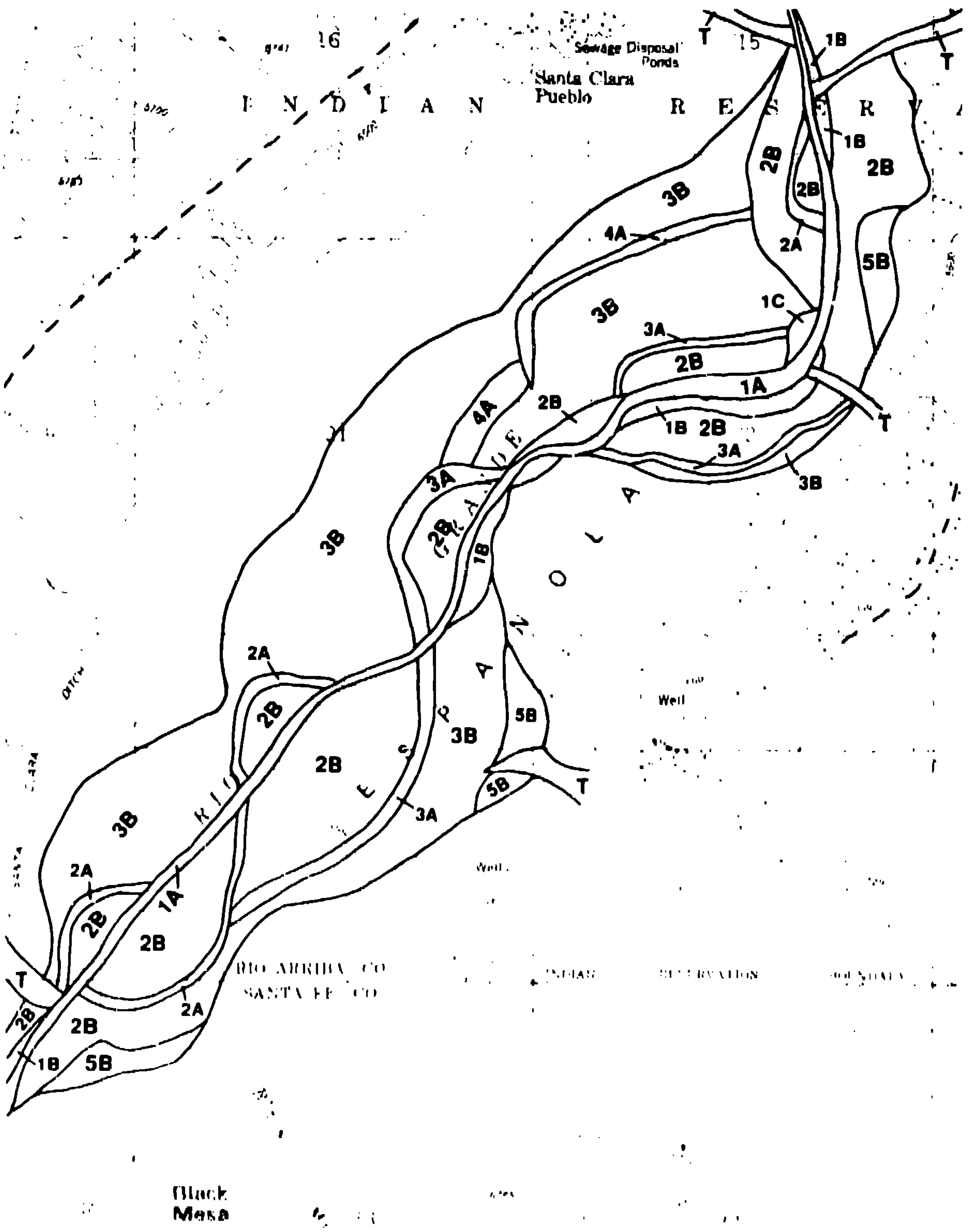


Figure 12.4 Geomorphic map of the Santa Clara representative reach. See number 1 in Figure 12.2 for location. Labeled areas on the map: 1A, Active channel, 1990; 1B, Active flood plain, 1990; 1C, Abandoned flood plain, active during the 1970s; 2A, Abandoned channel, active 1941-1968; 2B, Abandoned flood plain, active 1941-1968; 3A, Abandoned braided channel, active prior to 1941; 3B, Abandoned flood plain, active prior to 1941, 4A, Abandoned channel, active in the 1930s or earlier, older than the unit mapped as 3A and 3B; 5B, Abandoned flood plain, active in the 1920s or earlier; T, Tributary alluvial fan materials and channel fills.

entrenchment of a single channel that eventually would be the dominant one, or by filling of the small secondary channels. The 1968 flood followed the dominant channel left from this shrinkage process and defined a single channel with a pattern that was relatively straight compared to configurations that had existed previously. After 1968, changes were minor, and represented only slight modifications of the newly established, relatively straight, single channel. Flash floods in tributaries contributed minor deposits on top of the flood plains and abandoned channels of the main river.

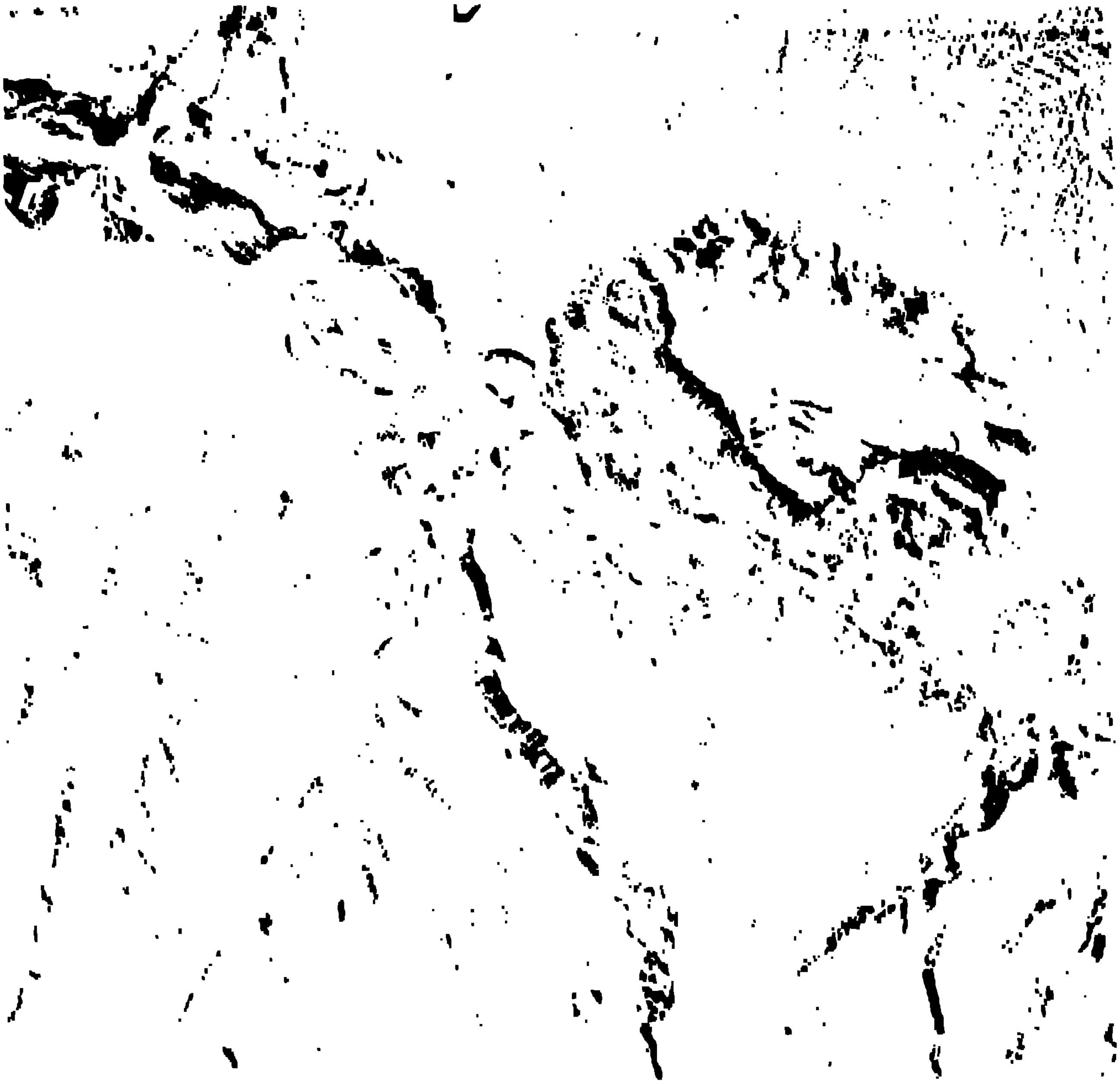
The vegetation communities in the Santa Clara reach have boundaries that often approximate the locations of the abandoned braided channels of the 1930s, the abandoned threads of the 1941-1968 system, and the flood plains of various episodes. Cottonwood and russian olive dominate most of the reach, but the community structure is highly variable from one place to another, depending on the history of the location. For example, open canopies of cottonwood and russian olive are common on the flood plains that were active in the pre-1941 period, while the same species occur in very dense stands with substantial growth close to the surface in abandoned braided and single thread channels.

The geomorphic map of the Santa Clara representative reach shows that the area has deposits from several different time periods and of several different types (Figure 12.4). The tributary deposits are coarse sands and gravels, forming fans radiating outward from the tributary mouths. Abandoned braided channels are sandy. Abandoned single thread channels are clearly defined in the field as linear depressions in the otherwise relatively flat flood plain. Sometimes the depressions are floored with a veneer of fine-grained materials. Those channels filled with fine materials and abandoned during the 1941-1968 period are likely to contain more fallout plutonium than other deposits in the reach.

Recently collected samples from the Santa Clara reach illustrate the relationship between geomorphic history and plutonium concentrations in flood plain sediments. The plutonium concentration in sediment from a flood plain that was active during the 1960s (2B at the top of Figure 12.4), a time of peak fallout loading, was 0.0266 pCi/g. The channel that was active at that time yielded sediments with a concentration of 0.0081 pCi/g (a tributary of 2A at the top of Figure 12.4). Both samples were from a portion of the near channel environment commonly referred to as "flood plain," but clearly the landform is complex as shown in Figure 12.4. Both these values exceed the concentration in sediments from the present active channel nearby, where the value was only 0.0038 pCi/g. All the plutonium in this reach is from fallout derived from erosion upstream and none is from Los Alamos.

12.3 Otowi Reach

The Otowi representative reach extends 4 km downstream on the Rio Grande into White Rock Canyon (Figure 12.5), and includes the lower 2 km of Los Alamos Canyon. The reach is significant, because it includes the point of introduction of plutonium into the main stream from Los Alamos National Laboratory. The confluence of Los Alamos Canyon and the Rio Grande has been unstable during the 1945-1988



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period. Historical ground photographs show that during the early and mid-1940s the tributary stream included a distributary channel that entered the main river north of the general location of the bridges. The highway (New Mexico Route 4) passed over a small suspension bridge that spanned the Rio Grande, and then crossed the distributary in a water-level crossing. Completion of a larger truss bridge across the Rio Grande in 1947 included filling in the distributary to provide an embankment for the roadway.

The general alignment seen in the late 1980s dates from 1947, though there have been changes of detail. For example, because the Los Alamos stream had a bend which encroached on the highway, engineering works stabilized the channel by introducing reveted banks and a cleared, artificially formed channel. In 1988 a deck bridge replaced the truss structure, though the original small suspension bridge remains as an unused crossing. These engineering activities, supplemented with levee construction and channelization on the tributary, established and then maintained the present confluence location southwest of the bridge area, though its exact configuration has changed during several floods.

The arrangement of the channel of the Rio Grande in this reach has changed relatively little between the mid-1940s and the late 1980s (Figures 12.6 and 12.7). Writers give impressionistic descriptions of the early 1940s channel in the vicinity of the house and garden of Edith Warner, who lived immediately north of the present location of the bridges.[4] Sandy banks lined with cottonwoods were common. Historical ground photographs indicate that in the 1930s and early 1940s the channel had more gravel and boulders than in the late 1980s. There has been some narrowing of the channel with deposition of sand along the margins. Significant deposition began in the 1930s along the north bank immediately downstream from the confluence with Los Alamos Canyon, and subsequent colonization of the deposits by cottonwood has resulted in three groups of mature trees (Figure 12.6). Newer sediments deposited during the 1958 and 1967 floods bury the root collars of the trees which date from the 1930s. Flood sediments from Los Alamos Canyon that were swept partly into the main channel and flood plain area provide additional recognizable deposits that have mostly russian olive as a vegetation cover, differentiating them from the older deposits (Figure 12.7). The area is a typical slack water depositional zone immediately downstream from the alluvial fan created by the Los Alamos stream.

The geomorphic map showing the late 1980s conditions suggests that the primary potential storage sites for plutonium from Los Alamos include the flood plain and terrace of Los Alamos Canyon and the slack water depositional site on the north bank of the Rio Grande immediately downstream from the confluence (12A, 1B, and 2B on Figure 12.7). These environments are most likely to have received materials from tributary floods. The meandering nature of the stream in Los Alamos Canyon has produced a series of abandoned channel courses and flood plains that are recognizable in the field from vegetation and geomorphological indicators. Sediments along the main channel at the north end of the bridge area are not be likely to yield useful plutonium information, because construction activities have disrupted the entire area several times. Deposits along the channel margin north of the bridge are likely to

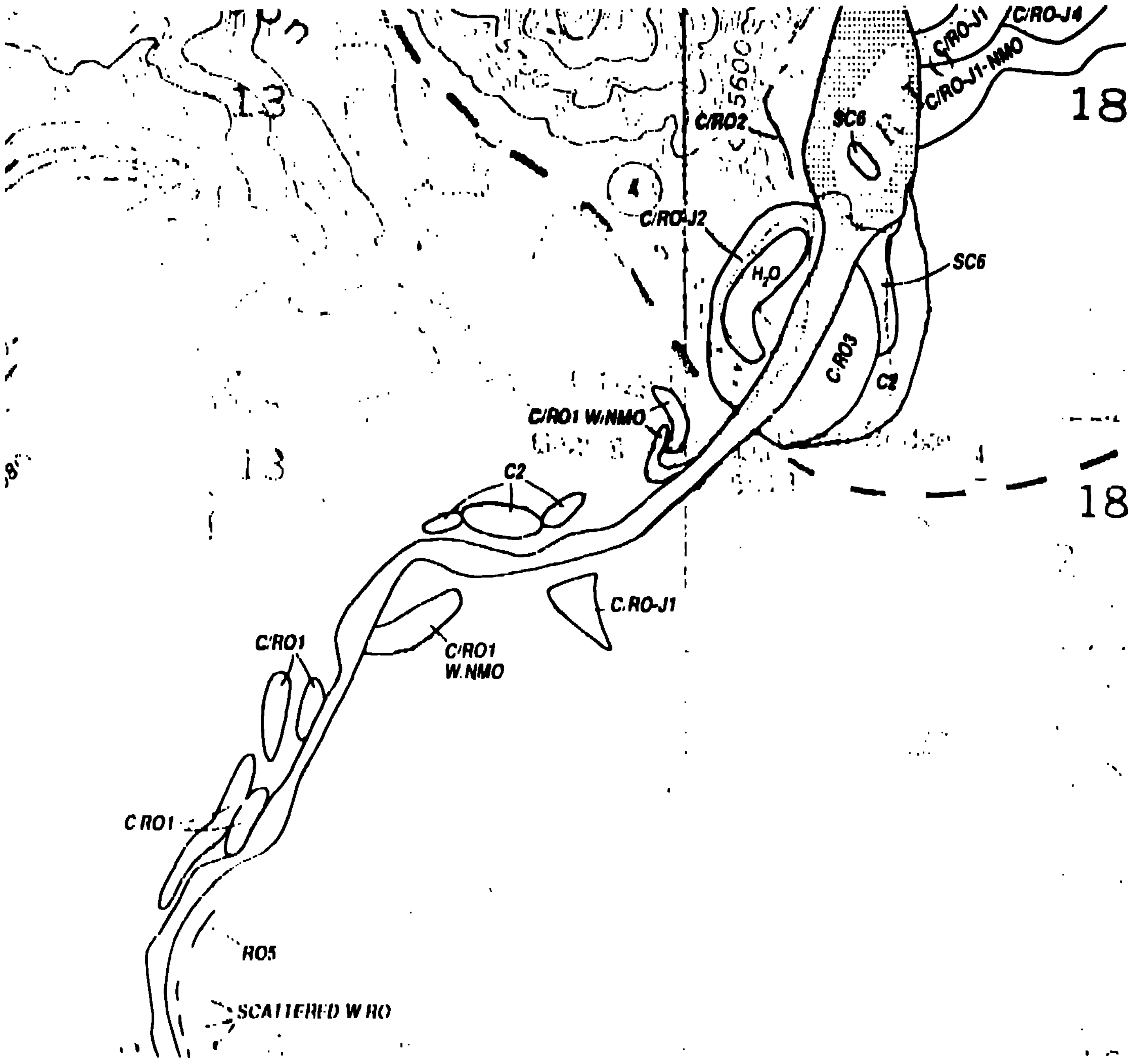

Figure 12.6 Riparian vegetation communities along the Otowi representative reach. See number 2 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

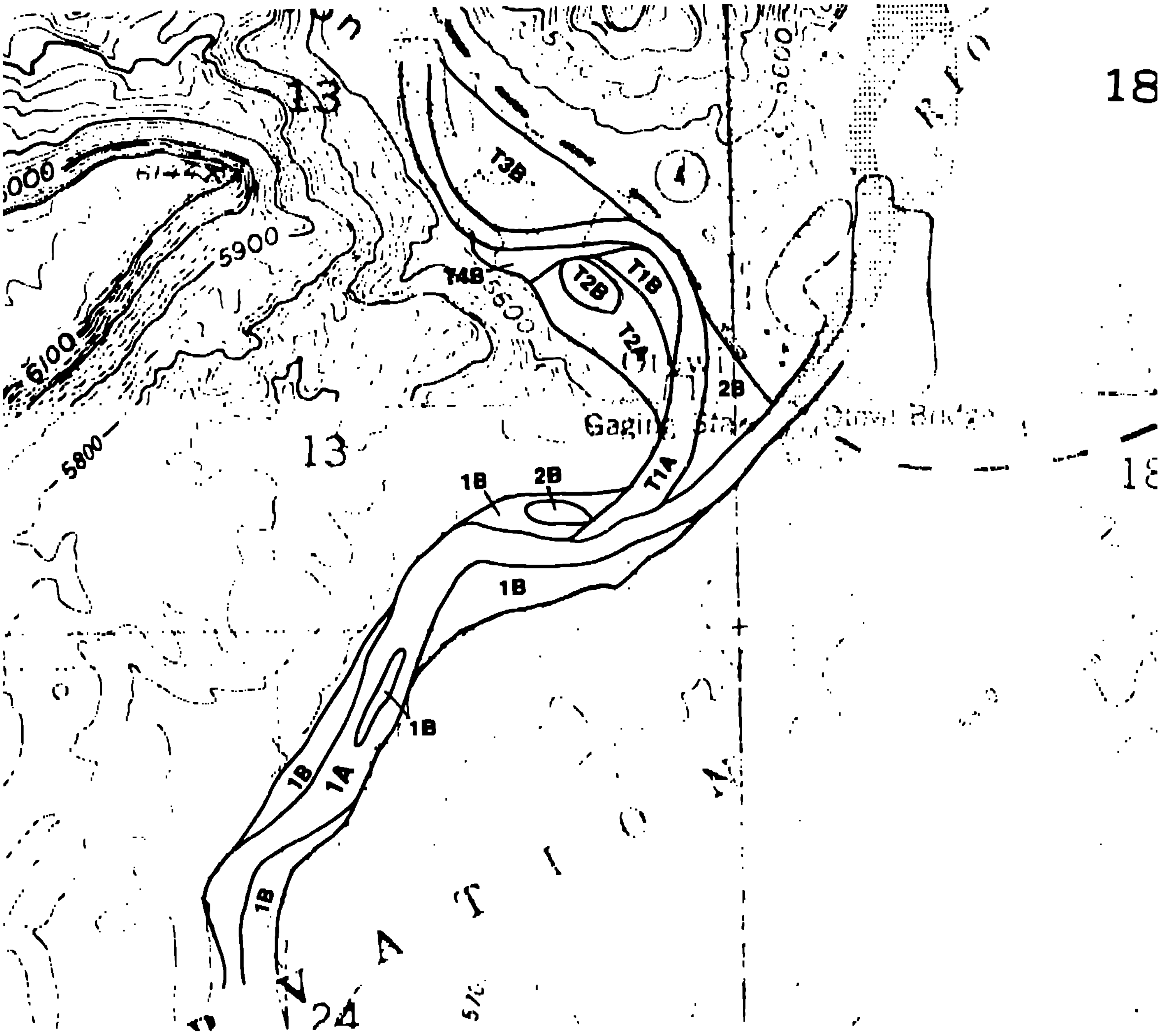

Figure 12.7 Geomorphic map of the Otowi representative reach. See number 2 in Figure 12.2 for location. Labeled areas on the map: 1A, 1981 channel of the Rio Grande; 1B, 1981 active flood plain and bar surfaces of the Rio Grande; 2B, flood plain deposited either in 1958 or 1967 flood; T1A, 1981 active channel of the tributary stream in Los Alamos Canyon; T1B, 1981 active flood plain and overflow channels of the tributary stream, active since at least 1954, and probably since 1947 when the northeast outlet of the tributary was sealed by construction related to the truss bridge, T2A, younger pre-1954 active channel; T3B, younger pre-1954 flood plain; T4B, older pre-1954 active channel; T5B, older pre-1954 flood plain.

contain only fallout plutonium since road-building closed the distributary channel from Los Alamos Canyon.

Because the Otowi reach is the entry-point into the main stream for plutonium that originates at Los Alamos National Laboratory, the laboratory has conducted extensive sediemnt sampling over a period of several years to assess plutonium concentrations. A dozen samples from almost as many years taken from active bedload in the Los Alamos stream near Otowi have revealed plutonium concentrations ranging from 0.001 to 0.528 pCi/g, with a mean value of 0.127 pCi/g. Active bedload sediments in the Rio Grande near Otowi have produced a range of 0.002 to 0.065 pCi/g from a similar number of samples. The mean concentration in the sediments from the Rio Grande was 0.011 pCi/g. A difference of means test shows that there is a significantly higher level of plutonium in the Los Alamos Canyon stream than in the main river. The main stream must quickly dillute the concentrations in sediments contributed from Los Alamos, however, because mean concentrations of plutonium in sediments in Cochiti Reservoir (probably including bedload and suspended load from the Rio Grande) are only 0.0134 pCi/g, similar to the sediments of the Rio Grande without the infusions of plutonium from Los Alamos.

12.4 Buckman Reach

The Buckman reach represents the portions of the Rio Grande that flow in canyon segments with floors up to 1 km wide. The reach extends about 5 km from Buckman Mesa, past the alluvial fan of Cañada Wash, to a bedrock restriction in White Rock Canyon (Figure 12.5, 12.8, and 12.9). The reach is located about 5 km downstream from the confluence of Los Alamos Canyon and the Rio Grande, so that sediments in the Buckman area combine inputs from the main river, Los Alamos Canyon, and two nearby tributaries. In the vicinity of Buckman, Cañada Wash (from the south) and Sandia Canyon (from the north) empty large amounts of sandy sediment into the main stream. The Rio Grande channel reflects the influence of these fans by transcribing a curving course around their bases. Buckman was a sawmill town established in 1899 on a Pleistocene terrace on the southeast side of the channel.[5] It later served as a railroad stop on the Chili Line, the narrow gauge route along the Rio Grande, with its well supplying water for steam engines.[6] The area is now uninhabited, but an active well field remains, supplying pumped water to Santa Fe.

The Rio Grande channel in the vicinity of Buckman has consistently become more narrow since at least 1912. Historical photography in the Museum of New Mexico at Santa Fe shows that before 1920, the channel was braided and spanned the 0.5 km valley floor from one terrace to the other. Sedimentation in the area caused progressive abandonment and filling of channels and attachment of bars to channel banks. In the bend of the river at Buckman, the early 1900s channel was braided. A large mid channel bar developed in the reach in the mid- and late 1920s that produced two smaller channels by splitting the main stream. The southeastern channel on the outside of the bend, next to Buckman, developed into a slough, a relatively inactive channel except for flood periods. During the 1940-1958 period the

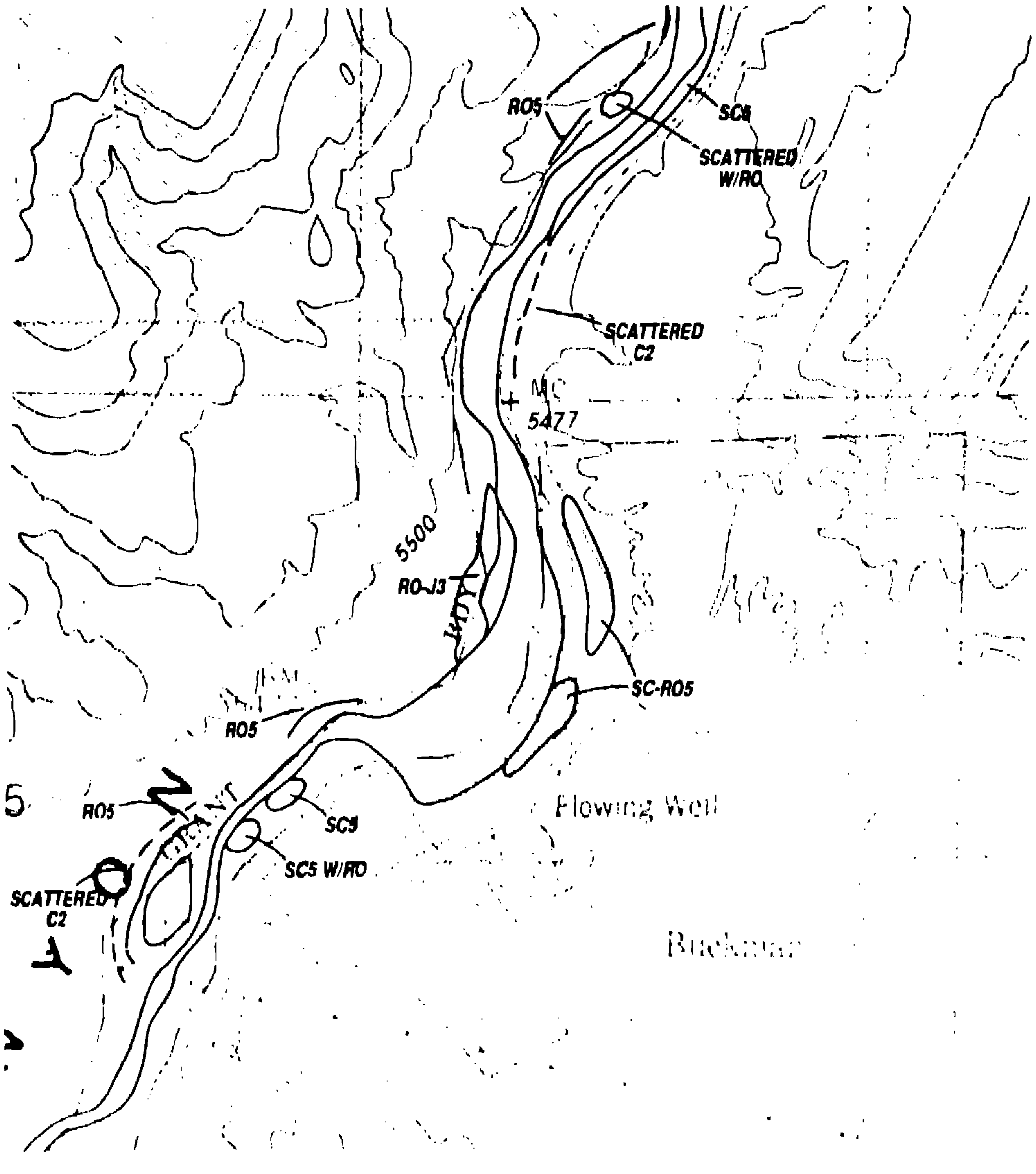

Figure 12.8 Riparian vegetation communities along the Buckman representative reach. See number 3 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

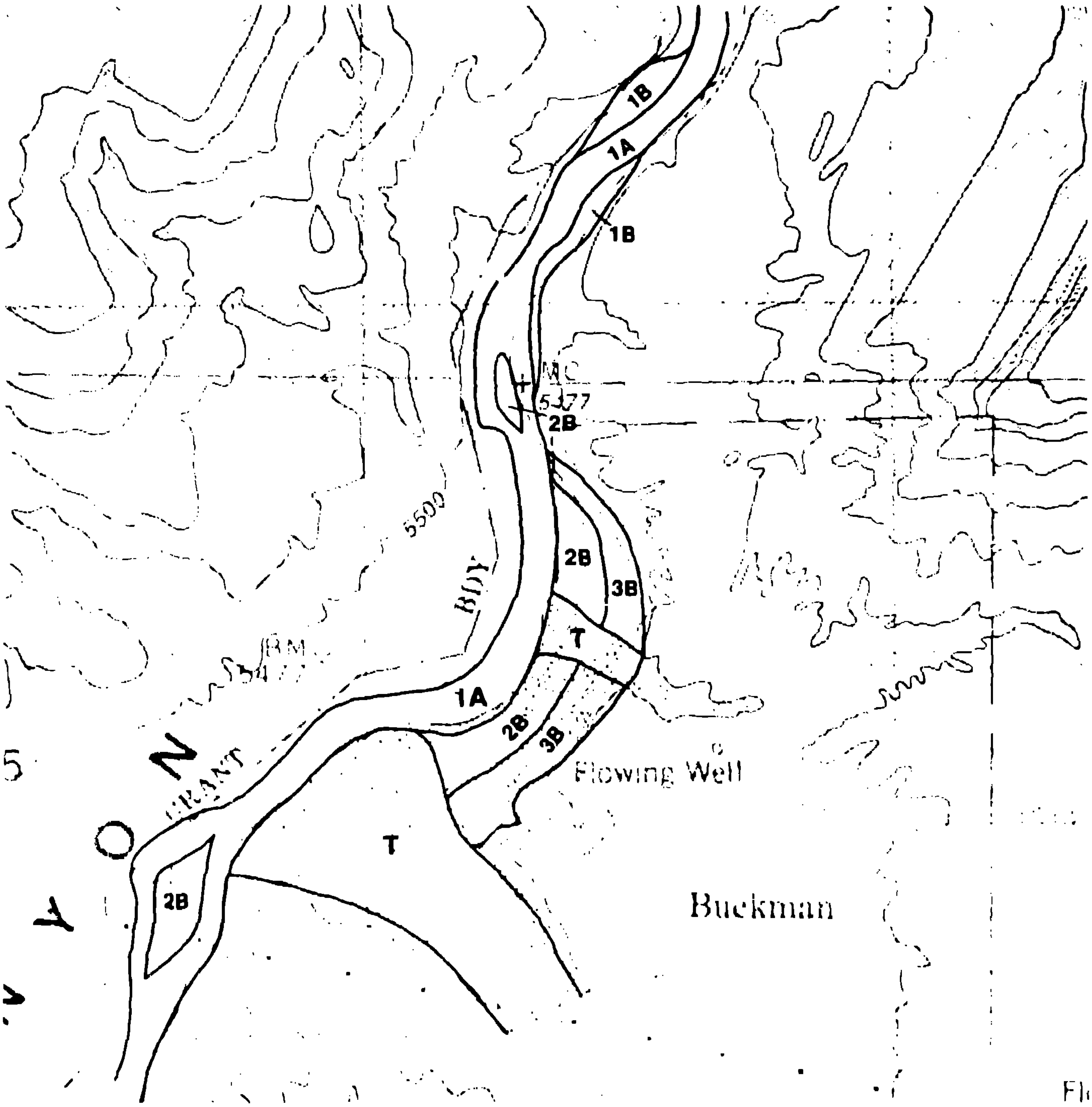

Figure 12.9 Geomorphic map of the Buckman representative reach. See number 3 in Figure 12.2 for location. Labeled areas on the map are: 1A, 1981 active channel; 1B, 1981 active flood plain; 2B, two mid-channel islands; southern-most island has existed since pre-1940s, northern-most island is a bar that detached from the east channel side between 1976 and 1981--the 2B area at Buckman is a channel overflow area that was a channel in 1912, widened in 1913 flood, and was a frequent overflow area until isolated by the 1958 or 1967 flood; 3B, pre-1912 channel location maintained as a decreasing channel until the 1958 or 1967 flood; during 1940-1958 or 1967 period it was a slough, T, tributary alluvium.

slough gradually filled with sediment, and after the 1967 flood, slack water had filled it completely with sediment. Thereafter, the Rio Grande had a single narrow channel northwest of the bar, and the bend in the river's single-thread course is now less pronounced than it was previously.

Tree vegetation in the Buckman area consists mostly of scattered individuals of cottonwood, russian olive, and juniper (Figure 12.8), but the ecological data from the early 1980s did not show the extensive tamarisk revealed in the present work.[7] Although tamarisk dominates (in percentage terms) the trees found on the two mapping units representing the old bar and slough, the tree count is radically different between the two. One unit, the abandoned slough, has two to three times as many trees as the bar area. The slough also has sediments with about twice as much fine material as the bar.

Historical information, aerial photographic evidence, and field-derived data for the vegetation and sediment permit mapping of distinct geomorphic features and associated sediment deposits in the Buckman reach (Figure 12.9). The geomorphic map outlines the slough and bar areas with sandy sediments from tributaries draped over the older Rio Grande deposits. The slough (unit 3B on Figure 12.9) is a primary site to sample for plutonium storage because it is a short distance (6-7 km) downstream from Los Alamos Canyon, and because its arrangement formed an ideal trap for fine sediments during periods when the river was likely to have been transporting plutonium from Los Alamos and from fallout. The bar, with its coarser sediments and earlier stabilization, is likely to store less plutonium.

Recent measurements of plutonium concentrations confirm that the highest concentration (0.017 pCi/g) occurs in a the slough area south of the tributary (3B in Figure 12.9). This area stored materials during the early releases from Los Alamos Canyon and from the period of maximum fallout. Mean concentrations of plutonium are about 50 percent higher in the slough than in the bar area (2B in Figure 12.9). Concentrations in presently active channel sediments (0.0027 pCi/g) are lower than those in the historical deposits, while sediments from the tributary are lowest of all (0.0008 pCi/g). Concentrations in the tributary sediments are one-fourth those in the present Rio Grande and one-eighth those of historical sediments stored in the reach.

Sedimentary deposits of the Rio Grande can be distinguished from those derived from local tributaries not influenced by Los Alamos on the basis of plutonium concentrations. However, the data from deposits at Santa Clara (unaffected by Los Alamos) and Buckman (likely to have both Los Alamos and fallout contributions) [illegible] not statistically different from each other. Thus, in this case fallout pollution and laboratory pollution cannot be distinguished from each other on the basis of plutonium concentrations alone. It is possible that isotopic ratios may serve this discriminating function. Data from Los Alamos Canyon indicates that the ratio of plutonium-239,240 to plutonium-238 in alluvium impacted by laboratory releases is about 100. The same isotopic ratio for global fallout is less than 30. Therefore, deposits derived from fallout might be expected to have isotopic ratios that are lower than ratios from deposits with pure Los Alamos plutonium or with plutonium from both sources. Data from the Santa

Clara and Buckman deposits suggest that this expected trend occurs in the Rio Grande. The mean plutonium-239,240 to plutonium-238 ratio from Santa Clara is 4.3, while at Buckman, impacted by infusions from Los Alamos, the ratio is 27.1, with one sample showing a ratio of 72.3.

A special study of isotopic ratios using the geomorphic data generated by the present work as a sampling guide, also shows that mixing of fallout and Los Alamos plutonium is occurring in flood-plain sediments. D. B. Curtis, R. E. Perrin, and D. W. Efurd investigated the ratio of plutonium-240 to plutonium-239 from three flood-plain deposits. In the flood plain at Santa Clara where presumably only fallout products occur, the 240/239 ratio is 0.120, which compares favorably with the global fallout value of 0.130. In a sample from Acid Canyon, a site directly impacted by inputs from Los Alamos, the ratio was one tenth as much, 0.013, consistent with laboratory records for material processed during the late 1940s to mid-1950s period. In a sample from the slough area at Buckman, presumably showing the mixing of plutonium from both fallout and laboratory sources, the 240/239 ratio was 0.077, mid-way between the values of samples affected by only one source. A reasonable conclusion is that plutonium in flood plains downstream from Los Alamos Canyon in White Rock Canyon include contributions from fallout and the laboratory.

12.5 Frijoles Canyon Reach

The Frijoles Canyon representative reach is typical of the confluences of large tributaries with the Rio Grande in White Rock Canyon. It is also typical of narrow canyon reaches and of those few junctions with relatively short tributaries draining plateau and canyon country west of the main stream (Figures 12.10 and 12.11). Frijoles Canyon contains a stream draining the southeastern flank of the Jemez Mountains that flows through a defile cut into the Pajarito Plateau. Quaternary Bandelier Tuff, particularly the rhyolitic Tshirege Member constitute the rocks of the tributary canyon walls and contribute sandy sediments to the stream.[8] In terms of their mineroloqy, these materials are distinctly different from the sediments of the Rio Grande. The tributary materials have accumulated in a large alluvial fan at the junction of the tributary and the main stream (Figure 12.11). The Rio Grande has a single-thread channel largely confined by the resistant older basalt of the Santa Fe Group in the walls of White Rock Canyon. Fluvial deposits are not voluminous along the channel, and consist only of scattered terrace remnants and limited active channel deposits.

The Frijoles Canyon Reach also represents the upstream slack water area of Cochiti Reservoir. Although Cochiti Dam closed in 1973, high runoff periods and operations of the dam did not produce a full reservoir until the early and mid-1980s. High lake levels intruded into the Frijoles Canyon reach for extensive periods by 1985 and with water depths of about 15 m in the area, so that Rio Grande flows deposited materials in the reach by lacustrine processes. Sedimentation during the high lake water periods draped 1.0-1.5 m of lake sediment over the fluvial materials from the main stream and the alluvial fan of the tributary. In the late 1980s, the lake level declined and abandoned the reach to channel processes. The reactivated Rio Grande

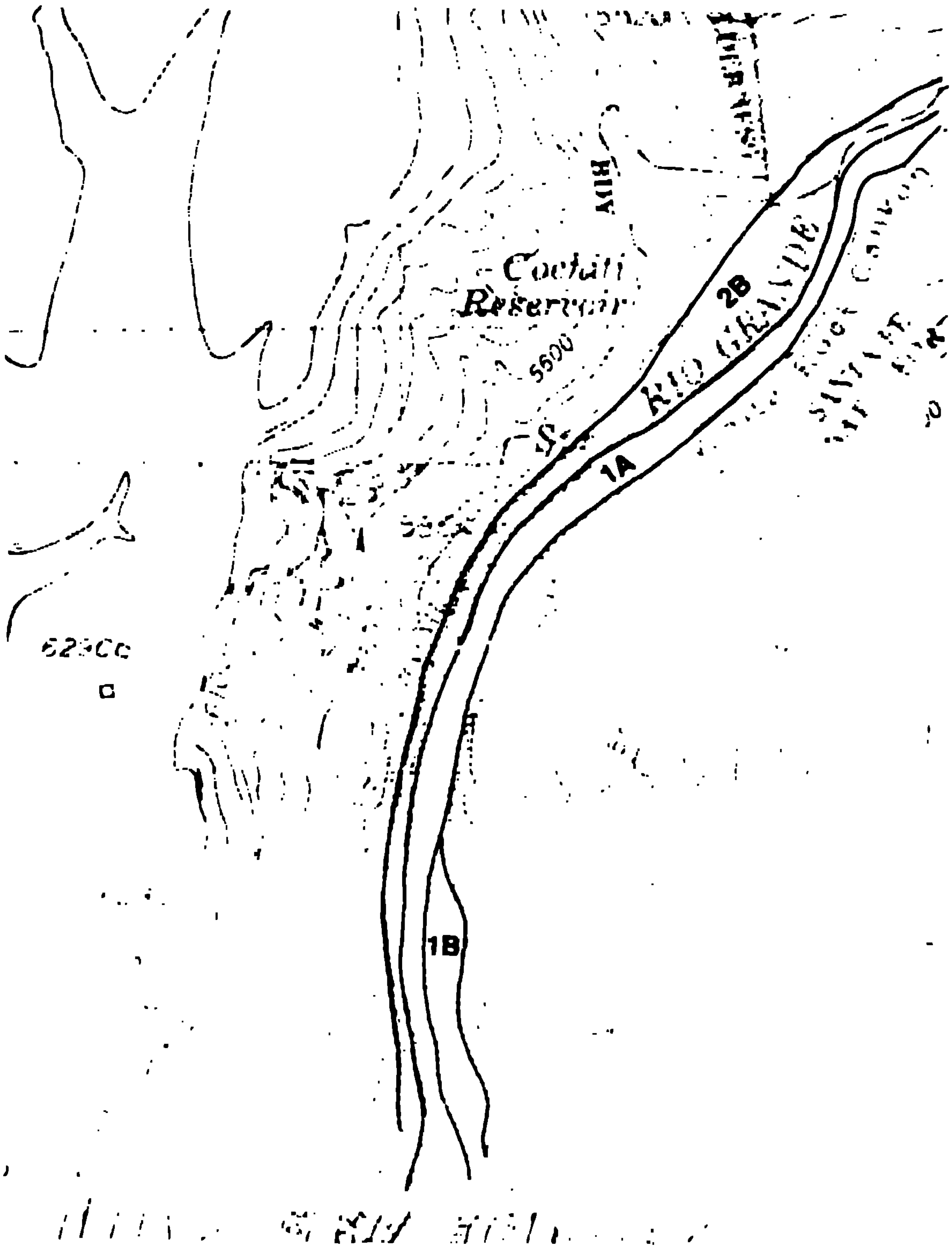

Figure 12.10 Geomorphic map of the Frijoles representative reach. See number 4 in Figure 12.2 for location. Labeled areas on the map are: 1A, 1981 active channel, 1B, younger pre-1950 flood plain, active depositon and erosion, gradual net erosion through 1981; field evidence in 1988 indicated partial burial by reservoir sedimentation in mid-1980s; 2B, older pre-1950 flood plain and alluvial fan deposits from Frijoles Canyon, field evidence in 1988 indicates partial burial by reservoir sedimentation in mid 1980s;

channel eroded a course through the lake sediments and returned to its original single-thread configuration. The channel margins exposed vertical sections of lake and fluvial sediments in 1988.

The riparian vegetation in the Frijoles Canyon reach before inundation by Cochiti Lake was mostly on the alluvial fan. The area included a cottonwood forest and considerable tamarisk growth. The 1985 inundation was deep enough and lasted long enough to kill all the trees on the fan, and by summer 1988 regrowth was minimal. Vegetation elsewhere in the reach was mostly upland species that returned after the recession of the lake waters. The distribution of riparian vegetation reflects the arrangement of pre-lake sediments and is not informative for the lacustrine materials that now dominate the surfaces of the reach.

The sediments in the reach are of three groups: the materials of the active Rio Grande channel, the sediments from the tributary, and the lake sediments. The main stream has bed sediments that are relatively coarse with less than 5 percent of their bulk as silt and clay. At the time of sample collection (summer 1988), the channel in the reach was still excavating its course into the underlying sediments, and its gradient was steeper than normal as it cut its way through accumulated materials at the head of the lake. As a result, fine materials were transported further downstream, leaving more coarse sediments behind. The sediments from Frijoles Canyon in the alluvial fan are also relatively coarse (fine materials about 7 percent). The lake sediments are very fine (40-50 percent silt and clay), representing materials that were deposited from the suspended load of the main stream as it entered the lake. The sediments from the two sources have radically different appearances, especially where channel incision has produced banks that expose them. The lake sediments form banks that are nearly vertical, probably because of their cohesive characteristics derived from the high content of fine particles. Sandy material from Frijoles Canyon, on the other hand, does not form vertical banks along the channel of the Rio Grande. Because the sandy materials underlie the finer ones, undercutting of banks is common.

Plutonium storage in the sediments of the reach is highly variable. The total volume of stored sediments in this restricted canyon reach is small, and the tributary sediments from Frijoles Canyon are coarse and therefore unlikely to contain large amounts of fallout. The lacustrine sediments may represent a significant storage location for plutonium from fallout and possibly from Los Alamos. Recent samples of fine sediments from the middle and lower portions of Cochiti Reservoir show concentrations of plutonium 238 and plutonium 239,240 (combined concentraton of 0.0134 pCi/g) higher than most other soil and sediment samples.[9] It is likely that the sediments exposed along the river in the Frijoles Canyon reach also contain higher than average levels. The ratio of plutonium 239,240 to plutonium 238 is 20-25, similar to the ratio for world wide fallout, indicating that the plutonium in the sediments is likely to have come from the Rio Grande watershed. The only exception is a sample collected in the upper reservoir area in 1987 when high water extended into the Frijoles Canyon reach. The plutonium ratio for the sample was 85,[10] similar to ratios earlier recorded in lower Los Alamos Canyon.[11] The plutonium in sediments deposited near the head of the delta during the high lake stand was therefore derived from runoff from the Los Alamos area.

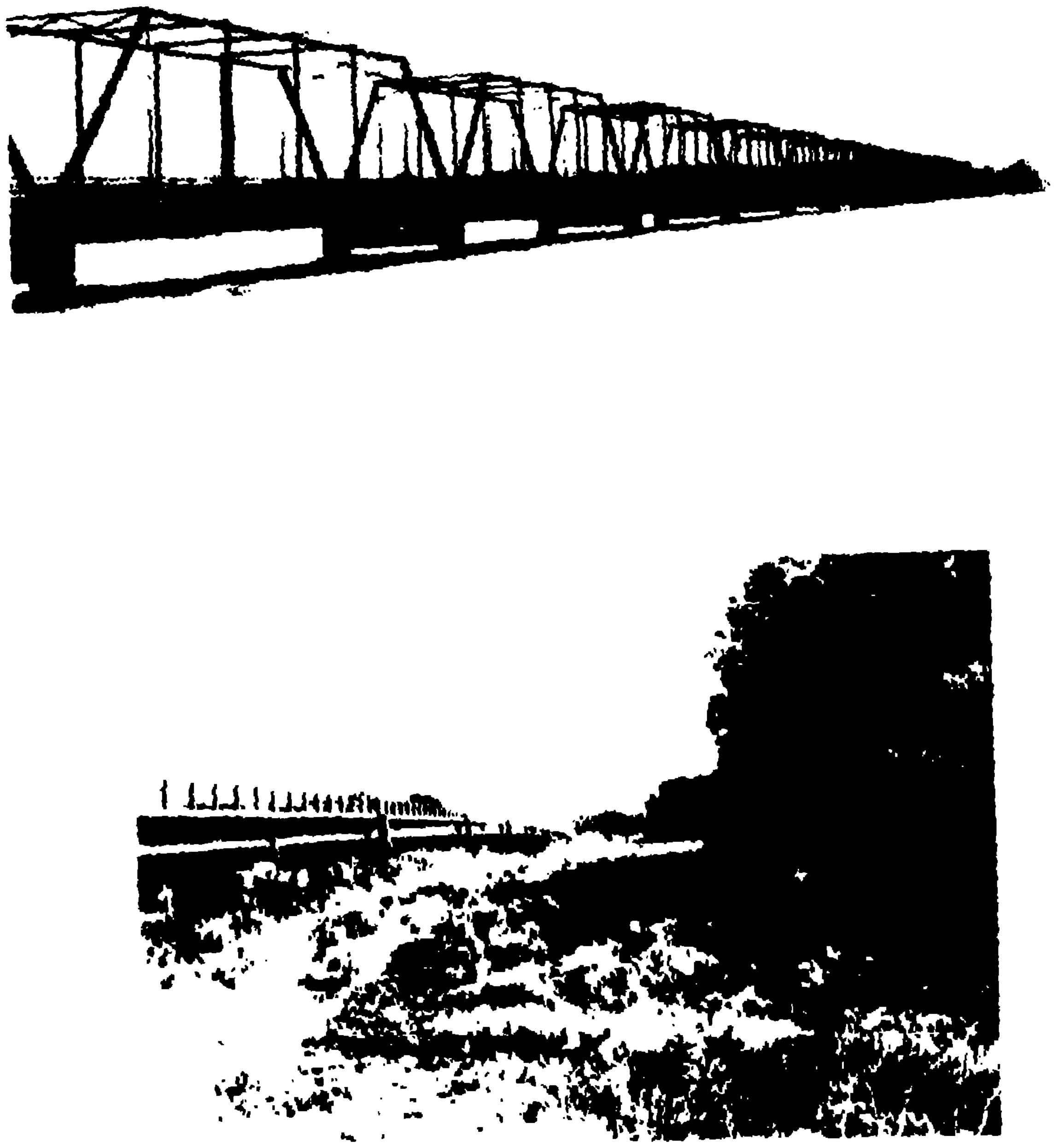

Figure 13.1 The Rio Grande has become progressively more narrow in the vicinity of Albuquerque during the past century. Above, view looking east across the stream at the Old Town Bridge about 1895 showing a broad channel in flood (Photographer unknown, Colorado State Historical Society Photo J 78041 4623). Below, same view showing a modern bridge over a considerably smaller channel in 1989 (W. L. Graf Photo 77-13)

CHAPTER 13. SEDIMENT AND PLUTONIUM STORAGE NEAR ALBUQUERQUE

13.1 Peña Blanca

Downstream from White Rock Canyon and the reaches discussed in the previous chapter, the Rio Grande takes on a different character because of the presence of Cochiti Dam at the lower end of the canyon. From that point downstream, the river's present appearence and behavior reflect the influence of the dam which was closed in 1973. Although the channel has become more narrow thorughout the length of the Rio Grande after the 1930s, the change is most pronounced south of Cochiti Dam.

The Peña Blanca reach, a 5 km channel section, represents conditions common along 40 km of the Northern Rio Grande between Cochiti Pueblo (site of Cochiti Dam) and the confluence with the Jemez River. The river passes Peña Blanca, a settlement based on irrigated agriculture dating from the early nineteenth century. The reach is typical of the conditions in a portion of the river where the flood plain is several times the width of the channel (Figures 13.2 and 13.3), and where the channel has been exceedingly unstable. The reach is also instructive concerning the results of levee construction (in 1953) and dam closure (in 1973).

Channel behavior in the Peña Blanca reach between the early 1940s and about 1990 has consistently included locational instability and progressive adjustment from a broad braided configuration to a narrow, more straight alignment. In the 1940s, the channel was broad and unstable, with numerous major and minor threads, but gradual reduction in water yield and radical reduction in the annual flood peaks resulted in the progressive isolation and closure of secondary channels. Certainly the installation of Cochiti Dam accelerated those changes, but they were already well established before the dam. The product of the changes is a single remaining channel with many abandoned channels and flood plain deposits on both sides. Present vegetation patterns are complex reflections of this complicated history (Figure 13.3).

The most critical time in the channel evolution was the low flood period about 1955 which caused the closure and abandonment of many of the secondary channels in the reach (see Figure 4.6 for the flood history). Immediately west of Peña Blanca, for example, a sinuous channel and associated flood plain displayed a prominent westward loop (4A in Figure 13.3). After 1955 this loop was no longer active, and overbank flows from the active main channel filled the inactive loop with fine sediment. Similar wider segments of abandoned braided channel occur along the eastern side of the present channel throughout the reach (3A on Figure 13.3).

Between about 1955 and the 1967 spring flood, the channel pattern resembled later arrangements, except that it was wider and occupied a different alignment. After the 1967 flood, the alignment remained relatively unchanging, though the channel became more narrow, partly as a result of reduced outflows from Cochiti Dam. Erosion of the channel bed by relatively sediment-free flows from the dam after 1973 has probably contributed to its locational stability.

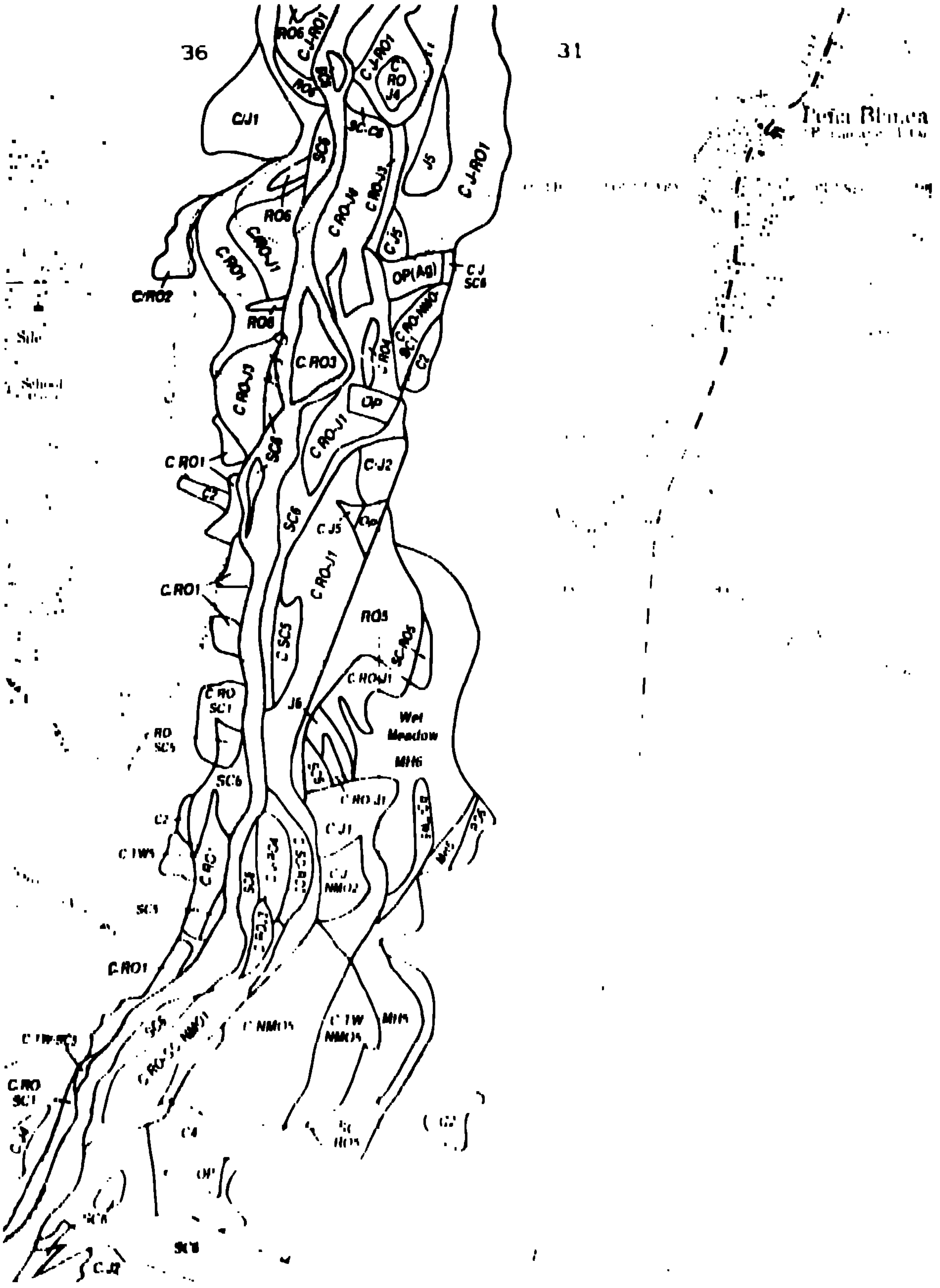

Figure 13.2 Riparian vegetation communities along the Peña Blanca representative reach. See number 5 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

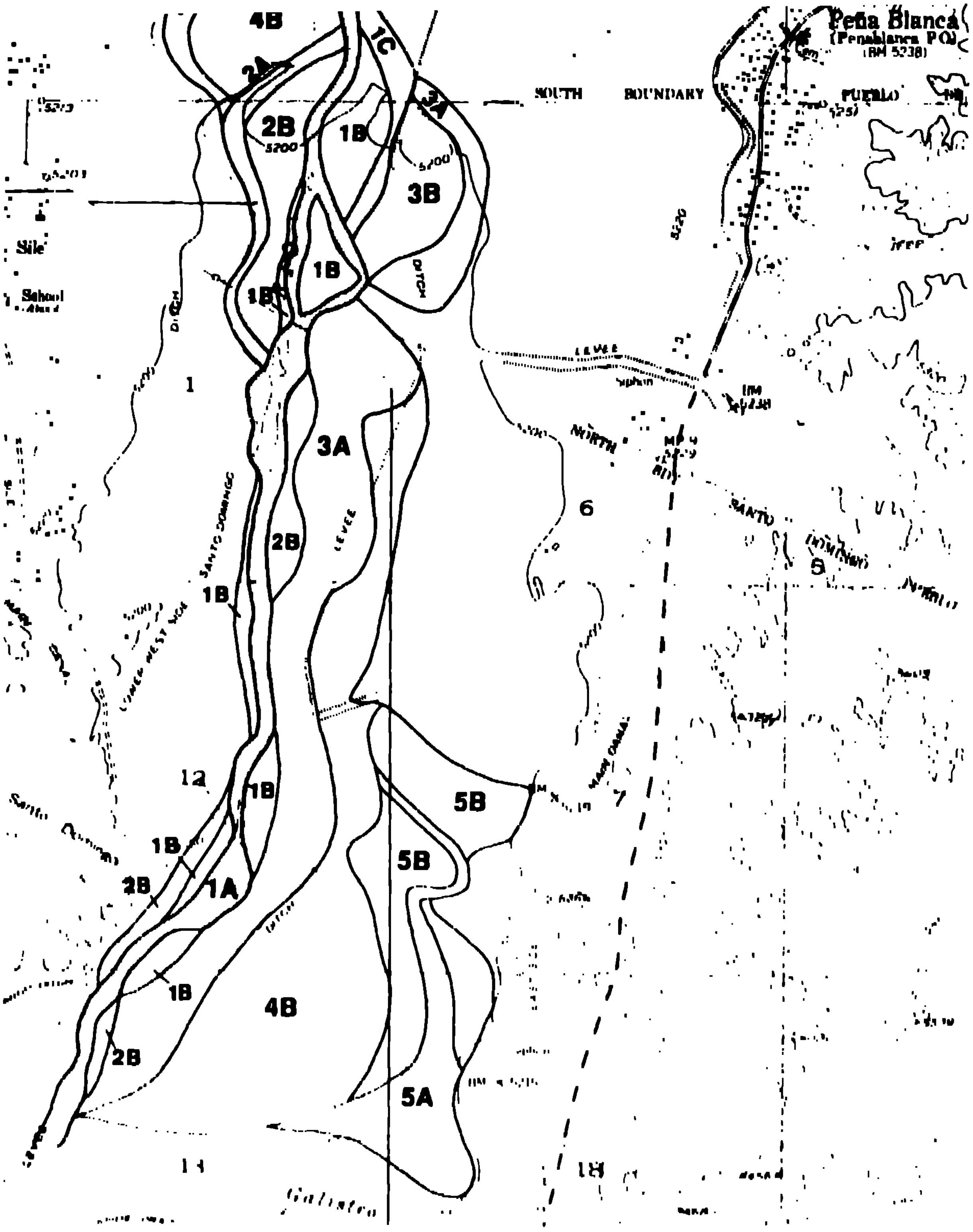

Figure 13.3 Geomorphic map of the Peña Blanca representative reach. See number 5 in Figure 12.2 for location. Labeled areas on the map are: 1A, 1982 active channel; 1B, 1982 active flood plain; 1C, 1975 - 1980(?) channel; 2A, 1954-1967 channel, closed by 1967 flood; 2B, 1954 1967 flood plain; 3A, mid 1940s-1955 channel, 3B, mid 1940s 1955 flood plain, 4A, 1941-1955 channel; 4B, 1941 1955 flood plain (includes older area cutoff by dike on the east side of the channel system), 5A, pre 1940 channel; 5B, pre 1940 flood plain.

