USHP000299

GJO-99-117-TAR
Rev. 1

UMTRA
Ground Water Project

Final Site Observational Work Plan for the UMTRA Project Site at Shiprock, New Mexico

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Prepared by the
U.S. Department of Energy
Grand Junction Office

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SHP 005.02(D)

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Project Number UGW-511-0020-10-000
Document Number U066001

Work Performed Under DOE Contract Number DE-AC13-96GJ87335

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Acronyms and Abbreviations

ACL	alternate concentration limit
AEC	U.S. Atomic Energy Commission
AML	abandoned mine lands
ASTM	American Society for Testing and Materials
BLRA	baseline risk assessment
BLS	below land surface
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	*Code of Federal Regulations*
cfs	cubic feet per second
cm/s	centimeters per second
CoC	chain of custody
COC	contaminants of concern
COPC	contaminants of potential concern
CV	coefficient of variation
DOE	U.S. Department of Energy
EA	environmental assessment
EHPA	di(2-ethylhexyl) phosphoric acid
EPA	U.S. Environmental Protection Agency
ERA	ecological risk assessment
ESC	expedited site characterization
ESL	Environmental Sciences Laboratory
FOD	frequency of detection
FR	*Federal Register*
ft	foot (feet)
ft^2	square feet
ft^3	cubic feet
ft/day	foot (feet) per day
ft^2/day	square feet per day
ft^3/day	cubic feet per day
ft^3/year	cubic feet per year
g	grams
GCAP	Ground Water Compliance Action Plan
GIS	geographic information system
GJO	Grand Junction Office
gpm	gallons per minute
GPS	global positioning system
HDPE	high-density polyethylene
HI	hazard index
HQ	hazard quotient
in.	inches
IX	ion exchange
ITRD	Innovative Treatment Remediation Demonstration
Kd	distribution coefficient
MAP	management action process
MCL	maximum contaminant level
MDRD	minimum detectable relative difference

µm	micrometer
MGD	million gallons per day
mg	milligrams
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mi	mile(s)
mi^2	square miles
mL	milliliters
mL/g	milliliters per gram
µg/L	micrograms per liter
mm	millimeters
NABIR	Natural and Accelerated Bioremediation Research (Program)
NAPI	Navajo Agricultural Products Industries
NECA	Navajo Engineering and Construction Authority
NEPA	National Environmental Policy Act
NGVD	National Geodetic Vertical Datum
NIA	Navajo Irrigation Authority
NOAEL	no observed adverse effect level
NRC	U.S. Nuclear Regulatory Commission
NTUA	Navajo Tribal Utility Authority
O&M	operating and maintenance
OMB	Office of Management and Budget
PEIS	Programmatic Environmental Impact Statement
PVC	polyvinyl chloride
RAP	remedial action plan
RBC	risk-based concentration
Rd	distribution ratio
RfD	reference dose
RO	reverse osmosis
RRM	residual radioactive material
SBR	sequencing batched reactors
SDWA	Safe Drinking Water Act
SOWP	site observational work plan
SX	solvent extraction
TBP	tributyl phosphate
T&E	threatened and endangered
TDS	total dissolved solids
UCL95	95 percent upper confidence limit
UMTRA	Uranium Mill Tailings Remedial Action (Project)
UMTRCA	Uranium Mill Tailings Radiation Control Act
µs/cm	microsiemens per centimeter
U.S.C.	United States Code
USGS	U. S. Geological Survey
VCA	Vanadium Corporation of America
ZVI	zero-valent iron

Executive Summary

Ground water beneath the Shiprock, New Mexico, site was contaminated by uranium and vanadium ore-processing operations conducted at the Navajo mill from 1954 through 1968. The two tailings piles at the site were combined and stabilized in one disposal cell along with material from the nearby raffinate ponds. Cleanup of surface contamination and placement of this material in the disposal cell was completed in 1986. This remediation was conducted in accordance with criteria established by the U.S. Environmental Protection Agency (EPA) in 40 *Code of Federal Regulations* (CFR) Part 192 Subpart A as part of the Uranium Mill Tailings Remedial Action (UMTRA) Surface Project. During milling operations and before remediation was completed, contaminants infiltrated ground water in both the terrace system (alluvial material and weathered Mancos Shale) and the adjacent floodplain alluvial aquifer along the San Juan River.

Additional characterization conducted in 1998 and early 1999 by the U.S. Department of Energy (DOE) Grand Junction Office (GJO) and presented in this final Site Observational Work Plan (SOWP) has revealed that contamination from former mill operations is more extensive than previously known. The contamination affected not only the floodplain aquifer and the terrace ground water in the area immediately adjacent to the disposal cell but also extends on the terrace to irrigated areas up to 1.5 miles northwest and 0.6 mile southeast of the disposal cell. Contaminated ground water in the terrace system appears at the surface in Bob Lee Wash and Many Devils Wash. Concentrations of uranium, nitrate, and sulfate are high in surface water samples collected in both washes, and interim actions are proposed for both washes that entail fencing and covering the contaminated surface water.