Riparian vegetation in the Peña Blanca reach is primarily cottonwood (Figure 13.2). The flood plains once associated with the abandoned channel areas are distinctive because they contain significant amounts of tamarisk (up to 74 percent of the trees) which favors the fine-grained soils on these forms. The vegetation communities and clear topographic expression of the abandoned channels as minor troughs 1.0-1.5 m deep permits field differentiation of channels and the planar surfaces of flood plains. Sediment characteristics of the two forms are highly variable. The amount of fine sediments in the abandoned channels and flood plains that date from the 1941-1955 period is similar, about 20-25 percent silt and clay. Pre-1940 flood-plain sediments are much finer with about 40-60 percent silt and clay.

Plutonium in the Peña Blanca reach is likely to be associated with abandoned flood plains and channels that were active during the 1941-1967 period that was coincidental with three of the four years of maximum plutonium discharge from Los Alamos Canyon (1951, 1952, and 1967). These features (3A, 3B, 4A, and 4B on Figure 13.3) are highly variable in terms of their content of fine materials, and further field sampling is required to define the locations of concentrated fine materials. Flood plains that received overbank flows and abandoned sloughs that were active during the 1960s (such as the loop west of Peña Blanca) are likely locations for future exploratory sampling

13.2 Coronado

The Coronado reach represents an example of the Northern Rio Grande significantly influenced by a major tributary (Figures 13.4 and 13.5). In this reach, inputs from the Jemez River contribute large amounts of sediment to the main stream, producing a pronounced widening of the flood plain below the confluence. The modern active channel is only about 100-125 m wide, but the flood plain spans more than 2 km between terraces on either side. The reach also exemplifies the complicating factor of levee construction that substantially restricts the available space for channel relocations. Conditions in the 5 km reach are typical of 25 km section of the main stream from the Jemez through Bernalillo to Albuquerque. Near Bernalillo, the river passes Coronado State Monument, the location of an outpost established by Coronado in 1540 among the ruins of Kuau, the northern most Tiwa village

The main channel of the Rio Grande in the Coronado reach has responded to flood events on the main stream and in the watershed of the Jemez River. From the mid 1940s until the early 1960s its configuration was intricately braided and highly unstable because of periodic inputs of water and sediment from the tributary. During this period, the gradual channel narrowing observed in the Peña Blanca reach immediately upstream occurred in the Coronado reach, but large floods in 1945, 1946, 1950, 1951, and 1958 in the Jemez River interrupted the general trend. Between 1955 and 1962 a narrow looping overflow channel existed on the west side of the river south of Canjilon Hill, and between the loop and the channel was a braided channel area. Both forms were products of highly fluctuating discharges and high sediment loads

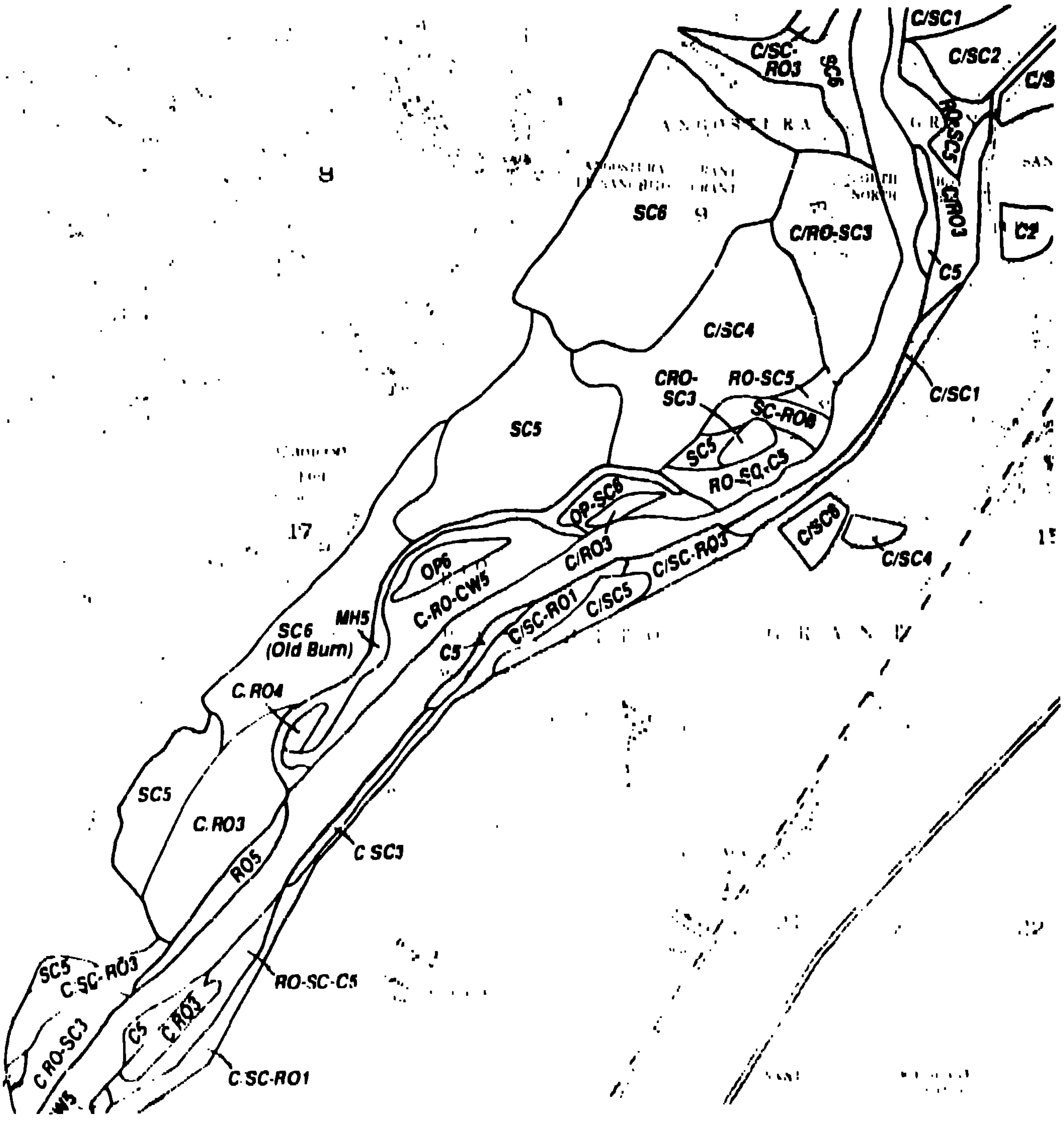

Figure 13.4 Riparian vegetation communities along the Coronado representative reach. See number 6 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

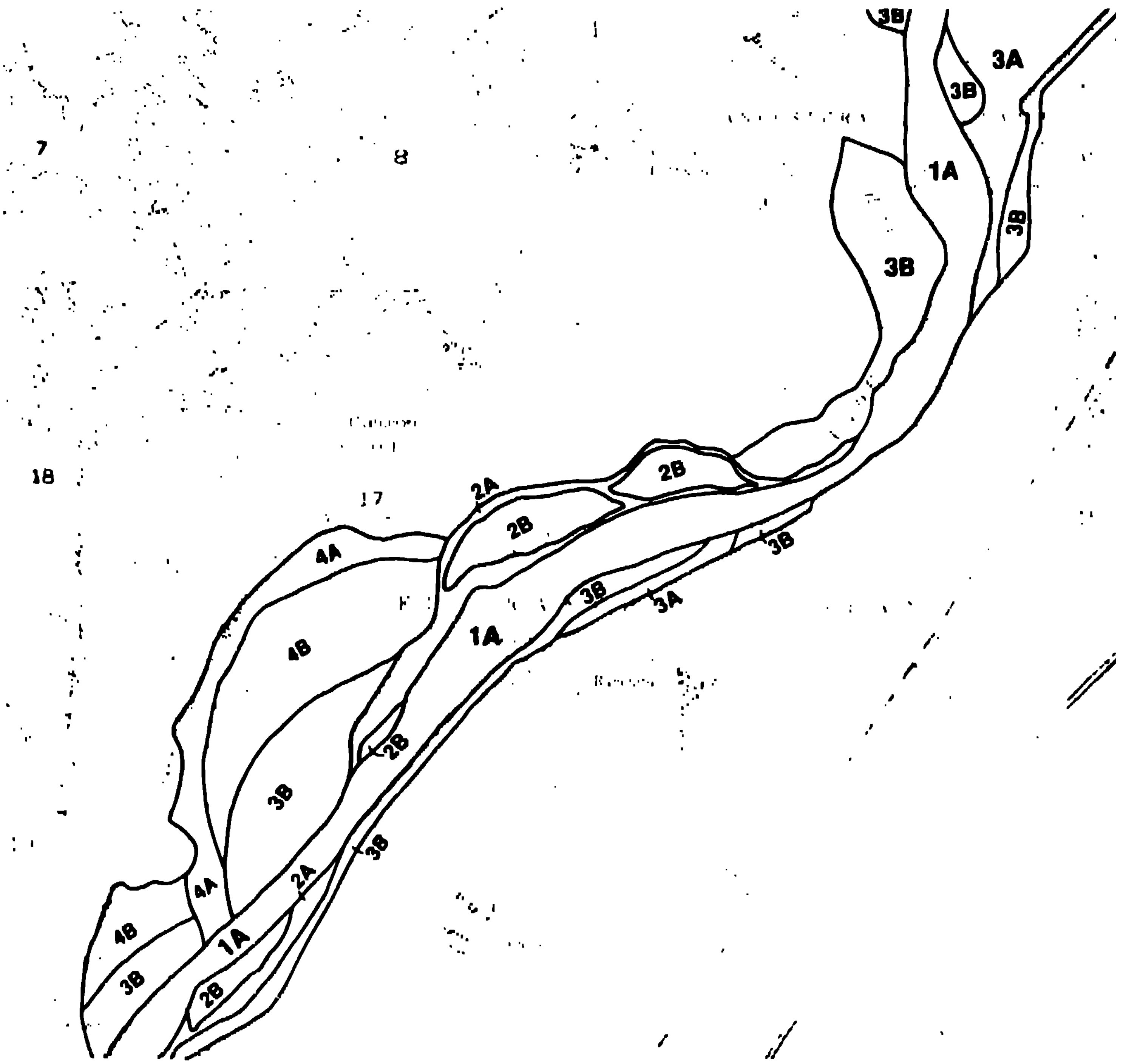

Figure 13.5 Geomorphic map of the Coronado representative reach See number 6 in Figure 12.2 for location. Labeled areas on the map are 1A, 1982 active channel, 2A, mid-1940s--1961 channel; east of Canjilon Hill, dates of activity are mid-1940s--1952, 2B, mid-1940s--1961 flood plain; east of Canjilon Hill, dates are mid-1940s--1952; active lateral accretion in early 1980s near Rivajana; 3A, mid-1940s--1961 channel; at Jemez River, flood plain that was active in late 1940s, perhaps as a result of flooding on the Jemez; 3B, pre-1940s - early 1940s braided channel; at Jemez River active in late 1940s; 4A, 1955-1961 Overflow channel; 4B, 1955-1961 Braided channel, site of flood control fences established shortly before 1961.

The 1952 closure of Jemez Dam on the tributary contributed to the stability of the reach by reducing flood magnitudes and sediment input to the main stream. The Corps of Engineers installed an extensive series of Kellner jack systems in the braided channel areas of the reach and established a narrow, relatively straight pilot channel through the reach. The agency also completed an extensive levee on the east side of the river in late 1961 that restricted channel mobility and isolated some of the flood plain from active channel processes.

Cottonwood and willow are common on older flood plains of the reach, but the dominant riparian vegetation in the area is tamarisk (Figure 13.4). Dense thickets of tamarisk (up to 77 percent of the trees) now occupy the areas of braided channel where the Kellner jacks stabilize the once active braided channel. Russian olive outlines the margins of presently active channels and some that were recently abandoned. The present vegetation distribution strongly reflects the geomorphologic changes, with vegetation boundaries clearly outlining the abandoned channel system. The abandoned braided channels have dense tamarisk growth, while the single-thread channels have almost no tamarisk but substantial amounts of willow. In 1953 clearing operations removed tamarisk from extensive areas, but the species quickly reestablished itself, and the clearing left no lasting impact on the vegetation communities.

Sediments in the Coronado reach are not as variable as in some other reaches. The active channel sediments contain about 36 percent silt and clay, a typical value for most of the Northern Rio Grande. Abandoned braided channels (3B and 4B in Figure 13.5) have less fine material (about 22 percent silt and clay), a tendency observed on the surface and at various depths below the surface down to 90 cm. Flood-plain materials (2B in Figure 13.5) are different: at the surface they contain more fines than the channel (about 52 percent). Subsurface investigations show a typical "fining upward sequence" whereby the materials become progressively finer approaching the surface.[1] In the Coronado reach samples collected 90 cm below one example flood plain surface contained only 5 percent silt and clay, while at the surface in the same location, the fines were 44 percent of the bulk sample (see data in Appendix C1).

The geomorphologic map of the Coronado reach, constructed with evidence from aerial photography and field data for vegetation, sediment, and surface forms, shows an active channel of variable width with a narrow strip of abandoned surfaces on the southeast side and a much wider zone of abandoned deposits on the northwest side (Figure 13.5). Plutonium may occur in the abandoned overflow channel that formed a loop south of Canjilon Hill (4A on Figure 13.5), because the loop was active during the late 1950s and early 1960s. It experienced gradual deposition and plugging with sediments that may have included plutonium from fallout and from Los Alamos. However, sediment from the Jemez River is likely to have diluted plutonium concentrations in the main stream because of the large amounts of material contributed by the tributary.

On the southeast side of the river, immediately north of the settlement of Ranchito, levee construction truncated a meander of a braided channel active between the mid-1940s and 1961. A portion of the channel, an extension of 3A in Figure 13.5 north of Ranchito, now lies outside the levee and is isolated from present river processes. The site contains preserved sediments that represent conditions in the late 1950s without subsequent interference from flood events.

13.3 Los Griegos

The Los Griegos reach is representative of the state of the Northern Rio Grande in the Albuquerque area (Figures 13.6 and 13.7). Los Griegos (Spanish for "the Greeks" and named after an early family in the area) is a northern suburb of Albuquerque. The 5 km representative reach is similar to the 25 km of river through the city where levees on both sides constrain the active fluvial zone to a narrow strip 0.5 km or less in width. The reach is heavily engineered, with bridges, Kellner jack fields, pilot channels, and designed levees. As a result, fluvial processes in the reach produce features that are different from the other reaches.

From the early 1940s to the late 1980s, the channel has narrowed somewhat, and has undergone a conversion from a broad, slightly braided channel to a single thread version that exhibits a limited degree of meandering. The braided channel had a meandering configuration, but the extensive engineering efforts completed in 1960 produced a partially designed channel with a relatively straight alignment. Subsequent flood events altered the planned arrangement, however, and by the late 1980s the single thread meandered in a course that crisscrossed previous paths and deposits.

The most common riparian vegetation in the Los Griegos reach is cottonwood which grows in mature stands on flood plain areas (Figure 13.6). Abandoned channels have less mature cottonwood with other species, including russian olive and tamarisk. The distribution of the communities is directly related to the fluvial history of the strip between the two levees. On the east side, south of the Alameda Bridge, for example, a narrow band of mature cottonwood forest (with cottonwood consistituting 66 percent of the trees; C2 on Figure 13.6) exactly outlines the remnant of a flood plain several decades old. A zone of juvenile cottonwood, siberian elm, willow, and tamarisk surrounds the older forest and occupies the surface of a braided channel area that was active until 1960 (C-SE-CW6 on Figure 13.6). The species composition of the communities varies dramatically from one surface type to another. One braided channel active from the early 1940s until 1954 and another active until 1960 have a variety of species not found on the old flood plain (51 percent of the trees are tamaarisk, 11 percent cottonwood, 11 percent willow, and 26 percent russian olive).

Sediments reflect the differentiation between flood plain and abandoned braided channels in the reach. The older flood plain surface materials have about 30 percent silt and clay, with a fining upward sequence from a depth of 60 cm. The braided channel, abandoned in 1960, has highly variable amounts of fine particles, with the mean value of 37 percent reflecting overbank deposition in the area after abandonment. The pre-1954 braided channel northwest of the Alameda Bridge did not experience overbank deposition, and it exhibits the relative lack of fine materials (3.8 percent) typical of a braided channel.

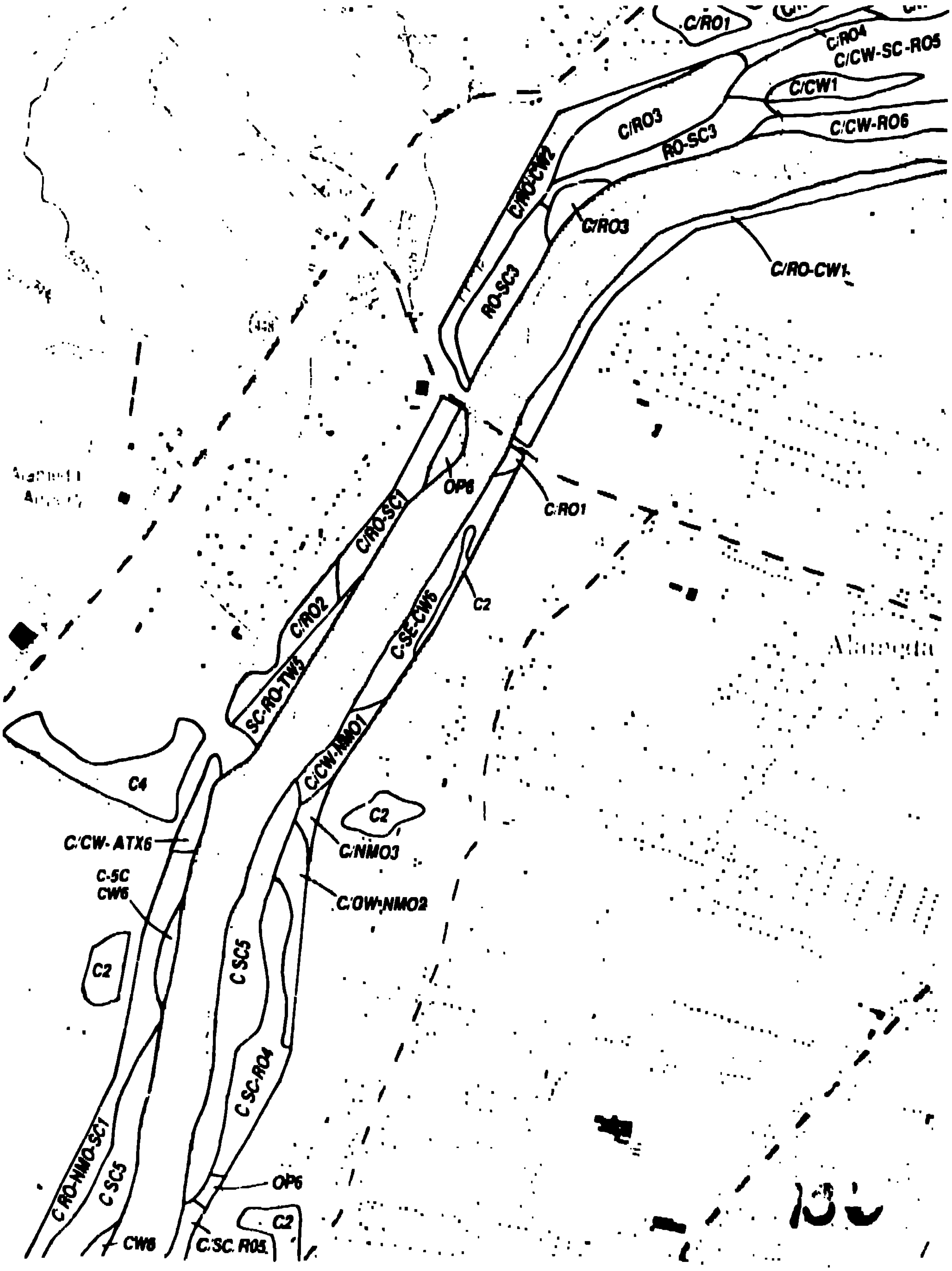

Figure 13.6 Riparian vegetation communities along the Los Griegos representative reach See number 7 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

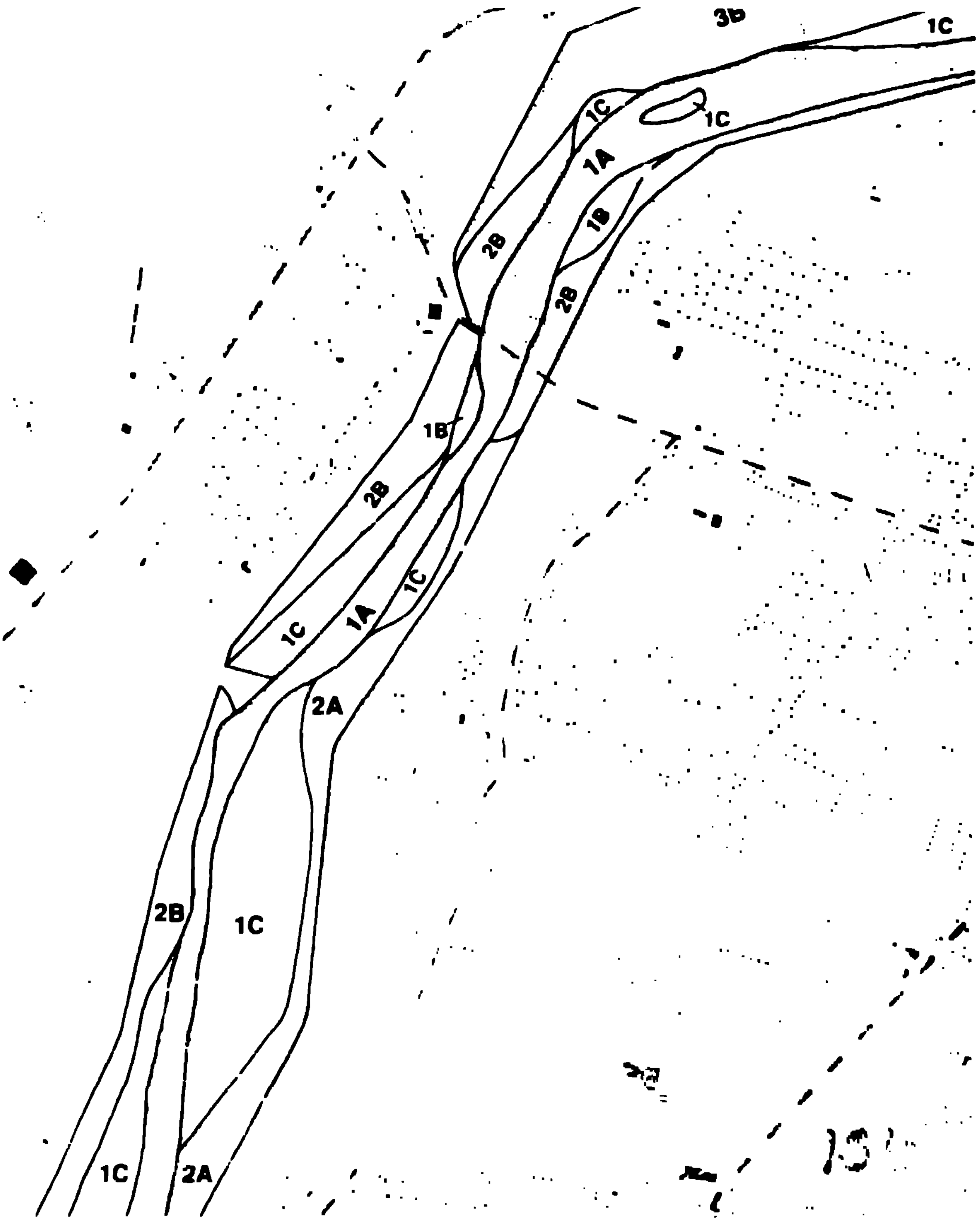

Figure 13.7 Geomorphic map of the Los Griegos representative reach. See number 7 in Figure 12.2 for location. Labeled areas on the map are 1A, 1982 active channel, 1B, 1982 active flood plain, 1C, braided channel and overflow area, pre-mid-1940s - 1960; 2A, pre mid-1940s--1960 braided channel area; 2B, pre mid-1940s--1960 flood plain, except NW of Alameda Bridge where it was a channel overflow and slough area, pre-mid-1940s--1954. 3B, pre-mid-1940s--1954 flood plain

The geomorphologic map of the Los Griegos reach (Figure 13.7) shows a suite of landforms and deposits unlikely to contain large quantities of sediment or plutonium. The constriction of the river by levees reduced depositonal areas, and though sedimentation has occurred in the area during the past several decades (resulting in local flooding), the total quantity of material is limited. Fine materials, possibly containing some plutonium, appear mostly on limited flood plains.

13.4 Los Lunas

The 5-km Los Lunas reach is representative of about 70 km of the Northern Rio Grande in the transition from urban to rural landuse along the river from south Albuquerque to Bernardo (Figures 13.8 and 13.9). Los Lunas is an agricultural settlement south of Albuquerque named after the Luna family, prominent early Hispanic settlers in Rio Grande Valley.[2] In this general segment, engineering works on both sides continue to restrict the course of the river, but the distance between the levees is greater than in the urban area. In the Albuquerque area the levees have alignments suited to the needs of the city, while downstream the levees conform to the late 1950s arrangement of the channel. At that time, the channel was braided, somewhat meandering, and included wide bends that still appear as the inherited positions of the levees. Since the late 1950s, however, the channel has shrunk because of irrigation withdrawals, decreased precipitation inputs, and the effects of upstream dams. The present channel is more straight than its predecessor, so that it crosses meandering deposits left by the earlier, more complex channel (Figure 13.9).

The consequences of this history appear northeast of the Los Lunas Bridge that carries New Mexico Route 49 across the Rio Grande, where the levee configuration includes a prominent elbow-shaped area. This bulge in the plan shape of the levee system accommodated a bend in the pre-1960 braided channel system. Subsequent narrowing and simplification of the channel to a single thread has left the elbow as an anomalous feature that then behaved as a sediment trap during floods (3A on Figure 13.9).

Mature cottonwood forest is common in the Los Lunas reach, occupying the older flood plain surfaces and braided channels that were abandoned before about 1965. On those meandering segments of abandoned channel that are not part of the present active channel, species composition differs from the flood plains by including tamarisk and willow (Figure 13.8). The newer deposits also have less mature community structures. Willow is clearly associated with finer materials of filled channels, accounting for as much as 74 percent of the trees in such areas.

The sediments in the Los Lunas reach show variation vertically and horizontally. In abandoned braided channel zones, sediments are coarse with 5 percent or less as silt and clay In abandoned flood plain zones, the fines constitute an average of 50 percent of the materials. In the elbow area described above, the surface sediments are fine (54 percent silt and clay) because of the slack water overbank deposition in the area during flood periods in the last 20 years Subsurface samples, however, show that these fine materials are less than 45 cm deep, because a sample from 45

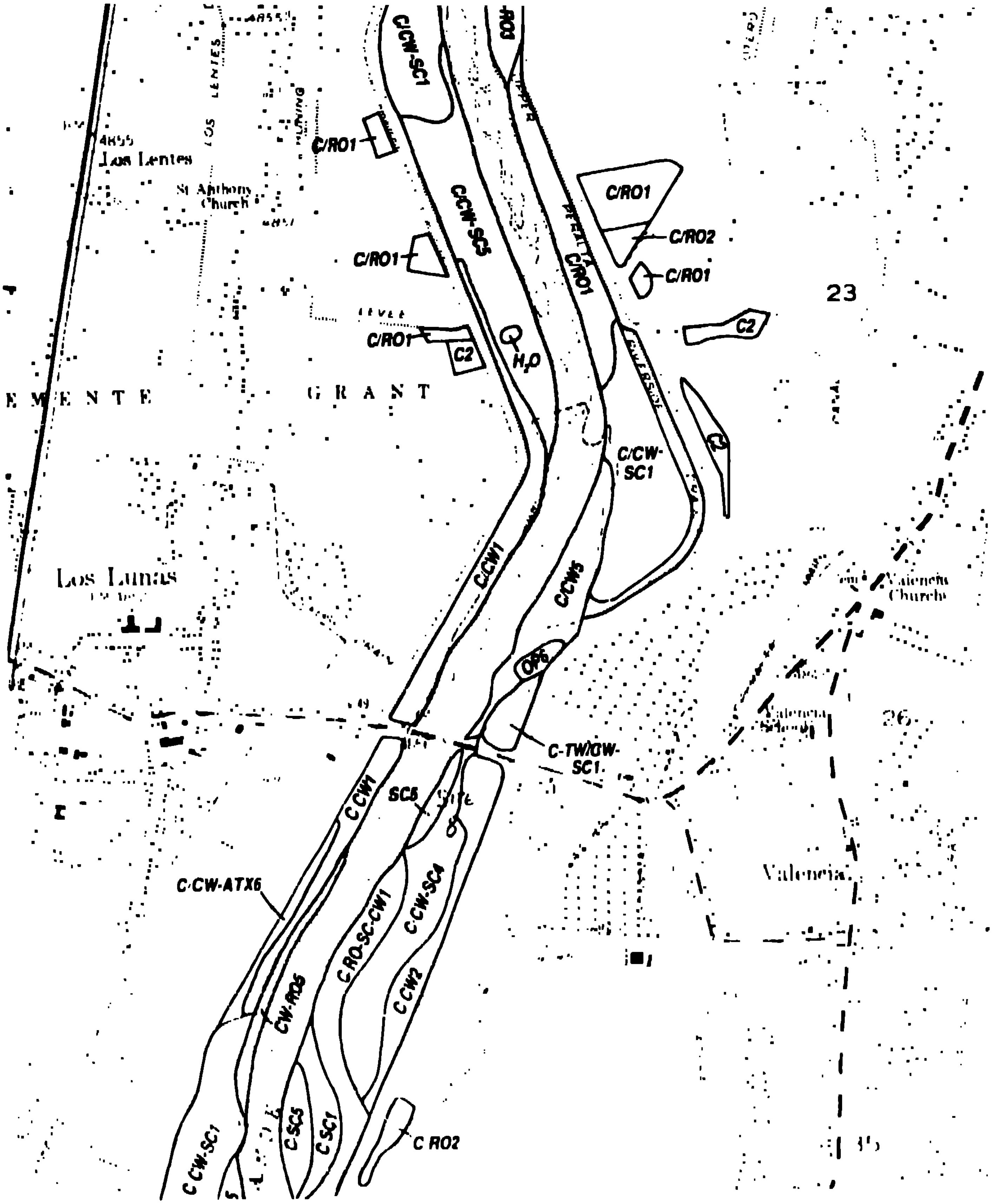

Figure 13.8 Riparian vegetation communities along the Los Lunas representative reach. See number 8 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

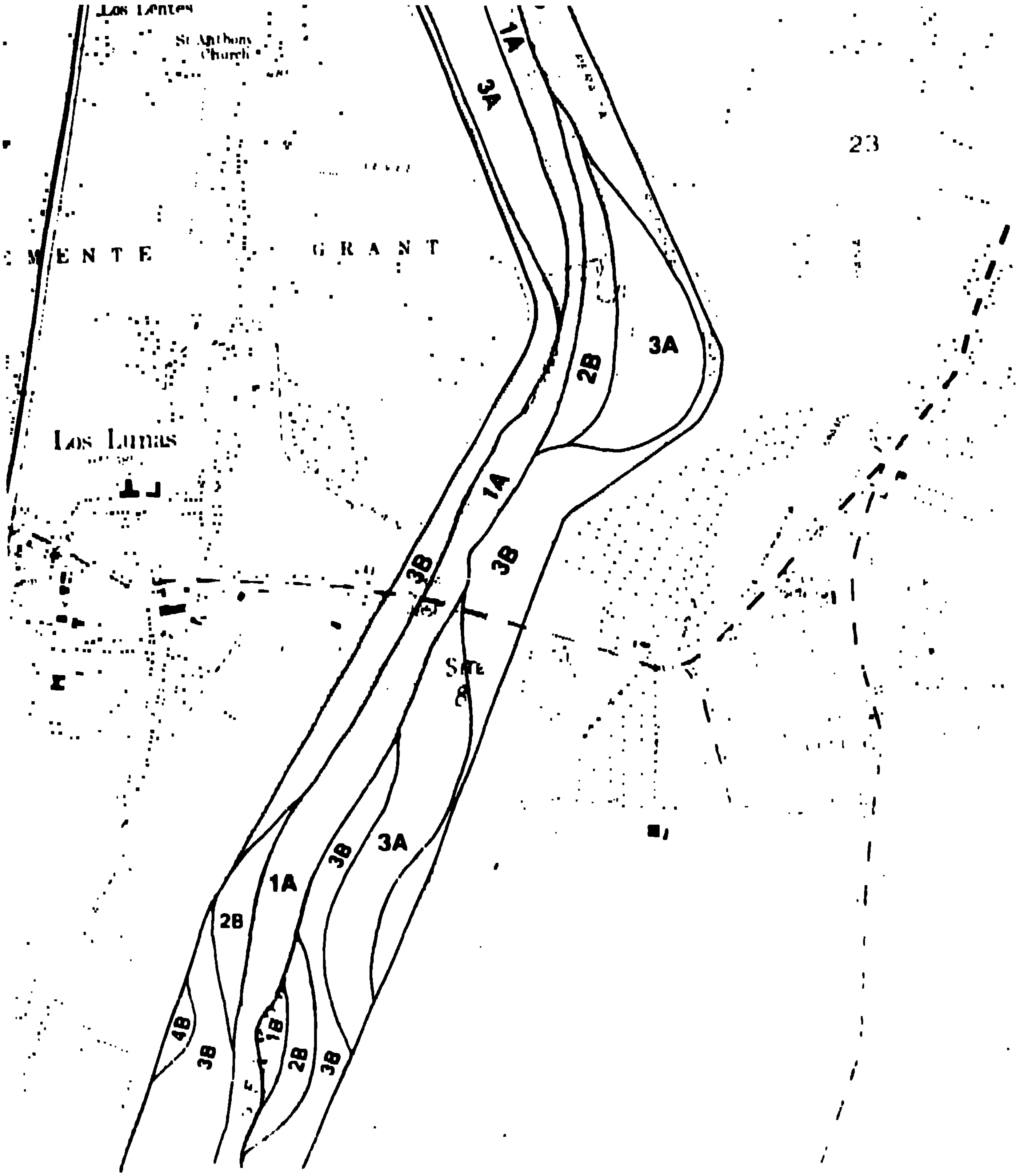

Figure 13.9 Geomorphic map of the Los Lunas representative reach. See number 8 in Figure 12.2 for location. Labeled areas on the map are 1A, 1984 active channel; 1B, channel side bar established between 1963 and 1971, 2B, pre 1941 to 1960 channel area; 3A, pre 1941 to 1941 braided channel; 3B, pre 1941 -1941 flood plain; in a small segment NE of the bridge pre 1941 to 1960 channel; 4B, pre 1941 overflow channel

cm below the surface revealed materials with only 2 percent fines, sediments typical of the original abandoned braided channel deposits.

The geomorphologic interpretation of the Los Lunas reach indicates that it is unlikely to harbor significant quantities of plutonium though no direct measurements are available. Fine materials deposited during the 1950s and early 1960s are relatively scarce, occurring on a few small flood plain segments partly destroyed by the modern channel. The fine deposits trapped in the elbow area northeast of the Los Lunas Bridge date from the last 20 years, a period during which Cochiti Dam prevented inputs of plutonium to the lower river from mountain fallout sources and from Los Alamos. If any plutonium occurs in the deposit, it is from remobilized materials that had been previously deposited elsewhere upstream and then entrained a second time. Mixing and dilution by tributary sediments has probably been extensive.

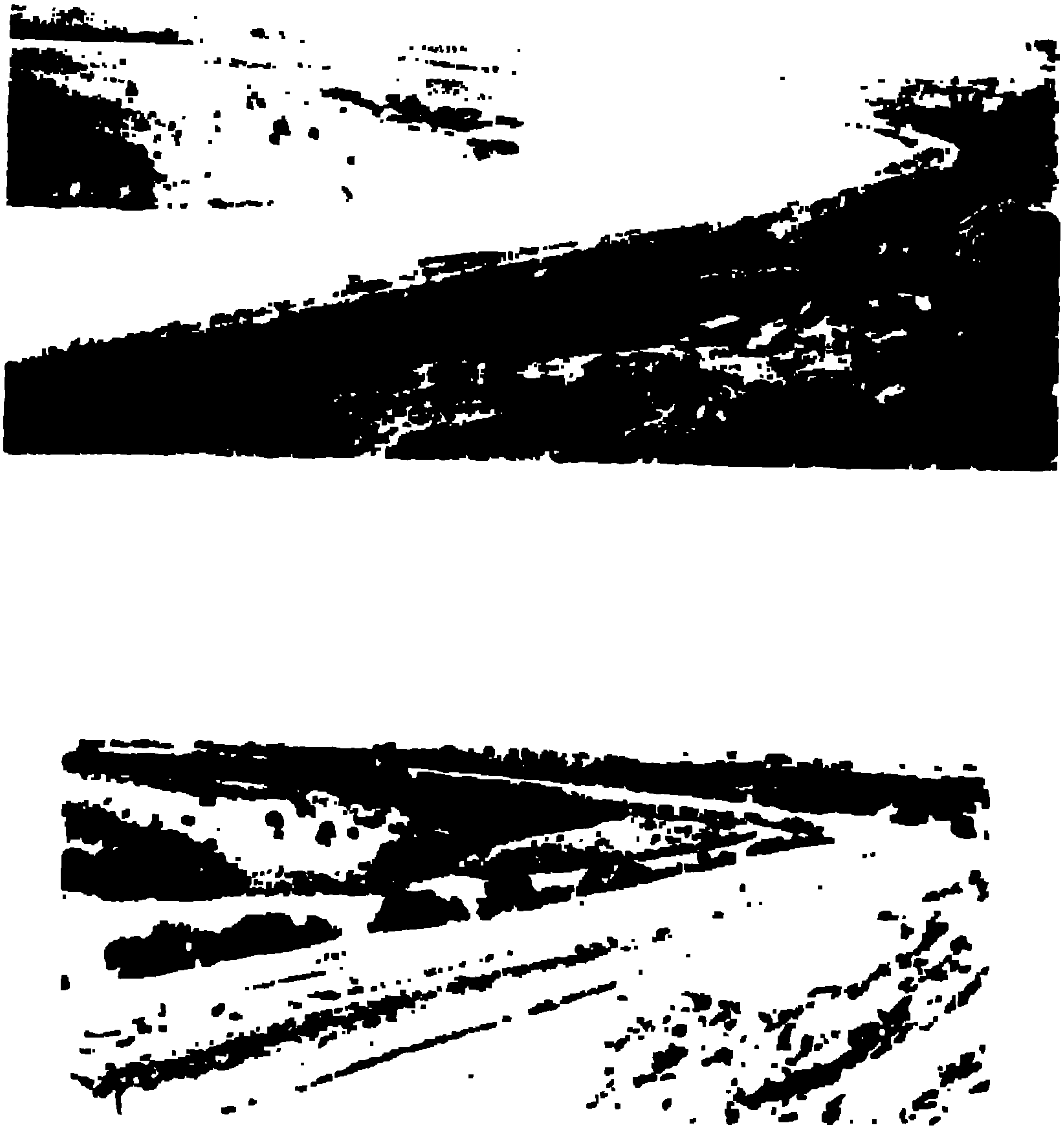

Figure [illegible]. Engineering works have produced a partly artificial channel that is more stable and narrow than the original natural channel in the reach immediately below [illegible]

CHAPTER 14. STORAGE SOUTH OF THE RIO PUERCO

14.1 San Geronimo

Downstream from the Los Lunas representative reach (which ends at Bernardo as described in the previous chapter), the character of the Rio Grande changes radically. Immediately below Bernardo, the Rio Puerco joins the main river, bringing with it a huge load of sediment. The Rio Grande Valley becomes much wider below Bernardo, and the twentieth-century narrowing of the channel, aided by engineering works, is even more pronounced than in upstream areas (Figure 14.1), while the vegetation community is dominated by tamarisk. The final three representative reaches outlined in this chapter share common features of great valley width, extensive channel changes, and wide-spread impacts of engineering works.

The 5-km San Geronimo reach is similar to the 25-km segment of the Northern Rio Grande between the highway bridge at Bernardo and San Acacia Diversion Dam (Figures 14.2 and 14.3). The reach has a levee and drain system on the east side, while the embankment of the Southern Pacific Rail Road strongly impacts the west side. San Geronimo was a stop on the railroad, but it is now abandoned. The embankment constrains the lateral movement of the active channel and isolates a backswamp and lake area on the west side. The flood plain and abandoned channel area is more than 2.5 km wide and is bounded by sharply defined Pleistocene terraces of sand and gravel.

Channel change in the San Geronimo reach between the early 1940s and about 1990 has been an adjustment from a winding braided channel to a meandering single thread, and finally to a relatively straight single thread. Through the 1940s the channel was up to 1.0 km wide and nearly filled the available valley floor between La Joya, situated on an east side terrace, and the railroad embankment on the west side. Near San Geronimo, the railroad embankment confined the channel, but further south the river broadened again. A remnant of this 1940s channel (4B on Figure 14.3) still exists north of La Joya.

Declining water yields and smaller flood peaks after the early 1940s led to the establishment of a narrower, meandering single channel in the early 1950s (see Figure 4.5 for the annual water yield history and Figure 4.7 for the flood history). Moderate floods in 1957 and 1958 brought minor adjustments, and another moderate flood in 1967 straightened the alignment. The abandoned, sinuous channel and its associated flood plains appear as remnants on the valley floor throughout the reach (2A and 2B on Figure 14.3). After 1967, only minor adjustments occurred, usually by the addition of channel side bars.

The riparian vegetation in the San Geronimo reach is not as variable as it is in reaches upstream (Figure 14.2). Data and historical maps indicate that tamarisk was already established in dense thickets by the mid 1930s.[1] Tamarisk is by far the most common species, providing a continuous, mono-species, cover in many areas. Changes in the community structure, however, reflect the variation in underlying

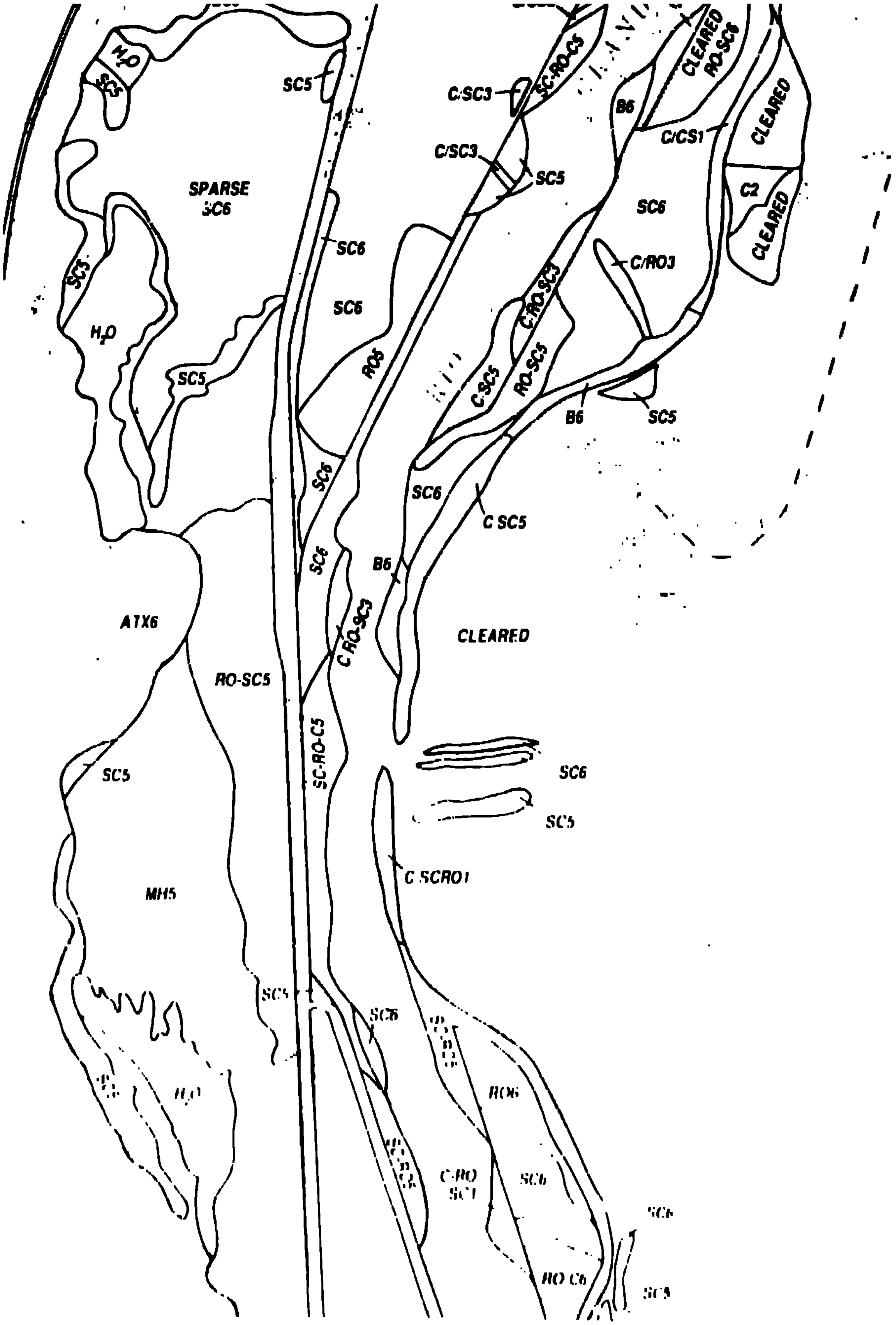

Figure 14.2 Riparian vegetation communities along the San Geronimo representative reach. See number 9 in Figure 12.2 for location and Table 12.1 for symbols. Modified from Hink and Ohmart, 1984.

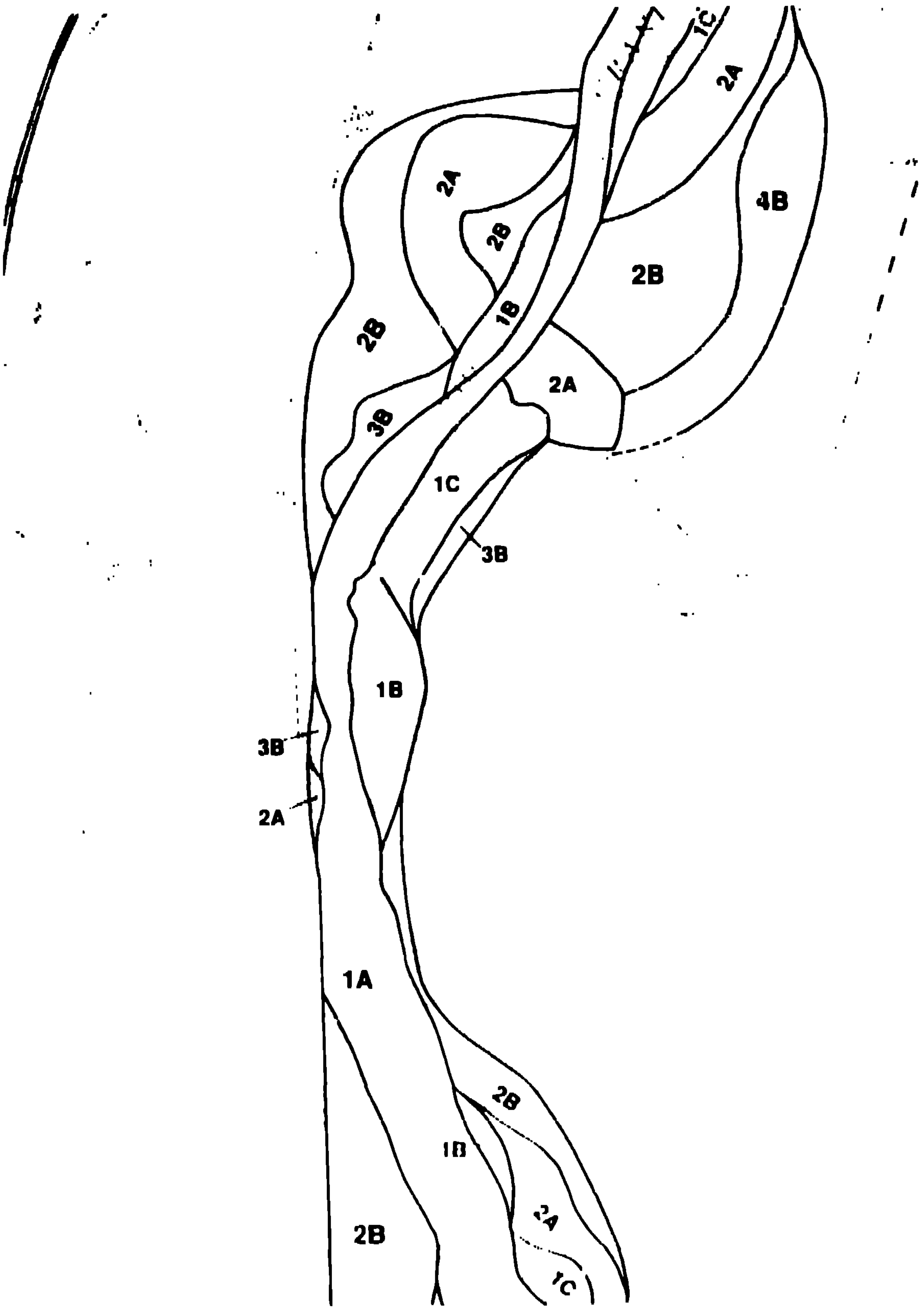

Figure 14.3 Geomorphic map of the San Geronimo representative reach. See number 9 in Figure 12.2 for location. Labeled areas on the map are 1A, 1984 active channel; 1B, 1984 flood plain; 1C, 1984 overflow area, part of a braided channel and bar system; 2A, 1950–1967 channel, pre mid 1940s to 1950 a braided channel; 2B, 1950–1967 flood plain, pre mid 1940s to 1950 a braided channel; 3B, 1950–1971 flood plain; 4B, 1940s–1950 flood plain and braided channel.

deposits. Mature forest stands with canopies several tens of meters above the surface are rare, but there is considerable variation in structures with vegetation closer to the ground. Less dense growth occupies the younger deposits. Two anomalies are the cottonwood forest growing along the abandoned 1940s channel north of La Joya (C/CS1 in Figure 14.2), and the willow lining the modern active channel.

Unlike the vegetation, sediment composition in the San Geronimo reach is distinctly variable from place to place and shows strong connections to fluvial history. Sediments from an abandoned braided channel that was active between 1950 and 1967 (2A in Figure 14.3) have modest amounts of fine material (about 28 percent), but abandoned flood plains active during the same period (2B in Figure 14.3) have significantly more (45 percent). A pre-1940s flood-plain surface has similar high contents of fine particles. Subsurface samples from depths down to 90 cm show a fining upward sequence in all the features (data in Appendix C1).

The geomorphic map shows the contrast between the winding course of deposits of the river during the pre-1967 era contrasted with the straighter course of the present channel. The railroad embankment forms a resistant boundary on the west side of the reach, and since the 1940s the channel has stored little material along its length near San Geronimo, because the bend in the river forces flows against the barrier. Agricultural activities have obscured the surfaces of the deposits southwest of La Joya, but their forms and materials remain relatively undisturbed in the northern portion of the representative reach.

The flood-plain deposits associated with the 1948-1967 channel systems are the most likely areas for plutonium storage. These areas have fine-grained materials deposited during the period of maximum plutonium input into the system from fallout and Los Alamos. Dilution of the plutonium concentrations is likely, however, because the San Geronimo reach is immediately downstream from the confluence with the Rio Puerco. The tributary contributes huge quantities of sediment with low concentrations of plutonium that mix with those of the main stream, reducing the concentrations of the contaminant carried by the Rio Grande. The influx of sediment also contributes to massive flood-plain deposits extending up to 3.5 km across the valley in the reach.

14.2 Chamizal

The Chamizal reach contains 5 of the 40 km between the San Acacia Diversion Dam and the San Antonio Bridge (Figure 14.4). Because the reach lies below the confluences of the Northern Rio Grande with the Rio Puerco and Rio Salado, the system is flooded with sediments from tributaries, resulting in a flood plain that is 2.5-3.5 km wide. During the 1940s, the channel was as much as 1 km wide with a gently winding course that lacked the extreme wandering seen in the channel near La Joya in the San Geronimo reach. Only one pronounced bend or elbow occurred in the Chamizal reach near the settlement of Chamizal. Abandonment of the broad braided channel was in stages, with some parts abandoned under natural processes by the late 1950s (3A and 3B in Figure 14.4) and others abandoned as a result of

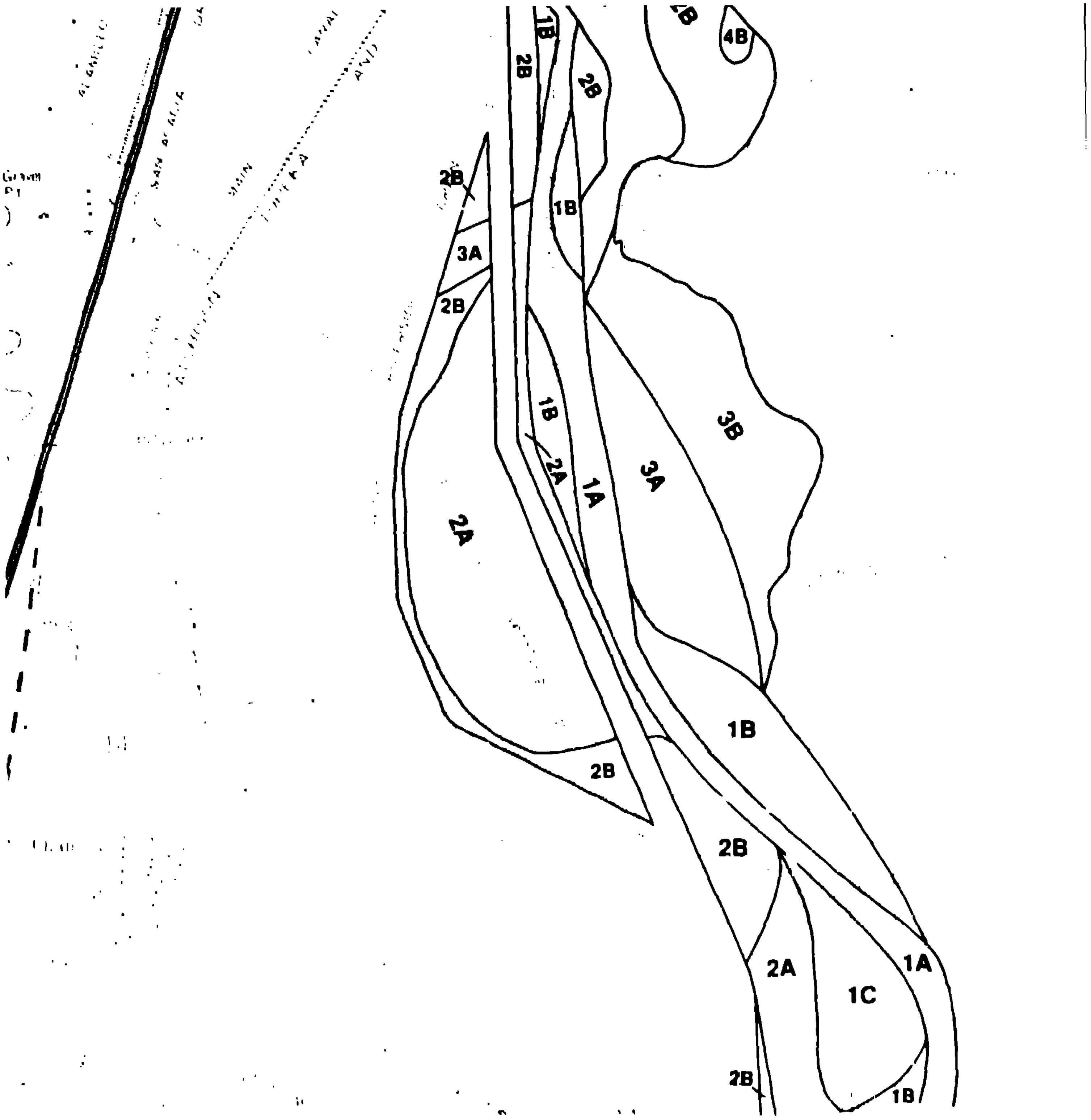

Figure 12.4 Geomorphic map of the Chamizal representative reach. See number 10 in Figure 12.2 for location. Labeled areas on the map are 1A, 1984 active channel; 1B, pre-mid-1940s--1984 flood plain; 1C, pre-mid-1940s--late 1970s flood plain and overflow area for braided channel; 2A, pre-mid-1940s--1962 braided channel; 2B, pre-mid-1940s--1962 flood plain; 3A, pre-mid-1940s--late 1950s braided channel; 3B, pre-mid-1940s--late 1950s flood plain; 4B, cleared area on unit 2B.

engineering activities (2A and 2B in Figure 14.4).

A significant feature of the reach is the elbow in the vicinity of Chamizal. Activities of the Middle Rio Grande Conservancy District in the 1920s produced the Lemitar Riverside Drain and its levee on the outside edge of the elbow. During the construction associated with the Middle Rio Grande Project, engineers installed a pilot channel consisting of straight segments (shown on Figure 14.4). They built a levee that cut off the Chamizal bend in 1959. The Bureau of Reclamation christened the newly isolated area between the old and new levees the "San Lorenzo Settling Basin" because it trapped sediments from San Lorenzo Arroyo, a tributary to the main channel.

Floods in the Chamizal reach result from activities of the Rio Grande, Rio Puerco, and Rio Salado, wherein major flow events in 1967, 1972, and the early 1980s caused channel adjustments. Although the engineering works completed in 1959 produced a straight channel, this configuration did not represent an equilibrium geometry. The subsequent channel adjustments reproduced the original channel geometry of a gently meandering course, somewhat constrained by the west-side levee.

Although previous workers did not map vegetation in detail in the Chamizal reach (or the San Marcial reach immediately downstream), field investigations in the present project provide some useful data. Tamarisk is the most common riparian species in the Chamizal reach. On the narrow strip that is the active flood plain, its coverage approaches 100%, and in many places there are no other tree species. In channel and flood-plain areas abandoned by active processes after 1959, cottonwood is beginning to be a recognizable component of the riparian community. In the San Lorenzo Settling Basin, cottonwood is flourishing, but in those areas still subject to overbank flows from the modern channel, tamarisk maintains its dominance. Because tamarisk is so common and other species are not especially variable from place to place, the riparian vegetation is not a reliable indicator of the distribution of fluvial forms and sediments in the reach.

Sedimentary characteristics are useful tools in differentiating deposits in the Chamizal reach. Flood plains have consistently finer materials than abandoned channels, and flood plains of different ages have different amounts of fine sediments. The sediments in the major abandoned braided channel in the area (2A in Figure 14.4), excluding the settling basin, have less than one percent silt and clay. Among the flood plain sediments, the more recent the feature, the more fine material it contains. The modern active flood plain sediments have a mean of 53 percent silt and clay, while the flood plain abandoned in the late 1950s (2B in Figure 14.4) has 43% and the one abandoned somewhat earlier (3B in Figure 14.4) has 29%. As is often the case with braided stream deposits, there is vertical variation in particle size below the surface

The geomorphic map of the Chamizal reach shows mostly post 1941 features, all related to gently curving channels that have changed from a braided to a single thread configuration. Given the location of the reach far downstream from plutonium source areas (almost 250 km south of Española) and downstream from major sediment sources (the Rio Puerco and Rio Salado), sediments in the reach are not likely to contain high concentrations of plutonium from mountain fallout areas or from Los Alamos. Sediments from depths below 30 cm probably reflect the materials in transport through the system in 1959. Comparisons with modern active sediments would reveal any temporal trends in plutonium loading of the stream, but there are no radionuclide data presently available in the reach.

14.3 San Marcial

The 8 km San Marcial reach represents channel conditions between the San Antonio Bridge and the San Marcial Bridge, site of a major U.S. Geological Survey stream gage and the downstream end of the study area (Figure 14 5). San Marcial was founded as a mid- nineteenth century trading town, and was destroyed by floods in 1866 and 1929. Sedimentation within the reach has produced a flood plain that is up to 4 km wide, but the active channel is relatively narrow, less than 60 m wide, because of transmission losses, irrigation withdrawals, and the maintenance of a conveyance channel that diverts low flows into a canal separate from the natural channel. The reach has some characteristics similar to the San Geronimo reach in that the Southern Pacific Railroad embankment has isolated a part of the previously active flood plain from the active channel for more than century. This isolated area at San Marcial was a backswamp under natural conditions, and included San Marcial Lake. Following the installation of the railroad, the lake filled with sediment and organic debris, and it no longer exists as a body of water.

Channel changes in the San Marcial reach have a complex history. Before 1941, the channel in the reach was a winding, braided system that narrowed as it passed Mesa del Contadero and Mesa Peak. This braided arrangement (3A and 3B in Figure 14.5) survived a series of floods through the late 1930s, with the largest flows of record in 1905 and 1929 (see Figure 4.7 for the flood history of the Rio Grande at San Marcial). The arrangement included a flood plain zone along most of the reach (3C in Figure 14.5). During the 1930s, the flow was confined to a channel on the west side of the valley.[2] Floods in the late 1930s and in 1941 established a new configuration that included a broad overflow area or flood plain immediately north of Black Mesa (2D in Figure 14.5). Low flows bifurcated, with one branch flowing along the west side of the valley (2A in Figure 14 5) and the other along the east side

The Middle Rio Grande Project, completed in 1953, resulted in the abandonment of the west branch and the direction of flows into the eastern branch The broad overflow surface is now isolated from the active channel by levees Subsequent engineering efforts defined a relatively straight channel that cut off some meanders along the single thread eastern channel (1B in Figure 14 5).

Riparian vegetation in the San Marcial reach is predominantly tamarisk The bedrock constriction offered by Black Mesa and Mesa Peak forces ground water to the surface in the reach, producing ideal conditions for phreatophyte growth In one

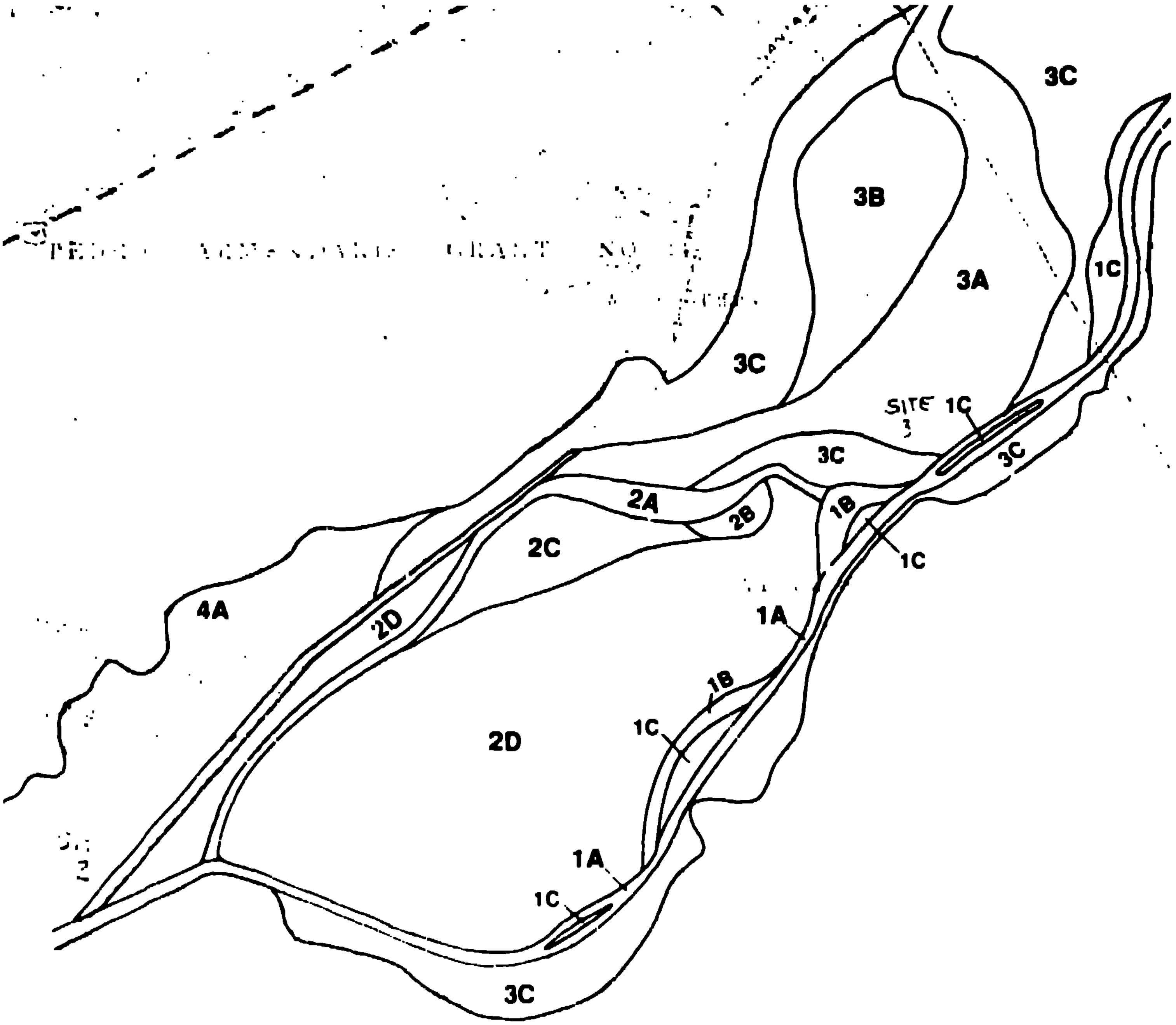

Figure 14.5 Geomorphic map of the San Marcial representative reach. See number 11 in Figure 12.2 for location Labeled areas on the map are 1A, 1984 active channel; 1B, 1984 overflow channel; active channel during the 1970s and early 1980s; 1C, 1984 flood plain; active at least from the early 1970s to present; 2A, pre-mid-1940s to 1960s active channel; 2B pre-mid-1940s to 1960s flood plain; 2C, pre-mid-1940s to 1960s flood plain; 2D, pre-mid-1940s to 1960s flood plain and overflow area, probably overflowed in 1941 which established geometry; flood flow bifurcated with one split on each valley side; 3A, pre-1941 channel; 3B, pre-1941 flood plain; 3C, pre-1941 mid-channel island and channel side bar; 4A, pre-1941 lake and backswamp area isolated by rail road embankment; sedimented in by 1970s; probably not a depositon site for main channel materials after construction of the railroad.

test plot in the present study, the density of tamarisk is more than half a million plants per sq km. The only truly diverse riparian community in the reach grows in the 1920s-1930s abandoned channel, where tamarisk shares available space with cottonwood, russian olive, and willow (areas 3A, 3B, and 3C in Figure 14.5). The density of tamarisk in other areas apparently excludes competitors. Community structure is a useful indicator of the distribution of some geomorphic and sedimentologic features. The west branch of the 1941-1953 channel, for example, is sparsely populated by trees and is easily defined in aerial photography and in the field.

The 1941-1953 west channel (2A in Figure 14.5) also has distinct sedimentary characteristics, containing less than 3 percent silt and clay. The flood plain that was associated with the channel (2D in Figure 14.5) has sediments with an average of 35 percent fines. As in reaches further upstream, age of deposit appears to be inversely related to percent fine material. The flood plain of the 1920s and 1930s contains about 26 percent silt and clay.

The geomorphic and sedimentolgic map of the reach that results from the application of aerial photographic, field, vegetation, and sediment evidence shows that the present channel arrangement bears little connection to the older channels and their deposits. The reach preserves both channel and flood-plain deposits from three separate periods, 1920s-1930s, 1941-1953, and post 1953. The last series, the most likely to contain plutonium if it were available from upstream sources, is the most limited in a geographic and volumetric sense. Given this fact, along with the dilution of sediments by tributary additions and the great distance from upstream sources (313 km from Española), it is unlikely that plutonium occurs within the reach in major concentrations.

14.4 Summary

The foregoing review (in Chapters 12, 13, and 14) of detailed channel changes and resulting fluvial deposits and forms in eleven representative reaches of the Northern Rio Grande produces the following general conclusions

1 The channel has become consistently more narrow over the past several decades, a process that began before the closure of Cochiti Dam and that appears in places not affected by the dam

2 The channel has metamorphosed from a braided system to a single thread system

3 Riparian vegetation communities have composition and/or structures that provide direct links to underlying forms and sediments. Landform and materials control the geographical patterns of the vegetation within each reach, though not necessarily in the same way throughout the entire Northern Rio Grande

4 Sediment characteristics within each reach are also directly linked to their fluvial history. The variations are not consistent throughout the study area because of tributary infusions. A flood plain in a northern reach may therefore have

different particle size characteristics than a flood plain in a southern reach, but in both cases they have finer sediments than nearby abandoned channels. The post-1941 sediments are less than 1.5 m deep, and usually less than 1.0 m deep.

5. Plutonium from mountain fallout zones and from Los Alamos is most likely to be found in those reaches of the river upstream from Cochiti Dam and possibly in the reaches between Cochiti Dam and the Jemez River. As downstream distance increases from the confluence with the Jemez River, the contribution of plutonium to the system from Los Alamos is likely to become so small that it is unrecognizable, though plutonium from fallout is likely to be present in small quantities.

Figure [illegible] channel [illegible] for channel change [illegible] channel changes [illegible] view looking east in [illegible] Geological Survey [illegible] with water [illegible] planned in the [illegible]

PART 5. DYNAMICS OF PLUTONIUM IN RIO GRANDE SEDIMENTS

CHAPTER 15. THE SIMULATION MODEL

15.1 Objectives of the Model

The empirical data reviewed in the previous chapters indicate that plutonium occurs in sediments of the Rio Grande system at low levels. It is not readily apparent why the concentrations are low, given that concentrations in sediments of upper Los Alamos Canyon are one to three orders of magnitude greater than those in the main river. The explanation of observed concentrations probably lies in the complexities of the water and sediment system Flash floods on the tributary occasionally evacuate some of the relatively plutonium-rich sediments into the Rio Grande, but when they enter the main river, they are subject to two river processes that produce low plutonium concentrations in sedimentary deposits: mixing and dispersal. Dilution through mixing occurs when the sediments from Los Alamos Canyon combine with sediments from the upper Rio Grande and from tributaries (Figure 15.1) containing fewer contaminants. Dispersal at the scale of tens of kilometers along the river also causes a general decline in concentrations, though as demonstrated previously, river processes deposit the contaminated materials in specific places rather than diffusing them completely throughout the river system.

Further understanding of the consequences of the river's complex contaminated sediment processes might be obtained from three sources: direct measurement, laboratory experiments, or numerical simulation, but only the last alternative is a workable possibility. The direct observation of these mixing, diffusion, and deposition processes in the Rio Grande is impossible, so that detailed empirical data about them is unavailable. In order to be workable, laboratory experiments must duplicate the significant components of the real system using flumes, and physical models of the system require changes in scale that may result in inaccurate representations of the actual system Sediment in physical models must be smaller than in their real counterparts, for example, but because the water cannot be "scaled down" in the model, the fine sediment in the laboratory behaves differently from the more coarse sediment it represents in the real system. It is therefore likely that the only avenue to detailed analysis of the operations of the system of contaminant transport and storage in the Rio Grande is through a numerical simulation model

The term "model" has a variety of meanings, but in the present context it refers to an intellectual structure that is a simplification of reality.[1] The river system is too complex for complete description, even using all the known relationships among river related variables The basic adjustable variables of the system are channel width, depth, gradient, velocity of flow, amounts of water and sediment, sediment size, and hydraulic roughness.[2] Although hydraulic and geomorphic theories indicate how these variables are related to each other, the number of equations based in fundamental physical connections is less than the number of variables, so that the problem defies finite solution Simplifications and empirically derived functions substitute for the more desirable finite solutions, and the result is a representation that is an imperfect reflection of the real system. A general model is useful, however, because its operation obeys our best understanding of natural laws and it can render the complex real system more understandable. The model also permits the user to predict the course of future processes, assuming that the model is adequately calibrated to previously observed conditions and that no new variables intervene in future operations.

A numerical river simulation model is a computer program containing formulae that describe the operation of the real-world river system. The numerical components of such models are usually relatively simple mathematical statements that connect parameters describing various attributes of the river such as its dimensions, amounts of water and sediment in transport, and variables related to energy and momentum in the system. In a dynamic model that accounts for the passage of time, the numerical components also perform simple accounting functions such as keeping track of the total amounts of material that pass through the system or that are internally stored. Simulations are activities that use the program to mimic the operation of the system, including the changes that result from its own operation. Predictions result from simulations that extend beyond the presently available data.

The objective of the numerical model for analyzing the concentrations of plutonium in sediments of the Rio Grande is that it be a simple, dynamic, spatially variable sediment transport and storage model based on the distribution of force and resistance in the system.

1. **Simple**. The objective is to construct a program that operates in a personal computer environment without need for large machine support, with an interactive design so that the user does not need to be a specialist. Although some hydraulic models presently in use require detailed survey data, the objective is to make data demands simplistic, without need for expensive data not found in presently available data bases such as stream gauge records and aerial photography

2. **Dynamic** The model should be capable of simulating the passage of time by updating itself, taking into account changes to channel geometry resulting from sedimentation or erosion so that the next time unit in the simulation accurately accounts for the products of previous operations of the system.

3. **Spatially Variable** The model should take into account the variation from place to place in the physical characteristics of the stream channel and in the nature of the discharge of water and sediment. The model should be more than a simple input/output structure, and should depict internal geographic variation along the stream channel

4 **Transport and Storage** The model should be able to track the amounts of sediment and contaminants that are input, output, and stored at various locations within the system It is also necessary to account for remobilization of materials temporarily deposited within the system and near the channel

5. **Force and Resistance**. Because hydraulic force and resistance are the primary physical explanations for river processes, the model should represent these aspects of the system directly and should be able to assess the effects that changes in these aspects have on contaminant mobility.

15.2 Outline of the Model

The model developed for exploring the dynamics of sediment-borne plutonium in the Northern Rio Grande is the Riverine Accounting and Transport model, or RAT (Figure 15.2). The RAT is a computer program written in IBM Advanced BASIC language consisting of about 1300 statements based on known, simple equations. In Advanced BASIC, each statement performs only one action, so it is not as powerful as PASCAL, FORTRAN, or some other languages. The advantages of using BASIC are that it is automatically available on most IBM-compatible personal computers without the need for additional compilers, and it is easily modified by users who wish to enhance its calculations by inserting more sophisticated mathematical statements.

The general structure of the RAT is to define river processes in a series of linked channel segments. In this case, the simulation is limited to the Northern Rio Grande from Otowi to the headwaters of Cochiti Reservoir. Although it is theoretically possible to simulate the river over much greater lengths, the calculations become unwieldy. Simulations of present processes and predictions of future processes must focus on the Otowi Cochiti Reservoir reach, because the reservoir is the termination of downstream sediment transport. Each channel segment has its own physical characteristics such as length, width, depth, and gradient. The program mathematically passes water, sediment, and contaminants through the sequence of segments, calculating the force available for transport, the resistance of the segment, and resulting erosion or deposition within each segment.

After calculating the processes for one simulated day, the program changes the physical characteristics of each channel segment to account for erosion or deposition, and then begins again with calculations for the next day. An internal accounting system tracks the amounts of sediment and contaminants stored or lost from each segment as well as the amounts released from the lower end of the last segment (that is, deposited in Cochiti Reservoir under present conditions) The model calculations are mostly invisible to the user, who sees only a computer screen that asks for input of various kinds and that provides prompts to the user asking for choices in series of options exercised while the program is running

The specific structure of the RAT consists of a series of calculations contained within a loop and connected to a series of data matrices or arrays. The program begins by asking the user to select a river system for analyses Two options are available: a simplistic three segment synthetic test system for experimental purposes or the Northern Rio Grande The Northern Rio Grande option includes data describing 22 segments of the stream beginning at Otowi, immediately upstream from the confluence with Los Alamos Canyon, and ending at the headwaters of Cochiti

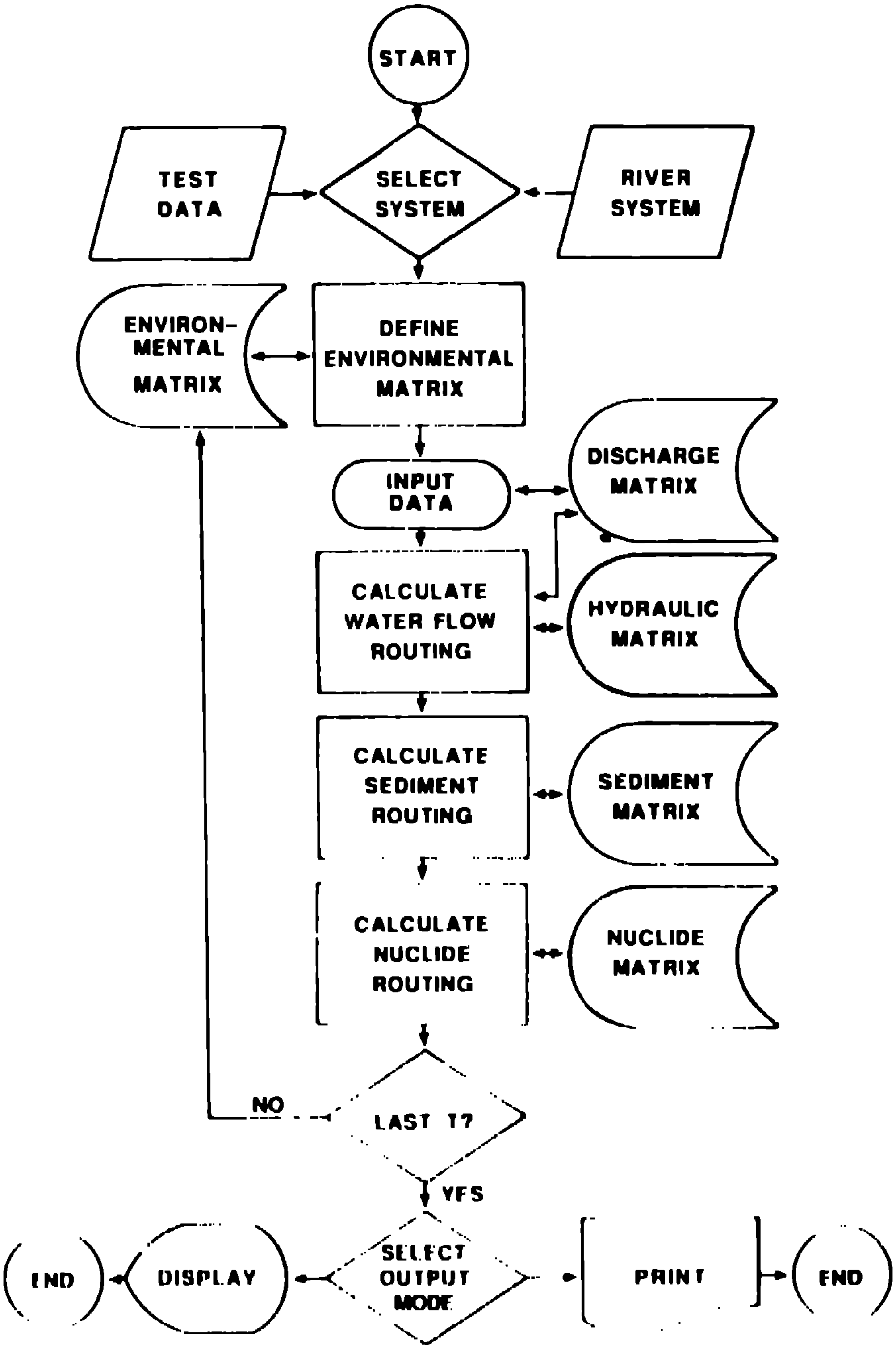

Figure 15.2 Flow diagram showing the structure of the RAT simulation model

Reservoir, downstream from the confluence with the Rio de los Frijoles (Figures 15.3, 15.4). After the user selects the desired option, the program reads the data describing the initial physical characteristics of each section (stored internally in the program), and establishes a geomorphological environmental matrix.

The environmental matrix has three dimensions: stream segment numbers, characteristics of each segment, and time units (Figure 15.5). The segment numbers range from 1 at Otowi Bridge to 22 at Cochiti Reservoir. The characteristics recorded for each segment are segment number, downstream distance of the end point of the segment from the beginning of the entire set of segments, the segment length, the elevation of the segment end point, the mean channel gradient, mean channel width, mean channel depth, hydraulic roughness of the channel, the cumulative channel bed area from the beginning of the entire set to the end point of the segment, a number to connect the segment to the passage of flood waves, and the time unit number. For the sake of simplicity, the calculations assume a rectangular channel (Figure 15.6). The channel segments are 200 - 2000 m long, with their specific starting and ending points determined by geomorphic conditions along the river. For example, narrow reaches for some segments while other segments are wider and contain some space for sediment storage. Generally, wide and narrow segments alternate with each other long the channel. The time units range from 1 day to any maximum number, but practical programming limits the realistic maximum number of simulated days to about 10.

Once the program establishes the initial geomorphological environmental matrix, the user inputs daily mean discharges that enter at the upstream beginning point of the entire set of segments. The input of discharge values by the user causes the program to establish a second data matrix or array for hydraulic values within each stream segment. The hydraulic matrix, like the one for the geomorphic parameters, has three dimensions: segment numbers, segment characteristics, and time units. Again the segment numbers range from 1 to 22 and the time units from 1 to about 10. The hydraulic characteristics of the channel segments are segment number, an unadjusted discharge value derived from the input data, the total within the segment, an adjusted discharge value that accounts for the transmission losses, depth of flow, velocity of flow, stream power per unit area of the channel bed, and stream power at the downstream end of the cross section. All the hydraulic calculations and subsequent sediment and plutonium transport calculations use the adjusted discharge. Calculations for the components of the hydraulic matrix use standard, widely accepted formulae employed by geomorphologists and hydraulic engineers (Appendix J).[1]

Using the hydraulic matrix, the RAT program calculates values for a third matrix or array that describes the sediment system segment by segment through the entire series. Like the other matrices, the sediment matrix has three dimensions: segment numbers, characteristics, and time units. As before, the segment numbers range from 1 to 22 and the time units from 1 to about 10. The characteristics recorded in the sediment matrix are segment number, sediment transport capacity, sediment input to the segment, sediment output from the segment, the change in sediment storage during each time unit, a running total to account for sediment stored or eroded from the segment from the beginning of

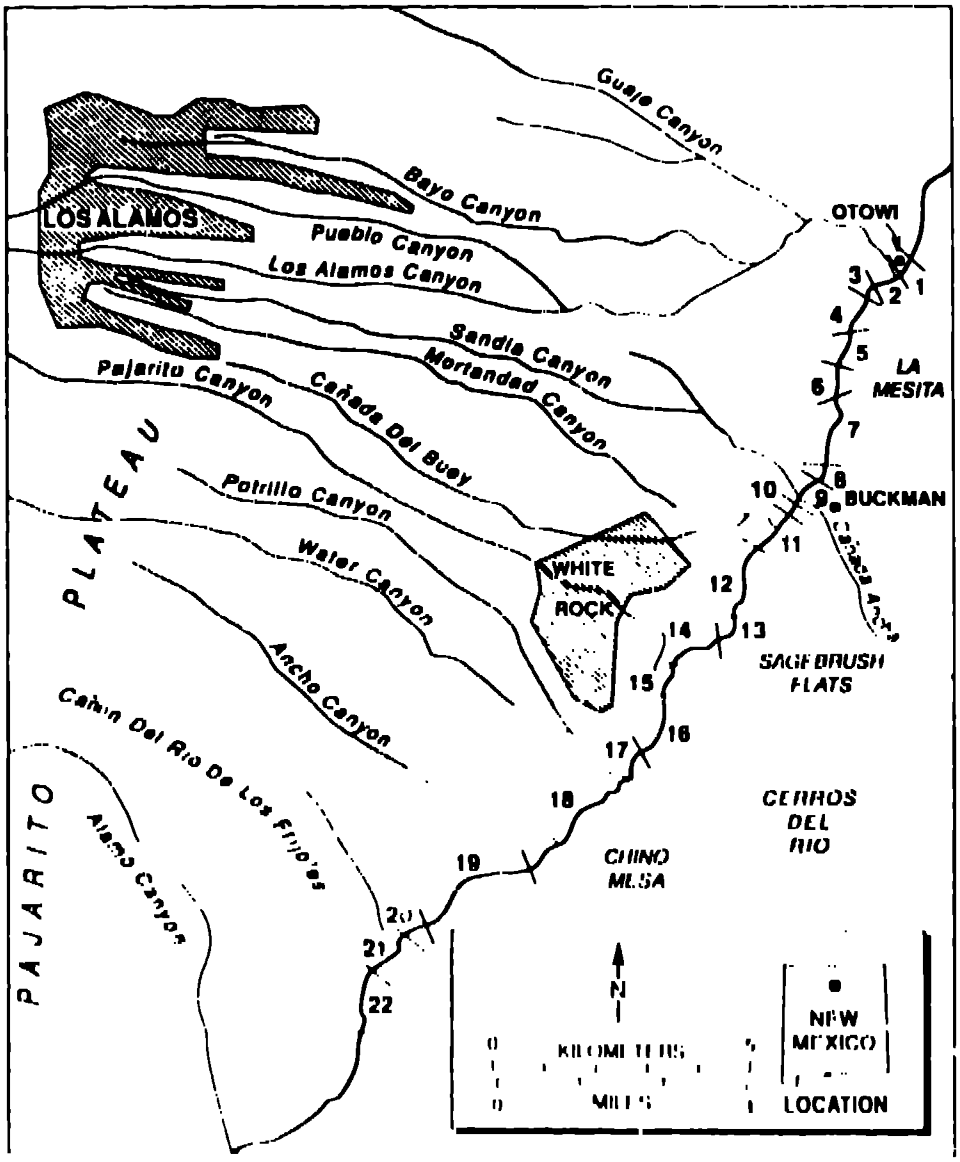

Figure 15.3 Map of the Northern Rio Grande near Los Alamos showing the 22 numbered segments used to define the system for the RAT simulation model.

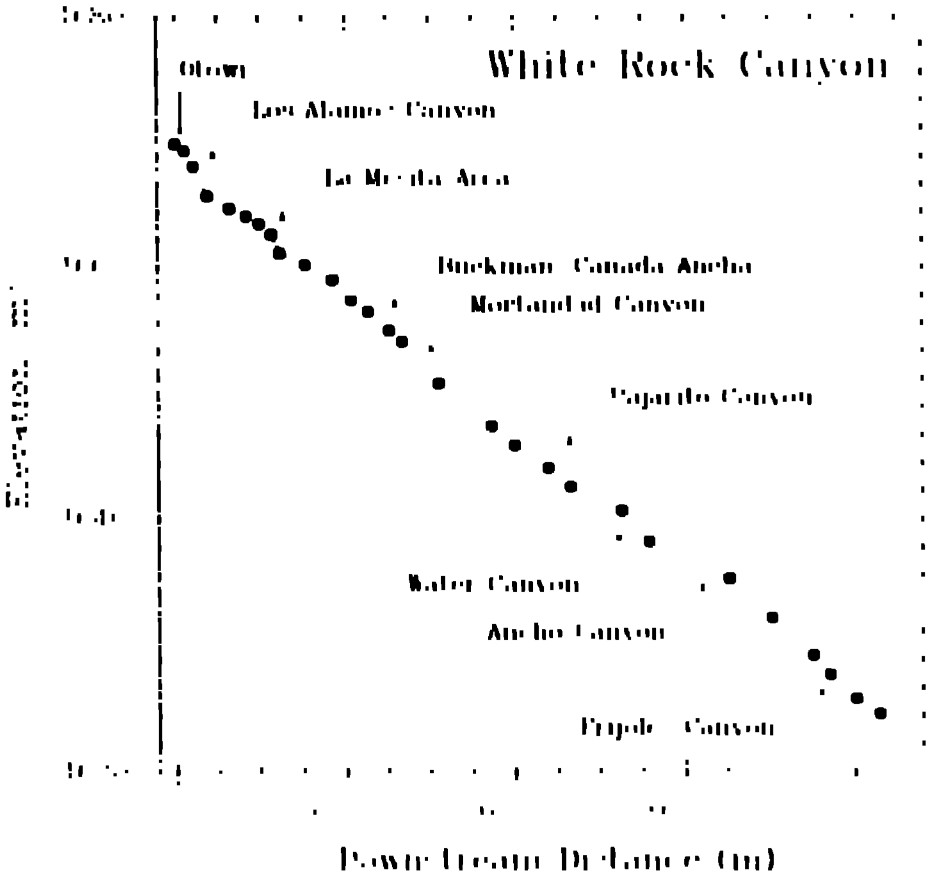

Figure 15.4 The gradient of the Rio Grande in White Rock Canyon from Otowi Bridge to the headwaters area of Cochiti Reservoir. The steep reaches generally correspond to narrow sections of the channel while the reaches with more shallow gradients are wider and have some space for sediment storage

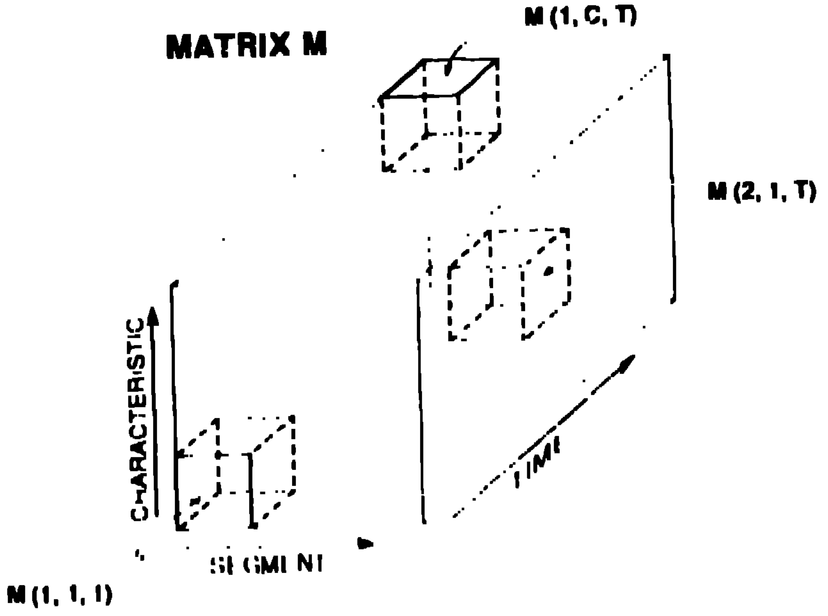

Figure 15.5 Conceptualization of an example data matrix from the RAT simulation model. The matrix is designated M, and each bit of data in the matrix is identified by three values, the segment number, the time unit, and the type of data or characteristic.

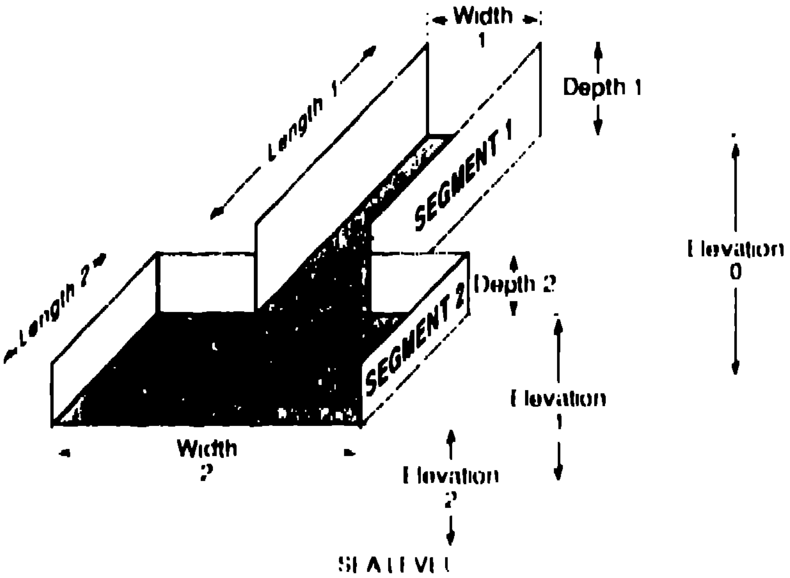

Figure 15.6 Sketch showing the simplified conceptualization of two sample segments of stream channel as used in the RAI simulation model.

the simulation, and the time unit number.

Calculations in the sediment matrix address only bedload, because the suspended load passes through the entire system without appreciable losses through storage or additions through erosion. The stream segments occur in White Rock Canyon for the most part, and there are no extensive flood plains that might otherwise interact with the suspended load. The program uses standard formulae for bedload transport that are simplistic and that are derived from first principles rather than from empirical data (Appendix J, Parts F, G, H, and I). It is also likely that contaminated sediment from Los Alamos Canyon travels as bedload, because of the relatively coarse materials involved. From a regulatory standpoint, bedload calculations are of greatest interest, because the infusions derived from Los Alamos are most likely to occur in coarse particles carried by the main river as bedload.

The user informs the program about the input of plutonium to the system by specifying the location and timing of the input (by segment number and time unit number), and by detailing the total mass of sediments and plutonium concentration of the input. The system therefore simulates an instantaneous release of contaminated sediment into the stream from an accidental spill, or the influx of contaminated sediment introduced by a flash flood on a tributary stream. In the case of the Northern Rio Grande, the simulations depict introduction of contaminated sediments from Los Alamos Canyon which joins the stream in segment number 2. The program assumes that fallout-derived plutonium in the system occurs in sediment entering the segment series from upstream in bedload concentrations of about 0.0025 pCi/g.

The RAT program completes its basic calculations by using these input data to track the plutonium within each segment and to construct a fourth matrix or array. The plutonium matrix has the usual three dimensions of segments, characteristics, and time units with the same size ranges as before. The plutonium matrix characteristics are segment number, mass of plutonium input, plutonium concentration of the input sediment, mass of plutonium output, plutonium concentration of the sediment output, mass of plutonium storage in each time unit, total mass of plutonium stored from the beginning of the simulation, concentration of plutonium in stored sediment, and time unit. These calculations amount to simple accounting (Appendix J, Parts J and K)

After completing the calculations and inserting the resulting values in the respective matrices, the RAT determines whether or not the simulation is complete. If the user has specified the simulation of only one day, the program proceeds to preparing the data for display. If the user has specified more than one simulated day, the program returns to the environmental matrix and adjusts the initial conditions and segment characteristics to reflect the results of the processes during the first day. The program changes segments with stored sediment by making them more narrow and shallow, and changes elevations that ultimately cause changes in gradient. The program mathematically distributes the stored sediments throughout the segment evenly in the downstream direction, while reductions in the cross sectional area are such that 80 percent of the reduction occurs in the depth and only 20 percent in the width. In other words, when channel aggradation occurs, it is mostly by vertical accretion. If erosion is the case, the program mathematically enlarges the channel by removing sediment evenly in the long dimension. Cross sectional changes during erosion are such that 80 percent of the sediment removed comes from increasing the channel width and 20 percent from increasing the channel depth. Thus, during erosion, bank erosion is most important. These deposition and erosion scenarios reflect the observed changes that have historically occurred in the channel.

During simulations of multiple days, the newly updated environmental matrix is the starting point of a new round of calculations for the hydraulic, sediment, and plutonium matrices as described previously. Additional updates of the environmental matrix and additional subsequent calculations occur until the program has simulated requested number of days. At that point, the program prepares the resulting data for output. The RAT displays data either on the screen or in hardcopy form through the printer. After output processing, the program ends.

15.3 Model Input

User-supplied input for the RAT includes the primary data concerning water discharge in the main channel and the infusion of sediment and plutonium from Los Alamos Canyon. The daily discharge values for the Rio Grande may be actual values taken from the gauging record at Otowi so that the resulting simulation represents an interpretation of a known event. The discharge values might also come from hydrologic simulations of past or anticipated future events, or they could be experimental values used to test the response of the system to a variety of inputs. Realistic values for discharge range from tens to hundreds of cubic meters per second (Table 15.1, Figure 15.7). Stream gage records show that over periods of ten to twenty days the discharge in the Rio Grande varies by 15 percent or less under the conditions prevailing at the times of the major infusions from Los Alamos Canyon. At other times, changes of an order of magnitude are possible

The program assumes for the purposes of simulation that the Rio Grande transports an amount of bedload sediment that is equal to its bedload transport capacity. Therefore, once the user assigns an input discharge, the program calculates the amount of bedload that the discharge can transport given the considerations of the geomorphology of the channel. The calculations use that value as the input and output of bedload sediment for the first segment For subsequent segments downstream, however, the amounts of input and output may be different for each segment, because the input depends on conditions upstream, while output depends on conditions within the segment The differences between input and output lead to erosion or sedimentation within each segment

The user specifies the nature of the infusion of sediments into the main channel from Los Alamos Canyon in four ways location, time, amount of sediment, and plutonium concentration Because of the spatial structure of the model, Los Alamos Canyon enters the main stream in segment number 2, and time unit refers to the simulated day of the infusion, generally the first day The quantities of sediment emptied into the main channel by flash floods on the tributary, assumed to enter all on

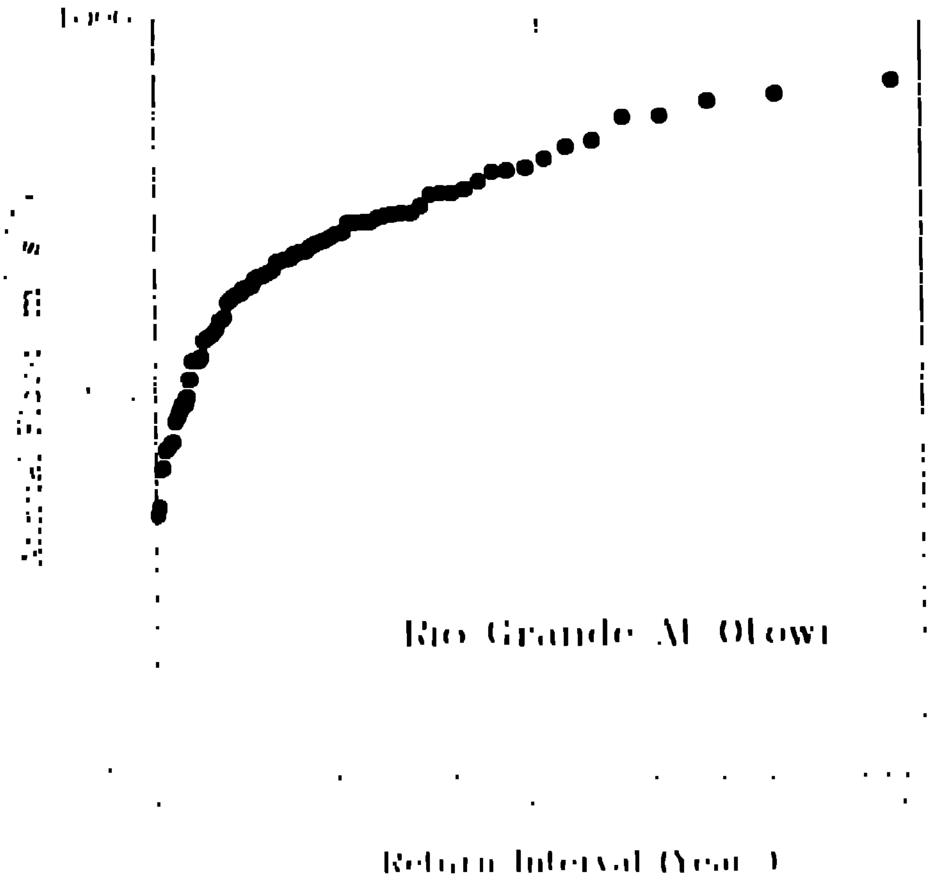

Figure 15.7 The annual flood series of the Rio Grande at Otowi, showing the probable return interval of annual floods of various magnitudes. For example, an annual flood of about 400 $m^3 s^{-1}$ is likely to occur about once every ten years.

TABLE 15.1 DISCHARGE OF THE RIO GRANDE AT OTOWI

Event	Discharge ($m^3 s^{-1}$)
Daily Minimum Flow	2
Maximum Flow of Record	623
Daily Mean Flow	43
Flood Flows:	
1 Year	48
2 Year	217
5 Year	342
10 Year	429
25 Year	606
50 Year	615
100 Year	700

Note: Flood flows estimated from annual flood series; other values from U.S. Geological Survey data.

a single day, reasonably would be 5,000-15,000 Mg. The concentrations of plutonium during the four years of primary concern, 1951, 1952, 1957, and 1968 were probably 1.700-3.000 pCi/g (Table 15.2), with lower quantities of sediment and lower concentrations in other events. The amount of water contributed to the main channel by flash floods in Los Alamos Canyon is small compared to the amount in the main channel, so the program does not take the tributary contribution into account.

15.4 Model Output

The program presents data resulting from the calculations as tables of numbers extracted from the various matrices or arrays within the program. Four types of data are available. In each case, the data are organized by stream segment and time unit.

1. **Geomorphologic data** describe the channel characteristics such as width and depth, and derive from the environmental matrix. These data can reveal the responses of the channel to various inflows of water and sediment.
2. **Hydraulic data** describe the behavior of the water flow in the channel segments and are mostly useful for program calculations. They describe the amount of power available to transport sediment through the system
3. **Sediment data** describe the movement and storage of bedload sediment in the entire channel system segment by segment. Changes in storage in a particular segment through time can help explain the dynamics of plutonium in the system
4. **Plutonium data**, including inventory amounts and concentrations in bedload within each segment, represent the most important output of the model. The data can trace mixing and diffusion processes from the segment where the infusion occurred

In presenting these data to the user, the RAT constructs data tables for display on the computer screen or printed on paper The program presents the data organized according to spatial or temporal variation For the spatial variation approach, the table contains the type of data chosen by the user represented for one time period through all the segments In this form, plutonium data can reveal the geographic locations (identified by segment number) of plutonium storage within the system For the temporal variation approach, the table of data contains values describing conditions in a single segment (chosen by the user) over all the time periods simulated by the program In the temporal form the program shows time based changes in plutonium inventory and concentration for a particular stream segment of interest

Regardless of the method of organizing the data for output, the program indicates the amount of plutonium that passes completely through the series of stream segments. This plutonium was probably deposited in and along channels downstream

TABLE 15.2 TRIBUTARY INPUTS FOR RAT SIMULATION OF CRITICAL YEARS

	Sediment		Total Plutonium	
Year	Tons	Mg	mCi	fCi/g
1951	9814	8901	16.90	1898
1952	6316	5730	17.61	3073
1957	16470	14942	43.95	2941
1968	14120	12810	21.82	1708

Note: Data from unpublished calculations by L. J. Lane in support of Lane, Purtymun, and Becker (1985) from White Rock Canyon before late 1973, but after that year, it was deposited in Cochiti Reservoir. Simulations of future system behavior must assume that the reservoir will contain this "pass-through" amount. The program also calculates the probable concentration of plutonium in these downstream deposits.

At present there is insufficient empirical data to completely assess the accuracy of the model predictions, though some comparisons between model predictions and observed conditions are possible. For example, model predictions of the concentration of plutonium in stored bedload sediments at Buckman (segment number 8) are the same order of magnitude as those actually found in the sediments by recent sampling. Given that the amounts of plutonium are extremely small in relationship to the amounts of sediment involved, prediction of concentration values within an order of magnitude of actual values is probably the best that can be expected, even with more sophisticated calculations. The inventories of stored plutonium are reasonably accurate, because the problem of prediction is actually an issue of distributing a reasonably well known quantity of input material.

In summary, the RAT is a simple computer program that simulates river processes that occur over a period of days within 22 river segments along the Northern Rio Grande. The program allows the non-expert user to simulate past events or to experiment with hypothetical situations that might develop in the future. The program produces information about plutonium concentrations and inventories that are accurate at least to within an order of magnitude. The primary value of the simulations is to determine geographic and temporal variations in concentrations or inventories.

CHAPTER 16. SIMULATION RESULTS

16.1 Introduction

Simulations using the RAT program outlined in the previous chapter provide insight to the magnitude and speed of mixing, dispersal, and concentration of plutonium in the bedload sediments of the Northern Rio Grande. The model also can account for simple channel adjustments (Figure 16.1). This chapter explores the results of operating the model to define how plutonium concentrations in stored sediments along the Rio Grande respond to four major controls: 1) variation in the mass of input from Los Alamos Canyon, 2) variation in the concentration of input, 3) the passage of time and continuing operations of river processes in the main channel, and 4) increasing distance downstream away from Los Alamos Canyon.

While the results of the simulations could be presented as tables of numbers, interpretation of the data is easier if they are presented in graphic form. The numerical results of simulation runs provide data suitable for use with standard, commercially available graphics programs for use with personal computers. The graphs presented in this chapter are products of combining the data generated by simulations with SIGMAPLOT Version 4.0, a graph program created by Jandel Scientific, Inc. Results in each graph appear as lines that represent interpolations between the data points provided provided by the simulations. The lines are cubic spline curves that closely approximate the general trends of the data through mathematical smoothing and interpolation between given points. Each graph presents the results of 40-50 simulations. Because of the magnitude of potential error in the calculations, simplifications in the simulation process, and the smoothing of data, the graphs do not represent precise predictions. Values for a particular place at a particular time cannot be visually extracted from the diagrams. The graphs represent informative general trends, however, and they are useful sources of generalizations about the operation of the river and plutonium system.

16.2 Varying the Input Mass

Figure 16.2 shows the results of the RAT program for 10 simulated days of river processes in segment number 2 of the Rio Grande (located on Figure 15.3). The plutonium concentration in injected sediments was 3,000 pCi/g, a representative value (Table 15.2). Throughout this chapter, for precision and simplicity, measurements are in fCi/g (1 fCi/g = 0.001 pCi/g). The graph in Figure 16.2 indicates that if the input mass from Los Alamos Canyon was 2,500 Mg (an amount smaller than the injections during the four most important years) and the discharge of the Rio Grande was 50 cubic meters per second, after 10 days the concentration of plutonium in sediment stored along the Rio Grande in segment 2 would be about 130 fCi/g. After 10 days of mixing and dispersion the concentration of plutonium in the bedload declined more than 95 percent from the value seen in the input from Los Alamos.

A simulation for about 10 days is a reasonable approximation to what probably happens in the Northern Rio Grande. In that period of time it is likely that sediment

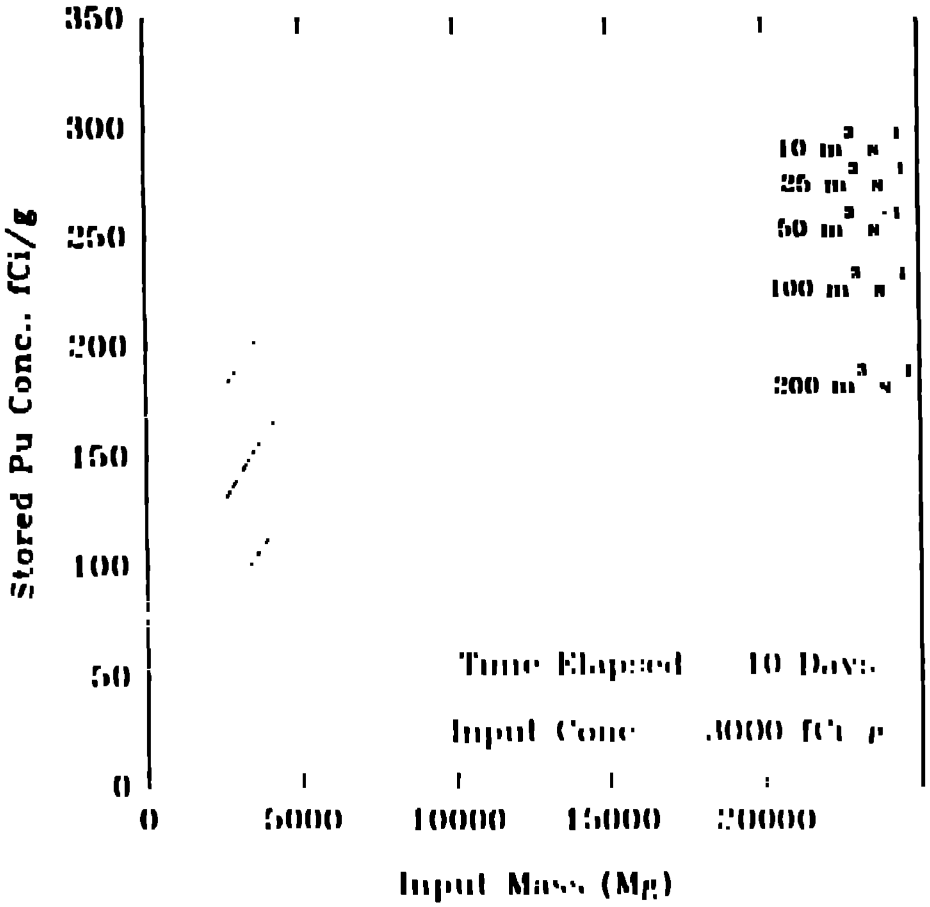

Figure 16.2 RAT simulation results showing plutonium concentrations in stored sediments along the Rio Grande as a result of varying input masses. The individual lines in the diagram represent conditions with different discharge conditions in the Rio Grande, ranging from low flow (10 m^3 s^{-1}) to major flood (200 m^3 s^{-1}).

would have entered the river, mixed with other materials, and been deposited at some point downstream. Remobilization, remixing, and further dispersal probably results in further reductions in plutonium concentrations. Therefore, we would expect that the simulation results produce maximum probable values for plutonium concentration. In actual measurements, we would expect to observe lesser concentrations than predicted by the RAT program.