Contaminants of concern (COCs) in the terrace ground water system are ammonium, manganese, nitrate, selenium, sulfate, and uranium. Highest concentrations of these COCs are identified in ground water samples obtained in areas adjacent to the former mill, including the two washes. Irrigated areas to the northwest have much lower concentrations because of the natural flushing effects of irrigation. Maximum concentrations of uranium in recent ground and surface water samples are approximately 3 milligrams per liter (mg/L) in the Bob Lee Wash area but decrease rapidly to the west and south and are near the UMTRA maximum concentration limit (MCL) of 0.044 mg/L in the irrigated areas to the northwest. Maximum nitrate concentrations are 7,500 mg/L in recent ground water samples collected in the areas west and south of the disposal cell; these concentrations also decrease in samples from the irrigated area but still exceed the UMTRA standard of 44 mg/L in places. No ground water standards have been established for sulfate; however, concentrations exceed 10,000 mg/L in samples collected as far as 3,500 feet west of the disposal cell and decrease to generally less than 5,000 mg/L in samples from the irrigated area. High selenium concentrations (up to nearly 7 mg/L) occur in ground water samples from an area about 2,000 to 3,500 feet west and southwest of the disposal cell. Farther west in the irrigated area, the selenium concentrations in ground water samples decrease to less than 1 mg/L but still exceed the UMTRA MCL of 0.01 mg/L in most locations. No ground water standards have been established for ammonium and manganese; however, concentrations reach 2,000 mg/L and 35 mg/L, respectively, in samples from areas adjacent to the disposal cell.

Concentrations of COCs in ground water are generally highest along the escarpment base just north of the disposal cell and north toward the San Juan River. Concentrations are lowest in the northwest area where surface water from Bob Lee Wash, containing the relatively clean ground water from the flowing artesian well 648, acts to naturally flush the ground water. COCs in the floodplain alluvial aquifer are manganese, nitrate, selenium, sulfate, and uranium. Concentrations of uranium exceed 2 mg/L in ground water samples obtained along the base of the escarpment just north of the disposal cell and reach almost 4 mg/L in samples collected north near the San Juan River. Nitrate concentrations in ground water are generally between 2,000 and 3,500 mg/L in samples collected along the escarpment base just north of the disposal cell and north to the river. In the west part of the floodplain, both uranium and nitrate concentrations in ground water samples drop to below their respective UMTRA MCLs in the area flushed by water from Bob Lee Wash. Sulfate concentrations are about 10,000 mg/L in samples collected along the base of the escarpment, but reach nearly 25,000 mg/L in samples obtained north near the river. Selenium concentrations exceed the UMTRA MCL and are generally 0.1 to 1.0 mg/L in samples obtained along the escarpment base; however, these high concentrations do not extend northward. Manganese concentrations are generally from 5 to 10 mg/L in samples collected along the base of the escarpment and north to the river; these concentrations compare to background floodplain concentrations of about 2 mg/L.

The goal of the DOE is to implement a cost-effective strategy to remediate the ground water at the former Navajo millsite at Shiprock that complies with the EPA ground water standards and protects human health and the environment. The requirements for ground water compliance for UMTRA Project sites, including the Shiprock site, are in the Uranium Mill Tailings Radiation Control Act (42 *United States Code* [U.S.C]. §7901 *et seq.*) and EPA's Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (40 CFR Part 192; 60 *Federal Register* 2854). The compliance framework was developed in the UMTRA *Final Programmatic Environmental Impact Statement for the Uranium Mill Tailings Ground Water Project* (DOE 1996b).

The proposed compliance strategy for the terrace ground water system at the Shiprock site is active remediation involving pumping the most highly contaminated ground water with extraction wells and treating it with spray evaporation. This treatment would continue until the terrace ground water is depleted and human health and the environment are protected. Proposed interim actions in Bob Lee Wash and Many Devils Wash will prevent humans or animals from accessing surface water and, therefore, will also protect human health and the environment. For the floodplain alluvial aquifer at Shiprock, the proposed compliance strategy is active remediation involving pumping ground water with extraction wells from the highly contaminated area of the floodplain along the base of the escarpment, just north of the disposal cell. This contaminated water would be pumped and piped up to the treatment area on the terrace where the water would be treated by spray evaporation. The remainder of the contaminant plume in the floodplain will undergo natural flushing in combination with institutional controls. Numerical modeling of ground water flow and transport indicates that when the contaminant source to the floodplain is contained, the concentrations of uranium will decrease to UMTRA standards during the 100-year natural flushing period.

Further characterization is proposed to delineate areas about 1.5 miles to the northwest and about 0.6 mile southeast of the disposal cell where contaminant levels exceed MCLs. This work will be conducted in fall 1999, and an addendum to this SOWP will be issued in 2000. Proposed compliance strategies for the irrigated parts of the terrace system as well as for the Many Devils Wash area will be addressed in the SOWP addendum.