This decline in concentration is the product of mixing with the sediment moving downstream through the main channel in quanitities that are huge in comparison with the amount of material introduced from Los Alamos Canyon. Because the bedload sediment decending the river from upstream contains only 2.5 fCi/g of plutonium from fallout, the mixing rapidly decreases the concentrations from the tributary. The mixing process is powerful, because even if we consider input masses as large as 20,000 Mg (a mass more than 50 percent greater than any actual input), the resulting concentration of plutonium in stored bedload in segment number 2 increases only to about 260 fCi/g. In other words, although the amount of sediment from Los Alamos Canyon is increased by a factor of 4, the concentrations in stored sediments in the main channel increase only by a factor of 2. This arrangement is common in river processes that are dominated by nonlinear mathematical relationships.[1]

These operations of the model show why plutonium concentrations are relatively low in bedload deposits along the main channel. The simulation indicates that using realistic values for the 1952 infusions from Los Alamos Canyon (original concentrations of about 3,000 fCi/g in about 6,000 Mg of input to the main river flowing at about 68 cubic meters per second), concentrations of plutonium in stored sediment along the Rio Grande would be about 190 fCi/g after 10 days. Because the system probably operated for a longer period before the final deposition of these sediments, it is likely that further mixing occurred and that the value of 190 fCi/g is an expected maximum.

The amount of discharge in the Rio Grande also strongly influences the concentration of stored plutonium, because low discharges produce relatively slow mixing, while high discharges accelerate the mixing and produce declining concentrations. For example, continuing the example of the 1952 conditions outlined above but assuming a discharge of 200 cubic meters per second, the resulting stored plutonium concentrations are not 190 fCi/g but are depressed to about 80 fCi/g. At high discharges, immense quantities of sediment (with low plutonium concentrations) enter the system from upstream.

In another example, using realistic values for the 1957 infusions (instead of those of 1952) from Los Alamos Canyon (concentration of about 3,000 fCi/g, about 15,000 Mg of input, and main channel discharge of about 120 cubic meters per second), simulations represented in Figure 16.2 suggest resulting storage concentrations of about 200 fCi/g. These results explain why deposits dating from 1952 (with concentrations of about 190 fCi/g) and 1957 may reasonably be expected to contain similar concentrations of plutonium, even though the 1952 sediments were derived from an infusion mass that was only one third as large as the 1957 infusion

In the latter year, river discharge was twice as great as in the earlier example, nearly compensating for the larger input mass by more vigorous mixing in the main river.

16.3 Varying the Input Concentration

The variation in plutonium concentration in releases from Los Alamos Canyon also impacts the concentrations that ultimately occur in sedimentary deposits along the main channel. Simulations with the RAT program show that concentrations of plutonium in bedload decline by about 50 percent within a single day of their introduction into the main channel (Figure 16.3). Dispersion of the sediments probably explains this precipitous decline, with dilution by main-channel sediments with low plutonium concentrations also playing a role. Increasingly high discharges in the main channel cause increasingly large decreases in plutonium concentrations through mixing even on a restricted time scale of one day. Discharge variation has a greater depressive effect on the higher concentrations as shown in Figure 16.3.

The range of discharge values that probably occurred during the actual infusions of plutonium from Los Alamos Canyon in the years 1951, 1952, 1957, and 1968 was about 15-120 cubic meters per second. The mass used in the simulations shown in Figure 16.3 was the amount from the 1952 case when concentrations in the tributary sediments was close to 3,000 fCi/g. After a single simulated day, the concentrations in main channel sediments in segment number 2 were about 1,200 fCi/g. Subsequent operations of the system resulted in further decreases in plutonium concentrations, and deposition of the materials is not likely to have occurred until at least several days later when discharges decreased.

Simulation results shown in Figure 16.3 indicate discharges in the Rio Grande dampen the range of variation in input concentration. For example, consider the input concentrations that are 1,000-5,000 fCi/g. At discharges of less than about 20 cubic meters per second, plutonium concentrations in main channel deposits have a range of nearly 2,000 fCi/g. At discharges of greater than 200 cubic meters per second, however, channel deposit concentrations have a range of only about 1,000 fCi/g.

16.4 The Effect of Time

Once materials from Los Alamos Canyon enter the Rio Grande, mixing and downstream dispersion occur quickly as a result of surprisingly powerful main stream processes, even at low discharges. Simulations using the RAT program to mimic the operation of the system over simulated ten day periods show that during the simulated period, plutonium concentrations in bedload sediment decline by about 80-90 percent depending on the discharge in the main channel (Figure 16.4). The declines result because the amounts of sediment from the tributary are small with respect to the amounts in transit in the main channel, and because the plutonium concentrations in the bedload contributed by the main channel from upstream fallout are relatively low.

The 1952 case is a useful example of the changes over time in plutonium concentration in segment number 2, where Los Alamos Canyon joins the Rio Grande

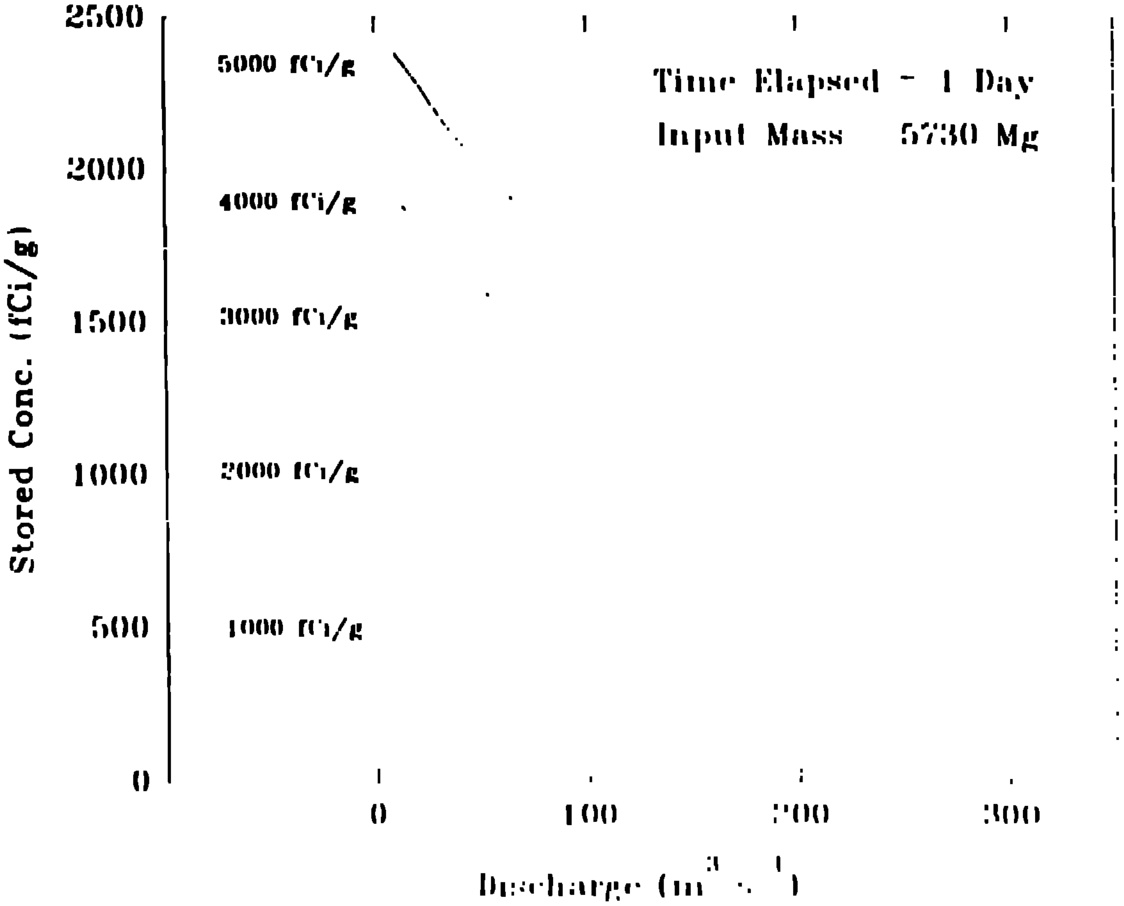

Figure 16.3 RAT simulation results showing plutonium concentrations in stored sediments along the Rio Grande as a result of varying discharges in the Rio Grande. The individual lines in the diagram represent different concentrations in the input masses discharged from Los Alamos Canyon, ranging from 1,000 fCi/g to 5,000 fCi/g

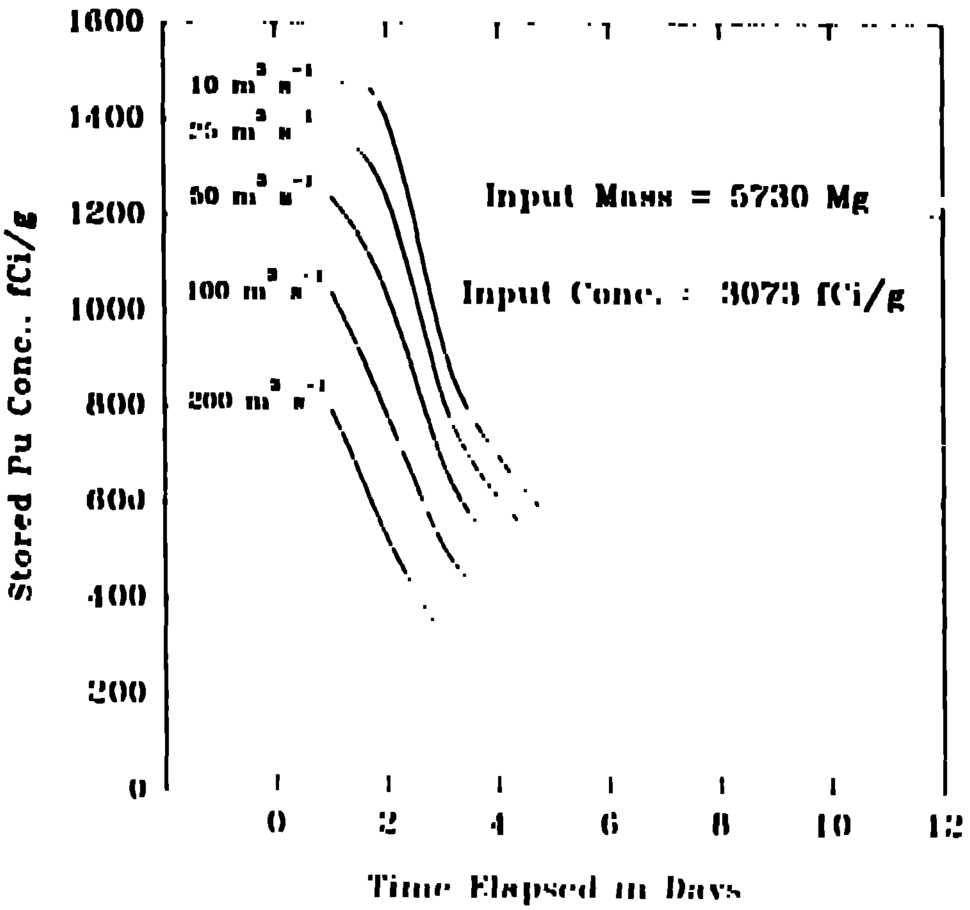

Figure 16.4 RAT simulation results showing plutonium concentrations in stored sediments along the Rio Grande as a result of varying lengths of time for mixing and dispersion. The individual lines in the diagram represent conditions with different dicharge conditions in the Rio Grande, ranging from low flow (10 m^3 s^{-1}) to major flood (200 m^3 s^{-1})

In that year, Los Alamos Canyon contributed by flash flood 5,730 Mg of bedload sediment with 3,073 fCi/g of plutonium to the Rio Grande when the discharge in the main stream was about 68 cubic meters per second. After 10 simulated days, the plutonium concentration in bedload sediments in segment number 2 was about 200 fCi/g. Although this scenario is probably a simplification of actual events, it indicates why the resulting deposits along the main channel were likely to contain relatively low concentrations of plutonium even though they began their journey in Los Alamos Canyon with relatively high concentrations. All samples of sediment collected in the field from near-channel deposits along the Rio Grande show plutonium concentrations below this probable maximum value.[2]

As in previous simulations, increasingly high discharges result in decreasing plutonium concentrations in bedload sediments of the main channel. Irrespective of the magnitude of discharge, however, the greatest mixing and dispersion (with attending declines in plutonium concentrations) occurred during the first four to six days (Figure 16.4). Thereafter, changes were more gradual in all the discharge examples. The slight increase in concentrations between days one and two for the discharge of 10 cubic meters per second in Figure 16.4 is an artifact of the cubic spine curve used to represent the data rather than an actual increase.

Over periods of several days, operations of the main river cause infusions of different concentrations to decrease toward a common, relatively low value. Figure 16.5 shows the results of simulations for the 1952 case by plotting the plutonium concentrations in segment number two for a variety of initial concentrations. The line in Figure 16.5 representing 3,000 fCi/g is close to the probable actual value for 1952. Although the range in concentrations on simulated day one was 4,000 fCi/g (that is, the range from 1,000 to 5,000 fCi/g), after 10 simulated days this range had declined to only 250 fCi/g. Deposits along the main channel from a variety of infusions from Los Alamos therefore may not exhibit radically different plutonium concentrations even if they had such differences at the times of injection. The primary differences, up to an order of magnitude, that are likely to be observable in deposits are those between materials derived from Los Alamos and those derived from the upper basins of the Rio Grande. Such differences are in fact observed in deposits described previously for a depositional area at Buckman (see Chapter 12)

16.5 Geographic Variation

The calculations described above have referenced processes occurring in a single segment of the Rio Grande, the confluence area with Los Alamos Canyon. As sediment and plutonium move downstream through a series of successive segments in the Rio Grande, some segments store materials while others merely transport the materials through to the next segment downstream. The result is substantial geographic variation in plutonium concentrations and inventory in sediments along the Rio Grande.

As an example, calculations using the RAT program provided data for three simulated days and the 1952 case values (input mass = 5,730 Mg, input plutonium

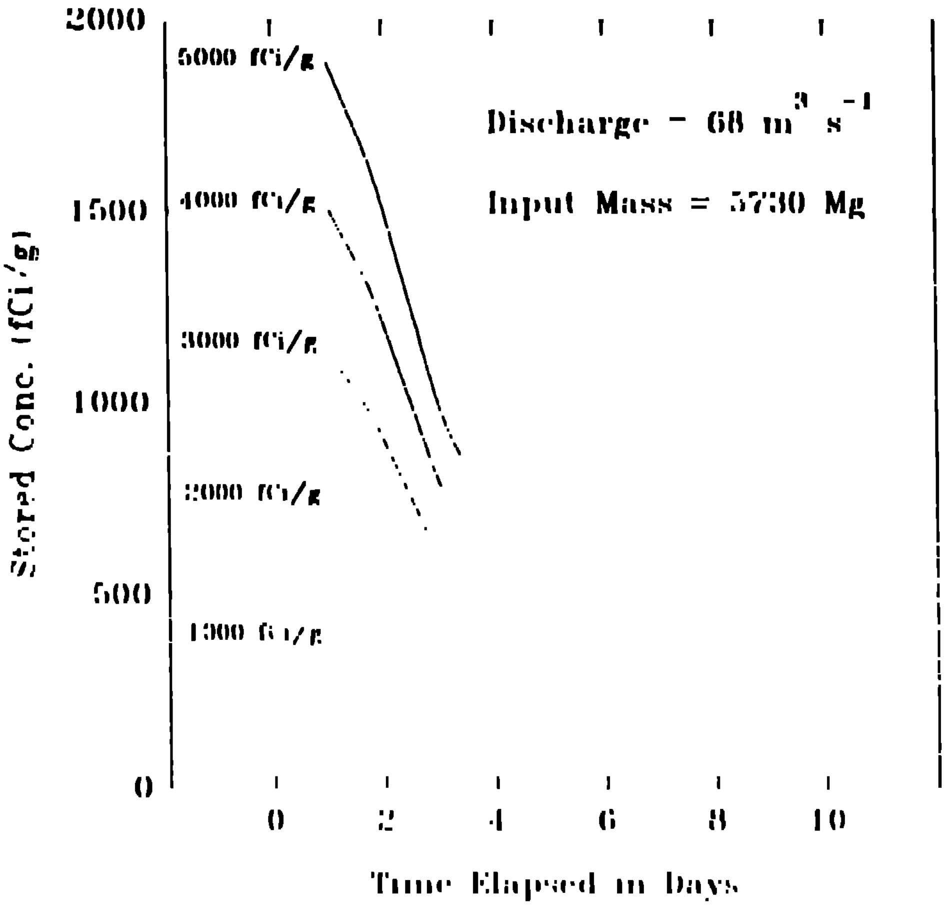

Figure 16.5 RAT simulation results showing plutonium concentrations in stored sediments along the Rio Grande as a result of varying lengths of time for mixing and dispersion. The individual lines in the diagram represent different concentrations of plutonium in the input masses from Los Alamos Canyon

concentration = 3,073 fCi/g, input plutonium amount = 17.6 mCi, and Rio Grande discharge = 68 cubic meters per second). The calculations indicated the plutonium inventory for each of the 22 segments of the Rio Grande between Otowi and the headwaters of Cochiti Reservoir, as well as the inventory of plutonium exiting the canyon and depositing in the reservoir sediments (Figure 16.6).

At a first level of analysis, there is an alternating pattern of segments that store materials with those that do not. This gross pattern is the result of the geomorphology of White Rock Canyon as described in Section 15.2 and as incorporated within the model. In the field, these alternating segments are obvious, because those with storage have shallow gradients, sediments along the channel edges, and sometimes mid-channel bars at low-water periods. The segments without storage have steep gradients, no mid-channel bars, and canyon walls that decend to the channel margins.

Several variables control the amounts of sediment and associated plutonium in those segments with storage. Although the amounts of sediment moving downstream exert some impact on inventories, the geomorphic and hydraulic characteristics of the storage segments are also important. One segment may store large quantities simply because space has been available for the material on the canyon floor, as is the case in segment number 2 at the mouth of Los Alamos Canyon or number 8 near Buckman (see locations on Figure 15.3). Other segments, such as number 18 in the depths of White Rock Canyon, have relatively little storage, even though they are long, because steep slopes near the channel restrict available space for deposition

The distribution of stored plutonium shown in Figure 16.6 that resulted from three simulated days of river processes shows that the greatest inventory of stored materials occurs in segment number 2 at the mouth of Los Alamos Canyon, but there is no consistent decrease in inventories downstream from the entry segment. Inventories generally decrease to segment number 10, but are larger thereafter. The amount stored in the Cochiti Reservoir segment is larger than in segments immediately upstream, because the reservoir segment collects all the material exiting the canyon system. This circumstance occurs under present conditions with the reservoir in place, but dispersed deposition of most bedload from White Rock Canyon probably occurred in the Cochiti Pueblo Santo Domingo Pueblo reaches of the Rio Grande (typified by the Peña Blanca representative reach described in Chapter 13) in the pre reservoir period

Longer simulated periods show that without large floods, there is a slow movement of plutonium from the large inventory at the mouth of Los Alamos Canyon through White Rock Canyon to the reservoir segment at the downstream end. Large floods accelerate the movement. The proportion of the total plutonium inventory stored within each segment remains consistent with the largest amounts (in addition to the mass at Los Alamos Canyon and immediately downstream to Buckman) located between the confluences of the Rio Grande with Pajarito and Water Canyons and below the confluence with Frijoles Canyon (Figures 15.3 and 16.6). The ultimate fate of the plutonium stored along the main channel downstream from Otowi is transport into Cochiti Reservoir, a process likely to require decades, or centuries, depending on

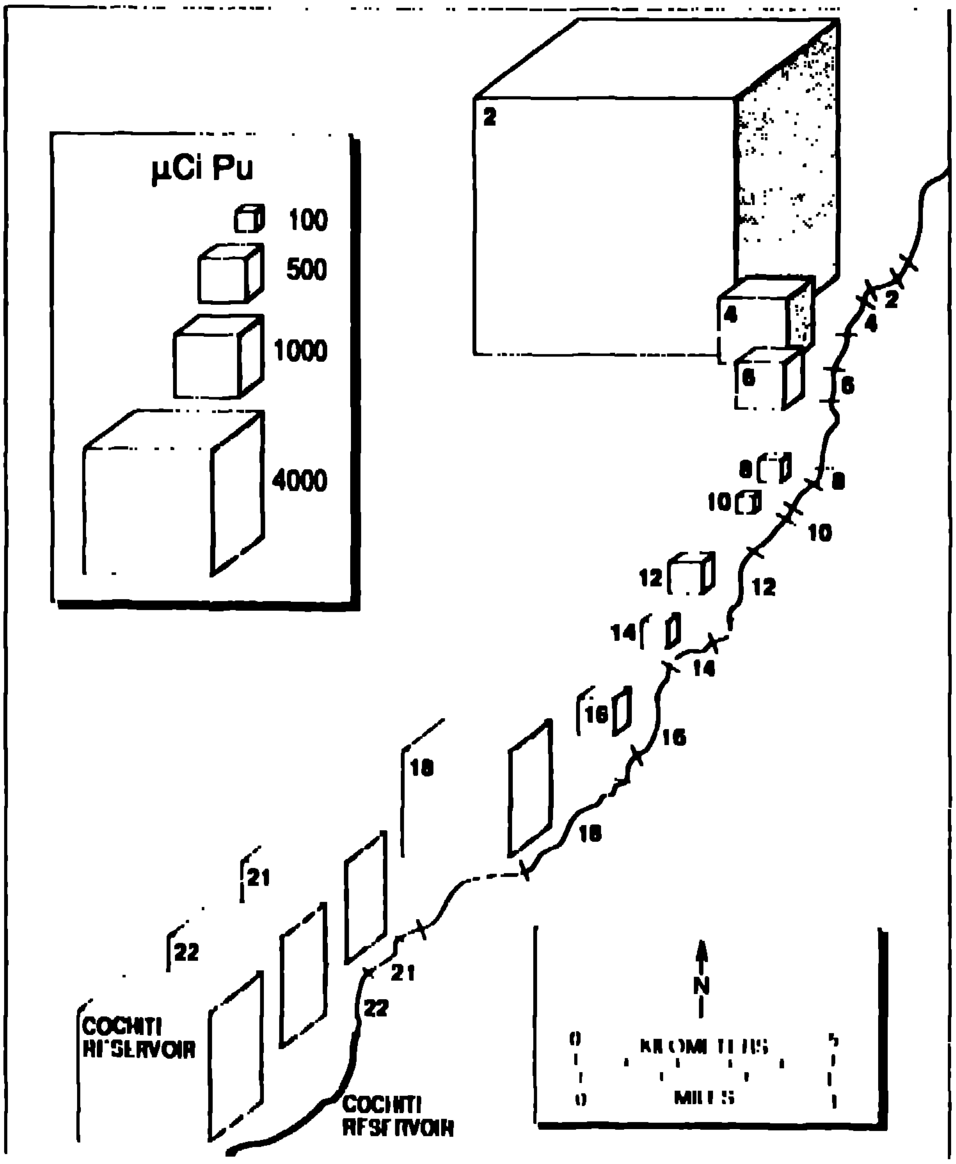

Figure 16.6 RAT simulation results showing the geographic variation of amounts of stored plutonium resulting from three simulated days of transport and storage after an injection of contaminated sediment from a flash flood in Los Alamos Canyon, a tributary in segment 2. The simulation parameters were similar to the conditions likely to have occurred in 1952. The sizes of the cubes are proportional to the amount of plutonium stored in each segment, with the number in the cube identifying its corresponding segment. Segments without stored sediment or plutonium are not represented by cubes. See Figure 15.2 for a more detailed location map.

the discharge regime of the Rio Grande. Higher discharges will produce more rapid movement. The trends established by simulations show that if dispersion and mixing continue over relatively long time periods (approaching 100 days), the plutonium concentrations will decline to values that approach levels resulting from fallout contributions alone (Figure 16.7).

The concentrations of plutonium in the stored sediments depend on the concentrations introduced from Los Alamos Canyon and the amount of stored sediment. Simulations show that the concentrations are generally low, in many cases approaching the range of less than 100 fCi/g after 20 simulated days of river processes. The plutonium concentrations in sediments impacted by a single event vary by about 50 percent as a result of differential mixing, deposition, and then subsequent remobilization. Therefore, the deposits resulting from one release from Los Alamos Canyon and stored in several different segments of the Rio Grande may not all have the same plutonium concentrations.

16.6 Conclusions from Simulations

Simulations of river processes using the RAT program produce the following generalizations about the fate of bedload plutonium released into the main stream by flash floods in Los Alamos Canyon.

1. Mixing with large quantities of sediment from the Upper Rio Grande basin and downstream dispersion causes a decline in plutonium concentration in sediments impacted by contributions from Los Alamos Canyon. River processes and the geomorphology of White Rock Canyon result in concentration of stored plutonium at particular locations along the main channel, and there may not be a decline in downstream concentrations.

2. Plutonium concentrations in sediments released from Los Alamos Canyon decrease by about 50 percent upon entry into the Rio Grande.

3. If discharges in the Rio Grande do not decline precipitously, plutonium concentrations decrease rapidly within the first 4-6 days after the release, with more gradual decreases thereafter.

4. By the time that plutonium-bearing sediments are deposited, plutonium concentrations decrease to the range of < 100 fCi/g.

5. Because of the complexity of differing input masses, input concentrations, time to deposition in the main channel, and discharge variation in the Rio Grande, different releases from Los Alamos Canyon may have similar or radically different plutonium concentrations after deposition irrespective of their initial concentrations.

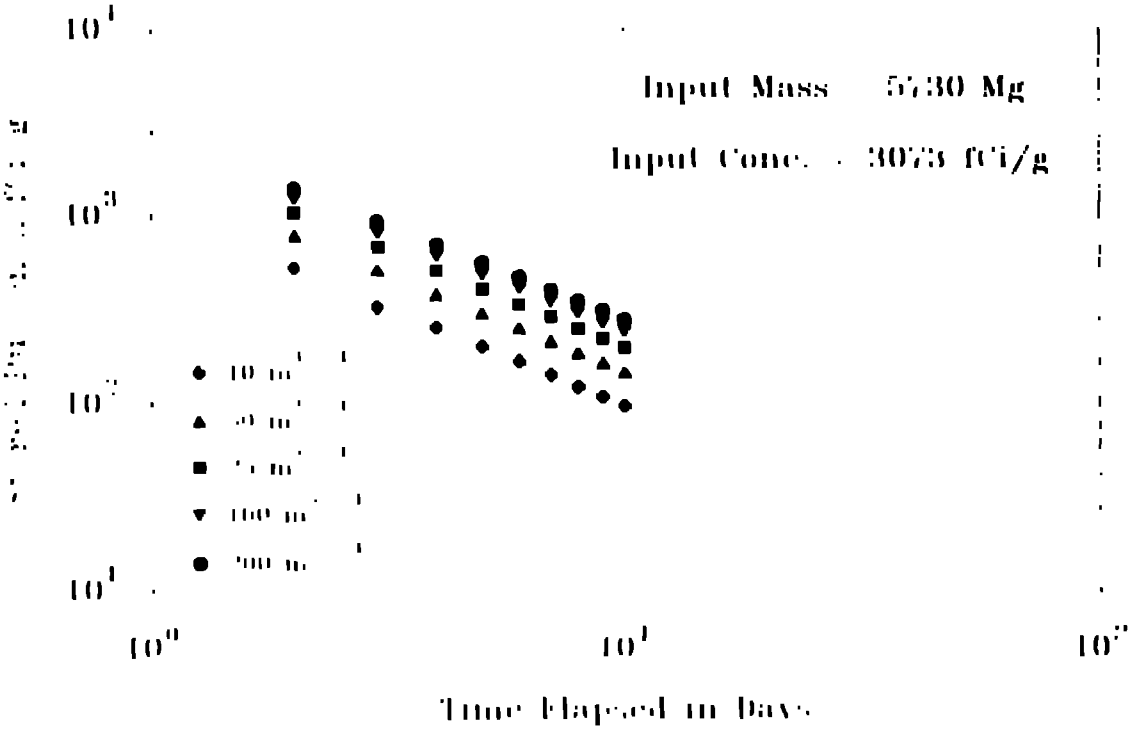

Figure 16.7 Long term results of the RAT simulation showing the decline in plutonium concentrations in sediments stored along the Rio Grande. Each line of symbols represents different discharge conditions in the Rio Grande, ranging from low flow (10 $m^3 s^{-1}$) to the unlikely case of a sustained major flood (200 $m^3 s^{-1}$). The solid lines define the envelope of extrapolated concentrations ranging from one simulated day of mixing and dispersion to 100 simulated days.

6. Of the plutonium released from Los Alamos Canyon in bedload, most is likely to remain within the White Canyon segments of the Rio Grande. Before the closure of Cochiti Dam in 1973, some sediments probably deposited in the Cochiti Pueblo-Santo Domingo Pueblo reaches, and after the closure of the dam the materials were deposited in the reservoir.

7. Over a period of decades or centuries, it is likely that almost all of the plutonium presently stored within White Rock Canyon and at the mouth of Los Alamos Canyon will move to deposition sites within the reservoir.

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PART 6. CONCLUSIONS

CHAPTER 17. SUMMARY AND CONCLUSIONS

17.1 General Program Recommendations

Los Alamos National Laboratory operates under legal requirements that include sampling and monitoring the environment for potential effects of laboratory activities, including the release of plutonium. The legal requirements include compliance with more than 20 federal and state laws related to environmental quality, including the federal Clean Water Act and Clean Air Act. The laboratory operates its surveillance and monitoring according to specific U. S. Department of Energy orders: number 5400.1, "General Environmental Protection Program," and number 5484.1, "Environmental Protection, Safety, and Health Protection Information Reporting Requirements." The general philosophy underlying these regulations and the approach of the laboratory to meeting them is to provide data to document compliance, identify temporal trends, provide knowledge to the public, and to enhance general understanding of environmental processes. Because of potential hazards to human health, the program emphasizes sampling of air, water, soils, and foods.

The laboratory efforts focus on three geographic areas. First, workers sample a series of "regional" sites in northern New Mexico with the intention of providing information from environments unaffected by laboratory operations. Second, "perimeter" sites within about 4 km of the laboratory boundaries provide data on areas potentially affected by the laboratory and that serve as a "trip wire" to detect any significant movement of contaminants from the laboratory. These sites include areas frequently used by the general public. Third, "on site" sample locations within the laboratory boundaries assess potentially impacted areas that are not generally accessible to the public.

The results of the present work in the Northern Rio Grande indicate that laboratory surveillance and monitoring for plutonium should include a more refined program for sediment quality. The movement of sediment from Los Alamos Canyon and other potentially contaminated canyons is the most likely vector by which plutonium will exit the laboratory site. As indicated by Lane et al. (1985), this process is relatively slow, but inevitable, so that eventually all the plutonium stored in canyon alluvium will move into the Rio Grande. The results of the present study indicate that these materials are likely to be stored a short distance down the main river as alluvial deposits either directly accessible to the public (as at Buckman) or indirectly accessible to the public as reservoir deposits (in Cochiti Reservoir).

A refined sampling and monitoring program for plutonium in sediment should be driven by a philosophy that has the following general objectives:

1. An accurate inventory of plutonium stored in sediments in Los Alamos Canyon. An accurate assessment of the amount of plutonium stored in Los Alamos Canyon is not yet available. Estimates from administrative records suggest as little as

150 mCi, but reasonably reliable estimates of yearly outputs from the canyon between 1944 and 1980 indicate that more than 150 mCi has already been eroded from the canyon. Other data indicate large amounts of plutonium still in sediments of the canyon, so that the 150 mCi estimate is clearly too low. It is not possible to design well-informed management programs if the magnitude of the contaminant loading remains little known. Further studies of channel and flood-plain alluvium in Los Alamos Canyon that include a more dense sampling network to supplement data already collected and published may provide a useful assessment of the total amount of plutonium in the system.

2. **An accurate understanding of the temporal trends in the movement of plutonium into the Rio Grande.** The movement of plutonium into the Rio Grande is an irregular process that has been estimated using the methods established by Lane et al. (1985). This model should be solved each year and the predicted outputs of plutonium should be periodically collated and published. Otherwise, the significance of the plutonium inventory in the canyon and its impact on the main river and Cochiti Reservoir cannot be assessed.

3. **An accurate understanding of the geography of plutonium in sediments near the laboratory, including detailed mapping of sediments and their plutonium content in Los Alamos Canyon and along the Rio Grande between Otowi and Cochiti Reservoir.** The results of the present work indicate that plutonium in sediments is likely to be spatially variable. Most of the monitoring efforts of the laboratory heretofore have focused on temporal variability. In the case of plutonium in sediments, it appears that the geographical location of the deposit (combined with its age) is the most important predictive factor in assessing its potential for plutonium contents. The sediments in Los Alamos Canyon should therefore be sampled and mapped at a scale that reflects this variation, rather than merely sampling "a channel area" and "a flood plain area." The present work indicates that detailed mapping with periodic updates would be prudent for the depositional areas between the confluence of Los Alamos Canyon and the Rio Grande and Cochiti Reservoir.

4. **An accurate assessment of the distribution of sediments and plutonium in Cochiti Reservoir.** An accurate interpretation of plutonium concentrations in sediments from Cochiti Reservoir is not possible given present monitoring methods. The reservoir has a complex distribution of deltaic and deep water sediments that remains unknown, and the nature of these deposits influences the information available from samples. The samples must be characterized according to their process histories (such as delta, turbidity current deposit, and deep water fine deposit) and precise location on the reservoir floor rather than merely a label such as "upper," "middle," or "lower reservoir." As the twenty first century approaches and more plutonium from the laboratory enters the sediment system, the reservoir will become an increasingly important monitoring target, because it represents the ultimate resting place of all contaminates in the sediment system above the dam. To prepare for this certainty, the reservoir sedimentation processes and deposits should be mapped in detail and monitored from a sedimentological perspective as well as from a radiological one.

5. A two-part approach to the above points that includes engineering-modeling activities and empirical-scientific verification of the conclusions. Two primary approaches to explanation for the environmental processes with which a monitoring and surveillance program must deal are those based on engineering-models and those based on empirical-scientific methods. Both approaches are required. Engineering models such as the computer models by the Hydraulic Engineering Center for estimating water surface profiles, sedimentation, and scour (known by their acronyms HEC2 and HEC6) provide useful and detailed predictions Their major weaknesses are that they include many assumptions not adequately met in an unstable channel environment, and they require large amounts of high-resolution input Scientific models based on empirical data (such as the present work) provide more convincing conclusions because the data are "real" rather than generated, but the empirical approach is severely limited by lack of data from critical locations Both approaches suffer from the requirement to sometimes make weakening assumptions such as stationarity for time or spatial series. As a result, long term averages substitute for variable data, and potentially important details are lost For these reasons, a combination of the two approaches is most likely to supply useful explanations for the movement and storage of sediment borne plutonium

6. The development of simple computer-based models that accept as input the annual surveillance data and that produce as outputs annual assessments of plutonium flux and storage in the on site and perimeter stream systems. The explanation of sediment and sediment borne plutonium mobility and storage can be most effective for a monitoring and sampling program if the explanation results in a simple general model established for use by non specialists. The model should be simple, because detailed specifications for the environment of its application are likely to be limited For example, while maps with contour intervals of less than 1 meter may exist for Los Alamos Canyon, they are not available for the Rio Grande between Otowi and Cochiti Reservoir The maintenance of such maps would be prohibitively expensive in any case because the configuration of the channel of the river changes with each major flood Therefore, a model that includes simplifying assumptions and that makes calculations for mean conditions rather than specific events is most likely to be effective Such a model would accept as input information from stream gaging sites for water and sediment discharges as well as the products of the ongoing plutonium sampling efforts The model should be workable in an interactive program designed for standard, low level personal computer so that it can be used by non specialists and can be explained in non technical language to regulators and the public

7. The establishment of a regional context that includes budgets for all the major contaminants for which the laboratory has a monitoring responsibility in order to provide an environmental context for the laboratory operations. No established national standards exist for chemical and radiological quality in sediment, so that reported concentrations and amounts of flux and storage of plutonium are difficult to assess. For the near future, the solution to the interpretation problem is to provide a context for reported data. Concentration data provide an incomplete picture of regional processes without including the annual mass fluxes, and annual mass storages. The geographic locations of storage sites should be included in the context because of the radical variability and discontinuous nature of distribution of contaminants in sediments. On a longer term basis, the laboratory should consider the development of national sediment quality standards for plutonium and other contaminants.

8. The development of a program to assess isotopic ratios in order to discriminate plutonium contributions of fallout from those derived from Los Alamos. The present budget analysis and computer modelling show that contributions of plutonium from fallout and from Los Alamos are within an order of magnitude of each other in the general system. In specific bedload deposits for particular years immediately below Otowi, the contribution of Los Alamos may be larger, while in other deposits the contribution of fallout may dominate. Contributions to Cochiti Reservoir, whatever their origin, are higher than in other reservoirs in the area. An improved monitoring program requires the ability to discriminate between the two sources for plutonium in sediment storage. For worldwide fallout, the ratio between plutonium-238 and plutonium-239,240 is about 21, while for plutonium released from Los Alamos, the ratio is much higher. Plutonium isotopic ratios for sediments in Los Alamos Canyon are significantly different from those for fallout, so that it may be possible to use the ratios as labels for plutonium found in flood plain or reservoir sediments. Because of the relatively high levels of plutonium in Cochiti Reservoir, establishing the origin of the material will provide improved understanding of the plutonium budget. A similar approach using lead/zinc/copper ratios has proven workable in a dryland stream in Arizona (Graf et al., 1991). Erel et al. (1991) have suggested the same strategy for lead/cadmium ratios in a Sierra Nevada stream.

17.2 Specific Procedural Recommendations

The specific procedures for collecting sediment samples in the field for plutonium analysis can be improved from a geomorphological perspective with the adoption of the following points.

1. Sample site selection for dynamic interpretations. Wherever possible, samples for the analysis of plutonium content in river sediments should be collected at stream gage sites. Collection should include suspended sediments and bedload sediments at Chamita on the Rio Chama, Embudo and Otowi on the Rio Grande, and at gaging sites in Los Alamos and Frijoles canyons. These collection sites provide the framework for understanding the movement and storage of total amounts of plutonium in the sediments near Los Alamos. At Otowi, the location of the sample site is especially critical, because sediment for analysis must be taken at the gage site or immediately upstream. If it is taken even a few meters downstream from the gage location, the samples may include material from Los Alamos Canyon, thus providing a false impression of the amounts in transit in the Rio Grande before it reaches the confluence with the tributary

2. Sample collection from both suspended and bedload materials. Previous analyses by the Environmental Surveillance Group (various years) has shown that the plutonium content of suspended sediment is greater than the content of bedload sediment. The present work shows that the difference is critical in understanding the regional dynamics of plutonium as it moves through the river system. Further, inputs from Los Alamos are likely to emphasize bedload. Therefore, both types of sediment should be sampled from each collection site on the river. The majority of "river sediment" samples assessed for plutonium content in the past have been bedload samples drawn from the margin of the active channel. Plutonium content of these samples is useful information, but it should be supplemented with data concerning the sediments in suspension which have a different size distribution and different plutonium concentrations. Having data for both types of sediment will make interpretation of reservoir data more informative. For example, it should be expected that sediments on the floor of Cochiti Reservoir (derived mostly from suspended sediments) have a different plutonium content than what have been referred to as "river sediment" samples (heretofore mostly bedload) collected in White Rock Canyon.

3. Particle size data for sediment and soil samples. The interpretation of plutonium concentration data for suspended sediment, bedload sediment, and soil samples is severely limited in the absence of information on sediment particle sizes. The reporting process should include for each sample some indication of the particle size distribution. The simplest approach is an assessment of the percent fine material in the sample: the percent by weight of the sample composed of particles smaller than 63 microns in diameter. Particle size data are critical, because most of the fallout plutonium is associated with the smallest particles, while most of the plutonium from Los Alamos is associated with larger particles.

4. Documentation of sample sites. It is unlikely that annual surveillance reports have enough space to completely document each and every sample site for every part of the report. Interpretation of the sediment data, however, requires improved reporting of the location of the sample site that includes a detailed map of the sample area at a scale of at least 1:24,000. For each site, a copy of a small section of the U.S. Geological Survey quadrangle covering the area with the site prominently marked would serve as a useful record that could be used by future workers who need to reoccupy the site to maintain a continuous record of samples. This accurate geographic record would also improve interpretation of the reported plutonium concentrations by future researchers, regulators, and the public.

5. Improve the sample design in White Rock Canyon. With the passage of time, the movement of plutonium derived from Los Alamos and contributed to the Rio Grande will result in larger amounts of plutonium from the laboratory in the general river system. The movement of this plutonium through White Rock Canyon to Cochiti Reservoir will become a point of increasing interest for the monitoring and surveillance program. At present, the sampling of "river sediment" (bedload materials) in White Rock Canyon is not clearly defined. Samples taken "at Pajarito Canyon, Sandia Canyon, Ancho Canyon," for example, might be taken above or below the confluence with the tributary in each case, a critical issue in interpreting whether or not the sample includes materials from the tributary. Whether the sample was drawn from the left or right bank is also an important issue. A standardized approach with a documented sample site at each location will enhance the monitoring effort and the utility of the data it produces. Flood plains within the canyon, though small, are critical unsampled locations under present procedures.

6. Specific identification of soil sample sites. Each sample drawn for assessment of plutonium in soil should be reported along with a statement on the geomorphic origin of the soil material. Hillslope materials are likely to contain less plutonium than materials found at the foot of the same slope because of erosion and deposition of shallow materials carrying fallout. Soil samples from flood plains, as shown by the present work, may contain variable amounts of plutonium depending on the date of emplacement. Soils on flood-plain surfaces established during the 1950s or 1960s, for example, might reasonably be expected to contain more plutonium than surfaces established in other decades.

17.3 Control Sites

Data for plutonium in the environment of Los Alamos can be useful in monitoring the laboratory contribution to the system only if sufficient background information is available for comparative purposes. Previous sampling efforts for river sediments have not adequately addressed the need for control sites that are clearly unaffected by laboratory. The regional reservoir sampling program, in effect since 1979, has produced valuable information and should be continued. The focus of the program should be on Cochiti Reservoir as the primary recipient of inputs from Los Alamos and fallout plutonium. The major control site for the reservoir program should continue to be Abiquiu Reservoir, because it is located upstream from the laboratory, but Rio Grande Reservoir, in the headwaters of the system, should also be regularly included. The fallout plutonium entering the Rio Grande Reservoir is a useful comparative value for Cochiti because the mountain reservoir probably represents the maximum loading to be expected without laboratory contributions. Abiquiu represents local conditions near Los Alamos, but because there are two major reservoirs upstream from it on the Rio Chama, Abiquiu is not likely to receive much of the fallout plutonium eroded from the high elevation portions of the watershed where it was probably deposited in the greatest quantities.

Frijoles Canyon in Bandelier National Monument should be sampled annually for plutonium in suspended sediments and in bedload materials. Frijoles Canyon provides the best control site (with conditions unaffected by laboratory releases) for conditions in Los Alamos Canyon. Both stream systems originate in the upper slopes of the Jemez Mountains, have steep gradients to the Rio Grande, transport high quantities of sand and larger size particles, derived most of their sediments from the Bandelier Tuff, and have a semiarid climate with similar natural vegetation. Suspended and bedload materials in the Rio Grande at Bernalillo also provide important contextual information in assessing the impact of Los Alamos on the entire system.

Flood plain areas in the Santa Clara reach, the portion of the Rio Grande between Española and Otowi provide useful control sites for flood plains and channel deposits below the confluence of Los Alamos Canyon and the main stream. The river has had a history of channel changes in the Santa Clara Pueblo area that is similar to changes downstream, and the reach can provide sediment samples whose plutonium content can serve as a standard for samples taken below Los Alamos Canyon to assess the impact of the laboratory contributions.

17.4 Summary

This work began with the statement of two general objectives: to define general hydro-geomorphic principles for the dynamics of plutonium in a representative dryland drainage basin and to contribute to the specific development of an increasingly effective sampling and monitoring program for Los Alamos National Laboratory. The work has shown that plutonium yield from the 71,740 sq km system above Elephant Butte Reservoir is about 23-80 mCi per year. Monitoring data and budget information show that almost all of the plutonium dynamics in the system are related to sediment transport. Temporal data show that the processes of transport and storage are episodic for both fallout and industrial plutonium. Geographic data show that the processes of transport and storage are discontinuous and highly variable from one place to another, but storage is in predictable locations: flood plains, abandoned channels, and channel side bars. Valley width determines the general locations of these storage areas.

This chapter contains specific recommendations for enhancement of the sampling and monitoring effort by Los Alamos National Laboratory. In general, these recommendations emphasize more accurate reporting of the location of samples, inclusion of sediment size characteristics in data collected, and more attention to flood plain reservoir sites in areas close to Los Alamos and to suspended sediments.

This work also began with a series of eight specific objectives. The following paragraphs summarize the conclusions regarding their points.

The Environmental Context. The physical environmental context of the laboratory includes a variety of process regions. The mountain areas contribute most of the water in the system, some of the sediment, and significant amounts of the plutonium because of fallout. Erodible soils are scattered throughout the Northern Rio Grande Basin, but they are especially prominent in the central and lower basin.

Water and Sediment Budgets. The mass budgets for water and sediment in the Northern Rio Grande show that downstream from Otowi, the amount of water available for sediment transport declines. Sediment storage is therefore prominent in the central and lower areas of the basin. On an average basis, only 50 percent of the suspended sediment and 20 percent of the bedload that enter the system leave to be deposited in Elephant Butte Reservoir. The remainder, 50 percent of the suspended load and 80 percent of the bedload remains in internal storage

River Channel Change. The major changes within the channel system resulting from this storage process have included increasingly wide flood plains, abandoned and clogged channels, expanded bars, and the conversion of the braided channel of the 1930s to the single thread channel of the 1990s. These expanded deposition areas are so large that despite the large amounts of sediment added to them, the mean depth of accumulation since the 1940s is less than one meter. Engineering works have generally enhanced the deposition, except for channel erosion below Cochiti Dam.

Mapping Techniques. The near-channel deposits resulting from the deposition of sediments can be identified and mapped using historical aerial photography, vegetation associations, and field reconnaissance. Standard U.S. Geological Survey maps are useful base maps that can be modified to show the distributions of deposits of various ages.

Representative Reaches. The detailed analysis of eleven representative reaches along the Northern Rio Grande shows a variety of forms and dates of deposition, but deposits in the vicinity of Otowi and Buckman are the most likely to contain plutonium from Los Alamos. Many deposits along the river are likely to contain plutonium from fallout. The plutonium content varies from one deposit to another as a function of the date of deposition, origin of sediments, and sediment size characteristics.

Plutonium Budget. The regional plutonium budget shows that fallout contributes about 90 percent of the total plutonium moving through the system in any given year. Los Alamos contributes the remaining 10 percent. Because of the removal of plutonium from Los Alamos Canyon by natural erosion and its deposition in the Rio Grande, and because sediment in the canyon has relatively high percentages of coarse material carried in bedload, the laboratory contribution to the total budget is most significant for bedload materials. Because discharges from Los Alamos Canyon to the main river were prominent only during 1951, 1952, 1957, and 1967, bedload deposits from those years represent the major impact of the laboratory releases. Concentrations in such deposits, however, are below hazardous levels.

Geography of Storage. The importance of bedload transport and the likelihood of early deposition of such materials below the confluence of Los Alamos Canyon and the Rio Grande mean that the geographic distribution of plutonium from the laboratory in the system is limited. Plutonium from Los Alamos is likely to occur in deposits near Otowi and near Buckman. Before the closure of Cochiti Dam in 1973, it may have traveled as far south as Peña Blanca. Transport of laboratory materials in identifiable quantities below Peña Blanca is unlikely, and dilution with sediments from other sources probably makes recognition of laboratory contributions below Peña Blanca impossible. After 1973, almost all plutonium in the fluvial sediments near Los Alamos have been stored as reservoir sediments behind Cochiti Dam.

Sampling Program. The design of a simple, defensible sampling program for surveillance and monitoring by Los Alamos National Laboratory depends on the use of data provided by this report concerning the location of probable storage areas for plutonium in flood plains and reservoir sediments. An ongoing program should sample suspended and bedload sediment in a systematic, repetitive fashion in mapped, marked sites associated with stream gages where possible. Control sites enhance the utility of reported values from primary monitoring sites.

Data Bank. The appendices of this report provide a compilation of the available data concerning the fluvial properties of the Northern Rio Grande. The data are empirical and are not generated by model operations. However, the data provide the input for the operation of a computer program designed to model the movement and storage of sediment and associated plutonium in the system. The model will be completed shortly.

17.5 Probable Futures

The general nature of the Rio Grande is unlikely to ever again be as it once was (Figure 17.2). Changes in the system are uncertain, but some aspects of the future operation of the Northern Rio Grande are virtual certainties. The present work shows that the erosion and transportation of fallout plutonium through the system is occurring at a rate that is not likely to exhaust the total inventory for more than 2,000 years. If the rates of erosion and transport in Los Alamos Canyon observed over the past 40 years prevail, the canyon will contribute plutonium from Los Alamos for 100-600 years, depending on the magnitude of the original inventory. Rates of transfer of sediment and plutonium to the Rio Grande will continue to be a sporadic process, with radical variation in the magnitude of the contribution to the main stream. For the next several hundred years, Cochiti Reservoir will continue to store sediments and plutonium in increasing amounts from upstream sources. Over the same time period, the nature of the channel of the Rio Grande is likely to continue in a depositional mode with aggradation, but it is unlikely that upstream dams will completely eliminate large floods and associated channel adjustments.

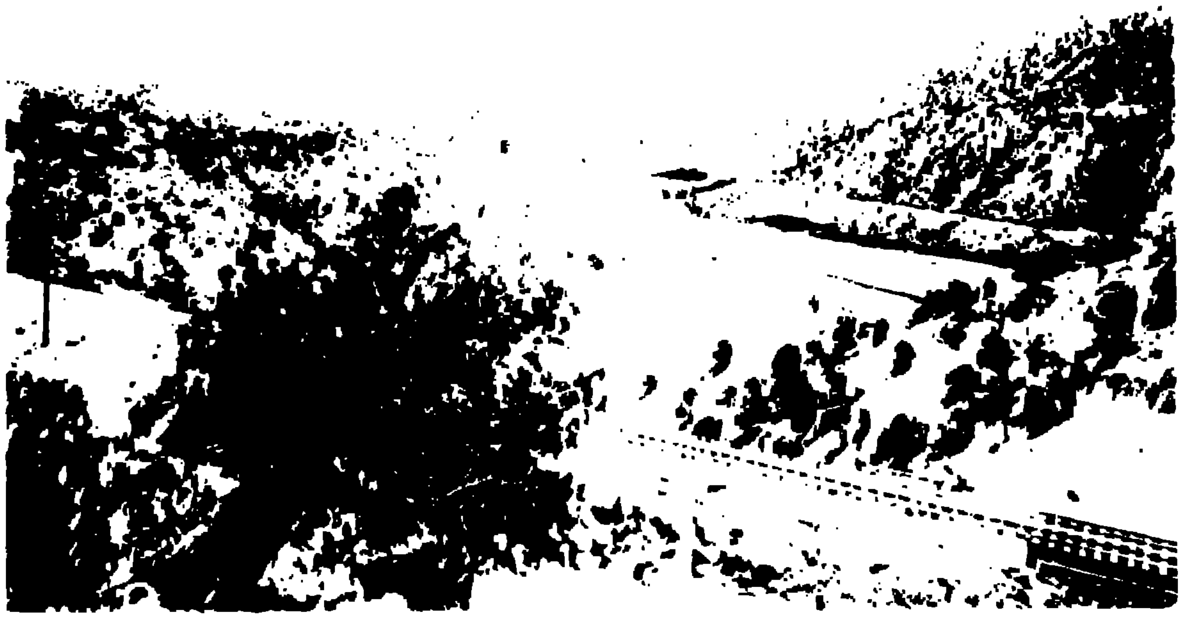
Channel changes with the establishment of a braided system followed by a gradual return to the present geometry are possible within a few hundred years. Sediment and plutonium stored in flood plains, abandoned channels, and channel side bars are likely to be remobilized during the changes, resuming their movement downstream. The result will be temporarily increased rates of deposition in Cochiti Reservoir.

Long term economic development may result in increased emphasis on control of the channel of the Rio Grande in the Española and Santa Clara Pueblo areas immediately upstream from Otowi. If such development produces engineering efforts that result in a straight, narrow channel of the river there, assessments of the potential erosion impacts at Otowi and Buckman would be required. Remobilization of previously stored sediment and plutonium occurred along the Rio Grande downstream from channel works elsewhere in the system (as shown by the regional plutonium budget for the 1970s which responded to engineering works completed in the 1960s). A similar response is likely in the Española-to-Buckman reach with increased deposition in Cochiti Reservoir if channelization occurs in the Española area.

The natural environment of the river system is unstable over long time periods,

Figure 17.2 An early 1800s woodcut showing the character of the Rio Grande in northern and central New Mexico before the channel changes and engineering works of the past century (Denver Public Library, Western History Collection, Photo #07031).

but so is the regulatory environment within which Los Alamos National Laboratory must operate. Over the past 30 years, environmental regulations related to rivers have become progressively more restrictive, reflecting a national culture that has become increasingly conscious of environmental quality. It seems reasonable that this trend will continue. Part of any regulatory program is the assignment of responsibility, with producers of potential pollutants accountable for their individual contributions to the environment. It seems likely that Los Alamos National Laboratory will someday have to define what part of the total plutonium loading in Cochiti Reservoir derives from the laboratory. Refinements of the isotopic ratio method of identifying the source of plutonium are wise investments in anticipation of more rigorous legal and licensing requirements likely to appear in the near future. The present work defining the regional plutonium budget indicates that the likely outcome of such efforts will be two-fold. First, the contribution of Los Alamos to the total regional plutonium system is a small fraction of the contribution by fallout products. Second, the contribution of Los Alamos to plutonium in some specific bedload deposits is likely to be definable.



[illegible]

APPENDICES

APPENDIX A. UNITS OF MEASURE

A.1 PREFIX TERMS FOR UNITS OF MEASURE

Term	Power of 10	Symbol
exa-	10^{18}	E
peta-	10^{15}	P
tera-	10^{12}	T
giga-	10^{9}	G
mega-	10^{6}	M
kilo-	10^{3}	k
hecto-	10^{2}	h
deca	10^{1}	da
deci	10^{-1}	d
centi	10^{-2}	c
milli	10^{-3}	m
micro	10^{-6}	u
nano	10^{-9}	n
pico	10^{-12}	p
femto	10^{-15}	f
atto	10^{-18}	a

Note. From Weast (1988, p. F-158).

A2. UNITS OF MEASURE FOR ISOTOPIC DECAY RATES

Medium	Pico-Curies	Common Useage	International System
Air	10^{12} uCi/ml	1 pCi/m^3	0.037 Bq/m^3
	10^{15} uCi/ml	0.001 pCi/m^3	0.000037 Bq/m^3
	10^{18} uCi/ml	10-6 pCi/m^3	3.7 x 10-8 Bq/m^3
Liquids	10^{9} uCi/ml	1 pCi/l	37 Bq/m^3
	10^{12} uCi/ml	0.001 pCi/l	0.037 Bq/m^3
Solids	1 pCi/g	1 pCi/g	37 Bq/kg
	1 fCi/g	0.001 pCi/g	0.037 Bq/kg

A3. CONCENTRATION AND RIVER FLOW CONVERSTIONS

	Metric Units	English Units
Concentrations	1 mg/l, 1 g/m^3	1 ppm
	1ug/l, 1 mg/m^3	1 ppb
River Flows	1 m^3	0.00084 ac ft
	1,220 m^3	1 ac ft, 43,560 ft^3
	1 l/s, 1 dm^3/s	15.9 gal/min, 0.0353 ft^3/s
	1 m^3/s	35.3 ft^3/s, 2.28 x 107 gal/d
	0.028 m^3/s	1 ft^3/s

APPENDIX B. WATER AND SEDIMENT TRANSPORT DATA

B1. WATER AND SEDIMENT DATA FROM STREAM GAGES

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
Gage 2795, RIO GRANDE AT EMBUDO			
1890	1030000	6070	
1891	1280000	8550	
1892	1040000	6660	
1893	633000	5100	
1894	529000		
1895	867000	5010	
1896	495000	2980	
1897	992000	8740	
1898	969000	4700	
1899	348000	1620	
1900	540000	5410	
1901	542000	7400	
1902	306000	2500	
1903	1020000	15900	
1904	250000		
1905	1500000		
1906	1200000		
1907	2000000		
1908	670000		
1909	1300000		
1910	890000		
1911	1100000		
1912	1500000		
1913	479000	2080	
1914	953000	7190	
1915	962400	7330	
1916	995000	8560	
1917	1220000	8600	
1918	485000	3580	
1919	975000	7280	
1920	1430000	12700	
1921	1170000	14400	
1922	911000	7500	
1923	772600	4640	
1924	1227000	8780	
1925	430400	1580	
1926	814100	5500	
1927	877200	9500	
1928	673300	5180	
1929	735600	5850	
1930	592300	2240	
1931	362000	1740	
1932	902000	7180	
1933	443000	4300	
1934	282100	832	
1935	643300	5900	
1936	522900	3630	
1937	892500	6690	
1938	790400	5440	
1939	522100	2410	
1940	316600	1990	
1941	1341000	12000	
1942	1503000	10800	
1943	418500	2220	
1944	955000	8770	
1945	674700	5380	
1946	308300	1950	
1947	474300	4080	
1948	993700	10200	
1949	859600	9990	
1950	341200	1470	
1951	246600	710	
1952	777300	8720	
1953	373300	2000	
1954	267600	1860	
1955	283400	2200	
1956	242000	1020	
1957	753400	5000	
1958	860500	6840	
1959	253900	2760	
1960	427900	2320	
1961	408200	2340	
1962	599300	3980	
1963	280800	966	
1964	226200	925	
1965	719200	5200	
1966	527600	1950	
1967	366300	3550	
1968	561800	3270	
1969	590500	3140	
1970	583900	2250	
1971	391100	1860	
1972	324800	1090	
1973	879700	6620	
1974	329000	1050	
1975	615900	3700	
1976	503600	2790	
1977	223100	2480	
1978	323200	1490	
1979	1128000	9000	

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1980	762300	5080	
1981	252300	2930	
1982	61[illegible]00	5010	
1983	861700	5660	
1984	734500	6010	
1985	1297000	8420	

GAGE 2900, RIO CHAMA AT CHAMITA

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1913	258000		
1914	469000		
1915	666000	5980	
1916	645000	6000	
1917	526000	4600	
1918	25000	2630	
1919	602000	5500	
1920	710000	15000	
1921	384700	2850	
1922	329300	3310	
1923	409000		
1924	547700		
1925	255400		
1926	488400		
1927	604600	6180	
1928	337200	5300	
1929	420000	10400	
1930	381600	5170	
1931	195000	3810	
1932	870000	[illegible]	
1933	327000	8040	
1934	115600	1600	
1935	354100	7100	
1936	505700	5510	
1937	769700	6610	
1938	446600	3360	
1939	321100	3600	
1940	232600	3360	
1941	875900	9910	
1942	851800	8350	
1943	289600	6100	
1944	327100	3190	
1945	436100	5490	
1946	144200	2360	
1947	260700	2670	
1948	358800	2590	216[illegible]00
1949	428000	2580	1650000
1950	394100	3160	1085000
1951	144500	1410	580701
1952	566500	5880	3390906
1953	167200	1340	616075
1954	176600	2000	10[illegible]8
1955	142300	5970	166[illegible]
1956	145600	1300	5[illegible]
1957	522900	[illegible]	1344250
1958	561000	4830	5467859
1959	246800	1580	1020528
1960	364400	2470	1466070
1961	244700	8000	1635055
1962	411600	3870	1017578
1963	269600	1830	613467
1964	147100	2190	702795
1965	421900	[illegible]	[illegible]

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1966	385700	3590	2227058
1967	209100	8150	3016743
1968	278900	2170	2013011
1969	416700	10000	984180
1970	265300	2270	677598
1971	188200	3880	373822
1972	170000	2350	319352
1973	437900	3310	668771
1974	337600	1180	283163
1975	409100	2790	
1976	385500	2210	
1977	199200	3880	
1978	343800	3150	
1979	471300	3410	
1980	667500	4330	
1981	283600	2220	
1982	481500	3730	
1983	569200	4140	
1984	533700	4840	
1985	536200	3920	

GAGE 3130, RIO GRANDE AT OTOWI

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1895		8630	
1896	777000	5250	
1897	1750000	15300	
1898	1260000	7010	
1899	567000	6710	
1900	739000	[illegible]	
1901	848000	8400	
1902	456000	6980	
1903	1650000	19600	
1904	360000		
1905	2190000	19800	
1906			
1907			
1908			
1909			
1910	1320000	12700	
1911	1660000	12300	
1912	2150000	21700	
1913	728000	9250	
1914	1430000	[illegible]	
1915	1640000		
1916	[illegible]	14100	
1917	[illegible]	10400	
1918	736000		
1919	1600000	13400	
1920	2160000	[illegible]	
1921	1585000	17000	
1922	[illegible]	10400	
1923	[illegible]	7550	
1924	[illegible]	14200	
1925	[illegible]	5340	
1926	1330000		
1927	1512000	10950	
1928	1069000	8990	
1929	[illegible]	11500	
1930	[illegible]	6520	
1931	[illegible]	11000	
1932	[illegible]	14500	
1933	[illegible]	6400	

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1934	414000	3180	
1935	1015000	8220	
1936	1062000	9350	
1937	1703000	10800	
1938	1264000	7740	
1939	888700	5770	
1940	554400	2330	
1941	2311000	25000	
1942	2405000	16400	
1943	717300	7100	
1944	1287000	10400	
1945	1140000	10400	
1946	456000	2610	
1947	730300	5740	
1948	1362000	12400	4306000
1949	1304000	10700	3681000
1950	663400	4590	1733000
1951	395400	3440	900743
1952	1378000	9700	4473402
1953	548600	3300	732109
1954	450600	3100	1329497
1955	432000	5140	2430691
1956	377100	1850	714319
1957	1297000	6650	4557348
1958	152600	11000	7562178
1959	509800	2740	1424491
1960	821000	4490	2074261
1961	675600	8700	1971899
1962	1040000	7400	3252975
1963	559800	2670	862093
1964	383700	2770	946606
1965	1178000	7660	3377878
1966	944800	3600	2755645
1967	580500	9520	2650962
1968	855700	4490	2573694
1969	1038000	6760	1823935
1970	906500	5860	1939043
1971	580500	7820	1105671
1972	513500	3440	1464464
1973	1394000	8350	3997338
1974	687400	1760	823348
1975	1066000	5070	1525534
1976	936400	4480	1849982
1977	435500	2620	896924
1978	700700	4020	1170813
1979	1706000	5200	2595964
1980	1490000	8270	1538125
[illegible]	560100	2340	416468
1982	1126000	5460	1579260
1983	1482000	8760	1466723
1984	1342000	9790	1468574
1985	1935000	12400	2727140

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
GAGE 3190, RIO GRANDE AT SAN FELIPE			
1926	1387000		
1927	1648000	14000	
1928	1154000	11000	
1929	1274000	22600	
1930	1077000	5840	
1931	613000	10500	
1932	1720000	14200	
1933	847000	6200	
1934	409300	2260	
1935	1051000	22000	
1936	1108000	10900	
1937	1844000	27300	
1938	1194000	12500	
1939	885700	6650	
1940	569800	3880	
1941	2463000	22600	
1942	2456000	18900	
1943	785500	10600	
1944	1317000	11600	
1945	1208000	11200	
1946	466500	4830	
1947	719900	5580	
1948	1343000	12500	
1949	1285000	10500	
1950	663000	3950	
1951	363900	3710	
1952	1350000	11500	
1953	527400	10200	
1954	427900	4660	
1955	447300	17400	
1956	366300	8700	
1957	1276000	12000	
1958	1499000	10700	
1959	490500	4400	
1960	803400	4450	
1961	670900	7440	
1962	1007000	7380	
1963	543400	3730	
1964	364900	2350	
1965	1143000	10900	
1966	927400	10600	
1967	606400	13700	
1968	899400	4140	
1969	1079000	5940	
1970	949600	3650	
1971	611600	6540	
1972	504200	6220	
1973	1432000	9270	

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1974	656500	1810	
1975	1010000	4710	
1976	862700	3130	
1977	395900	2720	
1978	651300	3640	
1979	1666000	7550	
1980	1450000	7130	
1981	528400	8850	
1982	1098000	5180	
1983	1516000	7100	
1984	1315000	9220	
1985	1755000	8290	

GAGE 3290, JEMEZ RIVER BELOW JEMEZ DAM

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1943		16300	
1944	45910	2420	
1945	75360	7360	
1946	13540	7670	
1947	20180	3510	
1948	42220	3570	
1949	54930	1300	502800
1950	10210	6430	255600
1951	13840	7000	790239
1952	33020	2700	515327
1953	7640	316	61695
1954	20180	1930	690970
1955	19730	1020	768258
1956	13200	1230	228489
1957	35050	704	319488
1958	111000	7870	687843
1959	27980	1990	
1960	47830	772	
1961	53070	1190	
1962	43840	1630	
1963	20910	606	
1964	15310	530	
1965	38310	618	
1966	29870	1800	
1967	31310	1850	
1968	51550	1290	
1969	56410	1340	
1970	43370	3000	
1971	14070	670	
1972	18670	1190	
1973	129000	2920	
1974	16060	320	
1975	81370	1750	
1976	14640	276	
1977	14150	208	
1978	36820	626	
1979	100000	4260	
1980	68290	713	
1981	18920	473	
1982	44180	662	
1983	101600	1380	
1984	55110	473	
1985	102206	1180	

GAGE 3300, RIO GRANDE AT ALBUQUERQUE

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1942	2455000	25000	
1943	540100	4490	
1944	1183000	11400	
1945	1065000	11700	
1946	282900	4700	
1947	549900	6460	
1948	1229000	13100	
1949	1206000	10800	
1950	490400	5200	
1951	241400	8940	
1952	1269000	9600	
1953	375200	7920	
1954	278400	5720	
1955	288000	7960	
1956	242600	4880	
1957	1199000	8780	
1958	1585000	12700	
1959	368600	2070	
1960	372700	4800	
1961	559200	6770	
1962	923600	6520	
1963	431700	2480	
1964	210800	1920	
1965	1049000	8720	
1965	817800	6650	
1967	439900	13300	
1968	761800	4360	
1969	938700	6480	
1970	833300	5840	3444903
1971	500200	6650	2544489
1972	383000	4380	2428212
1973	1421000	8570	8017443
1974	524700	2080	1045303
1975	979200	6160	2807587
1976	744400	3340	1621401
1977	257700	2190	491805
1978	531800	4580	774449
1979	1638000	8650	1846126
1980	1417000	7600	759946
1981	431100	2750	393773
1982	1015000	5460	849813
1983	1390000	7700	1325704
1984	1167000	9500	1197098
1985	1661000	9370	1443353

GAGE 3530, RIO PUERCO NEAR BERNARDO

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1940		7200	
1941	123500	18800	
1942	47080	12900	
1943	30970	11100	
1944	31410	11000	
1945	21720	6260	
1946	30760	5800	
1947	65280	9020	
1948	10500	[illegible]	1634000
1949	26260	1220	5760000
1950	12000	4140	2753000
1951	23000	4450	4613496
1952	13350	1820	2953332
1953	34150	5490	6951247
1954	78340	7920	14778779
1955	85270	8000	18315560

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1956	12280	5200	3423769
1957	85960	5680	18054868
1958	44150	5340	8072030
1959	21470	4020	5038884
1960	17560	3880	4156507
1961	22150	2470	4548008
1962	10150	900	1448532
1963	19890	1210	3026277
1964	18590	2640	2917346
1965	30410	3710	3807918
1966	19260	1800	3528635
1967	27780	7860	12257979
1968	27630	3470	4940551
1969	26210	3580	4919348
1970	26710	6940	2822326
1971	9130	1300	1888661
1972	61510	9270	9490327
1973	60310	3920	7958371
1974	6100	2980	1141388
1975	39160	3520	6829451
1976	7950	2280	1734453
1977	24040	3010	4355708
1978	3960	1330	478526
1979	25700	1960	3496564
1980	18650	2450	1810746
1981	15880	1620	2093080
1982	32300	3460	4408034
1983	17170	1580	1876008
1984	20550	1690	2678574
1985	34990	1400	1998587

GAGE 3540, RIO SALADO NEAR SAN ACACIA

1948	1651	1830	
1949	7063	4050	
1950	4491	8500	
1951	1,091	13200	
1952	5886	7800	
1953	8022	16600	
1954	20058	11000	
1955	22262	4500	
1956	4254	7100	
1957	19192	6260	
1958	837	15200	
1959	7082	6000	
1960	4733	4420	
1961	12912	10900	
1962	7831	6820	
1963	16397	15300	
1964	8596	10000	
1965	16449	16200	
1966	8592	9800	782442
1967	17409	17400	673140
1968	6296	16400	100200
1969	[illegible]	19100	[illegible]
1970	13863	4300	
1971	4110		[illegible]
1972	6405		[illegible]
1973	10689		[illegible]
1974	2611		[illegible]
1975	11253		[illegible]
1976	[illegible]		141869

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1977	11974		165950
1978	316		703
1979	507		562
1980	9494		220100
1981	2054		31200
1982	17319		320000
1983	895		
1984	7730		

GAGES 3584 AND 3585, RIO GRANDE AT SAN MARCIAL

1895		17900
1896	508500	5600
1897	1548000	21800
1898	1160000	16800
1899	741400	4660
1900	487000	8500
1901	617000	9110
1902	740300	14100
1903	1301000	19000
1904	178000	7900
1905	2839000	50000
1906	1413000	15300
1907	2277000	20600
1908	868700	4990
1909	1210000	14700
1910	961100	9360
1911	1347000	12000
1912	1924000	15300
1913	493800	11400
1914	1111000	8380
1915	1463000	14400
1916	1421000	15800
1917	1305000	11400
1918	379000	4500
1919	1527000	13200
1920	1970000	18000
1921	1470000	19400
1922	1044000	
1923	964000	9990
1924	1062000	13900
1925	321000	3370
1926	1120000	10900
1927	1100000	13900
1928	773000	7500
1929	1240000	47000
1930	930000	5800
1931	418000	8130
1932	1440000	12800
1933	717000	20600
1934	298300	9910
1935	917600	15000
1936	872900	9550
1937	1597000	60600
1938	1004000	7410
1939	515200	4820
1940	[illegible]	2910
1941	2440000	24600
1942	2122000	18400
1943	441000	4500
1944	905500	9650
1945	[illegible]	[illegible]

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)
1946	224900	2010	1442100
1947	419200	5680	3104449
1948	1036000	11700	4295000
1949	1031000	9560	4462000
1950	364100	2570	1211000
1951	132900	1760	1045075
1952	967000	7910	5445922
1953	286800	2200	1867315
1954	198500	3980	3016557
1955	257900	4160	4857440
1956	174800	1160	
1957	972300	8590	11636118
1958	1391000	9570	18137243
1959	341900	1820	2052034
1960	563400	4080	3723688
1961	437700	4300	2298082
1962	748100	5350	2454975
1963	405500	1760	136447
1964	164200	2260	69596
1965	294600	3720	5939886
1966	4890	1510	263992
1967	63010	6160	2633789
1968	201600	4240	6661067
1969	163900	3180	2888864
1970	69810	5120	1843799
1971	851	500	34691
1972	18900	2800	1400686
1973	486100	6400	10561149
1974	14650	1180	410605
1975	637800	6680	7791192
1976	419900	2920	2014487
1977	243200	6230	4460201
1978	384100	[illegible]	1595183
1979	1416000	6510	8519600
1980	1269000	6210	5873066
1981	327000	4180	2716584
1982	704100	5120	10760893
1983	1154000	5620	2688052
1984	457100	5620	1482351
1985	1062000	9110	3293562

Note U.S. Geological Survey data

B2. WATER, SEDIMENT, AND PLUTONIUM DATA FOR LOS ALAMOS CANYON

Year	Water (ac ft)	Flood (cfs)	Sediment (tons)	Σ Pu (mCi)	Pu (yr) (mCi)
1943	22	66	466	0.00	0
1944	198	631	8393	2.80	2.798
1945	0	0	61	2.83	0.03
1946	28	80	611	3.15	0.32
1947	1	2	65	3.20	0.05
1948	0	0	61	3.24	0.04
1949	0	0	61	3.29	0.05
1950	6	20	77	3.35	0.06
1951	236	687	9814	20.25	16.9
1952	209	386	6316	37.86	17.61
1953	2	4	12	37.89	0.03
1954	40	129	1006	40.75	2.86
1955	91	283	2783	49.58	8.83
1956	0	0	0	49.58	0
1957	433	549	16470	93.53	43.95
1958	63	203	2062	100.89	7.36
1959	33	55	542	102.63	1.74
1960	0	0	154	103.38	0.75
1961	18	53	443	105.78	2.4
1962	0	1	138	106.66	0.88
1963	88	283	2772	116.73	10.07
1964	0	0	0	116.73	0
1965	124	233	3163	126.61	9.88
1966	10	32	165	127.14	0.53
1967	129	361	4197	137.38	10.24
1968	287	924	14120	159.20	21.82
1969	124	149	2899	164.16	4.96
1970	0	0	0	164.16	0
1971	16	42	247	164.58	0.42
1972	0	0	0	164.58	0
1973	109	349	3955	172.79	8.2099
1974	6	20	139	173.12	0.3301
1975	4	6	99	173.42	0.3
1976	6	20	77	173.65	0.23
1977	1	4	8	173.68	0.0299
1978	108	293	3198	179.69	6.0162
1979	10	312	426	181.18	1.48
1980	0	0	183	181.98	0.8003
1981	0		0	181.98	0
1982	0		0	181.98	0
1983	43		24357	184.76	2.7800
1984	0		0	184.76	0
1985	43		41461	186.84	2.0800
1986	3		2460	188.43	1.5900

Note: 1943-1980 data from calculations by L. J. Lane in support of Lane, Purtymun, and Becker (1985), 1981-1986 data from Purtymun et al. (1990) using different techniques. The compatibility of the two data sets is unknown.

B3. SUMMARY DATA AND CORRELATIONS FOR GAGING STATIONS

(Values in English Units with Metric Units in Parentheses)

Station	Annual Mean (Standard Deviation)			Correlation Coefficient			Years
	Water Yield	Flood	Sediment	Wat/Fl	Wat/Sed	Fl/Sed	
1. Chama	390,623 (184,966)	4,451 (2,597)	1,513,500 (1,201,135)	0.56	0.64	0.43	73
2 Embudo	717,154 (367,802)	5,044 (3,312)		0.88			96
3. Otowi	1,059,493 (543,678)	8,526 (4930)	2,163,396 (1,431,926)	0.81	0.29	0.68	87
4 Alamos	63 98	165 (23.3)	2,241 (3,927)	0.90	0.98	0.93	18
5. Felipe	1,011,409 (489,610)	8,997 (5,537)		0.61			60
6 Jemez	42,689 (30,878)	2,443 (3,014)	482,071 (251,541)	0.20	0.34	0.39	43
7 Albuquer	834,593 (502,424)	7,233 (4,102)	1,936,961 (1,845,187)	0.72	0.26	0.16	44
8 Puerco	32,739 (25,351)	4,755 (3,637)	5,114,814 (4,318,408)	0.73	0.96	0.76	46
9 Salado	10,351 (11,163)	9,861 (7,408)	[illegible] [illegible]	0.23	*	*	12
10 Marcial	825,999 (609,206)	9,593 (8,446)	3,981,758 (3,786,497)	0.7[illegible]	0.61	0.63	91

Notes: no data

* insufficient data

B4. MASS BUDGET DATA SUMMARY NEAR LOS ALAMOS -- 1951

(Values in English Units and Metric Units in Parentheses)

Station	Water Yield (ac ft) and (10^6 m^3)	Max Flood (ft^3 s^{-1}) and (m^3 s^{-1})	Suspended Sediment (t) and (Mg)	Bedload Sediment (t) and (Mg)	Total Plutonium (mCi)
1. Rio Chama near Chamita	144,500 (176.290)	1,400 (39.2)	580,201 (526,358)	92,832 (84,217)	0.14
2. Rio Grande at Embudo	246,600 (300.852)	710 (19.9)	320,542 (290,796)	51,287 (46,528)	1.28
3. Rio Grande at Otowi Bridge	395,400 (428.369)	3,440 (96.3)	900,743 (817,154)	144,119 (130,745)	1.42
4. Los Alamos Canyon	236 (0.288)	687 (19.2)	9,814 (8,903)	9,814 (8,903)	16.90
5. Rio Grande in White Rock Canyon	395,636 (482.676)	3,440 (96.3)	910,557 (826,057)	153,933 (139,648)	18.32

B5. MASS BUDGET DATA SUMMARY NEAR LOS ALAMOS -- 1952

(Values in English Units and Metric Units in Parentheses)

Station	Water Yield (ac ft) and (10^6 m^3)	Max Flood (ft^3 s^{-1}) and (m^3 s^{-1})	Suspended Sediment (t) and (Mg)	Bedload Sediment (t) and (Mg)	Total Plutonium (mCi)
1. Rio Chama near Chamita	566,500 (691,130)	5,880 (164.6)	3,390,906 (3,076,230)	542,545 (492,197)	0.82
2 Rio Grande near Embudo	777,300 (948,306)	8,720 (244.2)	1,082,496 (982,040)	173,199 (157,126)	6.24
3. Rio Grande at Otowi Bridge	1,378,000 (1,681,160)	9,700 (271.6)	4,473,402 (4,058,270)	715,744 (649,323)	7.06
4. Los Alamos Canyon	236 (0.288)	687 (19.2)	9,814 (8,903)	9,814 (8,903)	16.90
5 Rio Grande in White Rock Canyon	1,378,236 (1,681,448)	9,700 (271.6)	4,483,216 (4,067,174)	725,558 (658,226)	24.67

B6. MASS BUDGET DATA SUMMARY NEAR LOS ALAMOS -- 1957

(Values in English Units and Metric Units in Parentheses)

Station	Water Yield (ac ft) and (10^6 m^3)	Max Flood (ft^3 s^{-1}) and (m^3 s^{-1})	Suspended Sediment (t) and (Mg)	Bedload Sediment (t) and (Mg)	Total Plutonium (mCi)
1. Rio Chama near Chamita	522,900 (637.938)	4,280 (119.8)	3,344,250 (3,033,904)	535,080 (485,425)	0.81
2. Rio Grande near Embudo	753,400 (919.148)	5,000 (140.0)	1,213,090 (1,100,515)	194,096 (176,084)	6.39
3 Rio Grande at Otowi Bridge	1,297,000 (1,582.340)	6,650 (186.2)	4,557,348 (4,134,426)	729,176 (661,508)	7.19
4. Los Alamos Canyon	433 (0.528)	649 (18.2)	16,470 (14,941)	16,470 (14,941)	43.95
5 Rio Grande in White Rock Canyon	1,297,433 (1,582.868)	6,650 (186.2)	4,573,818 (4,149,368)	745,646 (646,450)	51.14

B7. MASS BUDGET DATA SUMMARY NEAR LOS ALAMOS -- 1968

(Values in English Units and Metric Units in Parentheses)

Station	Water Yield (ac ft) and (10^6 m^3)	Max Flood (ft^3 s^{-1}) and (m^3 s^{-1})	Suspended Sediment (t) and (Mg)	Bedload Sediment (t) and (Mg)	Total Plutonium (mCi)
Rio Chama near Chamita	278,900 (340.258)	2,170 (60.8)	2,013,011 (1,826,203)	322,082 (292,193)	0.49
Rio Grande near Embudo	366,300 (446.886)	3,550 (99.4)	560,683 (508,652)	89,709 (81,384)	3.58
Rio Grande at Otowi Bridge	855,700 (1,043.954)	4,490 (125.7)	2,573,694 (2,334,855)	411,791 (373,577)	4.06
Los Alamos Canyon	287 (0.350)	924 (25.9)	14,125 (12,810)	14,120 (12,810)	21.82
Rio Grande in White Rock Canyon	855,987 (1,044.304)	4,490 (125.9)	2,587,814 (2,347,665)	425,911 (386,386)	25.88

B8. ASSUMPTIONS AND DATA SOURCES FOR MASS BUDGET CALCULATIONS

Station	Drainage Area (km^2)	Years of Record	Annual Mean Water (10^6 m^3)	Flood (m^3s^{-1})	Suspended (mg)	Bedload (mg)	Plutonium (mCi)
1. Rio Chama	1	1	1	1	1	4	8
2. Embudo	1	1	1	1	1	5	5
3. Otowi	1	1	1	1	1	4	8
4. Los Alamos	2	3	3	3	3	6	3
5. San Felipe	1	1	1	1	-	-	-
6. Jemez River	1	1	1	1	1	6	8
7. Albuquerque	1	1	1	1	1	4	9
8. Rio Puerco	1	1	1	1	1	7	10
9. Rio Salado	1	1	1	1	1	6	10
10. San Marcial	1	1	1	1	1	4	9

Sources:
1. U.S. Geological Survey data, WATSTORE and EarthInfo Inc.
2. Measured by digitizing U.S. Geological Survey topographic maps.
3. Data from L. J. Lane, used in preparation of Lane, Purtymun, and Becker (1985).
4. Calculated as 14% of total load (16% of suspended load): Garde and Raju (1985), p. 62.
5. Calculated as the difference between Rio Chama and Otowi stations.
6. Calculated as bedload equal to suspended load.
7. Calculated as 71% of total load (41% of suspended load): Simons et al. (1981), p. 53.
8. Calculated by multiplying concentrations times mass for suspended sediment and bedload and summing for total; concentrations calculated as mean values published by Los Alamos National Laboratory in various surveillance reports.
9. Calculated as in #8 using data for Rio Grande at Bernalillo
10. Calculated as in #8 using data for Frijoles Canyon, the most similar environment for which data exist

B9. ANNUAL BUDGET CALCULATIONS FOR SUSPENDED SEDIMENT, 1948-1985

(tons per year)

							Storage		
Year	Otowi	Alamos	Jemez	Albuquer	Puerco	Marcial	Oto-Alb	Alb Marc	Oto Marc
1948	4306000	61	514537	4364260	1634000	4295000	456338	1703260	2159598
1949	3681000	61	502800	3538210	5760000	4462000	645651	4836210	5481861
1950	1733000	77	255600	1961030	2753000	1211000	27647	3503030	3530677
1951	900743	9814	790239	3492734	4613496	1045075	-1791938	7061155	5269217
1952	4473402	6316	515327	3057870	2953332	5445922	1937175	565280	2502455
1953	732109	12	61695	3031635	6953247	1867315	-2237819	8117567	5879748
1954	1329497	1006	690970	2290725	14778779	3016557	-269252	14052947	13783695
1955	2430691	2783	768258	3103649	18315560	4857440	98083	16561769	16659852
1956	714319	0	228489	2007069	3423769	1113186	-1064261	4317652	3253391
1957	4557348	16470	319488	2804035	18054868	11636118	2089271	9222785	11312056
1958	7562178	2062	687843	3983688	8072030	18137243	4268395	-6081525	-1813130
1959	1424491	532	447031	896440	5038884	2052034	975614	3883290	4858904
1960	2074261	154	450960	1892193	4156507	3723688	633182	2325012	2958194
1961	1971899	443	471793	2489954	4548008	2298082	-45819	4739880	4694061
1962	3252975	138	466335	2158715	1448532	2454975	1560733	1152272	2713005
1963	862093	2772	397709	1004865	3026277	136447	257709	3894695	4152404
1964	946606	0	385539	945426	2917346	69596	386719	3793176	4179895
1965	3377878	3163	429616	2880804	3807918	5939886	929853	748836	1678689
1966	2255645	165	445454	2279176	3528635	263992	422088	5543819	5965907
1967	2650962	4197	449386	4956701	17257979	2633789	-1852156	14580891	12728735
1968	2573694	14120	471369	1475209	4940551	6661067	1583974	-245307	1338667
1969	1823935	2899	481511	2134149	4919348	2888864	174196	4164633	4338829
1970	1939043	0	501599	3444903	2822326	1843799	-1004261	4423430	3419169
1971	1105621	247	386979	2544489	1888661	34691	-1051642	4398459	3346817
1972	1464464	0	409308	2428212	9490327	1400686	-554440	10517853	9963413
1973	3997338	3955	654953	8017443	7958371	10561149	-3361197	5414665	2053468
1974	823348	129	381365	1045303	1141388	410605	159539	1776086	1935625
1975	1525534	99	541266	2807587	6829451	7791192	-740688	1845846	1105158
1976	1839982	77	377627	1621401	1734453	2014487	596285	1341367	1937652
1977	895924	8	374944	491805	4355708	4460201	780071	387312	1167383
1978	1170813	3198	427122	774449	478526	1595183	826684	-342208	484476
1979	2595964	426	637629	1846126	3496564	8519600	1387893	-3176910	-1789017
1980	1538125	183	486550	759946	1810746	5873066	1264912	-3302374	-2037462
1981	436468		390591	393773	2093080	2716584	433286	-229731	203555
1982	1578260		441433	849813	4408094	10760893	1169880	-5502986	-4333106
1983	1466723		564609	1325704	1876008	2888052	705628	313660	1019288
1984	1468574		456294	1197098	2678574	1482351	727770	2393321	3121091
1985	2722140		560476	1443353	3398587	3293362	1844213	1548578	3392791

Grand Total:: Storage, Otowi to Albuquerque = 12,369,316

Storage, Albuquerque to San Marcial = 130,247,695

Storage, Otowi to San Marcial = 142,617,011

Note Storage for Oto Alb reach overestimated due to regression inaccuracies that estimated values for Alb gage during years when data were not collected

B10. ANNUAL BUDGET CALCULATIONS FOR BEDLOAD SEDIMENT, 1948-1985

(calculated tons per year)

								Storage	
Year	Otowi	Alamos	Jemez	Albuquer	Puerco	Marcial	Oto-Alb	Alb-Marc	Oto-Marc
1948	688960	61	514537	698281.6	669940	687200	505276.4	681021.6	1186298
1949	588960	61	502800	566113.6	2361600	713920	525707.4	2213793.	2739501
1950	277260	77	255600	313764.8	1128730	193760	219192.2	1248734.	1467927
1951	144118.8	9814	790239	558837.4	1891533.	167212	385334.4	2283158.	2668493.
1952	715744.3	6316	515327	489259.2	1210866.	871347.5	748128.1	828777.8	1576905
1953	117137.4	12	61695	485061.6	2850831.	298770.4	-306217.	3037122.	2730905.
1954	212719.5	1006	690970	366516	6059299.	482649.1	538179.5	5943166.	6481345.
1955	388910.5	2783	768258	496583.8	7509379.	777190.4	663367.7	7228773.	789[illegible]140.
1956	114291.0	0	228489	321131.0	1403745.	178109.7	21649	1546766.	1568415.
1957	729175.6	16470	319488	448645.6	7402495.	1861778.	616488.0	5989362.	6605850.
1958	120994[illegible]	2062	687843	637390.0	3309532.	2901958.	1262463.	1044963.	2307426.
1959	227918.5	532	447031	143430.4	2065942.	328325.4	532051.1	1881047.	2413098.
1960	331881.7	154	450960	302750.8	1704167.	595790.0	480244.8	1411128.	1891373.
1961	315503.8	443	471793	398392.6	1864683.	367693.1	389347.2	1895382.	2284730
1962	520476	138	466335	345394.4	593898.1	392796	641554.6	546496.5	1188051.
1963	137934.8	2772	397709	160778.4	1240773.	21831.52	377637.4	1379720.	1757357.
1964	151456.9	0	385539	151268.1	1196111.	11135.36	385727.8	1336244	172197[illegible].
1965	540460.4	3163	429616	460928.6	1561246.	950381.7	512310.8	1071793.	1584104.
1966	360903.2	165	445454	364668.1	1446740.	42238.72	441854.0	1769169.	2211023.
1967	424153.9	4197	449386	793072.1	5025771.	421406.2	84664.76	5397437.	5482102.
1968	411791.0	14120	471369	236033.4	2025625.	1065770.	661246.6	1195888.	1857135.
1969	291829.6	2899	481511	341463.8	2016932.	462218.2	434775.7	1896178.	2330954.
1970	310246.8	0	501599	551184.4	1157153.	295007.8	260661.4	1413330.	1673991.
1971	176899.3	247	386979	407118.2	774351.0	5550.56	157007.1	1175918	1332925
1972	234314.2	0	409308	388513.9	3891034.	224109.7	255108.3	4055438	4310546.
1973	639574.0	3955	654953	1282790.	3262932.	1689783.	15691.2	2855939.	2871630.
1974	131735.6	129	381365	167248.4	467969.0	65696.8	345981.2	569520.7	915501.9
1975	244085.4	99	541266	449213.9	2800074.	1246590.	336236.5	2002698.	2338934.
1976	294397.1	77	377627	259424.1	711125.7	322317.9	412676.9	648231.9	1060908.
1977	143507.8	[illegible]	[illegible]	78688.8	1785840.	713632.1	439771.0	1150896.	1590667.
1978	187330.0	3198	[illegible]	123911.8	196195.6	255229.2	493738.2	64878.22	558616.4
1979	415354.2	426	63[illegible]	295380.1	1433591.	1363136	758029.0	365835.4	1123864.
1980	246100	183	486550	12[illegible]	742405.8	939690.5	611241.6	75693.3	535548.3
1981	69834.88	0	390591	63003.68	858162.8	434653.4	397422.2	486513.0	883935.2
1982	252521.6	0	441433	135970.0	1807318.	1721742.	557984.5	221545.7	779530.2
1983	234675.6	0	564609	212112.6	769163.2	462088.3	587172.0	519187.6	1106359.
1984	234971.8	0	456294	191535.6	1090215.	237176.1	499730.1	1052574	1552305.
1985	436342.4	0	560426	230936.4	1393420.	526937.9	765831.9	1097419.	1863251.
Sum							17015267	69430363	86445631

B11. ANNUAL BUDGET CALCULATIONS FOR TOTAL SEDIMENT, 1948-1985

(calculated tons per year)

	Storage		
Year	Oto Alb	Alb Marc	Oto Marc
1948	961614 4	2384281 6	3345896
1949	1171358 4	7050003 6	8221 62
1950	246839 2	4751764 5	[illegible]
1951	1406603 56	9344313 8	[illegible]
1952	2685303 12	1394057 8	4079360 92
1953	2544036 16	11154689 47	[illegible]
1954	268927 52	19996113 27	20265040 79
1955	761450 72	23790542 74	24551992 76
1956	1042612	5864418 57	4871806 57
1957	[illegible]	15212147 6	17917906 68
1958	[illegible]	[illegible]	494296 9
1959	1507665 16	[illegible]	7272002 56
1960	1113426 88	3736145 67	4849567 55
1961	[illegible]	[illegible]	6978791
1962	[illegible]	1698768 52	3901056 12
1963	[illegible]	5274415 45	[illegible]
1964	[illegible]	5129420 66	[illegible]
1965	[illegible]	[illegible]	[illegible]
1966	[illegible]	[illegible]	[illegible]
1967	1767491 24	[illegible]	[illegible]
1968	[illegible]	950581 63	[illegible]
1969	604971 76	6060811 78	[illegible]
1970	[illegible]	[illegible]	[illegible]
1971	[illegible]	[illegible]	[illegible]
1972	[illegible]	[illegible]	[illegible]
1973	[illegible]	8270604 [illegible]	[illegible]
1974	[illegible]	[illegible]	[illegible]
1975	[illegible]	1848544 11	[illegible]
1976	[illegible]	[illegible]	[illegible]
1977	[illegible]	[illegible]	[illegible]
1978	[illegible]	[illegible]	[illegible]
1979	[illegible]	[illegible]	[illegible]
1980	[illegible]	[illegible]	[illegible]
1981	[illegible]	[illegible]	[illegible]
1982	[illegible]	[illegible]	[illegible]
1983	[illegible]	[illegible]	2125647 64
1984	[illegible]	[illegible]	[illegible]
1985	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

B12. SUSPENDED, BED-, AND TOTAL LOAD SEDIMENT BUDGET SUMMARY,

CRITICAL YEARS

(Mg)

Station	1951	1952	1957	1968
SUSPENDED SEDIMENT:				
Otowi	817,154	4,058,270	4,134,426	2,334,855
Los Alamos	8,903	5,730	14,942	12,810
Jemez	716,905	467,505	289,840	427,626
Rio Puerco	4,185,364	2,679,263	16,379,376	4,487,068
San Marcial	948,092	4,940,540	10,556,286	6,042,920
Suspended Storage	4,780,234	2,270,226	10,262,298	1,214,439
BEDLOAD SEDIMENT:				
Otowi	130,745	649,323	661,508	373,577
Los Alamos	8,903	5,730	14,942	12,810
Jemez	716,905	467,505	289,840	427,626
Rio Puerco	1,715,999	1,098,498	6,715,544	1,837,648
San Marcial	151,695	790,486	1,689,006	966,867
Bedload Storage	2,420,857	1,430,370	5,331,370	1,684,794
TOTAL SEDIMENT LOAD				
Otowi	947,899	4,707,593	4,795,934	2,708,432
Los Alamos	17,806	11,460	29,884	25,620
Jemez	1,433,810	935,010	579,680	855,252
Rio Puerco	5,901,363	3,777,761	23,094,920	6,325,716
San Marcial	1,099,787	5,731,026	12,245,292	7,009,787
Total Storage	7,201,091	3,700,798	15,593,618	2,899,233

APPENDIX C. SEDIMENT PARTICLE SIZE DATA

SAN MARCIAL REPRESENTATIVE REACH:

Sample #		Map Unit	Landform Type	Sample Depth (cm)	Fines (%)
1	Marcial	1A	Active Channel	30	10.68
6	Marcial	1A	Active Channel	5	30.53
7	Marcial	1A	Active Channel	5	49.08
8	Marcial	1A	Active Channel	5	45.37
9	Marcial	2A	Abandoned Channel	30	2.57
10	Marcial	2A	Abandoned Channel	5	2.55
11	Marcial	2A	Abandoned Channel	5	0.84
12	Marcial	2A	Abandoned Channel	5	2 66
14	Marcial	2A	Abandoned Channel	60	0.99
16	Marcial	2D	Abandoned Flood Pl	30	22 85
17	Marcial	2D	Abandoned Flood Pl	5	33 84
18	Marcial	2D	Abandoned Flood Pl	5	30 59
19	Marcial	2D	Abandoned Flood Pl	5	40 01
20	Marcial	2D	Abandoned Flood Pl	60	28 09
21	Marcial	2D	Abandoned Flood Pl	90	33 43
22	Marcial	3A	Older Aband Channel	30	11 53
23	Marcial	3A	Older Aband Channel	5	13 45
24	Marcial	3A	Older Aband Channel	5	9 14
25	Marcial	3A	Older Aband Channel	5	16 85
26	Marcial	3C	Aband Fl Pl or Bar	30	17 66
27	Marcial	3C	Aband Fl Pl or Bar	5	28 95
28	Marcial	3C	Aband Fl Pl or Bar	5	27 69
29	Marcial	3C	Aband Fl Pl or Bar	5	22 11
30	Marcial	3C	Aband Fl Pl or Bar	60	30 20
31	Marcial	3C	Aband Fl Pl or Bar	90	54 34

CHAMIZAL REPRESENTATIVE REACH

Sample #		Map Unit	Landform Type	Sample Depth (cm)	Fines (%)
32	Chamizal	1B	Active Flood Plain	30	11 79
33	Chamizal	1B	Active Flood Plain	5	56 43
34	Chamizal	1B	Active Flood Plain	5	54 82
35	Chamizal	1B	Active Flood Plain	5	46 85
36	Chamizal	2A	Aband Braid Channel	30	44 54
37	Chamizal	2A	Aband Braid Channel	5	6 77
38	Chamizal	2A	Aband Braid Channel	5	7 34
39	Chamizal	2A	Aband Braid Channel	5	55 02
40	Chamizal	2B	Abandoned Flood Pl	30	45 58
41	Chamizal	2B	Abandoned Flood Pl	60	6 69
42	Chamizal	2B	Abandoned Flood Pl	75	38 37
43	Chamizal	2B	Abandoned Flood Pl	5	42 11
44	Chamizal	2B	Abandoned Flood Pl	5	43 53
45	Chamizal	2B	Abandoned Flood Pl	5	42 57
46	Chamizal	3B	Older Aband Fl Pl	30	43 07
47	Chamizal	3B	Older Aband Fl Pl	5	30 95
48	Chamizal	3B	Older Aband Fl Pl	5	23 09
49	Chamizal	3B	Older Aband Fl Pl	5	33 57
50	Chamizal	2B	Aband Braid Channel	30	0 63
51	Chamizal	2B	Aband Braid Channel	5	0 51
52	Chamizal	2B	Aband Braid Channel	5	0 51
53	Chamizal	2B	Aband Braid Channel	5	0 42

SAN GERONIMO REPRESENTATIVE REACH

Sample #		Map Unit	Landform Type	Sample Depth (cm)	Fines (%)
54	Geronimo	3B	Aband Older Fl Pl	30	42 59
55	Geronimo	3B	Aband Older Fl Pl	60	36 16
56	Geronimo	3B	Aband Older Fl Pl	5	37 10

57 Geronimo	2B Abandoned Flood Pl	30	61 00
58 Geronimo	4B Aband Older Fl Pl	5	40 43
59 Geronimo	4B Aband Older Fl Pl	5	47 30
60 Geronimo	2B Aband Flood Pl	60	28 75
61 Geronimo	2B Aband Flood Pl	75	28 15
62 Geronimo	2B Aband Flood Pl	5	40 16
63 Geronimo	2B Aband Flood Pl	5	42 65
64 Geronimo	2B Aband Flood Pl	5	42 75
65 Geronimo	2A Aband Flood Pl	10	20 85
66 Geronimo	2B Aband Flood Pl	10	45 64
67 Geronimo	2B Aband Flood Pl	5	46 93
68 Geronimo	2B Aband Flood Pl	5	52 53
69 Geronimo	2B Aband Flood Pl	5	43 78
70 Geronimo	2A Aband Braid Channel	5	28 71
71 Geronimo	2A Aband Braid Channel	5	28 07
72 Geronimo	2A Aband Braid Channel	5	26 67

LOS LUNAS REPRESENTATIVE REACH

73 Lunas	3A Aband Braid Channel	30	54 00
74 Lunas	3A Aband Braid Channel	45	1 74
75 Lunas	3A Aband Braid Channel	5	62 60
76 Lunas	3A Aband Braid Channel	5	62 91
77 Lunas	3A Aband Braid Channel	5	16 16
78 Lunas	3B Abandoned Flood Pl	10	34 60
79 Lunas	3B Abandoned Flood Pl	5	21 58
80 Lunas	3B Abandoned Flood Pl	5	37 74
81 Lunas	3B Abandoned Flood Pl	5	50 20
82 Lunas	3B Abandoned Flood Pl	5	62 74
83 Lunas	3A Aband Braid Channel	5	20 69
84 Lunas	3A Aband Braid Channel	[illegible]	4 20
85 Lunas	3A Aband Braid Channel	45	1 16
86 Lunas	3A Aband Braid Channel	5	1 25
87 Lunas	3A Aband Braid Channel	5	4 98
88 Lunas	3A Aband Braid Channel	5	5 10

[illegible] REPRESENTATIVE REACH

[illegible]	2A Aband Braid Channel	10	[illegible]
[illegible]	2A Aband Braid Channel	5	56 82
[illegible]	2A Aband Braid Channel	[illegible]	42 86
[illegible]	2A Aband Braid Channel	5	11 52
[illegible]	2B Abandoned Flood Pl	[illegible]	42 67
[illegible]	2B Abandoned Flood Pl	[illegible]	27 55
[illegible]	2B Abandoned Flood Pl	[illegible]	18 20
[illegible]	2B Abandoned Flood Pl	5	41 43
[illegible]	2B Abandoned Flood Pl	5	[illegible]
[illegible]	3B Older Aband Fl Pl	[illegible]	4 62
[illegible]	[illegible] Older Aband Fl Pl	[illegible]	1 60
[illegible]	4B Older Aband Fl Pl	[illegible]	1 43
[illegible]	4B Older Aband Fl Pl	[illegible]	[illegible]
[illegible]	4B Older Aband Fl Pl	[illegible]	[illegible]

[illegible] REPRESENTATIVE REACH

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

117	Coronado		2A	Abandoned Flood Pl	90	5.22
118	Coronado		2A	Abandoned Flood Pl	5	58.61
119	Coronado		2A	Abandoned Flood Pl	5	40.44
120	Coronado		2A	Abandoned Flood Pl	5	57.59
121	Coronado		1A	Active Channel	5	37.61
122	Coronado		1A	Active Channel	5	37.79
123	Coronado		1A	Active Channel	5	33.12

RIO PUERCO 2 KM ABOVE RIO GRANDE

124	Puerco	1A	Active Channel	5	29.59
125	Puerco	1A	Active Channel	5	29.56
126	Puerco	1A	Active Channel	5	26.53

RIO SALADO 2 KM ABOVE RIO GRANDE :

127	Salado	1A	Active Channel	5	6.71
128	Salado	1A	Active Channel	5	6.97
129	Salado	1A	Active Channel	5	7.15

PEÑA BLANCA REPRESENTATIVE REACH.

130	Peña	4A	Older Braid Channel	5	17.08
131	Peña	4A	Older Braid Channel	5	43.25
132	Peña	4A	Older Braid Channel	5	4.65
133	Peña	4A	Older Braid Channel	5	4.91
134	Peña	4B	Aband Braid Channel	5	11.33
135	Peña	4B	Aband Braid Channel	5	17.07
136	Peña	4B	Aband Braid Channel	5	6.83
137	Peña	4B	Aband Braid Channel	5	12.48
138	Pena	5B	Older Aband Fl Pl	5	19.11
139	Pena	5B	Older Aband Fl Pl	5	38.84
140	Pena	5B	Older Aband Fl Pl	5	38.87
141	Pena	5B	Older Aband Fl Pl	5	41.47
142	Pena	X	Aband Single Channel	5	22.92
143	Peña	X	Aband Single Channel	5	34.38
144	Pena	X	Aband Single Channel	5	23.72
145	Pena	X	Aband Single Channel	5	14.52

OTOWI REPRESENTATIVE REACH

146	Otowi	2B	Flood Bar	5	18.69
147	Otowi	2B	Flood Bar	5	5.03
148	Otowi	2B	Flood Bar	5	7.61
149	Otowi	2B	Flood Bar	5	11.28

LOS ALAMOS CANYON

150	Alamos		11A	Outlet Channel	5	0.94
151	Alamos		11A	Outlet Channel	5	1.95
152	Alamos		11A	Outlet Channel	5	0.58
153	Alamos		11A	Outlet Channel	5	1.[illegible]
154	Alamos		11A	Active Channel	5	1.18
155	Alamos		11A	Active Channel	5	1.49
156	Alamos		11A	Active Channel	5	1.35
157	Alamos		11A	Active Channel	5	1.35
158	Alamos		11B	Active Flood Plain	5	48.18
159	Alamos		11B	Active Flood Plain	5	64.68
160	Alamos		11B	Active Flood Plain	5	52.54
161	Alamos		11B	Active Flood Plain	5	55.[illegible]
164	Alamos		[illegible]	Older Outlet Channel	5	28.05
165	Alamos		[illegible]	Older Outlet Channel	[illegible]	[illegible]
166	Alamos		[illegible]	Older Outlet Channel	5	23.80
167	Alamos		[illegible]	Older Outlet Channel	5	24.[illegible]
168	Alamos	W#4	11A	Active Channel	5	14.50
169	Alamos	W#4	11A	Active Channel	5	8.54
170	Alamos	W#4	11A	Active Channel	5	4.23
172	Alamos	W#4	11A	Active Channel	5	1.[illegible]

173	Alamos	Road	11A Active Channel	5	6.21
174	Alamos	Road	11A Active Channel	5	2.72
175	Alamos	Road	11A Active Channel	5	2.07
176	Alamos	Road	11A Active Channel	5	5.02
202	Alamos	Mid	11A Active Channel	5	0.61
203	Alamos	Mid	11A Active Channel	5	9.23
204	Alamos	Mid	11A Active Channel	5	0.17
205	Alamos	Mid	11A Active Flood Plain	5	25.66

BUCKMAN REPRESENTATIVE REACH:

177	Buckman	2B Inactive Bar, Lower	5	16.89
178	Buckman	2B Inactive Bar, Lower	5	4.87
179	Buckman	2B Inactive Bar, Lower	5	7.16
180	Buckman	2B Inactive Bar, Lower	5	8.01
181	Buckman	1A Active Channel	5	46.43
182	Buckman	1A Active Channel	5	49.60
183	Buckman	1A Active Channel	5	47.43
184	Buckman	1A Active Channel	5	46.39
185	Buckman	3B Aband Single Channel	5	19.33
186	Buckman	3B Aband Single Channel	5	18.71
187	Buckman	3B Aband Single Channel	5	21.07
188	Buckman	3B Aband Single Channel	5	23.37
189	Buckman	2B Inactive Bar, Upper	5	6.24
190	Buckman	2B Inactive Bar, Upper	5	6.86
191	Buckman	2B Inactive Bar, Upper	5	8.77
192	Buckman	2B Inactive Bar, Upper	5	12.43

FRIJOLES REPRESENTATIVE REACH

195	Frijoles	X Tributary Fan	5	3.48
196	Frijoles	X Tributary Fan	5	4.22
197	Frijoles	X Tributary Fan	5	4.17
199	Frijoles	X Tributary Fan	5	7.45
198	Frijoles	X Lacustrine	5	10.85
200	Frijoles	X Lacustrine	5	41.08
201	Frijoles	X Lacustrine	5	43.13

Note: For map units, see maps of various representative reaches in Chapters 12, 13, and 14

APPENDIX D. GEOMORPHOLOGICAL DATA

D1. PARTITIONS FOR CHANNEL AND FLOOD PLAIN AREA MEASUREMENTS

Partition	Starting Point	Ending Point
1	Old Española Bridge	Midpoint #1
2	Midpoint #1	Otowi Bridge
3.	Otowi Bridge	Midpoint #3
4	Midpoint #3	Rio de los Frijoles
5	Rio de los Frijoles	Reservoir Center
6.	Reservoir Center	Cochiti Dam
7	Cochiti Dam	Midpoint #5
8	Midpoint #5	Galesteo Bridge
9.	Galesteo Bridge	Midpoint #7
10	Midpoint #7	San Felipe Bridge
11	San Felipe Bridge	Midpoint #9
12	Midpoint #9	Jemez River
13	Jemez River	Midpoint #11
14	Midpoint #11	Bernalillo Bridge
15	Bernalillo Bridge	Midpoint #13
16	Midpoint #13	Alameda Bridge
17	Alameda Bridge	Midpoint #15
18	Midpoint #15	Old Town Bridge
19	Old Town Bridge	Midpoint #17
20	Midpoint #17	Barcelona Bridge
21	Barcelona Bridge	Midpoint #19
22	Midpoint #19	I 25 Bridge
23	I 25 Bridge	Midpoint #21
24	Midpoint #21	Los Lunas Bridge
25	Los Lunas Bridge	Midpoint #23
26	Midpoint #26	Tome Grant Boundary
27	Tome Grant Boundary	Midpoint #25
28	Midpoint #25	Belen Bridge
29	Belen Bridge	Midpoint #27
30	Midpoint #27	Bosque Bridge
31	Bosque Bridge	Midpoint #29
32	Midpoint #29	Bernardo Bridge
33	Bernardo Bridge	Midpoint #31
34	Midpoint #31	Cañada Ancha
35	Cañada Ancha	Midpoint #33
36	Midpoint #34	San Acacia Dam
37	San Acacia Dam	Midpoint #35
38	Midpoint #35	Pueblito Bridge
39	Pueblito Bridge	Midpoint #37
40	Midpoint #37	South Socorro Ford
41	South Socorro Ford	Midpoint #39
42	Midpoint #39	San Antonio Bridge
43	San Antonio Bridge	Midpoint #41
44	Midpoint #44	Bosque Curve
45	Bosque Curve	Midpoint #43
46	Midpoint #43	San Marcial Bridge

Notes. The partitions defined above were used to measure channel and flood plain areas along the Rio Grande. The area of flood plain and channel within each partition are given together with down distances in Appendix D2.

D7. CHANNEL AND FLOOD PLAIN AREA MEASUREMENTS

						Channel	Fl Plain
Partion	Distance	Cum Dist	Tot Area	Chan Area	Dep Area	sq km/km	sq km/km
1	7 03975	7.03975	4 69411	0.59045	4.10366	0.083873	0 582976
2	9 91318	16.95293	5 90572	1.41684	4.48888	0.142924	0.452819
3	13.67914	30 63207	1 5048	0.98522	0.51958	0 072023	0.037983
4	13 14933	43.7814	1.17924	1.02673	0.15251	0.078082	0.011598
5	11	54.7814	0	0	0	0	0
6	11.53	66 3114	0	0	0	0	0
7	7 09787	73 40927	6 10936	1 07485	5 03451	0.151432	0 709298
8	3 17856	76 58783	4 68561	0 48142	4 20419	0 151458	1.322671
9	5 95558	82 54341	4 08531	0 86268	3.22263	0.144852	0 541111
10	4 85008	87 39349	4.45269	0 9019	3 55079	0 185955	0.732109
11	5 07425	92 46774	3 04981	0 43824	2 61157	0.086365	0 514671
12	4 14835	96 61609	4 32898	0 72578	3 6032	0 174956	0 868586
13	1 48807	98 10416	2 29926	0 37613	1 92313	0 252763	1 292365
14	5 61298	103 7171	2 93642	1 05513	1 88129	0 187980	0 335167
15	11 08483	114 8019	6 06395	2 43155	3 6324	0 219358	0 327691
16	6 81665	121 6186	4 07511	1 4842	2 59091	0 217731	0 380085
17	4 20661	125 8252	1 97712	0 9031	1 07402	0 214685	0 255317
18	9 49885	135 3240	4 89788	1 74168	3 1562	0 183356	0 332271
19	5 08169	140 4057	2 54363	1 03545	1 50818	0 203760	0 296787
20	2 89497	143 3007	1 37318	0 49593	0 87725	0 171307	0 303025
21	5 55539	148 8561	3 23404	1 02174	2 2123	0 183918	0 398225
22	3 52804	152 3841	2 13323	0 70181	1 43142	0 198923	0 405726
23	5 10473	157 4889	5 00975	0 86754	4 14221	0 169948	0 811445
24	12 61346	170 1023	10 33094	2 22161	8 10933	0 176140	0 642910
25	2 93605	173 0384	2 12035	0 52042	1 59993	0 177251	0 544926
26	2 13768	175 1760	1 74448	0 48079	1 26369	0 224912	0 591150
27	5 83177	181 0078	3 89308	1 17794	2 71514	0 201986	0 465577
28	6 59455	187 6024	3 87315	1 05826	2 81489	0 160474	0 426850
29	7 59550	195 198	4 86347	1 0694	3 79407	0 140792	0 499509
30	5 88289	201 0808	2 99945	0 69388	2 30557	0 117948	0 391911
31	7 99193	209 0728	6 07346	1 13638	4 93708	0 142190	0 617758
32	7 54002	216 6136	5 81143	1 28867	4 52276	0 170902	0 599770
33	6 62606	223 2397	12 49168	1 06536	11 42632	0 160783	1 724451
34	9 38056	232 6202	17 58926	2 07333	15 51593	0 221024	1 654051
35	1 6958	234 3160	0 44114	0 12819	0 31295	0 075592	0 184544
36	5 57141	239 8874	5 83071	1 33317	4 49754	0 239287	0 807251
37	7 62521	247 5126	5 89874	1 19798	4 70076	0 157149	0 616487
38	8 45222	255 9648	7 73216	2 53789	5 19427	0 300263	0 614545
39	[illegible]	[illegible]	6 81063	1 57685	5 23378	0 234400	0 778006
40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
42	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
43	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
44	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
45	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
46	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sum	[illegible]		[illegible]	[illegible]	[illegible]		
Mean						[illegible]	[illegible]

Note: For definition of the downstream partitions, see Appendix D1

APPENDIX E. PLUTONIUM DATA

E1. PLUTONIUM CONCENTRATIONS IN RIVER WATER (pCi/l), NORTHERN RIO GRANDE

Sample Site	Plutonium-238			Plutonium-239,240		
	mean	st. dev.	#	mean	st. dev.	#
1977 1988:						
Rio Chama at Chamita	0.0041	0.0115	17	0.0128	0.0224	17
Rio Grande at Embudo	0.0103	0.0215	18	0.0106	0.0344	18
Rio Grande at Otowi	0.0016	0.0125	17	0.0040	0.0133	17
Rio Grande at Cochiti	0.0028	0.0180	18	0.0024	0.0194	18
Rio Grande at Bernalillo	0.0017	0.0123	18	0.0049	0.0315	18
Jemez River at Jemez	0.0629	0.2825	18	0.0004	0.0257	18
All Sites, 1977 1988	0.0078	0.0521	106	0.0050	0.0246	106
1976						
All Sites	0.0082		18	0.0016		18
1975						
All Sites	0.0060		18	0.0090		18
1974						
All Sites	0.0030		24	0.0010		24
ALL DATA, 1974 1988	0.0048		166	0.0041		166

Note Data from Los Alamos National Laboratory, published Environmental Surveillance Reports

E2. PLUTONIUM CONCENTRATIONS IN RIVER WATER (pCi/l),

TRIBUTARIES IN THE VICINITY OF LOS ALAMOS

Sample Site	Plutonium-238			Plutonium-239,240		
	mean	st. dev.	#	mean	st. dev.	#
1977-1988:						
Los Alamos Reservoir	0.0047	0.0215	16	0.0116	0.0228	16
Guaje Canyon in Upper Area	0.0005	0.0208	15	0.0101	0.0171	15
Frijoles Canyon at Park HQ	0.0126	0.0240	17	0.0142	0.0249	17
Frijoles Canyon at Outlet	0.0013	0.0137	8	0.0071	0.0097	8
Pajarito Canyon at Outlet	0.0035	0.0126	8	0.0016	0.0105	8
Ancho Canyon at Outlet	0.0057	0.0130	9	0.0079	0.0107	9
All Sites	0.0053	0.0191	73	0.0090	0.0178	73

Note. Data from Los Alamos National Laboratory, published Environmental Surveillance Reports

E3. PLUTONIUM CONCENTRATIONS IN BEDLOAD SEDIMENTS (pCi/g), NORTHERN RIO GRANDE

Sample Site	Plutonium-238			Plutonium-239,240		
	mean	st. dev.	#	mean	st. dev.	#
1974-1986:						
Rio Chama at Chamita	0.0001	0.0008	15	0.0015	0.0029	15
Rio Grande at Embudo	0.0003	0.0011	16	0.0033	0.0025	16
Rio Grande at Otowi	0.0003	0.0014	16	0.0106	0.0171	16
Rio Grande at Sandia Canyon	-0.0011	0.0027	8	0.0071	0.0072	8
Rio Gande at Pajarito Canyon	-0.0007	0.0024	7	0.0073	0.0031	7
Rio Grande at Ancho Canyon	-0.0014	0.0026	8	0.0069	0.0065	8
Rio Grande at Frijoles Canyon	0.0010	0.0056	6	0.0025	0.0040	6
Rio Grande at Cochiti	-0.0024	0.0079	7	0.0092	0.0149	7
Rio Grande at Bernalillo	0.0004	0.0014	14	0.0050	0.0041	14
Jemez River at Jemez	0.0005	0.0016	15	0.0040	0.0044	15
All Sites, 1974-1986	0.0002	0.0003	113	0.0048	0.0086	113

Note: Data from Los Alamos National Laboratory, published by Purtymun et al., 1987

E4. PLUTONIUM CONCENTRATIONS IN FLOOD-PLAIN SEDIMENTS (pCi/g), NORTHERN RIO GRANDE

Sample Site	Plutonium-238			Plutonium-239,240		
	mean	st. dev.	#	mean	st. dev.	#
Active Bed Sediments	0.0018	2.3759	2	0.0027	0.0003	2
Levee, Bar, Santa Clara Flood Plain	0.0006	0.0010	5	0.0049	0.0041	5
Slough, Santa Clara Aband. Channel	0.0013	0.0017	3	0.0097	0.0118	3
Tributary Channel Across Flood Plain	0.0002	-	1	0.0006	-	1
Mean "Flood Plain" (2nd & 3rd above)	0.0009	0.0012	8	0.0067	0.0075	8

E5. PLUTONIUM CONCENTRATIONS IN RESERVOIR SEDIMENTS (pCi/g).

NORTHERN RIO GRANDE

Reservoir	Year	Plutonium-238			Plutonium-239,240		
		mean	st. dev.	#	mean	st. dev.	#
Rio Grande	1986	0.0009	0 0011	3	0.0177	0.0184	3
Heron	1982	0.0006	0.0007	3	0.0134	0.0122	3
	1984	0.0005	0.0005	3	0.0093	0.0155	3
	1985	0.0005	0.0003	3	0.0112	0.0064	3
	1982-1985	0.0005	0.0005	9	0.0114	0.0114	9
El Vado	1979						
	1982	0.0003	0.0006	3	0.0095	0.0077	3
	1984	0.0004	0.0001	3	0.0047	0.0072	3
	1985	0.0003	0.0001	3	0.0073	0.0005	3
	1982-1985	0 0003	0.0003	9	0.0073	0.0051	9
Abiquiu	1982	0 0005	0.0003	2	0.0097	0.0048	2
	1984	0.0007	0.0004	3	0.012[illegible]	0.0063	3
	1985	0.0007	0.0005	3	0.0088	0.0009	3
	1986	0.0003	0 0001	3	0.0075	0.0017	3
	1987	0.0002	0.0001	3	0.0038	0.0051	3
	1988	0.0003	0.0002	3	0.0074	0.0026	3
	1982-1988	0.0004	0.0003	17	0.0081	0.0031	17
Cochiti	1982	0.0009	0.0004	7	0.0178	0.0072	7
	1984	0 0007	0.0011	3	0 0197	0.0140	3
	1985	0.0016	0.0006	2	0.0241	0.0073	2
	1986	0.0012	0.0005	4	0.0212	0.0061	4
	1987	0 0008	0 0007	3	0.0175	0.0138	3
	1988	0 0017	0.0021	3	0.0121	0.0029	3
	1982-1988	0 0011	0.0013	22	0.0189	0.0082	22
All Reservoirs	1982-1988	0.0007	0 0007	60	0.0127	0.0073	60

Note Data from Los Alamos National Laboratory, published Environmental Surveillance Reports

E6. PLUTONIUM CONCENTRATIONS IN FLUVIAL SEDIMENTS (pCi/g),

LOS ALAMOS CANYON

Sample Site	Plutonium-238			Plutonium-239,240		
	mean	st. dev.	#	mean	st. dev.	#
Acid Canyon'						
Acid Wier (16,400)	0.1293	0.1788	12	13.3491	7.1115	12
DP Canyon'						
DPS-1 Site (13,980)	1.0883	1.4854	23	2.1574	2.4081	23
DPS-4 Site (13,680)	0.1218	0.0576	17	0.4797	0.2701	17
Pueblo Canyon'						
Hamilton Spring Bend (12,850)	0.0035	0.0034	14	0.4994	0.3947	14
Pueblo Site 1 (15,900)	0.0066	0.0158	11	0.0639	0.1665	11
Pueblo Site 2 (14,150)	0.0127	0.0094	11	1.8849	1.6705	11
Pueblo Site 3 (10,050)	0.0086	0.0171	12	2.0836	4.4321	12
Near SR 4 (7,650)	0.0037	0.0046	16	0.6581	0.7022	16
Los Alamos Canyon						
Reservoir Site (19,800)	0.0007	0.0009	3	0.0060	0.0037	3
Bridge Site (16,600)	0.0010	0.0014	12	0.0021	0.0024	12
LAO 1 Site (12,800)	0.0102	0.0167	17	0.6763	0.9696	17
GS 1 Site (11,000)	0.0622	0.8515	16	0.3572	0.2767	16
LAO 3 Site (9,500)	0.0765	0.0273	16	0.2581	0.2298	16
LAO 4.5 Site (8,000)	0.1033	0.0921	10	0.4068	0.4186	10
LAO 4 Site (7,500)	0.0790	0.0425	6	0.3313	0.1497	6
Near SR 4 (7,250)	0.0469	0.0355	15	0.2483	0.2032	15
Totavi (3,800)	0.0137	0.0174	15	0.2218	0.2186	15
Otowi (400)	0.0063	0.0098	15	0.1271	0.1318	15
Bayo Canyon'						
Near SR 4 (3,900)	0.0015	0.0017	13	0.0015	0.0011	13
Guaje Canyon'						
Near SR 4 (2,400)	0.0008	0.0014	12	0.0023	0.0010	12

Notes: "SR 4" refers to old New Mexico State Route 4

[e] Small canyons with waste disposal sites

[f] Connects Acid Canyon to Los Alamos Canyon.

[g] Canyons not directly affected by waste sites that are tributary to Los Alamos Canyon

APPENDIX F. TOPOGRAPHIC MAPS:

U.S.G.S. TOPOGRAPHIC QUADRANGLES, ESPAÑOLA TO ELEPHANT BUTTE

1:23,000 SCALE.

Española
Puye
White Rock
Frijoles
Cochiti Dam
Santo Domingo Pueblo
Santo Domingo Pueblo SW
San Felipe Pueblo
Santa Ana Pueblo
Bernalillo
Alameda
Los Griegos
Albuquerque West
Isleta
Los Lunas
Tome
Belen
Veguita
Abeytas
Lemitar
Socorro
Loma de las Canas
San Antonio
Val Verde
Fort Craig
Paraje Well
Romero Canyon
Lava
Black Bluffs
Elephant Butte

1:100,000 SCALE:

Los Alamos
Albuquerque
Belen
Socorro
Oscura Mountains
San Mateo Mountains
Truth or Consequences

Note: All maps are New Mexico

APPENDIX 6. SOURCES OF AERIAL PHOTOGRAPHY

U.S. Geological Survey, U.S. Bureau of Reclamation, U S Army, U.S. Air Force.

U.S. Geological Survey
EROS Data Center
Souix Falls, South Dakota 57198

U.S Department of Agriculture, Soil Conservation Service, Agricultural Stabilization and Commodity Service:

U.S. Department of Agriculture
Aerial Photography Field Office
User Services Branch
2222 West, 2300 South
P.O. Box 30010
Salt Lake City, Utah 84125

Pre 1941 Photography of U S Department of Agriculture Soil Conservation Service

General Services Administration
National Archives and Records Administration
Cartographic and Architectural Branch
Washington, D C 20408

Pre 1950 Fairchild Aerial Photography

Fairchild Aerial Photography Collection
c/o Dallas D Rhoads
Department of Geology
Whittier College
Whittier, California 90608

APPENDIX H. SOURCES OF HISTORICAL GROUND PHOTOGRAPHY

SOURCES IN NEW MEXICO

Los Alamos Historical Society
Attn Hedy Dunn
P O Box 43
Los Alamos, New Mexico

Albuquerque Museum
Albuquerque, New Mexico

Albuquerque Public Library
501 Copper Avenue, NW
Albuquerque, New Mexico

Maxwell Museum of Anthropology
University of New Mexico
Albuquerque, New Mexico

Special Collections
Main Library
University of New Mexico
Albuquerque, New Mexico

Middle Rio Grande Conservancy District
1931 Second Avenue, SW
Albuquerque, New Mexico

New Mexico Museum of Natural History
1801 Mountain Road, NW
Albuquerque, New Mexico

Photo Archives of New Mexico
110 Washington Avenue
Santa Fe, New Mexico

State Archives
404 Montezuma Avenue
Santa Fe, New Mexico

U.S. Bureau of Reclamation
505 Marquette Avenue, NW
Albuquerque, New Mexico

SOURCES OUTSIDE NEW MEXICO

Colorado Historical Society
Historical Photograph Collection
[illegible] Broadway, and Colfax Avenue
Denver, Colorado 80203

Denver Public Library
Western History Collection
Denver, Colorado 80203

U.S. Geological Survey
Photographic and Field Records File
Box 25046
Denver Federal Center
Denver, Colorado 80225

El Paso Public Library
[illegible]

El Paso, Texas

Library of Congress
U.S. National Archives
Reston, Virginia

National Anthropological Archives
BAE Holdings
Smithsonian Institution
Washington, D C 20560

Pomona Public Library
Special Collections
625 South Garey Avenue
Pomona, California

Southwest Museum
234 Museum Drive
Los Angeles, California 90065

APPENDIX I. CONTACT PERSONS FOR RIO GRANDE INFORMATION

U S Bureau of Reclamation

Drew Baird
Chief of River Assessment
505 766 1758

U S Army Corps of Engineers,
Albuquerque District

Frank Jaramillo
Chief Engineer
505 766 2635

Justice Edge
Sedimentation Specialist
505 766 1034

Mark Sifuentes
Environmental Specialist
505 766 3577

Frank Collins
Emergency Operations
505 766 [illegible]

Kim Zahm
Assistant Chief of Design
(Previously, Sedimentation)
505 766 2626

Middle Rio Grande Conservancy District

Subhas Shah
District Engineer
505 247 0234

APPENDIX J. BASIC FORMULAE USED IN THE RAT PROGRAM

A. Equation of Continuity

$$Q = WDV$$

where:

Q = original unadjusted discharge ($m^3 s^{-1}$)

W = channel width (m)

D = channel depth (m)

v = velocity ($m s^{-1}$)

B. Transmission Losses

$$Q_a = Q - L_t \left(\sum_{1}^{n} A_n \right)$$

where

Q_a adjusted discharge ($m^3 s^{-1}$)

Q original unadjusted dishcargo ($m^3 s^{-1}$)

L_t transmission loss rate ($m^3 s^{-1} m^{-2}$)

1,n channel segment number

A_n channel bed area in segment n (m^2)

C. Velocity of Flow

$$V = n^{-1} R^{2/3} S^{1/2}$$

where

V velocity ($m s^{-1}$)

n Manning's hydraulic roughness coefficient (0.015-0.045)

R hydraulic radius defined below (m)

S channel gradient

D. Hydraulic Radius

$$R = \frac{WD}{(2D + W)}$$

where: R = hydraulic radius (m)

W = channel width (m)

D = channel depth (m)

E. Depth of Flow

$$D = \frac{Q}{WV}$$

where: D = depth of flow (m)

Q = discharge ($m^3 s^{-1}$)

W = width of flow (m)

V = velocity of flow ($m s^{-1}$)

or, alternatively in some cases

$$D = \left(\frac{Qn}{(k W S^{1/2})} \right)^{0.6}$$

where k = shape parameter (1.0 for broad, shallow channels, < 1.0 for others)

F. Unit Stream Power

$$\omega = \rho g D V S$$

where ω = unit stream power ($N m^{-1} s^{-1}$ or $W m^{-2}$)

ρ = density of the fluid ($1 g cm^{-3}$)

g = acceleration of gravity ($9.81 m s^{-2}$)

D = depth of flow (m)

V = velocity of flow ($m s^{-1}$)

S = flow gradient

G. Stream Power

$$\Omega = \rho g D W V S = \rho Q = \omega W$$

where:

Ω = stream power (N s^{-1} or W)

ρ = density of the fluid (1 g cm^{-3})

g = acceleration of gravity (9.81 m s^{-2})

D = depth of flow (m)

W = width of flow (m)

V = velocity of flow (m s^{-1})

S = flow gradient

Q = discharge (m^3 s^{-1})

ω = unit stream power (defined above; N m^{-1} s^{-1} or W m^{-2})

H. Sediment Transport Capacity

$$i = \omega \left(\frac{e_b}{\tan\alpha} + 0.01 \frac{u}{v_{ss}} \right)$$

where:

i = total load transport (kg s^{-1})

ω = unit stream power (defined above, N m^{-1} s^{-1} or W m^{-2})

e_b = a bedload efficiency factor (usually $0.11 < e_b < 0.15$)

$\tan \alpha$ = coefficient of friction (about 1.0 for bedload particles)

u = velocity (m s^{-1})

v_{ss} = settling velocity of particles for a given size (m s^{-1})

Note: the first term inside the parentheses on the right side of the equation is for bedload, the second term inside the parenthese is for suspended load)

I. Sediment Continuity Equation

$$\frac{\partial M_t}{\partial t} = \frac{\partial M_i}{\partial t} - \frac{\partial M_o}{\partial t}$$

where:

M_t = sediment mass total in storage in a channel segment (Mg)

M_i = input mass from channel segment upstream (Mg)

M_o = ouput mass to channel segment downstream (Mg)

t = time unit (day)

J. Plutonium Continuity Equation

$$\frac{\partial P_t}{\partial t} = \frac{\partial P_i}{\partial t} - \frac{\partial P_o}{\partial t}$$

where:

P_t plutonium mass in storage in a channel segment (mCi)

P_i input plutonium mass from channel segment upstream (mCi)

P_o output plutonium mass to channel segment downstream (mCi)

t time unit (day)

K. Plutonium Concentration in Sediment

$$P_{conc_{t,i,o}} = \frac{P_{t,i,o}}{M_{t,i,o}}$$

where

P_{conc} plutonium concentration in stored, input, or output sediment

$P_{t,i,o}$ plutonium mass in stored, input, or output sediment mass (fCi/g)

$P_{t,i,o}$ plutonium mass in stored, input, or output sediment mass (fCi/g)

Sources: Chow (1959), Graf (1988)

NOTES

PART 1. INTRODUCITON

CHAPTER 1. INTRODUCTION

1. F. W. Whicker and V. Schultz, *Radioecology: Nuclear Energy and the Environment*, 2 vols. (Boca Raton, Florida: CRC Press, Inc., 1982).

2. T. E. Hakonson, R. L. Watters, and W. C. Hanson, "The Transport of Plutonium in Terrestrial Ecosystems," *Health Physics* 40(1981): 63-69.

3. A. Stoker, A. J. Ahlquist, D. L. Mayfield, W. R. Hansen, A. D. Tally, and W. D. Purtymun, *Radiological Survey of the Site of a Former Radioactive Liquid Waste Treatment Plant (TA-45) and the Effluent Receiving Areas of Acid, Pueblo, and Los Alamos Canyons, Los Alamos, New Mexico*, Los Alamos National Laboratory and U.S Department of Energy Report LA-8890-ENV, UC-70 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1981).

4. J. W. Nyhan, B. J. Drennon, W. V. Abeele, M. L. Wheeler, W. D. Purtymun, G. Trujillo, W. J. Herrera, and J. W. Booth, *Distribution of Radionuclides and Water in Bandelier Tuff Beneath a Former Los Alamos Liquid Waste Disposal Site After 33 Years*, Los Alamos National Laboratory Report LA-10159-LLWM (Los Alamos, New Mexico: Los Alamos National Laboratory, 1984).

5. W. D. Purtymun, *Storm Runoff and Transport of Radionuclides in DP Canyon, Los Alamos County, New Mexico*, Los Alamos National Laboratory Report LA-5744 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1974).

6. L. J. Lane, W. D. Purtymun, and N. M. Becker, *New Estimating Procedures for Surface Runoff, Sediment Yield, and Contaminant Transport in Los Alamos County, New Mexico*. Los Alamos National Laboratory Report LA-10335 MS, UC 11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1985).

7. Environmental Surveillance Group, *Environmental Surveillance at Los Alamos* (Los Alamos, New Mexico: Los Alamos National Laboratory, Annually, 1971-1991); W. D. Purtymun, R. J. Peters, T. E. Buhl, W. N. Maes, and F. H. Brown, *Background Concentrations of Radionuclides in Soils and River Sediments in Northern New Mexico, 1974-1986*, Los Alamos National Laboratory Report LA-11134 MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1987.

8. W. Solomons and U. Förstner, *Metals in the Hydrocycle* (Berlin: Springer Verlag, 1984).

9. W. C. Pfeiffer, M. Fiszman, and N. Carbonell, "Fate of Chromium in a Tributary of the Irajo River, Rio de Janeiro," *Environmental Pollution* 1(1980): 117-126.

10. K. H. Larson, J. L. Leitch, W. F. Dunn, J. W. Neel, J. H. Olafson, E. E. Held, J. Taylor, W. J. Cross, and A. W. Bellamy, *University of Califronia Report, Los Alamos*, University of California Report UCLA 108 (Berkeley, California: University of California 1951); V. F. Noshkin, "Ecological Aspects of Plutonium Dissemination in Aquatic Environments," *Health Physics* 22(1972):537; F. W. Whicker, C. A. Little, and T. F. Winsor, *Symposium on Environmental Surveillance Around Nuclear Installations*, September 5-9, 1973 (Warsaw, Poland: International Atomic Energy Commission, 1973); T. E. Hakonson, L. J. Johnson, and W. D. Purtymun, "The Distribution of Plutonium in

Liquid Waste Disposal Areas at Los Alamos," *Proceedings of the 3rd International Congress of the Radiation Protection Association*, September 9-14, 1973 (Washington, D.C.: Radiation Protection Association, 1973), 248-253; T. E. Hakonson, and L. J. Johnson, "Distribuiton of Environmental Plutonium in the Trinity Site Ecosystem After 27 Years," *Proceedings of the 3rd International Congress of the Radiation Protection Association*, September 9-14, 1973 (Washington, D.C.: Radiation Protection Association, 1973), 242-247.

11. R. C. Dahlman, C. T. Garten Jr., and T. E. Hakonson, "Comparative Distribution of Plutonium in Contaminated Ecosystems at Oak Ridge, Tennessee, and Los Alamos, New Mexico," in *Transuranic Elements in the Environment*, ed. W. C. Hanson (Washington, D.C.: U.S. Department of Energy and National Technical Information Center, 1980), 371-380.

12. J. M. Martin and M. Maybeck, "Elemental Mass Balance of Material Carried by Major World Rivers," *Marine Chemistry* 7(1979):173-206.

13. G. C. White and T. E. Hakonson, "Statistical Considerations and Survey of Plutonium Concentration Variability in Some Terrestrial Ecosystem Components," *Journal of Environmental Quality* 8(1979):176-182.

14. J. W. Nyhan, T. G. Schofield, G. C. White, and G. Trujillo, *Sampling Soils for Cs-137 Using Various Field Sampling Volumes*, Los Alamos National Laboratory Report LA-8951-MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1981).

15. T. E. Hakonson, "Environmental Pathways of Plutonium into Terrestrial Plants and Animals," *Health Physics* 29(1975):583-588

16. T. E. Hakonson, R. L. Watters, and W. C. Hanson, "Transport of Plutonium in Terrestrial Ecosystems," *Health Physics* 40(1981):63-69; E. M. Romney and J. J. Davis, "Ecological Dissemination of Plutonium in the Environment," *Health Physics* 21(1972):551. R. E. Wilding and T. R. Garland, "The Relationship of Microbial Processes to the Fate and Behavior of Transuranic Elements in Soils, Plants, and Animals," in *Transuranic Elements in the Environment*, U.S. Department of Energy Report DOE/TIC-22800 (Washington, D.C.: U.S. Department of Energy and National Technical Information Center, 1980). R. L. Watters, T. E. Hakonson, and L. J. Lane, "The Behavior of Actinides in the Environments," *Radiochimica Acta* 32(1983):89-103.

17. H. Nishita and R. M. Haug, "The Effect of Fulvic and Humic Acids and Inorganic Phase of Soil on the Sorption and Extractability of Pu(IV) 239 From Several Clay Minerals," *Soil Science* 128(1979):291-296.

18. H. Nishita and M. Hamilton, "The Influence of Serveral Soil Components and Their Interaction on Plutonium Extractability From a Calcareous Soil," *Soil Science* 131(1981):56-59.

19. J. W. Nyhan, F. R. Mera, and R. E. Neher, R. L., "Distribution of Plutonium in Trinity Soils After 28 Years," *Journal of Environmental Quality* 5(1976):431-437; J. W. Nyhan, T. G. Schofield, G. C. White, and G. Trujillo, *Sampling Soils for Cs-137 Using Various Field Sampling Volumes*, Los Alamos National Laboratory Report LA-8951-MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1981).

20. L. Jacobson P. Oversteret, "The Uptake by Plants of Plutonium and Some Productions of Nuclear Fission Adsorbed on Soil Colloids. *Soil Science* 65(1948):129-134

21. W. E. Prout, "Adsorption of Radioactive Wastes on Savannah River Plant Soil," *Soil Science* 86(1958):13-17

22 A. T. Jakubick, "Migration of Plutonium in Natural Soils," in *Transuranic Nuclides in the Environment*, International Atomic Energy Commission Report IAEA-SM-199/3 (Vienna, Austria: International Atomic Energy Agency, 1976); A. T. Jakubick, "In Situ Plutonium Transport in Geomedia, in *Migration of Long-Lived Radionuclides in the Geosphere* (Paris: OECD, 1979), 201-223.

23 J. L. Means, D. A. Crerar, M. P. Borcsik, and J. O. Duguid, "Adsorption of Co and Selected Actinides by Mn and Fe Oxides in Soils and Sediments," *Geochimica and Cosmochimica Acta* 42(1978):1763-1773.

24 S. R. Ashton and D. A. Stanners, D. A., "Observations on the Depositon, Mobility and Chemical Associations of Plutonium in Intertidal Sediments, in *Techniques for Identifying Transuranic Speciation in Aquatic Environments* International Atomic Energy Agency Report STI/PUB/613 (Vienna, Austria: International Atomic Energy Agency, 1981), 209-217. T. M. Beasley, R. Carpenter, and C. D. Jennings, "Plutonium, Am-241 and Cs-137 Ratios, Inventories and Vertical Profiles in Washington and Oregon Continental Shelf Sediments" *Geochimica and Cosmochimica Acta*, 46(1982) 1831-1946.

25 P. J. Coughtrey, D. Jackson, C. H. Jones, P. Kane, and M. C. Thorne, *Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, Volume 4: Plutonium and Neptunium* (Rotterdam: A. A. Balkema, 1984), 6

26 W. E. Prout, "Adsorption of Radioactive Wastes on Savannah River Plant Soil," *Soil Science* 86(1958):13-17

27 M. Yamamoto, T. Tanii, and M. Sakanoue, M., "Characteristics of Fallout Plutonium in Soil," *Journal of Radiation Research* 22(1981):134-142

28 M. J. Frissel, A. T. Jakubick, A. van der Klugt, R. Pennders, P. Poelstra, and F. Zwemmer, *Modelling of the Transport of Radionuclides of Strontium, Caesium, and Plutonium in Soil: Experimental Verification* (Brussels: Commission of the European Communities, 1980). A. T. Jakubick, "Migration of Plutonium in Natural Soils," in *Transuranic Nuclides in the Environment*, International Atomic Energy Commission Report IAEA-SM-199/3 (Vienna, Austria: International Atomic Energy Agency, 1976)

29 T. E. Hakonson and J. W. Nyhan, "Ecological Relationships of Plutonium in Southwest Ecosystems," in *Transuranic Elements in the Environment*, U.S. Department of Energy Report DOE/TIC-22800, ed. W. C. Hanson (Washington, D.C.: U.S. Department of Energy, and National Technical Information Service, 1980)

30 T. E. Hakonson, J. W. Nyhan, and W. D. Purtymun, "Accumulation and Transport of Soil Plutonium in Liquid Waste Discharge Areas at Los Alamos," in *Transuranium Nuclides in the Environment* (Vienna, Austria: International Atomic Energy Commission, 1976), 175-189

31 S. M. Wise, "Caesium-137 and Lead-210: A Review of the Techniques and Some Applications in Geomorphology," in *Timescales in Geomorphology*, ed. R. A. Cullingford, D. A. Davidson, and J. Lewin (Chichester, United Kingdom: John Wiley & Sons, 1980), 109-127

32 R. K. Schulz, R. Overstreet, and I. Barshad, "On the Soil Chemistry of Cesium 137," *Soil Science* 89(1960):16-27

33 A. S. Rogowski and T. Tamura, "Movement of Cesium 137 by Runoff, Erosion, and Infiltration on the Alluvial Captina Silt Loam," *Health Physics* 11(1965):1333-1340

34 J. C. Lance, S. C. McIntyre, J. W. Naney, and S. S. Rousseva, "Measuring Sediment Movement at Low Erosion Rates Using Cesium-137," *Soil Science Society of America Journal* [illegible]

35. J. C. Ritchie, J. R. McHenry, and A. C. Gill, "Dating recent reservoir sediments," *Limnology and Oceanography* 18(1973):254-263; B. L. Campbell, R. J. Loughran, G. L. Elliott, and D. J. Shelly, "Mapping Drainage Basin Sediment Sources Using Caesium-137," in *International Symposium on Drainage Basin Seidment Delivery*, International Association of Hydrological Sciences Publication 159 (Albuquerque, New Mexico: Internation Association of Hydrological Sciences, 1986); R. G. Kachanoski, "Comparison of Measured Soil Cesium-137 Losses and Erosion Rates," *Canadian Journal of Soil Science* 67(1987):199-203.

36. R. B.Brown, G. F. Kling, and N. H. Cutshall, "Agricultural Erosion Indicated by Cs-137 Redistribution," *Soil Science Society of America Proceedings* 45(1981):1191-1197; S. C McIntyre, J. C. Lance, B. L. Campbell, R. L. Miller, "Using Cesium-137 to Estimate Soil Erosion on a Clearcut Hillside," *Journal of Soil and Water Conservation* 42(1987):117-120; L W. Martz and E. de Jong, "Using Cesium-137 to Assess the Variability of Net Soil Erosion and Its Association With Topography in a Canadian Prairie Landscape," *Catena* 14(1987):439-451

37. R. J Loughran, B L. Campbell, and D E. Walling, "Soil Erosion and Sedimentation Indicated by Caesium 137, Jackmoor Brook Catchment, Devon, England," *Catena* 14(1987):201-212

38 W W Sayre, W W. and F. W Chang, F. W. *A Laboratory Investigation of Open-Channel Dispersion Processes for Dissolved, Suspended, and Floating Dispersants*, U.S. Geological Survey Professional Paper 433-E (Washington, D.C.: U.S. Geological Survey, 1968)

39 R. G Godfrey and B J Frederick, *Stream Dispersion at Selected Sites*, U.S Geological Survey Professional Paper 433 K (Washington, D C : U.S Geological Survey, 1970)

40 P H Carrigan Jr , *Radioactive Waste Distribution in the Clinch River, Eastern Tennessee*, U S Geological Survey Professional Paper 433 G (Washington, D C.: U S Geological Survey, 1968), P H Carrigan Jr , *Inventory of Radionuclides in Bottom Sediment of the Clinch River, Eastern Tennessee*, U S Geological Survey Professional Paper 433 I (Washington, D C U S Geological Survey, 1969)

41 R T Glover, *Dispersion of Dissolved or Suspended Materials in Flowing Streams* U S Geological Survey Professional Paper 433 B (Washington, D C U S Geological Survey, 1964)

42 W W Sayer, H P Guy, and A R Chamberlain, *Uptake and Transport of Radionuclides by Stream Sediments*, U S Geological Survey Professional Paper 433 A (Washington, D C U S Geological Survey, 1963), E A Jenne and J S Wahlberg, *Role of Certain Stream Sediment Components in Radioion Sorption*, U S Geological Survey Professional Paper 433 F (Washington, D C U S Geological Survey, 1968)

43 P. J Pickering, *Distribution of Radionuclides in Bottom Sediment of the Clinch River, Eastern Tennessee*, U S Geological Survey Professional Paper 433 H (Washington, D C U S Geological Survey, 1969), P H Carrigan Jr , *Inventory of Radionuclides in Bottom Sediment of the Clinch River, Eastern Tennessee*, U S Geological Survey Professional Paper 433 I (Washington, D C U S Geological Survey 1969)

44 W W Sayre and D W Hubbell, *Transport and Dispersion of Labeled Bed Material, North Loup River, Nebraska*, U S Geological Survey Professional Paper 433 C (Washington D C U S Geological Survey, 1965)

45 Luna B Leopold (Chief Water Resources Division, U S Geological Survey),

interview with author, Santa Fe, New Mexico, May 24, 1990; and David Dawdy (Hydrologist, Water Resources Division, U.S. Geological Survey), interview with author, Washington, D.C., May 28, 1989.

46. T. E. Hakonson, J. W. Nyhan, and W. D. Purtymun, "Accumulation and Transport of Soil Plutonium in Liquid Waste Discharge Areas at Los Alamos," in *Transuranic Nuclides in the Environment* (Vienna, Austria: International Atomic Energy Commission, 1976), 175-189.

47. T. E. Hakonson, R. L. Watters, and W. C. Hanson, "Transport of Plutonium in Terrestrial Ecosystems," *Health Physics* 40(1981):63-69

48. T. E. Hakonson and K. B. Bostick, "Cesium-137 and Plutonium in Liquid Waste Discharge Areas at Los Alamos," in *Radioecology and Energy Resources*, Special Publication No. 1, Ecological Society of America (Stroudsburg, Pennsylvania: Dowden, Hutchenson and Ross, 1976), 40-48.

49. R. L. Watters, T. E. Hakonson, and L. J. Lane, "The Behavior of Actinides in the Environments," *Radiochimica Acta* 32(1983):91.

50. M. R. Scott, "Thorium and Uranium Concentrations and Isotopic Ratios in River Sediments," *Earth and Planetary Science Letters* 4(1968):245-252; R. J. Gibbs, "Mechanisms of Trace Metal Transport in Rivers," *Science* 180(1973):71-73.

51. R. G. Menzel, "Enrichment Ratios for Water Quality Modeling," in *CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion From Agricultural Management Systems*, U.S Department of Agriculture Conservation Research Report 26 (Washington, D.C.: U.S. Department of Agriculture, 1980), 486-492

52. L. J. Lane and T. E. Hakonson, "Influence of Particle Sorting in Transport of Sediment Associated Contaminants," *Proceedings of the Wast Management Symposium*, Tucson, Arizona, 1982 (Tucson, Arizona: University of Arizona Press, 1982), 543-557.

53. W. C. Weimer, R. R. Kinnison, and J. H. Reeves, *Survey of Radionuclide Distributions Resulting From the Church Rock, New Mexico, Uranium Mill Tailings Pond Dam Failure*, U.S. Nuclear Regulatory Commission Report NUREG/CR-2449, PNL-4122 (Richland, Washington: Battelle Pacific Northwest Laboratory, 1981).

54. W. L. Graf, *Fluvial Processes in Dryland Rivers* (Berlin and New York: Springer Verlag, 1988)

55. W. L. Graf, "Fluvial dynamics of Thorium-230 in the Church Rock Event, Puerco River, New Mexico," *Annals of the Association of American Geographers* 80(1990):327-342

56. T. J. East, "Geomorphological Assessment of Sites and Impoundments for the Long Term Containment of Uranium Mill Tailings in the Alligator River Region," *Australian Geographer* 16(1986):16-[illegible].

57. T. J. East, R. F. Cull, A. S. Murray, and K. Duggan, "Fluvial Dispersion of Radioactive Mill Tailings in the Seasonally Wet Tropics, Northern Australia," in *Fluvial Geomorphology of Australia*, ed. R. F. Warner (Sidney: Academic Press, 1988), 303-322

58. R. F. Cull, K. Duggan, R. Martin, and A. S. Murray, "Tailings Transport and Deposition Downstream of the Northern Hercules (Moline) Mine in the Catchment of the Mary River, N.T.," in *Environmental Planning and Management for Mining and Energy* (Darwin: Northern Australia Mine Rehabilitation Workshop, 1986), 199-216

59. P. J. Jarvis, *Heavy Metal Pollution: An Annotated Bibliography, 1976-1980* (East Anglia, United Kingdom: Geobooks, 1983), p. 3

60. W. Salomons and U. Förstner, *Metals in the Hydrocycle* (Berlin: Springer

Verlag, 1984).

61. R. C. Weast, *Handbook of Chemistry and Physics* (Boca Raton, Florida: CRC Press).

62. D. B. Simons and F. Senturk, *Sediment Transport Technology* (Fort Collins, Colorado: Water Resources Publications).

63. K. E. Carpenter, "Fauna of Rivers Polluted by Lead Mining in the Aberystwyth District of Cariganshire," *Annals of Applied Biology* 11(1924):1-23; K. E. Carpenter, "On the Biological Factors Involved in the Destruction of River Fisheries by Pollution Due to Lead Mining," *Annals of Applied Biology* 12(1925):1-13.

64. J. R. E. Jones, "A Study of the Zinc-polluted River Ystwyth in Northern Cardiganshire, Wales," *Annals of Applied Biology* 27(1940):363-378; J. R. E. Jones, "A Further Study of the Zinc-Polluted River Ystwyth," *Journal of Animal Ecology* 27(1958):1-14; L. Newton, "Pollution of the Rivers of West Wales by Lead and Zinc Mine Effluent," *Annals of Applied Biology* 31(1944):1-11.

65. J. B. Wertz, "Logarithimic Pattern in River Placer Deposits," *Economic Geology* 44(1949):193-209; J. Lewin, B. E. Davies, and P. Wolfenden, "Interactions Between Channel Change and Historic Mining Sediments," in *River Channel Change*, ed. K. J. Gregory (Chichester, England: John Wiley & Sons, 1977), 353-367; P. Wolfenden and J. Lewin, "Distribution of Metal Pollutants in Active Stream Sediments," *Catena* 5(1978):67-78.

66. W. D. Payne, "The Role of Sulfides and Other Heavy Minerals in Copper Anomalous Stream Sediments" (Ph.D. diss., Stanford University, 1971); V. V. Plikarpochkin, "The Quantitative Estimation of Ore-bearing Areas from Sample Data of the Drainage System," in *Geochemical Exploration* (Toronto: Canadian Institute of Mining and Metallurgy, 1971), 585-586; G. Müller and U. Förstner, "Heavy metals in Sediments of the Rhine and Elbe Estuaries," *Environmental Geology* 1(1977):33-37; W. A. Marcus, "Copper Dispersion in Ephemeral Stream Sediments," *Earth Surface Processes and Landforms* 12(1987):117-128.

67. R. C. Lindholm, *Practical Approach to Sedimentology* (London: Allen & Unwin, 1987).

68. S. B. Bradley, "Sediment Quality Related to Discharge in a Mineralized Region of Wales," in *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield*, International Association of Scientific Hydrology Publication No. 137 (Paris: International Association of Scientific Hydrology, 1982), 341-350; S. B. Bradley, "Flood Effects on the Transport of Heavy Metals," *International Journal of Environmental Studies* 22(1984):225-230; S. B. Bradley, "Partitioning of Heavy Metals on Suspended Sediments During Floods on the River Ystwyth, Wales," *Trace Substances in Environmental Health* 18(1984):548-557; S. B. Bradley and J. J. Cox, "Heavy Metals in the Hamps and Manifold Valleys, North Staffordshire, U.K.: Distribution in Flood Plain Soils," *The Science of the Total Environment* 50(1986):103-128; M. G. Macklin and R. B. Dowsett, "The Chemical and Physical Speciation of Trace Metals in Fine Grained Overbank Flood Sediments in the Tyne Basin, North East England," *Catena* 16(1989):135-151; M. G. Macklin, "Floodplain Sedimentation in the Upper Axe Valley, Mendip, England," *Transactions of the Institute of British Geographers* 10 n.s. (1985):235-244; M. G. Macklin and D. G. Passmore, *Late Quaternary Sedimentation in the Lower Tyne Valley, North East England*, Seminar Paper 55 (Newcastle Upon Tyne, England: University of Newcastle Upon Tyne, Department of Geography, 1988).

69. B. E. Davies and J. Lewin, "Chronosequences in Alluvial Soils with Special Reference to Historic Lead Pollution in Cardiganshire, Wales," *Environmental Pollution* 6(1974):49-57; P. Wolfenden and J. Lewin, "Distribution of Metal Pollutants in Floodplain Sediments," *Catena* 4(1977):309-317; J. C. Knox, "Historic Valley Floor Sedimentation in the Upper Mississippi Valley," *Annals of the Association of American Geographers* 77(1987):224-244; W. L. Graf, S. L. Clark, M. T. Kammerer, T. Lehman, K. Randall, and R. Schröder, "Geomorphology of Heavy Metals in the Sediments of Queen Creek, Arizona, U.S.A.," *Catena* 18(1991):567-582.

70. D. C. Marron, "Physical and Chemical Characteristicsof a Metal Contaminated Overbank Deposit, West Central South Dakota, USA," *Earth Surface Processes and Landforms* 14(1989):419-432; W. L. Graf, S. L. Clark, M. T. Kammerer, T. Lehman, K. Randall, and R. Schröder, "Geomorphology of Heavy Metals in the Sediments of Queen Creek, Arizona, U.S.A.," *Catena* 18(1991):567-582.

71. K. R. Imhoff, P. Koppe, and F. Deitz, "Heavy Metals in the Ruhr River and Their Budget in the Catchment Area," *Progress in Water Technology* 12(1980):735-749.

72. W. L. Graf, "Mercury Tansport in Stream Sediments of the Colorado Plateau," *Annals of the Association of American Geographers* 75(1985):552-565.

73. H. Leenaers, *The Dispersal of Metal Mining Wastes in the Catchement of the river Geul, Belgium -- The Netherlands* (Utrecht, The Netherlands: Geograpfisch Instituut, Rijksuniveriteit, 1989).

74. D. C. Marron, "Physical and Chemical Characteristicsof a Metal Contaminated Overbank Deposit, West Central South Dakota, USA," *Earth Surface Processes and Landforms* 14(1989):419 432.

75. G. R. Foster, and T. E. Hakonson, "Erosional Losses of Fallout Plutonium," Mimeographed Typescript, *Proceedings of the Symposium on Environmental Research on Actinides in the Environment* (Washington, D.C: U.S. Department of Energy, 1983); G. R. Foster and T. E. Hakonson, "Predicted Erosion and Sediment Delivery of Fallout Plutonium," *Journal of Environmental Quality* 13(1984):595 602.

76. M. A. Devaurs, E. P. Springer, L. J. Lane, and G. J. Langhorst, "Contaminant Transport from Rangeland Watersheds," American Society of Agricultural Engineers, International Symposium on Modeling Agricultural, Forest and Rangeland Hydrology, Mimeographed Typescript, Los Alamos National Laboratory Report LA UR 88 2071 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1988)

77. L. J. Lane, W. D. Purtymun, and N. M. Becker, *New Estimating Procedures for Surface Runoff, Sediment Yield, and Contaminant Transport in Los Alamos County, New Mexico* Los Alamos National Laboratory Report LA 10335 MS, UC 11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1985)

78. F. W. Whicker and V. Schultz, *Radioecology: Nuclear Energy and the Environment*, 2 vols. (Boca Raton, Florida: CRC Press, Inc., 1982)

79. J. A. C. Fortescue, *Environmental Geochemistry: A Holistic Approach* (New York and Berlin: Springer Verlag, 1980), 249

80. P. J. Coughtrey, D. Jackson, C. H. Jones, P. Kane, and M. C. Thorne, *Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, Volume 4: Plutonium and Neptunium* (Rotterdam: A. A. Balkema, 1984), 12

81. W. Solomons and U. Förstner, *Metals in the Hydrosphere* (New York and Berlin: Springer Verlag, 1984)

82. A. A. Levinson, *Introduction to Exploration Geochemistry* (Wilmette, Illinois

Applied Publishing, 1980)

CHAPTER 2. PLUTONIUM AND LOS ALAMOS

1. R. Rhoads, *The Making of the Atomic Bomb* (New York: Simon and Schuster, 1986); L. Bickel, *The Dealy Element* (London: Stein and Day, 1980); G. Holton, *Thematic Oigins of Scientific Thought* (Cambridge, Massachussetts: Harvard University Press, 1973).

2. E. Curie, *Madame Curie* (Garden City, New York: Doubleday, 1938).

3. M. Oliphant, *Rutherford* (New York: Elsevier, 1972).

4. D. Wilson, *Rutherford* (Cambridge, Massachussetts: Massachussetts Institute of Technology Press, 1983).

5. S. Rozental (ed.), *Niels Bohr* (London: North Holland, 1967).

6. A. Romer (ed.), *Radiochemistry and the Discovery of Isotopes* (New York: Dover Publications, 1970).

7. R. H. Stuewer (ed.), *Nuclear Physics in Retrospect* (Minneapolis, Minnesota: University of Minnesota Press, 1979).

8. E. Segre, *From X-Rays to Quarks: Modern Physicists and Their Discoveries* (San Francisco: Freeman, 1980).

9. E. Segre, *Enrico Fermi, Physicist* (Chicago: University of Chicago Press, 1970).

10. G. T. Seaborg, *The Transuranic Elements* (Yale: Yale University Press, 1958).

11. G. T. Seaborg, *Early History of Heavy Isotope Production at Berkeley*, Lawrence Berkeley Laboratory Report (Berkeley: University of California, 1976).

12. G. T. Seaborg and W. D. Loveland, *The Elements Beyond Uranium* (New York: John Wiley and Sons, 1990).

13. G. T. Seaborg, quoted by Rhoads (1986, p. 414), *op. cit.* note 1.

14. R. G. Hewlett and O. E. Anderson, *The New World, 1939-1946* (University Park, Pennsylvania: Pennsylvania State University Press, 1962)

15. S. Groueff, *Manhattan Project* (Boston: Little, Brown, 1967)

16. A. K. Smith, "Manhattan Project: The Atomic Bomb," in *The Nuclear Almanac: Confronting the Atom in War and Peace*, ed. J. Dennis (Reading, Massachussetts: Addison-Wesley Publishing Company, 1984), 20-52

17. Los Alamos Historical Society, *Los Alamos: Beginning of an Era, 1943-1945* (Los Alamos: Los Alamos Historical Society, 1986)

18. J. W. Kunetka, *City of Fire: Los Alamos and the Atomic Age, 1943-1945* (Albuquerque, New Mexico: University of New Mexico Press, 1979)

19. F. M. Szasz, *The Day the Sun Rose Twice: The Story of the Trinity Site Nuclear Explosion, July 16, 1945* (Albuquerque, New Mexico: University of New Mexico Press, 1984)

20. Smith (1984, p. 27), *op. cit.* note 16

21. P. Goodchild, *J. Robert Oppenheimer: Shatterer of Worlds* (New York: Fromm International Publishing Corporation, 1985)

22. E. E. Morison, *Turmoil and Tradition: A Biography of Henry L. Stimson* (Boston: Houghton Mifflin, 1960), 620

23. R. Nash, *The Rights of Nature* (Madison, Wisconsin: University of Wisconsin Press, 1989)

24. Los Alamos Scientific Laboratory, Minutes of the Laboratory Advisory Board,

August 19, 1944," File Notes, Los Alamos National Laboratory, Los Alamos New Mexico.

25. R. S. Stone, "Health Protection Activities of the Plutonium Project," *Proceedings of the American Philosophical Society* 90(1946):11-19.

26. E. P. Odum, "Consideration of the Total Environment in Power Reactor Waste Disposal," *Proceedings of the International Conference on Peaceful Uses of Atomic Energy* 13(1956):350-358; A. M. Kuzin and A. A. Peredelsky, "Nature Conservancy and Some Aspects of Radioactive Ecological Relations," (in Russian) *Okhr. Prir. Zap. SSSR* 1(1956):65-70.

27. Szasz (1984, p. 63), *op. cit.* note 19.

28. L. M. Groves, *Now It Can Be Told: The Story of the Manhattan Project* (New York: Harper, 1962).

29. A. Stoker, A. J. Ahlquist, D. L. Mayfield, W. R. Hansen, A. D. Tally, and W. D. Purtymun, *Radiological Survey of the Site of a Former Radioacitve Liquid Waste Treatment Plant (TA-45) and the Effluent Receiving Areas of Acid, Pueblo, and Los Alamos Canyons, Los Alamos, New Mexico*, Report LA-8890-ENV. UC-70 (Los Alamos, New Mexico: Los Alamos National Laboratory and U.S. Department of Energy, 1981).

30. D. Rai, R. J. Serne, and J. L. Swanson, "Solution Species of Plutonium-239 (V) in the Environment," in *Waste Isolation Safety Assessment Program, Task 4, Second Information Meeting*, ed. R. J. Serne, Report PNL SA-7352 (Washington, D.C.: U.S. Department of Energy, 1978); D. M. Nelson and M. B. Lovett, "Measurement of the Oxidation State and Concentration of Plutonium in Interstitial Waters of the Irish Sea," in *Impacts of Radionuclides Released into the Marine Environment*, Report STI/PB/5651 (Vienna: International Commission on Atomic Energy, 1981).

31. R. K. Schulz, "Root Uptake of Transuranic Elements," in *Transuranics in Natural Environments*, Report NVO 178, ed. M. G. White and P. B. Dunaway (Washinton, D.C.: U.S. Energy Research and Development Administration, 1977).

32. International Commission on Radiological Protection, *The Metabolism of Compounds of Plutonium and Other Actinides*, International Commission on Radiological Protection Publication 19 (New York: Pergamon Press, 1972).

33. W. J. Bair, C. R. Richmond, and B. W. Wachholz, *Radiobiological Assessment on the Spatial Distribution of Radiation Dose from Inhaled Plutonium*, Report WASH 1320 (Washington, D.C.: U.S. Atomic Energy Commission, 1974).

34. W. J. Bair and R. C. Thompson, "Plutonium: Biomedical Research," *Science* 183(1974):715.

35. International Commission on Radiological Protection (1972), *op. cit.* note 32.

36. J. H. Olafson and K. H. Larson, "Plutonium: Its Biology and Environmental Persistence," in *Radioecology*, ed. V. Schultz and A. W. Klement (New York: Reinhold, 1963).

37. P. Beckmann, *The Health Hazards of Not Going Nuclear* (Boulder, Colorado: Golem Press, 1976).

38. F. W. Whicker and V. Schultz, *Radioecology: Nuclear Energy and the Environment*, 2 vols. (Boca Raton, Florida: CRC Press, Inc., 1982).

39. R. E. Lapp and H. L. Andrews, *Nuclear Radiation Physics* (Englewood Cliffs, New Jersey: Prentice Hall, 1972).

40. G. D. Chase and J. L. Rabinowitz, *Principles of Radioisotope Methodology* (Minneapolis, Minnesota: Burgess, 1967).

41. Bureau of Radiological Health and Training Institute, *Radiological Health*

Handbook, U.S. Public Health Service Publication 2016 (Washington, D.C.: U.S. Department of Health, Education, and Welfare, 1972).

42. International Commission on Radiological Protection, *Report of Committee IV on Evaluation of Radiation Doses to Body Tissues from Internal Contamination due to Occupational Exposures*, International Commission on Radiological Protection Publication 10 (Oxford: Pergamon Press, 1959); Stoker *et al.* (1981), *op. cit.* note 29.

43. H Leenaars, *The Dispersal of Metal Mining Wastes in the Catchement of the River Geul, Belgium--The Netherlands* (Utrecht, The Netherlands: Geograpfisch Instituut, Rijksuniversiteit, 1989).

PART 2. THE NORTHERN RIO GRANDE FLUVIAL SYSTEM

CHAPTER 3. THE DRAINAGE BASIN

1 "Gage" is the technical hydrologic term for "gauge," referring to an automatic recording device that measures characteristics of streamflow.

2. P. A. Emery, R. J Snipes, J. M. Dumeyer, and J. M. Klein, J. M., *Water in the San Luis Valley, south central Colorado*, Colorado Water Conservation Board Water-Resources Circular 18 (Denver: Colorado Water Conservation Board, 1973); D. Huntley, "Ground water Recharge to the Aquifers of Northern San Luis Valley, Colorado--Summary," *Geological Society of America Bulletin* 90(1979):707 709; G. A. Hearne and J D Dewey, *Hydrologic Analysis of the Rio Grande Basin North of Embudo, New Mexico, Colorado and New Mexico*, U.S Geological Survey Water-Resources Investigations Report 86 4113 (Washington, D C U.S. Geological Survey, 1988).

3 F. W Whicker and C M Loveless, "Relationships of Physiography and Microclimate to Fallout Deposition," *Ecology* 49(1968):363 368

4 C B Hunt, *Natural Regions of the United States and Canada* (San Francisco: W. H Freeman, 1974), K A Erickson and A W Smith, *Atlas of Colorado* (Boulder, Colorado Colorado Associated University Press, 1985); J. L Williams (ed), *New Mexico in Maps*, 2nd ed (Albuquerque, New Mexico University of New Mexico Press, 1986.

5 W W. Atwood and K F. Mather, *Physiography and Quaternary Geology of the San Juan Mountains, Colorado*, U S Geological Survey Professional Paper 166 (Washington, D C U S Geological Survey, 1932)

6 Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1987* (Los Alamos, New Mexico Los Alamos National Laboratory, 1987), 67

7 J E Upson, "Physiographic Subdivisions of the San Louis Valley, Southern Colorado," *Journal of Geology* 47(1939) 721 736

8 N M Fenneman, *Physiography of Western United States* (New York McGraw Hill Book Company, 1931), 530

9 C E Siebenthal, *Geology and Water Resources of the San Louis Valley, Colorado*, U S Geological Survey Water Supply Paper 240 (Washington, D C U S Geological Survey, 1910)

10 C K Cooperrider and B A Hendricks, *Soil Erosion and Stream Flow on Range and Forest Lands of the Upper Rio Grande Watershed in Relation to Land Resources and Human Welfare*, U S Department of Agriculture Technical Bulletin 567 (Washington, D C U S Department of Agriculture, 1937)

11 E S Larsen and W Cross, *Geology and Petrology of the San Juan Region*,

U.S. Geological Survey Professional Paper 258 (Washington, D.C.: U.S. Geological Survey, 1956).

12. Atwood and Mather, 1932, *op. cit.*, note 5; New Mexico Geological Society (ed.), *Guidebook of Southwestern San Juan Mountains, Colorado*, New Mexico Geological Society 8th Annual Field Conference Guidebook (Socorro, New Mexico: New Mexico Geological Society, 1957).

13. V. C. Kelly, "General Geology and Tectonics of the Western San Juan Mountains, Colorado," in New Mexico Geological Society (ed.), *Guidebook of Southwestern San Juan Mountains, Colorado*, New Mexico Geological Society 8th Annual Field Conference Guidebook (Socorro, New Mexico: New Mexico Geological Society, 1957), 154-162

14. O. Tweto, *Geologic Map of Colorado* (Reston, Virginia: U.S. Geological Survey, 1979).

15. R. H. De Voto, F. A. Peel, and W. H. Pierce, "Pennsylvanian and Permian Stratigraphy, Tectonism, and History, Northern Sangre de Cristo Range, Colorado, in *Guidebook of the San Luis Basin, Colorado*, New Mexico Geological Society 22nd Annual Field Conference Guidebook, ed. H. L. James (Socorro, New Mexico: New Mexico Geological Society, 1971), 141-164

16. J. R. Gaca and D. F. Karig, "Gravity Survey in the San Luis Area, Colorado," U.S. Geological Survey Open File Report, Unnumbered (Denver, Colorado: U.S. Geological Survey, 1965).

17. Hearne and Dewey, 1988, *op. cit.*, note 2

18. J. E. Upson, "Physiographic Subdivisions of the San Louis Valley, Southern Colorado (Reprinted with Additional Notes)," in *Guidebook of the San Louis Basin, Colorado*, New Mexico Geological Society 22nd Annual Field Conference Guidebook, ed. H. L. James (Socorro, New Mexico: New Mexico Geological Society, 1971), 113-122

19. W. Lambert, "Notes on the Late Cenozoic Geology of the Taos Questa Area, New Mexico," in *Guidebook of Taos Raton Spanish Peaks Country, New Mexico and Colorado*, New Mexico Geological Society 17th Annual Field Conference Guidebook, eds. S. A. Northrop and C. B. Read (Socorro, New Mexico: New Mexico Geological Society, 1966), 43-50

20. C. H. Dane and G. O. Bachman, *Geologic Map of New Mexico* (Reston, Virginia: U.S. Geological Survey, 1965)

21. M. A. Dungan, W. R. Muehlberger, L. Leininger, C. Peterson, N. J. Gunn, M. Lindstrom, and L. Haskin, "Volcanic and Sedimentary Stratigraphy of the Rio Grande Gorge and the Late Cenozoic Geologic Evolution of the Southern San Louis Valley," in *Rio Grande Rift: Northern New Mexico*, New Mexico Geological Society 35th Annual Field Conference Guidebook, eds. W. S. Baldridge, P. W. Dickerson, R. E. Riecker, and J. Zidek (Socorro, New Mexico: New Mexico Geological Society, 1984), 157-170

22. V. T. McLemore and R. M. North, "Occurrences of Precious Metals and Uranium Along the Rio Grande Rift in Northern New Mexico," in *Rio Grande Rift: Northern New Mexico*, New Mexico Geological Society 35th Annual Field Conference Guidebook, eds. W. S. Baldridge, P. W. Dickerson, R. E. Riecker, and J. Zidek (Socorro, New Mexico: New Mexico Geological Society, 1984), 205-212

23. L. Cordell, "Gravimetric Expression of Graben Faulting in Santa Fe Country and the Espanola Basin, New Mexico," in *Guidebook of Santa Fe Country, New Mexico*, New Mexico Geological Society 30th Annual Field Conference Guidebook, ed. R. V.

Ingersall (Socorro, New Mexico: New Mexico Geological Society, 1979), 59-64.

24. Dane and Backman, 1965, *op. cit.*, note 20.

25. S. J. May, "Neogene Stratigraphy and Structure of the Ojo Caliente-Rio Chama Area, Española Basin, New Mexico," in *Guidebook of Santa Fe Country, New Mexico*, New Mexico Geological Society 30th Annual Field Conference Guidebook, ed. R. V. Ingersall (Socorro, New Mexico: New Mexico Geological Society, 1979), 83-88.

26. D. P. Dethier and K. A. Demsey, "Erosional History and Soil Development on Quaternary Surfaces, Northwest Española Basin, New Mexico," in *Rio Grande Rift: Northern New Mexico*, New Mexico Geological Society 35th Annual Field Conference Guidebook, eds. W. S. Baldridge, P. W. Dickerson, R. E. Riecker, and J. Zidek (Socorro, New Mexico: New Mexico Geological Society, 1984), 227-233.

27. V. C. Kelly, "Geomorphology of Española Basin," in *Guidebook of Santa Fe Country, New Mexico*, New Mexico Geological Society 30th Annual Field Conference Guidebook, ed. R. V. Ingersall (Socorro, New Mexico: New Mexico Geological Society, 1979), 281-288.

28. W. L. Chenoweth, "Uranium in the Santa Fe Area, New Mexico," in *Guidebook of Santa Fe Country, New Mexico*, New Mexico Geological Society 30th Annual Field Conference Guidebook, ed. R. V. Ingersall (Socorro, New Mexico: New Mexico Geological Society, 1979), 261-264.

29. E. C. Beaumount and C. B. Read, *Guidebook of Rio Chama Country, New Mexico* (Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources, 1960); Dane and Bachman, 1965, *op. cit.*, note 20.

30. W. R. Muehlberger, G. T. Adams, T. E. Longgood Jr., and B. E. St. John, "Stratigraphy of the Chama Quadrangle, Northern Arriba County, New Mexico," in *Guidebook of Rio chama Country*, New Mexico Geological Society 11th Annual Field Conference Guidebook, eds. E. C. Beaumont and C. B. Read (Socorro, New Mexico: New Mexico Geological Society, 1960), 103-109; V. C. Kelly, *Geology of the Española Basin, New Mexico*, New Mexico Bureau of Mines and Mineral Resouces Geologic Map 48 (Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources, 1978).

31. E. A. Woodward, "Tectonics of Central Northern New Mexico," in *Silver Anniversary Guidebook: Ghost Ranch, Central Northern New Mexico*, New Mexico Geological Society 25th Annual Field Conference Guidebook, ed. C. T. Siemers (Socorro, New Mexico: New Mexico Geological Society, 1974), 123-130.

32. C. T. Siemers (ed.), *Silver Anniversary Guidebook: Ghost Ranch, Central Northern New Mexico*, New Mexico Geological Society 25th Annual Field Conference Guidebook (Socorro, New Mexico: New Mexico Geological Society, 1974).

33. W. L. Chenoweth, "Uranium Occurrences of the Nacimiento-Jemez Region, Sandoval and Rio Arriba Counties, New Mexico, in *Silver Anniversary Guidebook: Ghost Ranch, Central Northern New Mexico*, New Mexico Geological Society 25th Annual Field Conference Guidebook, ed. C. T. Siemers (Socorro, New Mexico: New Mexico Geological Society, 1974), 309-314.

34. R. L. Griggs, *Geology and Ground-Water Resources of the Los Alamos Area, New Mexico*, U.S. Geological Survey Water-Supply Paper 1753 (Washington, D.C.: U.S. Geological Survey, 1964).

35. *Ibid.*

36. C. D. Harrington and M. J. Aldrich, Jr., "Development and Deformation of Quaternary Surfaces on the Northeastern Flank of the Jemez Mountains," in

in *Rio Grande Rift: Northern New Mexico*, New Mexico Geological Society 35th Annual Field Conference Guidebook, eds. W. S. Baldridge, P. W. Dickerson, R. E. Riecker, and J. Zidek (Socorro, New Mexico: New Mexico Geological Society, 1984), 235-239.

37. S. A. Northrop (ed.), *Guidebook of the Albuquerque Country*, New Mexico Geological Society 12th Annual Field Conference Guidebook (Socorro, New Mexico: New Mexico Geological Society, 1961).

38. R. Y. Anderson, "Physiography, Climate, and Vegeation of the Albuquerque Region," in *Guidebook of the Albuquerque Country*, New Mexico Geological Society 12th Annual Field Conference Guidebook, ed. S. A. Northrop (Socorro, New Mexico: New Mexico Geological Society, 1961), 63-71.

39. J. C. Moore, "Uranium Deposits in the Galisteo Formation of the Hagan Basin, Sandoval County, New Mexico," in *Guidebook of Santa Fe Country, New Mexico*, New Mexico Geological Society 30th Annual Field Conference Guidebook, ed. R. V. Ingersall (Socorro, New Mexico: New Mexico Geological Society, 1979), 265-267.

40. H. R. Joesting, J. E. Case, and L. E. Cordell, "The Rio Grande Trough Near Albuquerque, New Mexico," in *Guidebook of the Albuquerque Country*, New Mexico Geological Society 12th Annual Field Conference Guidebook, ed. S. A. Northrop (Socorro, New Mexico: New Mexico Geological Society, 1961), 148-152.

41. R. H. Tedford, "Neogene Stratigraphy of the Northwestern Albuquerque Basin," in *Albuquerque Country II*, New Mexico Geological Society 33rd Annual Field Conference Guidebook, ed. J. A. Gramblin and S. G. Wells (Socorro, New Mexico: New Mexico Geological Society, 1982), 273-278.

42. Z. Speigel, "Late Cenozoic Sediments of the Lower Jemez River Region," in *Guidebook of the Albuquerque Country*, New Mexico Geological Society 12th Annual Field Conference Guidebook, ed. S. A. Northrop (Socorro, New Mexico: New Mexico Geological Society, 1961), 132-138.

43. C. F. Nordin Jr., *A Preliminary Study of Sediment Transport Parameters, Rio Puerco Near Bernardo, New Mexico*, U.S. Geological Survey Professional Paper 462-C (Washington, D.C.: U.S. Geological Survey, 1963).

44. D. W. Love and J. D. Young, "Progress Report on the Late Cenozoic Geologic Evolution of the Lower Rio Puerco," in *Socorro Region II*, New Mexico Geological Society 34th Annual Field Conference Guidebook, ed. C. E. Chapin (Socorro, New Mexico: New Mexico Geological Society, 1983), 277-284.

45. J. W. Hawley, D. W. Love, and S. G. Wells, "Summary of the Hydrology, Sedimentology, and Stratigraphy of the Rio Puerco Valley," in *Chaco Canyon Country*, American Geomorphological Field Group Conference Guidebook, ed. S. G. Wells, D. W. Love, and T. W. Gardner (Albuquerque, New Mexico: American Geomorphological Field Group, 1983), 33-36.

46. C. J. Popp, J. W. Hawley, and D. W. Love, *Radionuclide and Heavy Metal Distribution in Recent Sediments of Major Streams in the Grants Mineral Belt, New Mexico*, Final Project Report, Office of Surface Mining (Washington, D.C.: U.S. Department of Interior, 1983).

47. C. E. Chapin (ed.), *Socorro Region II*, New Mexico Geological Society 34th Annual Field Conference Guidebook (Socorro, New Mexico: New Mexico Geological Society, 1983).

48. Williams, 1986, *op. cit.*, note 4; Erickson and Smith, 1985, *op. cit.*, note 4.

49. Erickson and Smith, 1985, *op. cit.*, note 4.

50. L. B. Leopold, W. W. Emmett, and R. M. Myrick, *Channel and Hillslope Processes in a Semiarid Area, New Mexico*, U.S. Geological Survey Professional Paper 352-G (Washington, D.C.: U.S. Geological Survey, 1966), 193-253.

51. *Ibid.*

52. R B. Brown, C. H. Lowe, and C. P. Pase, *A Digitized Systematic Classification for Ecosystems with an Illustrated Summary of the Natural Vegeeation of North America*, Forest Service General Technical Report Rm-73 (Washington, D.C.: U.S. Department of Agriculture, 1980).

53. Cooperrider and Hendricks, 1937, *op. cit.*, note 10, 38.

54. C. P. Pase and E. F. Layser, "Classification of Riparian Habitat in the Southwest," in *Importance, Preservation, and Management of Riparian Habitat*, Forest Service General Technical Report RM-43 (Washington, D.C.: U.S. Department of Agriculture, 1977), 5-9.

CHAPTER 4. REGIONAL HYDROLOGY

1. A. H. Frazier and W. Heckler, *Embudo, New Mexico, Birthplace of Systematic Stream Gaging*, U.S. Geological Survey Professional Paper 778 (Washington, D.C.: U.S. Geological Survey, 1972).

2. E. M. Shaw, *Hydrology in Practice* (Berkshire: Van Nostrand Reinhold, U.K.: 1983), 301.

3. P. D. Komar, "Sediment Transport by Floods," in *Flood Geomorphology*, eds. V. R Baker, R. C. Kochel, and P. C. Patton (New York: Wiley and Sons, 1988), 97-112.

4 International Commission on Large Dams, *World Register of Dams* (Paris: International Commission on Large Dams, 1976); F W. Mermel, *Register of Dams in the United States: Completed, Under Construction and Proposed* (New York: McGraw-Hill, 1958).

5. S. W. Trimble and S. W. Lund, *Soil Conservation and the Reduction of Erosion and Sedimentation in the Cook Creek Basin, Wisconsin*, U.S Geological Survey Professional Paper 1234 (Washington, D.C.: U.S. Geological Survey, 1982).

6. G. C. Lusby, V. H. Reid, and O. D. Knipe, *Effects of Grazing on the Hydrology and Biology of the Badger Wash Basin in Western Colorado, 1953 1966*, U.S. Geological Survey Water Supply Paper 1532 D (Washington, D.C.: U.S Geological Survey, 1971).

7 W. L Graf, "Fluvial Erosion and Federal Public Policy in the Navajo Nation," *Physical Geography* 7(1986) 97 115.

8 J. C. Knox, "Historical Valley Floor Sedimentation in the Upper Mississippi Valley," *Annals of the Association of American Geographers* 77(1987):224 244.

9 C K Cooperrider and B A Hendricks, "*Soil Erosion and Stream Flow on Range and Forest Lands of the Upper Rio Grande Watershed in relation to Land Resources and Human Welfare*, U.S Department of Agriculture Technical Bulletin 567 (Washington, D.C. U.S Department of Agriculture, 1937)

10 W DeBuys, *Enchantment and Exploitation The Life and Hard Times of a New Mexico Mountain Range* (Albuquerque, New Mexico University of New Mexico Press, 1985), 227 230

11 P Stewart, "Watershed Characteristics, Part B Decreases in Flow in the Rio Grande," U.S Forest Service Report (Taos, New Mexico Carson National Forest, 1981)

12 K K Hirschboeck, "Flood Hydroclimatology " in *Flood Geomorphology* eds

V. R. Baker, R. C. Kochel, and P. C. Patton (New York: Wiley and Sons. 1988), 27-49.

13. R. S. Bradley, R. G. Barry, and G. Kiladis, *Climatic Fluctuations of the Western of the Western United States During the Period of Instrumental Records*, Department of Geography and Geology Contribution 42 (Amherst, Massachusetts: Department of Geography and Geology, University of Masschusetts, 1982), 67.

14. L. Wilson, *Future Water Issues, Taos County, New Mexico* (Santa Fe, New Mexico: Lee Wilson and Associates, Inc., 1980).

15. T. R. Karl and R. W. Knight, *Atlas of Monthly Hydrological Drought Indices for the Contiguous United States* (Asheville, North Carolina: National Climatic Data Center, 1985).

16. Data suggesting similar conclusions are in L. Wiard, *Floods in New Mexico, Magnitude and Frequency*, U.S. Geological Survey Circular 464 (Washington, D.C.: U.S. Geological Survey, 1962).

CHAPTER 5. FLUVIAL SEDIMENT

1. A. Stoker, A. J Ahlquist, D. L. Mayfield, W. R. Hansen, A D. Tally, and W. D. Purtymun, *Radiological Survey of the Site of a Former Radioacitve Liquid Waste Treatment Plant (TA-45) and the Effluent Receiving Areas of Acid, Pueblo, and Los Alamos Canyons, Los Alamos, New Mexico*, Report LA-8890-ENV, UC-70 (Los Alamos, New Mexico: Los Alamos National Laboratory and U S. Department of Energy, 1981); L. J. Lane, W. D Purtymun, and N. M. Becker, *New Estimating Procedures for Surface Runoff, Sediment Yield, and Contaminant Transport in Los Alamos County, New Mexico*, Los Alamos National Laboratory Report LA 10335 MS, UC 11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1985).

2. A. Goudie, ed., *Geomorphological Techniques* (London: George Allen & Unwin, 1981).

3 T. Dunne and L. B Leopold, *Water in Environmental Planning* (San Francisco: W. H. Freeman, 1978), 670.

4. G. E. Petts, *Impounded Rivers. Perspectives for Ecological Management* (New York: John Wiley and Sons, 1984).

5. H. Y. Hammad, "River Bed Degradation After Closure of Dams," *Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division* 98, HY9(1976):591 607; J. D Dewey, E. E. Roybal, and D F Funderburg, *Hydrologic Data on Channel Adjustments, 1970 to 1975, on the Rio Grande Downstream from Cochiti Dam, New Mexico, Before and After Closure*, National Technical Information Service Report PB 301 134(Washington, D C U S Geological Survey, 1979)

6 P F. Lagasse, *An Assessment of the Response of the Rio Grande to Dam Construction Cochiti to Isleta Reach*, 7 vols , Albuquerque District Office Technical Report (Albuquerque, New Mexico: U S Army Corps of Engineers, 1980)

7. G. P Williams and M G Wolman, *Downstream Effects of Dams on Alluvial Rivers*, U S Geological Survey Professional Paper 1286 (Washington, D C U S Geological Survey, 1984)

8. E L Pemberton, "Channel Changes in the Colorado River Below Glen Canyon Dam," *Proceedings of the Third Interagency Sedimentation Conference* (Denver, Colorado Interagency Sedimentation Conference, 1976), 5-61 5-73

9 D B Simons, R M Li, L Y Li, and M J Ballantine *Erosion and Sedimentation*

Analysis of Rio Puerco and Rio Salado Watersheds, Technical Report, U.S. Army Corps of Engineers, Albuquerque District Office (Fort Collins, Colorado: Simons, Li and Associates, 1981), 53.

10. Stoker *et al.*, 1981, *op. cit.*, note 1.

11. Dunne and Leopold, 1978, *op. cit.* note 3, 662.

12. R. J. Garde and K. G. Ranga-Raju, *Mechanics of Sediment Transportation and Alluvial Stream Problems* (New York: John Wiley and Sons, 1977), 62.

13. Simons *et al.*, 1981, *op. cit.*, note 9, 53.

14. Lagasse, 1980, *op. cit.*, note 6.

15. Lane *et al.*, 1985, *op. cit.*, note 2.

CHAPTER 6. FLUVIAL GEOMORPHOLOGY

1. K. J. Gregory, ed., *River Channel Change* (Chichester, England: John Wiley and Sons, 1977).

2. S. A. Schumm and H. R. Kahn, "Experimental and Isotopic Ratios in River Sediments," *Geological Society of America Bulletin* 83(1972):1755-1770; W. L. Graf, *Fluvial Processes in Dryland Rivers* (New York and Berlin: Springer-Verlag, 1988), 201-204.

3. M. R. Karlinger, T. R. Eschner, R. F. Hadley, and J. E. Kirchner, *Relation of Channel-Width Maintenance to Sediment Transport and River Morphology, Platte River, Nebraska*, U.S. Geological Survey Professional Paper 1277-E (Washington, D.C.: U.S. Geological Survey, 1983).

4. H. D. Miser, *The San Juan Canyon: Southeastern Utah*, U.S. Geological Survey Water-Supply Paper 538 (Washington, D.C.: U.S. Geological Survey, 1924); W. L. Graf, *The Colorado River: Change and Basin Management*, Association of American Geographers Resource Paper 85-2 (Washington, D.C.: Association of American Geographers, 1985).

5. G. P. Williams and M. G. Wolman, *Downstream Effects of Dams on Alluvial Rivers*, U.S. Geological Survey Professional Paper 1286 (Washington, D.C.: U.S. Geological Survey, 1984).

6. C. B. Hunt, P. Averitt, and R. L. Miller, *Geology and Geography of the Henry Mountains Region, Utah*, U.S. Geological Survey Professional Paper 228 (Washington, D.C.: U.S. Geological Survey, 1953); W. L. Graf, "Downstream Changes in Stream Power in the Henry Mountains, Utah," *Annals of the Association of American Geographers* 73(1983):97-115.

7. R. Hereford, "Modern Alluvial History of the Paria River Drainage Basin, Southern Utah," *Quaternary Research* 25(1986):293-311.

8. R. Hereford, "Climate Change and Ephemeral Stream Processes: Twentieth Century Geomorphology and Alluvial Stratigraphy of the Little Colorado River, Arizona," *Geological Society of America Bulletin* 95(1984):654-668.

9. D. E. Burkham, *Channel Changes of the Gila River in Safford Valley, Arizona*, U.S. Geological Survey Professional Paper 655-G (Washington, D.C.: U.S. Geological Survey, 1972).

10. P. Ackers and F. G. Charlton, "Meander Geometry Arising from Varying Flows," *Journal of Hydrology* 11(1970):230-252.

11. Hydraulic Engineering Center, *HEC-6: Scour and Deposition in Rivers and*

Reservoirs, U.S. Army Corps of Engineers User's Manual 723-G2-L2470 (Davis, California: Hydraulic Engineering Center, 1976).

12. M. G. Wolman and L. B. Leopold, *River Flood Plains: Some Observations on Their Formation*, U.S. Geological Survey Professional Paper 282-C (Washington, D.C.: U.S. Geological Survey, 1957), 87-107; R. Kellerhals, C. R. Neill, and D. I. Bray, "Classification and Analysis of River Processes," *American Society of Civil Engineers, Journal of the Hydraulics Division* 107(1976):813-829.

13. J. R. C. Allen, *Physical Processes of Sedimentation* (London: Allen & Unwin, 1970).

14. D. J. Cant and R. G. Walker, "Fluvial Processes and Facies Sequences in the Sandy Braided South Saskatchewan River, Canada," *Sedimentology* (1978):625-648.

15. A. P. Heward, "Alluvial Fan Sequence and Megasequence Models with Examples from Westphalian D-Stephanian B Coalfields, Northern Spain," in *Fluvial Sedimentology*, ed. A. D. Miall (Calgary, Alberta: Canadian Society of Petroleum Geologists, 1978), 669-702.

16. P. F. Lagasse, *An Assessment of the Response of the Rio Grande to Dam Construction Cochiti to Isleta Reach*, 7 vols. Albuquerque District Office Technical Report (Albuquerque, New Mexico: U.S. Army Corps of Engineers, 1980).

CHAPTER 7. ENGINEERING WORKS

1. A. Brookes, *Channelized Rivers: Perspectives for Environmental Management* (Chichester, England: John Wiley and Sons, 1988).

2. G. E. Petts, *Impounded Rivers: Perspectives for Ecological Managment* (New York: John Wiley and Sons, 1984).

3. F. Wendorf, "A Reconstruction of Northern Rio Grande Prehistory," *American Anthropologist* 56(1954):200-221.

4. A. F. Bandelier, *Documentary History of Rio Grande Pueblos* (New Haven, Connecticut: Yale University, 1929).

5. M. C. Meyer, *Water in the Hispanic Southwest: A Social and Legal History* (Tucson, Arizona: University of Arizona Press, 1984).

6. A. G. Harper, A. R. Cordova, and K. Oberg, *Man and Resources in the Middle Rio Grande Valley* (Albuquerque, New Mexico: University of New Mexico Press, 1943).

7. C. K. Cooperrider and B. A. Hendricks, *Soil Erosion and Stream Flow on Range and Forest Lands of teh Upper Rio Grande Watershed in Relation to Land Resources and Human Welfare*, U.S. Department of Agriculture Technical Bulletin 567 (Washington, D.C.: U.S. Department of Agriculture, 1937); S. A. Happ, "Sedimentation in the Middle Rio Grande Valley, New Mexico," *Geological Society of America Bulletin* 59(1948):1191-1215.

8. I. G. Clark, *Water in New Mexico: A History of Its Management and Use* (Albuquerque, New Mexico: University of New Mexico Press, 1987).

9. *Ibid.*, 212; U.S. House of Representatives, *Rio Grande and Tributaries, New Mexico*, 81st Congress, 1st Session, House Document 243 (Washington, D.C.: Government Printing Office, 1948).

10. H. F. Blaney, P. A. Ewing, O. W. Israelsen, C. Rohwer, and F. C. Scobey, *Investigations in the Upper Rio Grande Drainage Basin, Colorado New Mexico Texas* (Washington, D.C.: U.S. Government Printing Office, 1937).

11. National Resources Committee, *Regional Planning Part V Upper Rio Grande*

(Washington, D.C.: Government Printing Office, 1938).

12. C. E. Hyvarinen, "Channel Stabilization Practices on Middle Rio Grande," *Symposium on Channel Stabilization* (Corps of Engineers, 1963), Chap. 5.

13. U.S. House of Representatives, 1948, *op. cit.*, note 9.

14. M. E. Welsh, *U.S. Army Corps of Engineers: Albuquerque District, 1935-1985* (Albuquerque, New Mexico: University of New Mexico Press, 1987.

15. J. C. Thompson, *Channel Stabilization, Middle Rio Grande Project*, Technical Report 1, Symposium on Channel Stabilization Problems, Chap. 1, Vol. 3 (Vicksburg, Mississippi: U.S. Army Corps of Engineers, 1965).

16. R. C. Woodson, "Stabilization of the Middle Rio Grande," *American Society of Civil Engineers, Waterways and Harbor Division* 87(1961):1-15.

17. Interview, 21 June 1990, F. Collins, Engineer, U.S. Army Corps of Engineers, Abuquerque District, Albuquerque, New Mexico.

18. V. M. Simmons, *The San Louis Valley* (Boulder, Colorado: Pruett Publishing Company, 1979).

19. Clark, 1987, *op. cit.*, note 9, 91-98

20. *Ibid.*, 388.

21. Welsh, 1987, *op. cit.*, note 14, 189.

22. U.S. Bureau of Reclamation, *Annual Report, 1979* (Washington, D.C.: U.S. Bureau of Reclamation, 1979).

23. Environmental Surveillance Group, *Environmental Surveillance at Los Alamos, 1987* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1987).

24. *Ibid.*

CHAPTER 8. RIPARIAN VEGETATION

1. J. R. Hastings, "Vegetation Change and Arroyo Cutting in Southeastern Arizona," *Journal of the Arizona Academy of Science* 1(1959):60-67.

2. D. E. Brown, "Southwestern Wetlands: Their Classification and Characteristics," in *Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems*, U.S. Forest Service General Technical Report WO-12, R. R. Johnson and J. F. McCormick, eds. (Washington, D.C.: U.S. Department of Agriculture, 1978), 269-282.

3. G. P. Davis, "Man and Wildlife in Arizona: The Pre-Settlement Era, 1823-1864," unpublished MS Thesis, Arizona State University, Tempe, Arizona, 1973.

4. P. S. White, "Pattern, Process and Natural Disturbance in Vegetation," *Botanical Review* 45(1979):229-299; C. R. Hupp, "Stream-Grade Variation and Riparian-Forest Ecology Along Passage Creek, Virginia," *Bulletin Torrey Botanical Club* 109(1982):488-499.

5. J. W. Abert, "Notes of Lieutenant J. W. Abert," in *Notes of a Military Reconnaissance from Fort Leavenworth in Missouri to San Diego in California, Including Parts of Arkansas, Del Norte, and Gila Rivers*, Executive Document 41, 30th Congress, 1st Session, W. H. Emory (Washington, D.C.: Government Printing Office, 1848), 386-414; J. W. Abert, "Report of Lieutenant J. W. Abert of His Examination of New Mexico in the Years 1846-1847," in Emory, 1848, *ibid.*, 417-546; V. L. Burkholder, *Report of the Chief Engineer* (Albuquerque, New Mexico: Middle Rio Grande Conservancy District, 1928); H. Fergusson, *Rio Grande* (New York: McGraw-Hill Book Company, 1931).

6. J. R. Watson, "Plant Geography of North Central New Mexico," *Botanical Gazette* 54(1912):194-217.

7. Fergusson, 1931, *op. cit.*, note 5, 7-9.

8. M. Van Cleave, "Vegetation Changes in the Middle Rio Grande Conservancy District," Unpub. M.S. Thesis, Albuquerque, New Mexico: University of New Mexico, 1935.

9. V. C. Hink and R. D. Ohmart, *Middle Rio Grande Biological Survey: Final Report* Contract Report DACW47-81-C-0015 (Albuquerque, New Mexico: U.S. Army Corps of Engineers, 1984).

10. T. W. Robinson, *Phreatophytes*, U.S. Geological Survey Water-Supply Paper 1423 (Washington, D.C.: U.S. Geological Survey, 1958).

11. E. M. Christensen, "The Rate of Naturalization of *Tamairix* in Utah," *American Midland Naturalist* 68(1962):51-57.

12. C. B. Thompson, "Importance of Phreatophytes in Water Supply," *American Society of Civil Engineers, Proceedings of the Irrigation and Drainage Division* 84(1958):1502/1-1502/17; Robinson, 1958, *op. cit.*, note 10.

13. L. D. Potter, "Shoreline Ecology of Lake Powell," abst., *Program and Abstracts of the Geological Society of America Annual Meetings*, 1975, 125; B. L. Everitt, "Ecology of Saltcedar: A Plan for Research," *Environmental Geology* 3(1980):77-84.

14. M. D. Freehling, *Riparian Woodlands of the Middle Rio Grande Valley, New Mexico: A Study of Bird Population and Vegetation with Special Reference to Russian Olive (Elaeagnus angustifolia)*, U.S. Fish and Wildlife Service Report, Region 2 Office (Albuquerque, New Mexico: U.S. Fish and Wildlife Service, 1982).

15. C. J. Campbell and W. A. Dick-Peddie, "Comparison of Phreatophyte Communities on the Rio Grande in New Mexico," *Ecology* 45(1964):492-502.

16. Hink and Ohmart, *op. cit.*, note 9.

17. D. E. Brown, "Southwestern Wetlands: Their Classification and Characteristics," in *Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems*, Forest Service Technical Report WO-12, R. R. Johnson and J. F. McCormick, eds. (Washington, D.C.: U.S. Department of Agriculture, 1978), 269-282.

18. Robinson, 1958, *op. cit.*, note 10.

19. H. C. Fritts, *Tree Rings and Climate* (London: Academic Press, 1976).

20. R. E. Wildung and T. R. Garland, "The Relationship of Microbial Processes to the Fate and Behavior of Transuranic Elements in Soils, Plants, and Animals," in *Transuranic Elements in the Environment*, U.S. Department of Energy and National Technical Information Service Report DOE/TIC 22800, W. C. Hanson, ed. (Washington, D.C.: U.S. Department of Energy, 1980).

21. E. M. Romney and J. J. Davis, "Ecological Dissemination of Plutonium in the Environment," *Health Physics* 21(1972):551-560.

22. D. C. Adriano, A. Wallace, and E. M. Romney, "Uptake of Transuranic Nuclides From Soil by Plants Grown Under Controlled Environmental Conditions," in *Transuranic Elements in the Environment*, U.S. Department of Energy and National Technical Information Service Report DOE/TIC 22800, W. C. Hanson, ed. (Washington, D.C.: U.S. Department of Energy, 1980).

PART 3. THE NORTHERN RIO GRANDE PLUTONIUM SYSTEM

CHAPTER 9. SOURCES OF PLUTONIUM IN THE RIO GRANDE

1. Stockholm International Peace Research Institute, *SIPRI Annual Yearbook, World*

Armaments and Disarmament (Cambridge, Massachussetts: Massachussetts Institute of Technology Press, 1987).

2. S. Glasstone and J. W. Hawley, *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico--Guidebook to the Desert Project*, New Mexico Bureau of Mines and Mineral Resources Memoir 39 (Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources, 1981).

3. L. D. Hamilton, "Fallout and Countermeasures," *Bulletin of the Atomic Scientists* 19(1963):30-40.

4. H. Ball, *Justice Downwind: America's Atomic Testing Program in the 1950's* (Oxford: Oxford University Press, 1986).

5. K. L. Miller, *Under the Cloud: The Decades of Nuclear Testing* (New York: Free Press, 1986).

6. D. Deudney, "What Goes Up Must Come Down," *Bulletin of the Atomic Scientists* 40(3):10-11

7. R. W. Perkins and C. W. Thomas, "Worldwide Fallout," in *Transuranic Elements in the Environment*, U.S. Department of Energy and National Technical Information Service Document DOE/TIC 22800, W. C. Hanson, ed., (Washington, D.C.: U.S. Department of Energy, 1980).

8. E. P. Harley, P. W. Krey and H. L. Volchok, "Global Inventory and Distribution of Fallout Plutonium," *Nature* 241(1973):444

9. Stockholm International Peace Research Institute, 1987, *op. cit.*, note 1, 54-55.

10. Glasstone and Dolan, 1977, *op. cit.*, note 2, 449.

11. F. W. Whicker and V. Schultz, *Radioecology: Nuclear Energy and the Environment*, 2 vols. (Boca Raton, Florida: CRC Press, Inc., 1982).

12. G. R. Foster and T. E. Hakonson, "Estimating Erosional Losses of Fallout Plutonium," in *Environmental Surveillance at Los Alamos During 1982*, Environmental Surveillance Group, ed. (Los Alamos, New Mexico: Los Alamos National Laboratory, 1982), 83-84; G. R. Foster and T. E. Hakonson, "Predicted Erosion and Sediment Delivery of Fallout Plutonium," *Environmental Quality* 13(1984):595-602

13. Harley *et al.*, 1973, *op. cit.*, note 8

14. Foster and Hakonson, 1984, *op. cit.*, note 12

15. J. C. Ritchie, J. R. McHenry, and A. C. Gill, "Dating Recent Reservoir Sediments," *Limnology and Oceanography* 18(1973):254-263; J. C. Ritchie and J. R. McHenry, "Fallout Cs-137: A Tool in Conservation Research," *Journal of Soil and Water Conservation* 30(1975):283-285; J. R. McHenry and J. C. Ritchie, "Dating Recent Sediment in Impoundments," *Proceedings of the Symposium on Surface Water Impoundments*, American Society of Civil Engineers, Minneapolis, Minnesota, June 2-5, 1980, 1279-1289

16. W. H. Kingsley, *Survey of Los Alamos and Pueblo Canyon for Radioactive Contamination and Radioassay Test Run on Sewer Water Samples and Water and Soils Samples Taken from Los Alamos and Pueblo Canyons*, Los Alamos National Laboratory Report LAMS-516 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1947)

17. A. Stoker, A. J. Ahlquist, D. L. Mayfield, W. R. Hansen, A. D. Talley, and W. D. Purtymun, *Radiological Survey of the Site of a Former Radioactive Liquid Waste Treatment Plant (TA-45) and the Effluent Receiving Areas of Acid, Pueblo, and Los Alamos Canyons, Los Alamos, New Mexico*, Los Alamos National Laboratory and U.S. Department of Energy Report LA-8890-ENV, UC-70 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1981), 11-12.

18. *Ibid.*

19. L. J. Lane, W. D. Purtymun, and N. M. Becker, *New Estimating Procedures for Surface Runoff, Sediment Yield, and Contaminant Transport in Los Alamos County, New Mexico.* Los Alamos National Laboratory Report LA-10335-MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1985); Stoker *et al*., 1981, *op. cit.*, note 17, 49.

20. Lane *et al.*, 1985, *op. cit.*, note 19, 33.

21. R. O. Gilbert, L. L. Eberhardt, E. B. Fowler, E. M. Romney, E. H. Essington, and J. E. Kinnear, "Statistical Analysis of Pu239,240 and Am241 Contamination of Soil and Vegetation On NAEG Study Sites," in *The Radioecology of Plutonium and Other Transuranics in Desert Environments*, U.S. Atomic Energy Commission and National Technical Information Service Report NVO-153, M. G. White and P. B. Dunaway, eds. (Washington, D.C.: U.S. Atomic Energy Commission, 1975).

22. Lane *et al.*, 1985, *op. cit.*, note 19.

23. *Ibid.*

24. Data provided to the present author through personal communications with L. J. Lane, Research Hydrologist, Agricultural Research, Tucson, Arizona

25. W. D. Purtymun, *Storm Runoff and Transport of Radionuclides in DP Canyon, Los Alamos County, New Mexico*, Los Alamos National Laboratory Report LA-5744 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1974)

26. W. D. Purtymun, R. J. Peters, T. E. Buhl, W. N. Maes, and F. H. Brown, *Background Concentrations of Radionuclides in Soils and River Sediments in Northern New Mexico, 1974-1986*, Los Alamos National Laboratory Report LA-11134-MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1987).

27. *Ibid.*

CHAPTER 10. WATER, SEDIMENT, AND PLUTONIUM

1. R. C. Dahlman, C. T. Garten Jr., and T. E. Hakonson, "Comparative Distribution of Plutonium in Contaminated Ecosystems at Oak Ridge, Tennessee, and Los Alamos, New Mexico," in *Transuranic Elements in the Environment*, U.S. Department of Energy and National Technical Information Service Document DOE/TIC-22800, W. C. Hanson, ed. (Washington, D.C.: U.S. Department of Energy, 1980), 371-380; C. A. Little, "Plutonium in a Grassland Ecosystem," in *Transuranic Elements in the Environment*, U.S. Department of Energy and National Technical Information Service Document DOE/TIC-22800, W. C. Hanson, ed. (Washington, D.C.: U.S. Department of Energy, 1980), 188-195.

2. T. E. Hakonson and J. W. Nyhan, "Ecological Relationships of Plutonium in Southwest Ecosystems," in *Transuranic Elements in the Environment*, U.S. Department of Energy and National Technical Information Service Document DOE/TIC-22800, W. C. Hanson, ed. (Washington, D.C.: U.S. Department of Energy, 1980), 381-392.

3. Author interview with W. D. Purtymun, hydrogeologist, Los Alamos National Laboratory, September 25, 1990.

4. W. D. Purtymun, R. J. Peters, T. E. Buhl, W. N. Maes, and F. H. Brown, *Background Concentrations of Radionuclides in Soils and River Sediments in Northern New Mexico, 1974-1986*, Los Alamos National Laboratory Report LA-11134-MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1987).

5. G. E. Petts, *Impounded Rivers: Perspectives for Ecological Management* (New

York: Wiley and Sons, 1984).

6. J. R. C. Allen, *Physical Processes of Sedimentation* (London: Allen & Unwin, 1970).

7. M. R. Leeder, *Sedimentology: Processes and Product* (Boston: Allen & Unwin, 1982).

CHAPTER 11. ANNUAL PLUTONIUM BUDGET FOR THE RIO GRANDE

1. L. J. Lane, W. D. Purtymun, and N. M. Becker, *New Estimating Procedures for Surface Runoff, Sediment Yield, and Contaminant Transport in Los Alamos County, New Mexico* Los Alamos National Laboratory Report LA-10335-MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1985).

2. T. Dunne and L. B. Leopold, *Water in Environmental Planning* (San Francisco: W. H. Freeman, 1978).

3. G. R. Foster and T. E. Hakonson, "Estimating Erosional Losses of Fallout Plutonium," in *Environmental Surveillance at Los Alamos During 1982*, Environmental Surveillance Group, ed. (Los Alamos, New Mexico: Los Alamos National Laboratory, 1982), 83-84; G. R. Foster and T. E. Hakonson, "Predicted Erosion and Sediment Delivery of Fallout Plutonium," *Environmental Quality* 13(1984):595-602.

4. E. P. Harley, P. W. Krey, and H. L. Volchok, "Global Inventory and Distribution of Fallout Plutonium," *Nature* 241(1973):444.

5. Lane *et al.*, *op. cit.*, note 1.

6. L. J. Lane, Hydrologic Engineer, Agricultural Research Service, Tucson, Arizona.

7. W. H. Kingsley, *Survey of Los Alamos and Pueblo Canyon for Radioactive Contamination and Radioassay Test Run on Sewer Water Samples and Water and Soils Samples Taken from Los Alamos and Pueblo Canyons*, Los Alamos National Laboratory Report LAMS-516 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1947).

8. W. D. Purtymun, G. L. Johnson, and E. C. John, *Distribution of Radioactivity in Alluvium of a Disposal Area at Los Alamos, New Mexico*, U.S. Geological Survey Professional Paper 550-D, (Washington, D.C.: U.S. Geological Survey, 1966)

9. Lane *et al.*, *op. cit.*, note 1

10. W. C. Weimer, R. R. Kinnison, and J. H. Reeves, *Survey of Radionuclide Distributions Resulting from the Church Rock, New Mexico, Uranium Mill Tailings Pond Dam Failure* U.S. Nuclear Regulatory Commission Report NUREG/CR-2449, PNL-4122 (Richland, Washington: Battelle Pacific Northwest Laboratory, 1981)

PART 4. SEDIMENT AND PLUTONIUM STORAGE

CHAPTER 12. SEDIMENT AND PLUTONIUM STORAGE,SANTA CLARA TO COCHITI

1. V. C. Hink and R. D. Ohmart, *Middle Rio Grande Biological Survey Final Report*, U.S. Army Corps of Engineers Contract Report DACW47-81-C-0051 (Albuquerque, New Mexico: U.S. Army Corps of Engineers, 1984)

2. *Ibid.*

3. National Resources Council, *Regional Planning, Part V Upper Rio Grande* (Washington, D.C.: U.S. Government Printing Office, 1938), plate 12

4. P. P. Church, *The House at Otowi Bridge* (Albuquerque, New Mexico

University of New Mexico Press, 1959), F. Waters, *The Woman at Otowi Crossing* (Athens, Ohio: Swallow Press, 1966).

5. J. A. Gjevre, *The Chili Line: The Narrow Rail Trail to Santa Fe* (Española, New Mexico: Rio Grande Sun Press, 1971).

6. T. M. Pearce, *New Mexico Place Names* (Albuquerque, New Mexico: University of New Mexico Press).

7. Hink and Ohmart, 1984, *op. cit.*, note 1.

8. R. L. Griggs, *Geology and Ground-Water Resources of the Los Alamos Area, New Mexico*, U.S. Geological Survey Water-Supply Paper 1753 (Washington, D.C.: U.S. Geological Survey, 1964).

9. Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1982* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1982), p. 177; Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1984* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1984), p. 41; Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1985* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1985), p. 171; Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1986* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1986), p. 67; Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1987* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1987), p. 53-54; Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1988* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1988), p. 53-54.

10. Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1987* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1987), p. 54.

11. Environmental Surveillance Group, *Environmental Surveillance at Los Alamos During 1985* (Los Alamos, New Mexico: Los Alamos National Laboratory, 1985), p. 49.

CHAPTER 13. SEDIMENT AND PLUTONIUM STORAGE NEAR ALBUQUERQUE

1. J. R. L. Allen, *Physical Processes of Sedimentation* (London: Allen & Unwin, 1970).

2. C. Meine, *Aldo Leopold: His Life and Work* (Madison, Wisconsin: University of Wisconsin Press, 1988), 111-121.

CHAPTER 14. SEDIMENT AND PLUTONIUM STORAGE SOUTH OF THE RIO PUERCO

1. National Resources Council, *Regional Planning, Part V: Upper Rio Grande* (Washington, D.C.: Government Printing Office, 1938), plate 16.

2. *Ibid.*, plate 17.

PART 5. DYNAMICS OF PLUTONIUM IN RIO GRANDE SEDIMENTS

CHAPTER 15. THE SIMULATION MODEL

1. R. J. Chorley and P. Haggett, *Physical and Information Models in Geography* (London: Methuen, 1967), M. G. Anderson, "A Review of the Bases of Geomorphological

Modelling," in *Modelling Geomorphologic Systems*, M. G. Anderson, ed. (Chichester: John Wiley and Sons, 1988), 1-19.

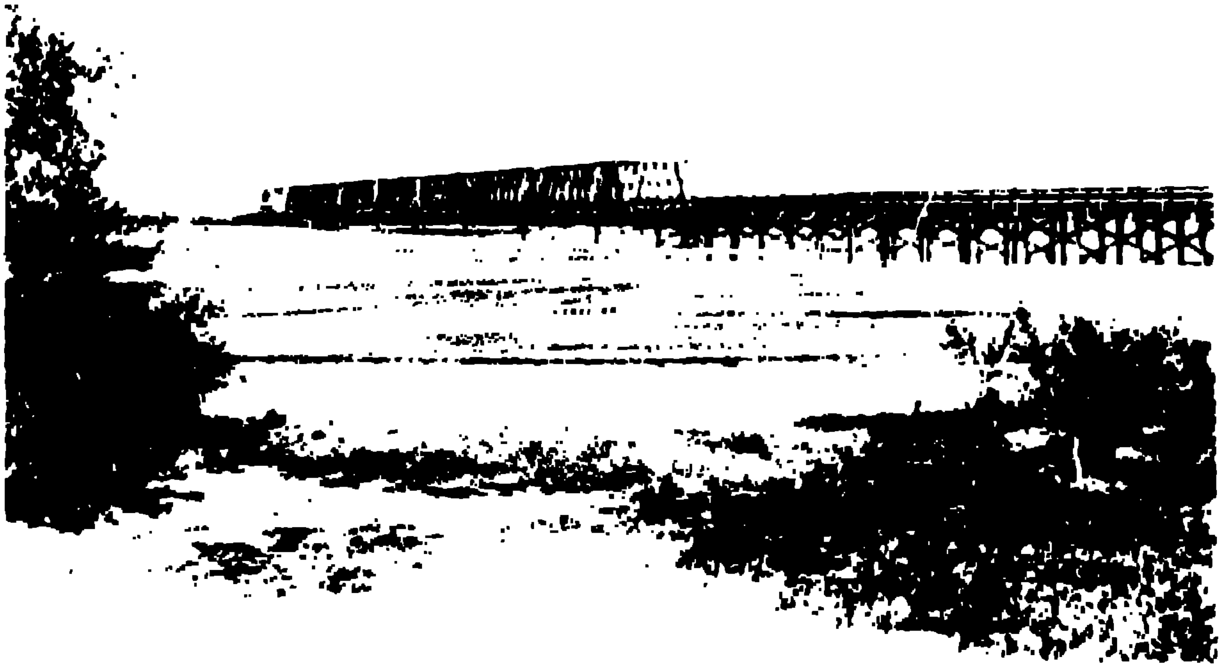
2. W. B. Langbein, "Geometry of River Channels," *Journal of the Hydraulics Divsision, American Society of Civil Engineers* 90(1964):301-312; R. D. Hey, "Dynamic Process-Response Model of River Channel Development," *Earth Surface Processes* 4(1979):59-72.

3. V. T. Chow, *Open-Channel Hydraulics* (New York, McGraw-Hill, 1959); W. L. Graf, *Fluvial Processes in Dryland Rivers* (Berlin and New York: Springer-Verlag, 1988).

CHAPTER 16. SIMULATION RESULTS

1. L. B. Leopold, M. G. Wolman, and J. P. Miller, *Fluvial Processes in Dryland Rivers* (San Francisco: W. H. Freeman, 1964).

2. W. D. Purtymun, G. L. Johnson, T. E. Buhl, W. N. Maes, and F. H. Brown, *Background Concentrations of Radionuclides in Soils and River Sediments in Northern New Mexico, 1974-1986*, Los Alamos National Laboratory Report LA-11134 MS, UC-11 (Los Alamos, New Mexico: Los Alamos National Laboratory, 1987).



REFERENCES

Abert, J. W. 1848. Notes of Lieutenant J. W. Abert, and Report of Lieutenant J. W. Abert of his examination of New Mexico in the years 1846-1847. Appendix No. 6 in Emory, W. H., *Notes of a Military Reconnaissence from Fort Leavenworth in Missouri to San Diego in California, Including Parts of Arkansas, Del Norte, and Gila Rivers*, 386-546. 30th Congress, First Session, Executive Document No. 41.

Ackers, P., and Charlton, F. G. 1970. "Meander geometry arising from varying flows." *Journal of Hydrology* 11:230-252.

Adriano, D. C., Wallace, A., and Romney, E. M. 1980. Uptake of transuranic nuclides from soil by plants grown under controlled environmental conditions. In *Transuranic Elements in the Environment*, U.S. Department of Energy Publication DOE/TIC-22800, edited by W. C. Hanson,. Washington, D. C.: U.S. Department of Energy and National Technical Information Service.

Allen, J. R. L. 1970. *Physical Processes of Sedimentation*. London: Allen & Unwin.

Anderson, M. G. 1988. "A review of the bases of geomorphological modelling." In *Modelling Geomorphologic Systems*, edited by M. G. Anderson, 1-19. Chichester: John Wiley and Sons.

Anderson, R. Y. 1961. "Physiography, climate, and vegetation of the Albuquerque Region." In Northrop, S. A. (ed.). *Guidebook of the Albuquerque Country*. New Mexico Geological Society 12th Field Conference Guidebook, edited by S. A. Northrop, 63-71. Socorro, New Mexico: New Mexico Geological Society.

Ashton, S. R., and Stanners, D. A. 1981. "Observations on the deposition, mobility and chemical associations of plutonium in intertidal sediments." In *Techniques for Identifying Transuranic Speciation in Aquatic Environments*. International Atomic Energy Agency Publication STI/PUB/613, 209-217. Vienna: International Atomic Energy Agency.

Atwood, W. W., and Mather, K. F. 1932. *Physiography and Quaternary Geology of the San Juan Mountains, Colorado*. U.S. Geological Survey Professional Paper 166. Washington, D.C.: U.S. Geological Survey.

Bagnold, R. A. 1966. *An Approach to the Sediment Transport Problem from General Physics*. U.S. Geological Survey Professional Paper 422-I. Washington, D.C.: U.S. Geological Survey.

Bagnold, R. A. 1977. "Bed load transport by natural rivers." *Water Resources Research* 13:303-312.

Bair, W. J., and Thompson, R. C. 1974. "Plutonium: biomedical research." *Science*

183:715.

Bair, W. J., Richmand, C. R., and Wachholz, B. W. 1974. *Radiobiological Assessment on the Spatial Distribution of Radiation Dose from Inhaled Plutonium*. U.S. Atomic Energy Commission Report WASH-1320. Washington, D.C.: U.S. Atomic Energy Commission.

Ball, H. 1986. *Justice Downwind: America's Atomic Testing Program in the 1950's*. Oxford: Oxford University Press.

Bandelier, A. E. 1929. *Documentary history of the Rio Grande Pueblos*. Part 2 of *Indians of the Rio Grande Valley*, edited by A. E. Bandelier and E. L. Hewitt. Albuquerque, New Mexico: University of New Mexico Press.

Beasley, T. M., Carpenter, R., and Jennings, C. D. 1982. "Plutonium, Am-241 and Cs-137 ratios, inventories and vertical profiles in Washington and Oregon continental shelf sediments." *Geochimica and Cosmochimica Acta*, 46:1831-1946.

Beaumont, E. C., and Read, C. B. 1960. *Guidebook of Rio Chama Country, New Mexico*. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

Beckmann, P. 1976. *The Health Hazards of Not Going Nuclear*. Boulder, CO: Golem Press.

Bickel, L. 1980. *The Deadly Element*. London: Stein and Day.

Black, P. E. 1987. *Conservation of Water and Related Land Resources*. 2nd ed. Totowa, NJ: Rowman & Littlefield.

Blaney, H. F., Ewing, P. A., Israelsen, O. W., Rohwer, C., and Scobey, F. C. 1937. *Investigations in the Upper Rio Grande Drainage Basin, Colorado New Mexico Texas*. Washington, D.C.: U.S. Government Printing Office.

Bradley, R. S., Barry, R. G., and Kiladis, G. 1982. *Climatic Fluctuations of the Western United States During the Period of Instrumental Records*. Department of Geology and Geography, University of Massachusetts, Contribution No. 42. Amherst, Massachusetts: University of Massachusetts.

Bradley, S. B. 1982. "Sediment quality related to discharge in a mineralized region of Wales." In *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield*, International Association of Scientific Hydrology Publication No. 137: 341-350. Paris: International Association of Scientific Hydrology.

Bradley, S. B. 1984. "Flood effects on the transport of heavy metals." *International Journal of Environmental Studies* 22:225-230.

Bradley, S. B. 1984. "Partitioning of heavy metals on suspended sediments during floods on the River Ystwyth, Wales." *Trace Substances in Environmental Health* 18:548-557.

Bradley, S. B., and Cox, J. J. 1986. "Heavy metals in the Hamps and Manifold Valleys, North Staffordshire, U.K.: Distribution in flood plain soils." *The Science of the Total Environment* 50:103-128.

Brookes, A. 1988. *Channelized Rivers: Perspectives for Environmental Management.* Chichester: John Wiley & Sons.

Brown, D. E. 1978. "Southwestern wetlands--their classification and characteristics." In *Stategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems*, U.S. Department of Agriculture, Forest Service, General Technical Report WO-12, edited by Johnson, R. R., and McCormick, J. F., 269-282. Washington, D.C.: U.S. Forest Service.

Brown, D. E., Lowe, C. H., and Pase, C. P. 1980. *A Digitized Systematic Classification for Ecosystems with an Illustrated Summary of the Natural Vegetation of North America*, U.S. Department of Agriculture, Forest Service General Technical Report RM-73. Fort Collins, Colorado: U.S. Forest Service.

Brown, R. B., Kling, G. F., and Cutshall, N. H. 1981. "Agricultural erosion indicated by Cs 137 redistribution: II. Estimates of erosion rates." *Soil Science Society of America Proceedings* 45:1191-1197.

Bureau of Radiological Health and Training Institute. 1972. *Radiological Health Handbook*. U.S. Public Health Service Publication 2016. Washington, D.C.: U.S. Department of Health, Education, and Welfare.

Burkham, D. E. 1972. *Channel changes of the Gila River in Safford Valley, Arizona*. U.S. Geological Survey Professional Paper 655-G. Washington, D.C.: U.S. Geological Survey.

Burkholder, V. L. 1928. *Report of the Chief Engineer*. Albuquerque: Middle Rio Grande Conservancy District, New Mexico.

Campbell, B. L., Loughran, R. J., Elliott, G. L., and Shelly, D. J. 1986. "Mapping drainage basin sediment sources using caesium 137." In *Proceedings of the International Symposium on Drainage Basin Sediment Delivery, Albuquerque, New Mexico*, International Association of Hydrological Sciences Publication 159, 437-446. Paris: International Association of Hydrological Sciences.

Campbell, C. J., and Dick-Peddie, W. A. 1964. "Comparison of phreatophyte communities on the Rio Grande in New Mexico." *Ecology* 45:492-502.

Cant, D. J., and Walker, R. G. 1978. "Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada." *Sedimentology* 25:625-648.

Carpenter, K. E. 1924. "A study of the fauna of rivers polluted by lead mining in the Aberystwyth District of Cardiganshire." *Annals of Applied Biology* 11:1-23.

Carpenter, K. E. 1925. "On the biological factors involved in the destruction of river fisheries by pollution due to lead mining." *Annals of Applied Biology* 12:1-13.

Carrigan, P. H., Jr. 1968. *Radioactive waste distribution in the Clinch River, Eastern Tennessee*, U.S. Geological Survey Professional Paper 433-G. Washington, D.C.: U.S. Geological Survey.

Carrigan, P. H., Jr. 1969. *Inventory of Radionuclides in Bottom Sediment of the Clinch River, Eastern Tennessee*, U.S. Geological Survey Professional Paper 433-I. Washington, D.C.: U.S. Geological Survey.

Chapin, C. E., ed. 1983. *Socorro Region II*, New Mexico Geological Society 34th Field Conference Guidebook. Socorro, New Mexico: New Mexico Geological Society.

Chase, G. D., and Rabinowitz, J. L. 1967. *Principles of Radioisotope Methodology*. Minneapolis, Minnesota: Burgess.

Chenoweth, W. L. 1974. "Uranium occurrences of the Nacimiento-Jemez region, Sandoval and Rio Arriba Counties, New Mexico." In *Ghost Ranch, Central Northern New Mexico*, Silver Anniversary Guidebook, New Mexico Geological Society 25th Field Conference Guidebook, edited by C. T. Siemers, 309-314. Socorro, New Mexico: New Mexico Geological Society.

Chenoweth, W. L. 1979. "Uranium in the Santa Fe area, New Mexico." In *Guidebook of Santa Fe Country*, New Mexico Geological Society 30th Field Conference Guidebook, edited by R. V. Ingersall, 261-264. Socorro, New Mexico: New Mexico Geological Society.

Chorley, R. J., and Haggett, P. 1967. *Physical and Information Models in Geography*. London: Methuen.

Christensen, E. M. 1962. "The rate of naturalization of Tamarix in Utah." *American Midland Naturalist* 68:51-57.

Church, P. P. 1959. *The House at Otowi Bridge*. Albuquerque: University of New Mexico Press.

Clark, I. G. 1987. *Water in New Mexico: A History of Its Management and Use*. Albuquerque: University of New Mexico Press.

Cooperrider, C. K., and Hendricks, B. A. 1937. *Soil Erosion and Stream Flow on Range and Forest Lands of the Upper Rio Gande Watershed in Relation to Land Resources and Human Welfare*, U.S. Department of Agriculture Technical Bulletin 567. Washington, D.C.: U.S. Department of Agriculture.

Cordell, L. 1979. "Gravimetric expression of graben faulting in Santa Fe Country and the Española Basin, New Mexico." In *Guidebook of Santa Fe Country*, New Mexico Geological Society 30th Field Conference Guidebook, edited by R. V. Ingersall, 59-64. Socorro, New Mexico: New Mexico Geological Society.

Coughtrey, P. J., Jackson, D., Jones, C. H., Kane, P., and Thorne, M. C. 1984. *Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, Volume 4: Plutonium and Neptunium*. Rotterdam: A. A. Balkema.

Cull, R. F., Duggan, K., East, T. J., Martin, R., and Murray, A. S. 1986. "Tailings transport and deposition downstream of the Northern Hercules (Moline) Mine in the catchment of the Mary River, N.T." In *Environmental Planning and Management for Mining and Energy*, edited by P. J. Broese, R. Von Groenou, and J. R. Burton, 199-216. Darwin. Northern Australia Mine Rehabilitation Workshop.

Curie, E. 1938. *Madame Curie*. Garden City, NY: Doubleday.

Dahlman, R. C., Garten, C. T., Jr., and Hakonson, T. E. 1980. "Comparative distribution of plutonium in contaminated ecosystems at Oak Ridge, Tennessee, and Los Alamos, New Mexico." In *Transuranic Elements in the Environment*, U.S. Department of Energy Publication DOE/TIC 22800, edited by W. C. Hanson,. Washington, D.C.: U.S. Department of Energy and National Technical Information Service.

Dane, C. H., and Bachman, G. O. 1965. *Geologic Map of New Mexico*. Scale, 1:500,000. Reston, VA: U.S. Geological Survey.

Davies, B. E., and Lewin, J. 1974. "Chronosequences in alluvial soils, with special reference to historic lead pollution in Cardiganshire, Wales." *Environmental Pollution* 6:49-57.

Davis, G. P. 1973. Man and wildlife in Arizona: the Pre-Settlement Era, 1823-1864. M.S. thesis, Arizona State University, Tempe.

De Voto, R. H., Peel, F. A., and Pierce, W. H. 1971. "Pennsylvanian and Permian stratigraphy, tectonism and history, northern Sangre de Cristo Range, Colorado." In *Guidebook of the San Luis Basin, Colorado*, New Mexico Geological Society 22nd Field Conference Guidebook, edited by H. L. James, 141-163. Socorro, New Mexico: New Mexico Geological Society.

deBuys, W. 1985. *Enchantment and Exploitation: The Life and hard Times of a New Mexico Mountain Range*. Albuquerque: University of New Mexico Press.

Department of Energy. 1981. *U.S. Department of Energy Order 5484.1, Chapter III, Effluent and Environmental Monitoring Program Requirements*. Washington, D. C.: U.S. Department of Energy.

Department of Energy. 1988. *U.S. Department of Energy Order 5400.1, General Environmental Protection Program*. Washington, D. C.: U.S. Department of Energy.

Dethier, D. P., and Demsey, K. A. 1984. "Erosional history and soil development on Quaternary surfaces, Northwest Española Basin, New Mexico." In *Rio Grande Rift: Northern New Mexico,* New Mexico Geological Society 35th Field Conference Guidebook, edited by W. S. Baldridge, P. W Dickerson, R. E. Reicker, and J Zidek, 227-233. Socorro, New Mexico: New Mexico Geological Society.

Deudney, D 1984. "What goes up must come down." *Bulletin of the Atomic Scientists* 40 (3): 10 11

Devaurs, M. A., Springer, E. P., Lane, L. J., and Langhorst, G J. 1988. "Prediction methodology for contaminant transport from rangeland watersheds." American Society of Agricultural Engineers, International Symposium on Modeling Agricultural, Forest and Rangeland Hydrology, December 12 13, Chicago, Il Los Alamos National Laboratory Report LA UR 88 2071 Mimeo.

Dewey, J D., Roybal, F. E., and Funderburg, D. E 1979 *Hydrologic data on channel adjustments, 1970 to 1975, on the Rio Grande downstream from Cochiti Dam, New Mexico, before and after closure* U S Geological Survey Water Resources Investigation and National Technical Information Service Report PB 301 134 Washington, D C U S Geological Survey

Dungan, M. A , Muehlberger, W R , Leininger, R., Peterson, C , McMillan, N J , Gunn, G , Lindstrom, M , and Haskin, L 1984 "Volcanic and sedimentary stratigraphy of the Rio Grande Gorge and the Late Cenozoic geologic evolution of the southern San Luis Valley *Rio Grande Rift Northern New Mexico,* New Mexico Geological Society 35th Field Conference Guidebook, edited by W S Baldridge, P W Dickerson, R E Riecker, and J Zidek, 157 170 Socorro, New Mexico New Mexico Geological Society

Dunne T , and Leopold, L B 1978 *Water in Environmental Planning* San Francisco W H Freeman

East, T J 1986 "Geomorphological assessment of sites and impoundments for the long term containment of uranium mill tailings in the Alligator Rivers region " *Australian Geographer* 16 16 22

East, T. J., Cull, R. F., Murray, A. S., and Duggan, K. 1988. "Fluvial dispersion of radioactive mill tailings in the seasonally-wet tropics, Northern Australia." In *Fluvial Geomorphology of Australia*, edited by R. F. Warner, 303-322. Sidney: Academic Press. 303-322.

Echeverria, J. D., Barrow, P., and Roos-Collins, R. 1989 *Rivers at Risk: The Concerned Citizen's Guide to Hydropower*. Washington, D.C.: Island Press.

Emery, P. A., Snipes, R. J., Dumeyer, J. M., and Klein, J. M. 1973. *Water in the San Luis Valley, south-central Colorado*, Colorado Water Conservation Board Water-Resources Circular 18. Denver, CO: Colorado Water Conservation Board.

Environmental Surveillance Group. 1971-1989. *Environmental Surveillance at Los Alamos* [Annual]. Los Alamos, New Mexico: Los Alamos National Laboratory.

Erel, Y., Morgan, J. J., and Patterson, C. C. 1991. "Natural levels of lead and zinc in a remote mountain stream." *Geochimica et Cosmochimica Acta* 55:707-719.

Erickson, K. A., and Smith, A. W. 1985. *Atlas of Colorado*. Boulder, CO: Colorado Associated University Press.

Everitt, B. L. 1980. "Ecology of saltcedar: a plan for research." *Environmental Geology* 3:77-84.

Fenneman, N. M. 1931. *Physiography of Western United States*. New York: McGraw-Hill Book Company.

Fergusson, H. 1931. *Rio Grande*. New York: William Morrow and Company.

Fortescue, J. A. C. 1980. *Environmental Geochemistry: A Holistic Approach*. New York: Springer-Verlag.

Foster, G. R., and Hakonson, T. E. 1982. "Estimating erosional losses of fallout plutonium." In *Environmental Surveillance at Los Alamos During 1982*, edited by the Environmental Surveillance Group, 83-84. Los Alamos: Los Alamos National Laboratory.

Foster, G. R., and Hakonson, T. E. 1983. Erosional losses of fallout plutonium. Proceedings of the Symposium on Environmental Research on Actinides in the Environment. Washington, D.C.: U.S. Department of Energy. Mimeo.

Foster, G. R., and Hakonson, T. E. 1984. "Predicted erosion and sediment delivery of fallout plutonium." *Journal of Environmental Quality* 13:595-602.

Frazier, A. H., and Heckler, W. 1972. *Embudo, New Mexico, Birthplace of Systematic Stream Gaging*. U.S. Geological Survey Professional Paper 778. Washington, D.C.: U.S. Geological Survey.

Freehling, M. D. 1982. *Riparian Woodlands of the Middle Rio Gande Valley, New Mexico: A Study of Bird Population and Vegetation with Special Reference to Russian Olive (Elaeagnus angustifolia)*, U.S. Fish and Wildlife Service Report of the Region 2 Office. Albuquerque, New Mexico: U.S. Fish and Wildlife Service.

Frissel, M. J., Jakubick, A. T., and van der Klugt, Pennders, R., Poelstra, P., and Zwemmer, E. 1980. *Modelling of the Transport of Radionuclides of Strontium, Caesium, and Plutonium in Soil. Experimental Verification.* Brussels: Commission of the European Communities.

Fritts, H. C. 1976. *Tree Rings and Climate.* London: Academic Press.

Gaca, J. R., and Karig, D. E. 1965. Gravity survey in the San Luis area, Colorado. U.S. Geological Survey, Unnumbered Open-File Report. Typescript.

Garde, R. J., and Ranga Raju, K. G. 1977. *Mechanics of Sediment Transportation and Alluvial Stream Problems.* New York: Wiley

Garland, T. R., Wildung, R. E., and Routson, R. C. 1976. "The chemistry of plutonium in soils. I. Plutonium solubility." In *Pacific Northwest Laboratory Annual Report for 1975 to the USERDA divsion of Biometical and Environmental Research. Part 2. Ecological Sciences*, Batelle Northwest Laboratory Report BNWL-2000. Seattle: Batelle Northwest Laboratory.

Gibbs, R. J. 1973. "Mechanisms of trace metal transport in rivers." *Science* 180:71-73.

Gilbert, R. O., Eberhardt, L. L., Fowler, E. B., Romney, E. M., Essington, E. H., and Kinnear, J. E. 1975. "Statistical analysis of Pu239,240 and Am241 contamination of soil and vegetation on NAEG Study sites." In *The Radioecology of Plutonium and Other Transuranics in Desert Environments*, U.S. Atomic Energy Commission Report NVO 153, edited by M. G. White and P. B. Dunaway. Springfield, Virginia: National Technical Information Service

Gile, L. H., Hawley, J. W., and Grossman, R. B. 1981. *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico: Guidebook to the Desert Project*, New Mexico Bureau of Mines and Mineral Resources Memoir 39. Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources

Gjevre, J. A. 1971. *Chili Line: The Narrow Rail Trail to Santa Fe.* Española, New Mexico: Rio Grande Sun Press

Glasstone, S. and Dolan, P. J., eds. 1977. *The Effects of Nuclear Weapons.* 3rd ed. Washington, D.C.: U.S. Department of Defense and the Energy Research and Development Administration

Glover, R. E. 1964. *Dispersion of Dissolved or Suspended Materials in Flowing*

Streams, U. S. Geological Survey Professional Paper 433-B. Washington, D.C.: U.S. Geological Survey.

Godfrey, R. G., and Frederick, B. J. 1970. *Stream Dispersion at Selected Sites*, U.S. Geological Survey Professional Paper 433-K. Washington, D.C.: U.S. Geological Survey.

Goodchild, P. 1985. *J. Robert Oppenheimer: Shatterer of Worlds*. New York: Fromm International Publishing Corp.

Goudie, A. (ed.). 1981. *Geomorphological Techniques*. London: George Allen & Unwin.

Graf, W. L. 1983. "Downstream changes in stream power in the Henry Mountains, Utah." *Annals of the Association of American Geographers* 73:373-387.

Graf, W. L. 1985. "Mercury transport in stream sediments of the Colorado Plateau." *Annals of the Association of American Geographers* 75:552-565.

Graf, W. L. 1985. *The Colorado River: Change and Basin Management* Washington, D. C.: Association of American Geographers.

Graf, W. L. 1986. "Fluvial erosion and federal public policy in the Navajo Nation." *Physical Geography* 7:97-115.

Graf, W. L. 1988. *Fluvial Processes in Dryland Rivers*. Berlin: Springer-Verlag.

Graf, W. L. 1990. "Fluvial dynamics of thorium 230 in the Church Rock Event, Puerco River, New Mexico." *Annals of the Association of American Geographers* 80:327-342.

Graf, W. L., Clark, S. L., Kammerer, M. T., Lehman, T., Randall, K., and Schröder, R. 1991. "Geomorphology of heavy metals in the sediments of Queen Creek, Arizona, USA." *Catena* 18:567-582.

Gregory, K. J. ed. 1977. *River Channel Change*. Chichester: Wiley.

Griggs, R. L. 1964. *Geology and Ground Water Resources of the Los Alamos Area, New Mexico*, U.S. Geological Survey Water Supply Paper 1753. Washington, D.C.: U.S. Geological Survey.

Groueff, S. 1967. *Manhattan Project: The Untold Story of the Making of the Atomic Bomb*. Boston: Little, Brown.

Groves, L. M. 1962. *Now it can be told: The Story of the Manhattan Project*. New York: Harper.

Hakonson, T. E. 1975. "Environmental pathways of plutonium into terrestrial plants and animals." *Health Physics* 29:583-588.

Hakonson, T. E., and Bostick, K. V. 1976. "Cesium 137 and plutonium in liquid waste discharge areas at Los Alamos." In *Radioecology and Energy Resources*, Special Publication No. 1, Ecological Society of America, edited by C. E. Cushing, Jr., 40-48. Stroudsburg, PA: Dowden, Hutchinson, & Ross.

Hakonson, T. E., and Johnson, L. J. 1973. "Distribution of environmental plutonium in the Trinity Site ecosystem after 27 years." In *Proceedings of the 3rd International Congress of the Radiation Protectional Association, 9-14 September 1973, 242-247*. Washington, D.C.: Radiation Protection Association.

Hakonson, T. E., and Nyhan, J. W. 1980. "Ecological relationships of plutonium in southwest ecosystems." In Hansen, W. C. (ed.), *Transuranic Elements in the Environment*, U.S. Department of Energy Publication DOE/TIC 22800, edited by W. C. Hansen. Washington, D.C.: U.S. Department of Energy and National Technical Information Service.

Hakonson, T. E., Johnson, L. J., and Purtymun, W. D. 1973. "The distribution of plutonium in liquid waste disposal areas at Los Alamos." *Proceedings of the 3rd International Congress of the Radiation Protection Association, 9-14 September 1973* 248-253. Radiation Protection Association. Washington, D.C.

Hakonson, T. E., Nyhan, J. W., and Purtymun, W. D. 1976. "Accumulation and transport of soil plutonium in liquid waste discharge areas at Los Alamos." In *Transuranic Nuclides in the Environment*, 175-189. Vienna, Austria: International Atomic Energy Agency.

Hakonson, T. E., Watters, R. L., and Hanson, W. C. 1981. "The transport of plutonium in terrestrial ecosystems." *Health Physics* 40:63-69.

Hamilton, E. D. 1963. "Fallout and countermeasures." *Bulletin of the Atomic Scientists* [illegible]-40.

Hammad, H. Y. 1972. "River bed degradation after closure of dams." *Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division* 98(HY4):591-607.

Happ, S. A. 1948. "Sedimentation in the Middle Rio Grande Valley, New Mexico." *Geological Society of America Bulletin* 59:1191-1216.

Hardy, E. P., Krey, P. W., and Volchok, H. L. 1973. "Global inventory and distribution of fallout plutonium." *Nature* 241:444.

Harper, A. G., Cordova, A. R., and Oberg, K. 1943. *Man and Resources in the*

Middle Rio Grande Valley. Albuquerque: University of New Mexico Press.

Harrington, C. D., and Aldrich, M. J., Jr. 1984. "Development and deformation of Quaternary surfaces on the northeastern flank of the Jemez Mountains." In *Rio Grande Rift: Northern New Mexico*, New Mexico Geological Society 35th Field Conference Guidebook, edited by W. S. Baldridge, P. W. Dickerson, R. E. Reicker, and J. Zidek, 235-239. Socorro, New Mexico: New Mexico Geological Society.

Hastings, J. R. 1959. "Vegetation change and arroyo cutting in southeastern Arizona." *Journal of the Arizona Academy of Science* 1:60-67.

Hawkins, D. 1947. *Manhattan District History, Project Y, The Los Alamos Project*. Los Alamos: Los Alamos Scientific Laboratory.

Hawley, J. W. (ed.). 1978. *Guidebook to Rio Grande Rift in New Mexico and Colorado*, New Mexico Bureau of Mines and Mineral Technology Circular 163. Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Technology.

Hawley, J. W., Love, D. W., and Wells, S. G. 1983. "Summary of the hydrology, sedimentology, and stratigraphy of the Rio Puerco Valley." In *Chaco Canyon Country*, edited by S. G. Wells, D. W. Love, and T. W. Gardner, 33-36. American Geomorphological Field Group. Albuquerque, New Mexico.

Hearne, G. A., and Dewey, J. D. 1988. *Hydrologic Analysis of the Rio Grande Basin North of Embudo, New Mexico, Colorado and New Mexico*. U.S. Geological Survey Water Resources Investigations Report 86-4113. Washington, D.C.: U.S. Geological Survey.

Hereford, R. 1984. "Climate change and ephemeral stream processes: twentieth century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona." *Geological Society of America Bulletin* 95:654-668.

Hereford, R. 1986. "Modern alluvial history of the Paria River drainage basin, southern Utah." *Quaternary Research* 25:293-311.

Heward, A. P. 1978. "Alluvial fan sequence and megasequence models, with examples from Westphalian D-Stephanian B coalfields, northern Spain." In *Fluvial Sedimentology*, edited by A. D. Miall, 669-702. Calgary: Canadian Society of Petroleum Geologists.

Hewlett, R. G., and Anderson, O. E. 1962. *The New World, 1939-1946*. University Park, Pennsylvania: Pennsylvania State University Press.

Hey, R. D. 1979. "Dynamic process-response model of river channel development." *Earth Surface Processes* 4:59-72.

Hink, V. C., and Ohmart, R. D. 1984. *Middle Rio Grande Biological Survey: Final Report*, U.S. Army Corps of Engineers Contract Report No. DACW47-81-C-0015. Albuquerque, New Mexico: U.S. Army Corps of Engineers.

Hirschboeck, K. K. 1988. "Flood hydroclimatology." In *Flood Geomorphology*, edited by V. R. Baker, R. C. Kochel, and P. C. Patton, 27-49. New York: Wiley and Sons.

Holton, G. 1973. *Thematic Origins of Scientific Thought*. Harvard, MA: Harvard University Press.

Hunt, C. B. 1974. *Natural Regions of the United States and Canada*. San Francisco: W. H. Freeman.

Hunt, C. B., Averitt, P., and Miller, R. L. 1953. *Geology and Geography of the Henry Mountains Region, Utah*, U.S. Geological Survey Professional Paper 228. Washington, D.C.: U.S. Geological Survey.

Huntley, D. 1976. "Ground water recharge to the aquifers of northern San Luis Valley, Colorado Summary." *Geological Society of America Bulletin* 90:707-709.

Hydraulic Engineering Center. 1976. *HEC 6: Scour and Deposition in Rivers and Reservoirs*, U.S. Army Corps of Engineers User's Manual 723-G2-L2470. Davis, California: U.S. Army Corps of Engineers Hydraulic Engineering Center.

Hydraulic Engineering Center. 1981. *HEC 2: Water Surface Profiles*. U.S. Army Corps of Engineers User's Manual 723-X6-L202A. Davis, California: U.S. Army Corps of Engineers Hydraulic Engineering Center.

Hyvarinen, C. E. 1963. "Channel stabilization practices on Middle Rio Grande in New Mexico." *Technical Report No. 1, Symposium on Channel Stabilization Problems*, Vol. 1, Chap. 5. Vicksburg, Mississippi: U.S. Army Corps of Engineers.

Imhoff, K. R., Koppe, P., Dietz, F. 1980. "Heavy metals in the Ruhr River and their budget in the catchment area." Progress in Water Technology 12:735-749.

International Commission on Large Dams. 1976. *World Register of Dams*. Paris: International Commission on Large Dams.

International Commission on Radiological Protection. 1968. *Report of Committee IV on Evaluation of Radiation Doses to Body Tissues from Internal Contamination due to Occupational Exposures*, International Commission on Radiological Protection Publication 10. Oxford: Pergamon Press.

International Commission on Radiological Protection. 1972. *The Metabolism of*

Compounds of Plutonium and Other Actinides, International Commission on Radiological Protection Publication 19. New York: Pergamon Press.

Jacobson, L., and Oversteret, P. 1948. "The uptake by plants of plutonium and some productions cf nuclear fission adsorbed on soil colloids." *Soil Science* 65:129-134.

Jakubick, A. T. 1976. "Migration of plutonium in natural soils." In *Transuranic Nuclides in the Environment*, International Atomic Energy Agency Publication IAEA-SM-199/3. Vienna: International Atomic Energy Agency.

Jakubick, A. T 1979. "In situ plutonium transport in geomedia." In *Migration of Long-Lived Radionuclides in the Geosphere*, 201-223. Paris: OECD.

James, H. L. ed. 1971. *Guidebook of the San Luis Basin, Colorado*, New Mexico Geological Society 22nd Field Conference Guidebook. Socorro, New Mexico: New Mexico Geological Society.

Jarvis, P. J. 1983. *Heavy Metal Pollution: An Annotated Bibliography: 1976 1980*. East Anglia: Geobooks.

Jenne, E. A., and Wahlberg, J. S. 1968. *Role of Certain Stream sediment Components in Radioion Sorption*, U.S. Geological Survey Professional Paper 433 E. Washington, D.C.: U.S. Geological Survey.

Joesting, H. R., Case, J. E., and Cordell, L. E. 1961. "The Rio Grande Trough near Albuquerque, New Mexico." In *Guidebook of the Albuquerque Country*, edited by S. A. Northrop, 148-152. New Mexico Geological Society 12th Field Conference Guidebook. Socorro, New Mexico: New Mexico Geological Society.

Jones, J. R. E. 1940. "A study of the zinc polluted River Ystwyth in northern Cardiganshire, Wales." *Annals of Applied Biology* 27:368-378.

Jones, J. R. E. 1958. "A further study of the zinc polluted River Ystwyth." *Journal of Animal Ecology* 27:1-14.

Kachanoski, R. G. 1987. "Comparison of measured soil Cesium-137 losses and erosion rates." *Canadian Journal of Soil Science* 67:199-203.

Karl, T. R., and Knight, R. W. 1985. *Atlas of Monthly Palmer Hydrological Drought Indices for the Contiguous United States*. Asheville, North Carolina: National Climatic Data Center.

Karlinger, M. R., Eschner, T. R., Hadley, R. F., and Kircher, J. E. 1983. *Relation of Channel Width Maintenance to Sediment Transport and River Morphology, Platte River, Nebraska*. U.S. Geological Survey Professional Paper 1277-E.

Washington, D.C.: U.S. Geological Survey.

Kellerhals, R., Meil, C. R., and Bray, D. I. 1976. "Classification and analysis of river processes." *American Society of Civil Engineers, Journal of the Hydraulics Division* 107:813-829.

Kelley, V. C. 1979. "Geomorphology of Española Basin." In *Guidebook of Santa Fe Country*, New Mexico Geological Society 30th Field Conference Guidebook, edited by R. V. Ingersall, 281-288. Socorro, New Mexico: New Mexico Geological Society.

Kelly, V. C. 1957. "General geology and tectonics of the western San Juan Mountains, Colorado." In *Guidebook of Southwestern San Juan Mountains, Colorado*, New Mexico Geological Society 8th Field Conference Guidebook, 154-162. Socorro, New Mexico: New Mexico Geological Society.

Kelly, V. C. 1977. *Geology of the Albuquerque Basin, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Memoir 33. Socorro, New Mexico. New Mexico Bureau of Mines and Mineral Resources.

Kelly, V. C. 1978. *Geology of the Española Basin, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Geologic Map 48. Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources.

Kelly, V. C., and Northrop, S. A. 1975. *Geology of Sandia Mountains and Vicinity, New Mexico*, New Mexico Bureau of Mines and Mineral Resources Memoir 29. Socorro, New Mexico. New Mexico Bureau of Mines and Mineral Resources.

Kennedy, V. C. 1965. *Mineralogy and Cation-exchange Capacity of Sediments from Selected Streams*, U.S. Geological Survey Professional Paper 433-D. Washington, D.C.: U.S. Geological Survey.

Kingsley, W. H. 1947. *Survey of Los Alamos and Pueblo Canyon for Radioactive Contamination and Radioassay Test Run on Sewer Water Samples and Water and Soil Samples Taken from Los Alamos and Pueblo Canyons*, Los Alamos National Laboratory Report LAMS-516. Los Alamos, New Mexico: Los Alamos National Laboratory.

Knox, J. C. 1987. "Historical valley floor sedimentation in the upper Mississippi Valley." *Annals of the Association of American Geographers* 77:224-244.

Komar, P. D. 1988. "Sediment transport by floods." In *Flood Geomorphology*, edited by V. R. Baker, R. C. Kochel, and P. C. Patton, 97-112. New York: Wiley and Sons. 97-112.

Kunetka, J. W. 1979. *City of Fire: Los Alamos and the Atomic Age, 1943-1945*. Albuquerque: University of New Mexico Press.

Kuzin, A. M., and Peredelskiy, A. A. 1956. "Nature conservancy and some aspects of radioactive-ecological relations" (in Russian). *Okhr. Prir. Zap. SSSR* 1:65-70.

Lagasse, P. F. 1980. *An Assessment of the Response of the Rio Grande to Dam Construction--Cochiti to Isleta Reach*. U.S. Army Corps of Engineers Albuquerque District Office Technical Report. Albuquerque, New Mexico: U.S. Army Corps of Engineers.

Lambert, W. 1966. "Notes on the Late Cenozoic geology of the Taos-Questa area, New Mexico." In *Guidebook of Taos--Raton--Spanish Peaks Country, New Mexico and Colorado*, New Mexico Geological Society 17th Field Conference Guidebook, edited by S. A. Northrop and C. B. Read, 43-50. Socorro, New Mexico: New Mexico Geological Society.

Lance, J. C., McIntyre, S. C., Naney, J. W., and Rousseva, S. S. 1986. "Measuring sediment movement at low erosion rates using cesium-137." *Soil Science Society of America Proceedings* 50:1303-1309.

Langbein, W. B. 1964. "Geometry of river channels." *Journal of the Hydraulics Division, American Society of Civil Engineers* 90:301-312.

Lane, L. J., and Hakonson T. E. 1982. "Influence of particle sorting in transport of sediment associated contaminants." *Proceedings of the Waste Management Symposium*, 543-557. Tucson, Arizona: University of Arizona Press.

Lane, L. J., Purtymun, W. D., and Becker, N. M. 1985. *New Estimating Procedures for Surface Runoff, Sediment Yield, and Contaminant Transport in Los Alamos County, New Mexico*, Los Alamos National Laboratory Report LA-10335-MS, UC-11. Los Alamos, New Mexico: Los Alamos National Laboratory.

Lapp, R. E., and Andrews, H. L. 1972. *Nuclear Radiation Physics*. Englewood Cliffs, New Jersey: Prentice Hall.

Larsen, E. S., and Cross, W. 1956. *Geology and petrology of the San Juan Region, Southwestern Colorado*, U.S. Geological Survey Professional Paper 258. Washington, D.C.: U.S. Geological Survey.

Larson, K. H., Leitch, J. L., Dunn, W. F., Neel, J. W., Olafson, J. H., Held, E. E., Taylor, J., Cross, W. J., and Bellamy, A. W. 1951. *Los Alamos*, University of California Report UCLA 108. Berkeley, California: University of California.

Leeder, M. R. 1982. *Sedimentology: Process and Product*. Boston: Allen & Unwin.

Leenaers, H. 1989. *The Dispersal of Metal Mining Wastes in the Catchment of the River Geul, Belgium - the Netherlands*. Utrecht, Netherlands: Geographisch Instituut, Rijksuniversiteit.

Leopold, L. B., Emmett, W. W., and Myrick, R. M. 1966. *Channel and hillslope processes in a semiarid area, New Mexico*, U.S. Geological Survey Professional Paper 352-G, 193-253 Washington, D.C.: U.S. Geological Survey.

Levinson, A. A. 1980. *Introduction to Exploration Geochemistry*. Wimette, Illinois: Applied Publishing.

Lewin, J., Davies, B. E., and Wolfenden, P. 1977. "Interactions between channel change and historic mining sediments." In *River Channel Change*, edited by K. J. Gregory. Chichester: Wiley. 353-367.

Lindolm, R. C. 1987. *A Practical Approach to Sedimentology*. London: Allen & Unwin.

Little, C A. 1980. "Plutonium in a grassland ecosystem." In *Transuranic Elements in the Environment*, edited by W. C. Hanse, U.S. Department of Engery Document DOE/TIC-22800 Springfield, Virginia: U.S. Department of Energy and National Technical Information Service.

Los Alamos Historical Society. 1986. *Los Alamos: Beginning of an Era, 1943-1945*. Los Alamos, New Mexico: Los Alamos Historical Society.

Los Alamos Scientific Laboratory. 1944. Minutes of the Laboratory Advisory Board, August 19, 1944. Los Alamos National Laboratory. Mimeo.

Loughran, R. J., Campbell, B. L., and Walling, D. E. 1987 "Soil erosion and sedimentation indicated by caesium 137: Jackmoor Brook Catchment, Devon, England." *Catena* 14:201-212.

Love D. W., and Young, J. D. 1983. "Progress report on the Late Cenozoic geologic evolution of the lower Rio Puerco." In *Socorro Region II*, New Mexico Geological Society 31th Field Conference Guidebook, edited by C. E. Chapin, 277-284. Socorro, New Mexico: New Mexico Geological Society.

Lusby, G. C., Reid, V. H., and Knipe, O D 1971. *Effects of Grazing on the Hydrology and Biology of the Badger Wash Basin in Western Colorado, 1953-1966*, U.S. Geological Survey Water Supply Paper 1532-D Washington, D.C.: U.S. Geological Survey.

Macklin, M G 1985 "Flood plain sedimentation in the upper Axe valley, Mendip, England." *Transactions of the Institute of British Geographers*, N S 10:235-244

Macklin, M G, and Dowsett, R B 1989 "The chemical and physical speciation of trace metals in fine grained overbank flood sediments in the Tyne Basin, north east England." *Catena* 16:135-151

Macklin, M. G., and Passmore, D. G. 1983. Late Quaternary sedimentation in the Lower Tyne Valley, North East England. Seminar Paper 55, University of Newcastle Upon Tyne, Department of Geography. Mimeo.

Marcus, W. A. 1987. "Copper Dispersion in ephemeral stream sediments." *Earth Surface Processes and Landforms* 12:117-128.

Mark, J. C. 1974. *A Short Account of Los Alamos Theoretical Work on Thermonuclear Weapons, 1946-1950*, Los Alamos Report LA-5647-MS. Los Alamos, New Mexico: Los Alamos National Laboratory.

Marron, D. C. 1989. "Physical and chemical characteristics of a metal contaminated overbank deposit, West Central South Dakota, USA." *Earth Surface Processes and Landforms* 14:419-432.

Martin, J. M., and Maybeck, M. 1979. "Elemental mass balance of material carried by major world rivers." *Marine Chemistry* 7:173-206.

Martz, L. W., and de Jong, E. 1987. "Using cesium-137 to assess the variability of net soil erosion and its association with topography in a Canadian Prairie landscape." *Catena* 14:439-451.

May, S. J. 1979. "Neogene stratigraphy and structure of the Ojo Caliente-Rio Chama Area, Española Basin, New Mexico." In *Guidebook of Santa Fe Country, New Mexico*, Geological Society 30th Field Conference Guidebook, edited by R. V. Ingersall, 83-88. Socorro, New Mexico: New Mexico Geological Society.

McHenry, J. R., and Ritchie, J. C. 1980. "Dating recent sediment in impoundments." In *Symposium on Surface Water Impoundments, American Society of Civil Engineers, Minneapolis, June 2-5, 1980*, 1279-1289. Washington, D.C.: American Society of Civil Engineers.

McIntyre, S. C., Lance, J. C., Campbell, B. L., and Miller, R. L. 1987. "Using cesium-137 to estimate soil erosion on a clearcut hillside." *Journal of Soil and Water Conservation* 42:117-120.

McLemore, V. T., and North, R. M. 1984. "Occurrences of Precious metals and uranium along the Rio Gande Rift in northern New Mexico." In *Rio Grande Rift: Northern New Mexico*, New Mexico Geological Society 35th Annual Field Conference Guidebook, edited by W. S. Baldridge, P. W. Dickerson, R. E. Riecker, and J. Zidek, 205-212. Socorro, New Mexico: New Mexico Geological Society.

Means, J. L., Crerar, D. A., Borcsik, M. P., and J. O. Duguid. 1978. "Adsorption of Co and selected actinides by Mn and Fe oxides in soils and sediments." *Geochimica et Cosmochimica Acta* 42:1763-1773.

Meine, C. 1988. *Aldo Leopold: His Life and Work*. Madison, Wisconsin: University of Wisconsin Press.

Menzel, R. G. 1980. "Enrichment ratios for water quality modeling." In *CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*, U.S. Department of Agriculture Conservation Research Report No. 26, III, 12, edited by W. G. Knisel, 486-492. Washington, D.C.: U.S. Department of Agriculture.

Mermel, T. W. 1958. *Register of Dams in the United States: Completed, Under Construction and Proposed*. New York: McGraw-Hill.

Meyer, M. C. 1984. *Water in the Hispanic Southwest: A Social and Legal History*. Tucson, Arizona: University of Arizona Press.

Miller, K. L. 1986. *Under the Cloud: the Decades of Nuclear Testing*. New York: The Free Press.

Miser, H. D. 1924. *The San Juan Canyon: Southeastern Utah*, U.S. Geological Survey Water Supply Paper 538. Washington, D.C.: U.S. Geological Survey.

Moore, J. C. 1979. "Uranium deposits in the Galisteo Formation of the Hagan Basin, Sandoval County, New Mexico." In *Guidebook of Santa Fe Country, New Mexico*, Geological Society 30th Field Conference Guidebook, edited by R. V. Ingersall, 265-267. Socorro, New Mexico.

Morain, S. A., Budge, T. K., and White, M. E. 1977. *Vegetation and Land Use in New Mexico*, New Mexico Bureau of Mines and Mineral Technology Resource Map RM 8, scale 1:1,000,000. Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Technology.

Morison, E. E. 1960. *Turmoil and Tradition: A Biography of Henry L. Stimson*. Boston: Houghton Mifflin Co.

Muehlberger, W. R., Adams, G. E., Longgood, T. E., Jr., and St. John, B. E. 1960. "Stratigraphy of the Chama quadrangle, northern Rio Arriba County, New Mexico." In *Guidebook of Rio Chama Country*. New Mexico Geological Society 11th Field Conference Guidebook, edited by E. C. Beaumont and C. B. Read, 103-109. Socorro, New Mexico: New Mexico Geological Society.

Muller, G., and Förstner, U. 1977. "Heavy metals in sediments of the Rhine and Elbe estuaries: mobilization or mixing effect?" *Environmental Geology* 1:33-39.

Nash, R. 1989. *The Rights of Nature*. Madison, Wisconsin: University of Wisconsin Press.

National Resources Council. 1938. *Regional Planning, Part V: Upper Rio Grande*

Washington, D.C.: U.S. Government Printing Office.

Nelson, D. M., and Lovett, M. B. 1981. "Measurement of the oxidation state and concentration of plutonium in interstitial waters of the Irish Sea." In *Impacts of Radionuclides Released into the Marine Environment*, International Commission on Atomic Energy Report STI/PUB/5651. Vienna: International Commission on Atomic Energy.

New Mexico Geological Society (ed). 1957. *Guidebook of Southwestern San Juan Mountains, Colorado*, New Mexico Geological Society 8th Field Conference Guidebook. Socorro, New Mexico: New Mexico Geological Society.

Newton, L. 1944. "Pollution of the rivers of west Wales by lead and zinc mine effluent." *Annals of Applied Biology* 31:1-11.

Nishita, H., and Hamilton, M. 1981. "The influence of serveral soil components and their interaction on plutonium extractability from a calcareous soil." *Soil Science* 131:56-59.

Nishita, H., and Haug, R. M. 1979. "The effect of fulvic and humic acids and inorganic phase of soil on the sorption and extractability of Pu(IV) 239 from several clay minerals." *Soil Science* 128:291-296.

Nordin, C. F., Jr. 1963. *A Preliminary Study of Sediment Transport Parameters, Rio Puerco near Bernardo, New Mexico*, U.S. Geological Survey Professional Paper 462-C. Washington, D.C.: U.S. Geological Survey.

Northrop, S. A., ed. 1961. *Guidebook of the Albuquerque Country*, New Mexico Geological Society 12th Field Conference Guidebook. Socorro, New Mexico: New Mexico Geological Society.

Noshkin, V. E. 1972 "Ecological aspects of plutonium dissemination in aquatic environments." *Health Physics* 22:537.

Nyhan, J. W., Drennon, B. J., Abeele, W. V., Wheeler, M. L., Purtymun, W. D., Trujillo, G., Herrera, W. J., and Booth, J. W. 1984. *Distribution of Radionuclides and Water in Bandelier Tuff Beneath a Former Los Alamos Liquid Waste Disposal Site After 33 Years*. Los Alamos National Laboratory Report LA 10159 LLWM. Los Alamos, New Mexico: Los Alamos National Laboratory.

Nyhan, J. W., Drennon, B. J., Abeele, W. V., Wheeler, M. L., Purtymun, W. D., Trujillo, G., Herrera, W. J., and Booth, J. W. 1985. "Distribution of plutonium and americium beneath a 33 year-old liquid waste disposal site." *Journal of Environmental Quality* 14:501 509.

Nyhan, J. W., Miera, F. R., and Neher, R. E. 1976. "Distribution of plutonium in Trinity soils after 28 years." *Journal of Environmental Quality* 5:431 437.

Nyhan, J. W., Mera, F. R., and Peters, R. J. 1976. "The distribution of plutonium and caesium in alluvial soils of the Los Alamos environs." In *Radioecology and Energy Resources*, Special Publication No. 1, Ecological Society of America, edited by C. E. Cushing, Jr., 49-57. Stroudsburg, Pennsylvania: Dowden, Hutchinson, & Ross.

Nyhan, J. W., Schofield, T. G., White, G. C., and Trujillo, G. 1981. *Sampling Soils for Cs-137 Using Various Field Sampling Volumes*, Los Alamos National Laboratory Report LA-8951-MS, UC-11. Los Alamos, New Mexico: Los Alamos National Laboratory.

Nyhan, J. W., White, G. C., and Trujillo, G. 1982. "Soil plutonium and caesium in stream channels and banks of Los Alamos liquid effluent receiving areas." *Health Physics* 43:531-541.

Odum, E. P. 1956. "Consideration of the total environment in power reactor waste disposal." *Proceedings of the International Conference on Peaceful Uses of Atomic Energy* 13:350-358.

Olafson, J. H., and Larson, K. H. 1963. "Plutonium, its biology and environmental persistence." In *Radioecology*, edited by V. Schultz and A. W. Klement, Jr. New York: Reinhold.

Oliphant, M. 1972. *Rutherford*. New York: Elsevier.

Pase, C. P., and Layser, E. F. 1977. "Classification of riparian habitat in the Southwest." In *Importance, Preservation, and Management of Riparian Habitat: A Symposium*. U.S. Department of Agriculture, Forest Service, General Technical Report RM-43, edited by R. R. Johnson and D. A. Jones, 5-9. Fort Collins, Colorado: U.S. Forest Service.

Payne, W. D. 1971. The role of sulfides and other heavy minerals in copper anomalous stream sediments. PhD Diss., Department of Geology, Stanford University.

Pearce, T. M. 1965. *New Mexico Place Names*. Albuquerque: University of New Mexico Press.

Pemberton, E. L. 1976. "Channel changes in the Colorado River below Glen Canyon Dam." *Proceedings of the Third Interagency Sedimentation Conference*, 5/61-5/73. Denver, Colorado: U.S. Government Printing Office.

Perkins, R. W., and Thomas, C. W. 1980. "Worldwide fallout." In Hansen, W. C. (ed.), *Transuranic Elements in the Environment*, U.S. Department of Energy Document DOE/TIC 22800. Washington, D.C.: U.S. Department of Energy and National Technical Information Service.

Petts, G. E. 1984. *Impounded Rivers: Perspectives for Ecological Management.* New York: John Wiley and Sons.

Pfeiffer, W. C., Fiszman, M., and Carbonell, N. 1980. "Fate of chromium in a tributary of the Irajo River, Rio de Janeiro." *Environmental Pollution* 1:117-126.

Pickering, R. J. 1969. *Distribution of Radionuclides in Bottom Sediment of the Clinch River, Eastern Tennessee*, U.S. Geological Survey Professional Paper 433-H. Washington, D.C.: U.S. Geological Survey.

Plikarpochkin, V. V. 1971. "The quantitative estimation of ore-bearing areas from sample data of the drainage system." In *Geochemical Exploration*, 585-586. Toronto: Canadian Institute of Mining and Metallurgy.

Popp, C. J., Hawley, J. W., and Love, D. W. 1983. *Radionuclide and heavy metal distribution in recent sediments of major streams in the Grants Mineral Belt, New Mexico*, Final Report to Office of Surface Mining. Washington, D. C.: U.S. Department of Interior.

Potter, L. D. 1975. Shoreline ecology of Lake Powell, abst. *Program and Abstracts of the Geological Society of America Annual Meetings, Salt Lake City Meeting*. Boulder, Colorado: Geological Society of America.

Prout, W. E. 1958. "Adsorption of radioactive wastes on Savannah River Plant soil." *Soil Science* 86:13-17.

Purtymun. W. D. 1974. *Storm Runoff and Transport of Radionuclides in DP Canyon, Los Alamos County, New Mexico*, Los Alamos National Laboratory Report LA-5744. Los Alamos, New Mexico: Los Alamos National Laboratory.

Purtymun, W. D., Johnson, G. L., and John, E. C. 1966. *Distribution of Radioactivity in the Alluvium of a Disposal Area at Los Alamos, New Mexico*, U.S. Geological Survey Professional Paper 550-D. Washington, D.C.: U.S. Geological Survey.

Purtymun, W. D., Peters, R. J., Buhl, T. E., Maes, M. N., and Brown, F. H. 1987. *Background Concentrations of Radionuclides in Soils and River Sediments in Northern New Meixco, 1974-1986*, Los Alamos National Laboratory Report LA-11134-MS, UC-11. Los Alamos, New Mexico: Los Alamos National Laboratory.

Purtymun, W. D., Peters, R., and Maes, M. N. 1990. *Transport of Plutonium in Snowmelt Runoff*, Los Alamos National Laboratory Report LA-11795-MS, UC-902. Los Alamos, New Mexico: Los Alamos National Laboratory.

Rai, D., Serne, R. J., and Swanson, J. L. 1978. "Solution species of plutonium-239(V) in the environment." In *Waste Isolation Safety Assessment Program, Task 4, Second Information Meeting*, U.S. Department of Energy Document

PNL-SA-7352, edited by R. J. Serne. Washington, D.C.: U.S. Department of Energy.

Rhoads, R. 1986. *The Making of the Atomic Bomb*. New York: Simon and Schuster.

Ritchie, J. C., and McHenry, J. R. 1975. "Fallout Cs-137: A tool in conservation research." Journal of Soil and Water Conservation 30:283- 285.

Ritchie, J. C., McHenry, J. R., Gill, A. C. 1973. "Dating recent reservoir sediments." *Limnology and Oceanography* 18:254-263.

Robinson, G. O. 1950. *The Oak Ridge Story*. Nashville, Tennessee: Southern Press.

Robinson, T. W. 1958. *Phreatophytes*, U.S Geological Survey Water-Supply Paper 1423. Washington, D.C.: U.S. Geological Survey.

Robinson, T. W. 1965. *Introduction, Spread, and Areal Effect of Saltcedar (Tamarix) in the Western States*, U.S. Geological Survey Professional Paper 491-A. Washington, D.C.: U.S. Geological Survey.

Rogowski, A. S., and Tamura, T. 1965. "Movement of cesium-137 by runoff, erosion, and infiltration on the alluvial Captina silt loam." *Health Physics* 11:1333-1340.

Romer, A., ed. 1970. *Radiochemistry and the Discovery of Isotopes*. New York: Dover Publications.

Romney, E. M., and Davis, J. J. 1972. "Ecological aspects of plutonium dissemination in terrestrial environments." *Health Physics* 22:551-557.

Rozental, S., ed. 1967. *Niels Bohr*. London: North-Holland.

Ruhe, R. V. 1967. *Geomorphic Surfaces and Surficial Deposits in Southern New Mexico*. New Mexico Bureau of Mines and Mineral Resources Memoir 18. Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources.

Rupp, C. R. 1982. "Stream grade variation in riparian forest ecology along Passage Creek, Virginia." *Bulletin Torr. Botanical Club* 109:488-499.

Sayre, W. W., and Chang, F. W. 1968. *A Laboratory Investigation of Open Channel Dispersion Processes for Dissolved, Suspended, and Floating Dispersants*, U.S. Geological Survey Professional Paper 433-E. Washington, D.C.: U.S. Geological Survey.

Sayre, W. W., and Hubbell, D. W. 1965. *Transport and Dispersion of Labeled Bed Material, North Loup River, Nebraska*, U.S. Geological Survey Professional Paper 433-C. Washington, D.C.: U.S. Geological Survey.

Sayre, W. W., Guy, H. P., and Chamberlain, A. R. 1963. *Uptake and Transport of Radionuclides by Stream Sediments*, U.S. Geological Survey Professional Paper 433-A. Washington, D.C.: U.S. Geological Survey.

Schulz, R. K. 1977. "Root uptake of transuranic elements." In *Transuranics in Natural Environments*, U.S. Energy Research and Development Administration Report NVO-178, edited by M. G. White and P. B. Dunaway. Washington, D.C.: U.S. Energy Research and Development Administration.

Schulz, R. K., Overstreet, R., and Barshad, I. 1960. "On the soil chemistry of cesium-137." *Soil Science* 89:16-27.

Schumm, S. A., and Kahn, H. R. 1972. "Experimental study of channel patterns." *Geological Society of America Bulletin* 83:1755-1770.

Scott, M. R. 1968. "Thorium and uranium concentrations and isotopic ratios in river sediments." *Earth and Planetary Science Letters* 4:245-252.

Seaborg, G. T. 1958. *The Transuranic Elements*. Yale: Yale University Press.

Seaborg, G. T. 1976. *Early History of Heavy Isotope Production at Berkeley*, Lawrence Berkeley Laboratory Report. Mimeo

Seaborg, G. T., and Loveland, W. D. 1990. *The Elements Beyond Uranium*. New York: John Wiley and Sons.

Segre, E. 1970. *Enrico Fermi, Physicist*. Chicago: University of Chicago Press.

Segre, E. 1980. *From X Rays to Quarks: Modern Physicists and Their Discoveries*. San Francisco: Freeman.

Siebenthal, C. E. 1910. *Geology and Water Resources of the San Luis Valley, Colorado*, U.S. Geological Survey Water Supply Paper 240. Washington, D.C.: U.S. Geological Survey.

Shaw, E. M. 1983. *Hydrology in Practice*. Berkshire: Van Nostrand Reinhold (U.K.).

Siemers, C. T., ed. *Silver Anniversary Guidebook: Ghost Ranch, Central Northern New Mexico*, New Mexico Geological Society 25th Field Conference Guidebook. Socorro, New Mexico: New Mexico Geological Society.

Simmons, V. M. 1979. *The San Luis Valley*. Boulder, CO: Pruett Publishing Company.

Simons, D. B., and Senturk, F. 1977. *Sediment Transport Technology*. Fort Collins, CO: Water Resources Publications.

Simons, D. B., Li, R-M., Li, L-Y., and Ballantine, M. J. 1981. *Erosion and Sedimentation Analysis of Rio Puerco and Rio Salado Watersheds*, Technical Report, Simons, Li & Associates for U.S. Army Corps of Engineers, Albuquerque District Office. Fort Collins, Colorado: Simons, Li & Associates.

Smith, A. K. 1984. "Manhattan Project: The Atomic Bomb". In *The Nuclear Almanac: Confronting the Atom in War and Peace*, edited by J. Dennis, 20-52. Reading, MA: Addion-Wesley Publishing Company.

Solomons, W., and Förstner, U. 1984. *Metals in the Hydrocycle*. Berlin: Springer-Verlag.

Spiegel, Z. 1961. "Late Cenozoic sediments of the lower Jemez River Region." In *Guidebook of the Albuquerque Country*, New Mexico Geological Society 12th Field Conference Guidebook, edited by S. A. Northrop, 132-138. Socorro, New Mexcio: New Mexico Geological Society.

Stewart, P. 1981. Watershed Characteristics, Part B: Decreases in Flow in the Rio Grande. U.S. Forest Service Report, Carson National Forest, Taos, New Mexico. Mimeo.

Stockholm International Peace Research Institute. 1987. *SIPRI Annual Yearbook, World Armaments and Disarmament*. Cambridge, MA: MIT Press.

Stoker, A., Ahlquist, A. J., Mayfield, D. L., Hanson, W. R., Talley, A. D., and Purtymun, W. D. 1981. *Radiological Survey of the Site of a Former Radioactive Liquid Waste Treatment Plant (TA-45) and the Effluent Receiving Areas of Acid, Pueblo, and Los Alamos Canyons, Los Alamos, New Mexico*, Department of Energy and Los Alamos National Laboratory Report LA-8890-ENV, UC-70. Los Alamos New Mexico: Los Alamos National Laboratory.

Stone, R. S. 1946. "Health protection activities of the plutonium project." *Proceedings of the American Philosophical Society* 90:11-19.

Stuewer, R. H., ed. 1979. *Nuclear Physics in Retrospect*. Minneapolis, Minnesota: University of Minnesota Press

Szaz, F. M. 1984. *The Day the Sun Rose Twice: The Story of the Trinity Site Nuclear Explosion, July 16, 1945*. Albuquerque: University of New Mexico Press

Tedford, R. H. 1982. "Neogene stratigraphy of the northwestern Albuquerque Basin." In *Albuquerque Country II*, New Mexico Geological Society 33rd Field Conference Guidebook, edited by J. A. Grambling and S. G. Wells, 273-278. Socorro, New Mexico: New Mexico Geological Society.

Templeton, W. L., Nakatani, R. E., and Held, E. E. 1971. In *Radioactivity in the Marine Environment*, edited by A. H. Seymour. Washington, D. C.: National Academy

Press.

Thompson, C. B. 1958. "Importance of phreatophytes in water supply." *American Society of Civil Engineers, Irrigation and Drainage Division, Proceedings* 84(IRI):1502/1-1502/17.

Thompson, J. C. 1965. "Channel stabilization, Middle Rio Grande Project." In *Technical Report No. 1, Symposium on Channel Stabilization Problems*, Vol. 3, Chap. 1. Vicksburg, Mississippi: U.S. Army Corps of Engineers.

Trimble, S. W., and Lund, S. W 1982. *Soil Conservation and the Reduction of Erosion and Sedimentation in the Coon Creek Basin, Wisconsin*, U.S. Geological Survey Professional Paper 1234. Washington, D.C.: U.S. Geological Survey.

Tweto, O. 1979. *Geologic Map of Colorado*, Scale, 1:500,000. Reston, Virginia: U.S. Geological Survey.

Upson, J. E. 1939. "Physiographic subdivisions of the San Luis Valley, southern Colorado." *Journal of Geology* 47:721-736.

Upson, J. E. 1971. "Physiographic subdivisions of the San Luis Valley, Southern Colorado (reprinted with additional notes)." In *Guidebook of the San Luis Basin*, Colorado, New Mexico Geological Society 22nd Field Conference Guidebook, edited by H. L. James, 113-122. Socorro, New Mexico: New Mexico Geological Society.

U.S. Bureau of Reclamation. 1979. *Annual Report, 1979*. Washington, D. C.: U.S. Bureau of Reclamation.

U.S. House of Representatives. 1948. *Rio Grande and Tributaries, New Mexico*. 81st Cong., 1st Sess., House Document No. 243.

Van Cleave, M. 1935. Vegetation changes in the Middle Rio Grande Conservancy District. M.S.thes., University of New Mexico, Albuquerque.

Warner, R. F., ed. 1988. *Fluvial Geomorphology of Australia*. Sidney: Academic Press.

Waters F. 1966. *The Woman at Otowi Crossing*. Athens, OH: Swallow Press.

Watson, J. R. 1913 (1912). "Plant geography of north central New Mexico." *Contributions from the Hull Botanical Laboratory* 160:194 217, reprinted from *Botanical Gazette* 54:194 217.

Watters, R. L. 1981. "Ecological transport." In *Actinides in Man and Animals*, edited by M. E. Wrenn, 503 507. Cleveland, Ohio. R. D. Press.

Watters, R. L., Edgington, D. N., Hakonson, T. E., Hanson, W. C., and Smith, M. H. 1980. "Synthesis of the research literature." In *Transuranic Elements in the Environment*, U.S. Department of Energy Document DOE/TIC-22800, edited by W. C. Hansen. Washington: U.S. Department of Energy and National Technical Information Center.

Watters, R. L., Hakonson, T. E., and Lane, L. J. 1983. "The behavior of actinides in the environments." *Radiochimica Acta* 32:89-103.

Weast, R. C. 1988. *CRC Handbook of Chemistry and Physics*. Boca Raton, Florida: CRC Press.

Weimer, W. C., Kinnison, R. R., and Reeves, J. H. 1981. *Survey of radionuclide distributions resulting from the Church Rock, New Mexico, uranium mill tailings pond dam failure*, U.S. Nuclear Regulatory Commission Report NUREG/DR-2449, PNL-4122. Richland, Washington: Battelle Pacific Northwest Laboratory.

Welsh, M. E. 1987. *U.S. Army corps of Engineers: Albuquerque District, 1935-1985*. Albuquerque: University of New Mexico Press.

Wendorf, F. 1954. "A reconstruction of Northern Rio Grande prehistory." *American Anthropologist* 56:200-221.

Wertz, J. B. 1949. "Logarithmic pattern in river placer deposits." *Economic Geology* 44:193-209.

Whicker, F. W., and Loveless, C. M. 1968. "Relationships of physiography and microclimate to fallout deposition." *Ecology* 49:363-368.

Whicker, F. W., and Schultz, V. 1982. *Radioecology: Nuclear Energy and the Environment*, 2 Vols. Boca Raton, Florida: CRC Press, Inc.

Whicker, F. W., Little, C. A., and Winsor, T. F. 1973. *Symposium on Environmental Surveillance Around Nuclear Installations, 5-9 November 1973*. Warsaw, Poland: International Atomic Energy Commission

White, G. C., and Hakonson, T. E. 1979. "Statistical considerations and survey of plutonium concentration variability in some terrestrial ecosystem components." *Journal of Environmental Quality* 8:176-182.

White, P. S. 1979. "Pattern, process and natural disturbance in vegetation." *Botanical Review* 45:229-299.

Wiard, L. 1962. *Floods in New Mexico, Magnitude and Frequency*, U.S. Geological Survey Circular 464. Washington, D.C.: U.S. Geological Survey.

Wildung, R. E., and Garland, T. R. 1980. "The relationship of microbial processes to the fate and behavior of transuranic elements in soils, plants, and animals." In *Transuranic Elements in the Environment*, U.S. Department of Energy Document DOE/TIC-22800, edited by W. C. Hansen. Washington, D.C.: U.S. Department of Energy and National Technical Information Service.

Williams, G. P., and Wolman, M. G. 1984. *Downstream Effects of Dams on Alluvial Rivers*. U.S. Geological Survey Professional Paper 1286. Washington, D.C.: U.S. Geological Survey.

Williams, J. L., ed. 1986. *New Mexico in Maps*, 2nd ed. Albuquerque, NM: University of New Mexico Press.

Wilson, D. 1983. *Rutherford*. Cambridge, MA: MIT Press.

Wilson, L. 1980. *Future Water Issues, Taos County, New Mexico*. Santa Fe: Lee Wilson and Associates, Inc.

Wise, S. M. 1980. "Cesium-137 and lead-210: a review of the techniques and some applications in geomorphology." In *Timescales in Geomorphology*, edited by R. A. Cullingford, D. A. Davidson, and J. Lewin, 110-127. Chichester, England: John Wiley & Sons.

Wolfenden, P. and Lewin, J. 1977. "Distribution of metal pollutants in floodplain sediments." *Catena* 4:309-317.

Wolfenden, P. and Lewin, J. 1978. "Distribution of metal pollutants in active stream sediments." *Catena* 5:67-78.

Wolman, M. G., and Leopold, L. B. 1957. *River Flood Plains: Some Observations on Their Formation*, U.S. Geological Survey 282-C, 87-107. Washington, D.C.: U.S. Geological Survey.

Woodson, R. C. 1961. "Stabilization of the Middle Rio Grande in New Mexico," *American Society of Civil Engineers, Journal of the Waterways and Harbor Division* 87:1-15.

Woodward, L. A. 1974 "Tectonics of Central-Northern New Mexico." In *Silver Anniversary Guidebook: Ghost Ranch, Central-Northern New Mexico*, New Mexico Geological Society 25th Field Conference Guidebook, edited by C. T. Siemers, 123-130. Socorro, New Mexico.

Yamamoto, M., Tanii, T., and Sakanoue, M. 1981. "Characteristics of fallout plutonium in soil." *Journal of Radiation Research* 22:134-142.