1.0 Introduction

1.1 Purpose and Scope

The Shiprock Uranium Mill Tailings Remedial Action (UMTRA) Project site is on the Navajo Indian Reservation (Navajo Nation) in northwestern New Mexico, approximately 1 mile (mi) south of Shiprock, New Mexico, and about 30 mi west of Farmington, New Mexico (Figure 1–1). The site is just south of the San Juan River and east of U.S. Highway 666, on an elevated gravel-covered terrace overlooking the river.

The U.S. Department of Energy (DOE) completed remedial action of surface and near-surface contamination in 1986. Contaminated materials were stabilized onsite in a disposal cell that covers approximately 76 acres. However, ground water affected by the uranium-ore processing at the site contains constituents in concentrations exceeding ground water protection standards established by the U.S. Environmental Protection Agency (EPA) in Title 40, Part 192 of the *Code of Federal Regulations* (40 CFR 192). Affected ground water is within the terrace material south of the San Juan River and also within an alluvial aquifer in the floodplain below.

DOE's goal is to implement a cost-effective compliance strategy that is protective of human health and the environment by remediating contaminated ground water at the Shiprock site to meet the EPA standards. This final site observational work plan (SOWP) documents the data collection and data evaluation leading to the selection of an overall compliance strategy and remedial alternative that meets the regulatory requirements for ground water. This document also provides a mechanism for stakeholder participation in the process of selecting remedial alternatives.

Compliance requirements for meeting the regulatory standards at the Shiprock site are presented in Section 2.0, "Regulatory Framework." Site background information, including an overview and history of the former milling operation and current water and land use, are reviewed in Section 3.0, "Site Background." Results of characterization activities conducted at the site are presented in Section 4.0, "Site Characterization Results." The site conceptual model is presented in Section 5.0, "Site Conceptual Model." Summaries of potential human health and ecological risks associated with ground water and surface water contamination are presented in Section 6.0, "Baseline Risk Assessment." The selected compliance strategies are presented in Section 7.0, "Ground Water Compliance Strategy," and a remedial alternatives evaluation and the proposed alternative are presented in Section 8.0, "Development and Evaluation of Active Remediation Alternatives." References are listed in Section 9.0, "References." Appendices include lithologic and well completion logs, summary of recent water sample analyses, analytical results of all sampling, concentration plots based on analytical results of ground water samples, and risk assessment data.

1.2 UMTRA Project Programmatic Documents

Programmatic documents that guide the SOWP include the *UMTRA Ground Water Project Management Action Process (MAP)* (DOE 1999g) and the *Final Programmatic Environmental Impact Statement for the Uranium Mill Tailings Remedial Action Ground Water Project* (PEIS)

(DOE 1996b). The MAP states the mission objectives of the UMTRA Ground Water Project and provides a technical and management approach for conducting the project. The PEIS is the programmatic decision-making framework for conducting the UMTRA Ground Water Project. DOE follows PEIS guidelines to assess the potential programmatic impacts of the Ground Water Project, to determine site-specific ground water compliance strategies, and to prepare site-specific environmental impact analyses more efficiently.

1.3 Relationship to Site-Specific Documents

The surface remedial action plan (RAP) (DOE 1985) provides early site characterization information. However, no ground water protection strategy was determined for the Shiprock disposal site because the RAP was approved in 1987, before the proposed EPA ground water standards. The characterization information in the RAP was used in developing the SOWP to strengthen the site conceptual model. After the ground water compliance strategy and remedial alternatives are selected for this site, a draft and final ground water compliance action plan (GCAP) will be prepared to document the remediation decision.

In 1994, DOE prepared a baseline risk assessment (BLRA) (DOE 1994) and supplement (DOE 1996d) that identified potential public health and environmental risks at the site. Potential risks identified in the BLRA are considered and updated in this SOWP to ensure that the proposed compliance strategy is protective of human health and the environment.

After a proposed compliance strategy is identified in the SOWP and described in the GCAP, a site-specific National Environmental Policy Act (NEPA) document (e.g., an environmental assessment) will be prepared, as required by the NEPA process, to determine the potential effects, if any, of implementing the proposed compliance strategy.

1.4 SOWP Revisions

The SOWP is a multiyear process of sequenced document preparation and field data-collection activities consisting of two versions: Revision 0 (draft) and Revision 1 (final). The draft SOWP was prepared in 1995 and included all previous information about the site. The draft SOWP presented a proposed compliance strategy and defined additional data that were necessary to support the most likely compliance strategy. DOE prepared a work plan detailing characterization activities (DOE 1998c) and, in conjunction with stakeholder review, conducted fieldwork in 1998 and 1999 to address the data gaps identified in the draft SOWP. Following the evaluation of the new data, additional data gaps were identified and are described in this SOWP, primarily related to the extent of contamination in the terrace area and a potential continued source of contamination on the floodplain. However, the existing data set is complete enough to move forward with an overall proposed ground water compliance strategy and remedial alternatives while continuing the collection of additional data. Therefore, this final SOWP will be followed by an addendum, which will contain an evaluation of the additional data described in Section 4.7, "Summary of Additional Data Needs."

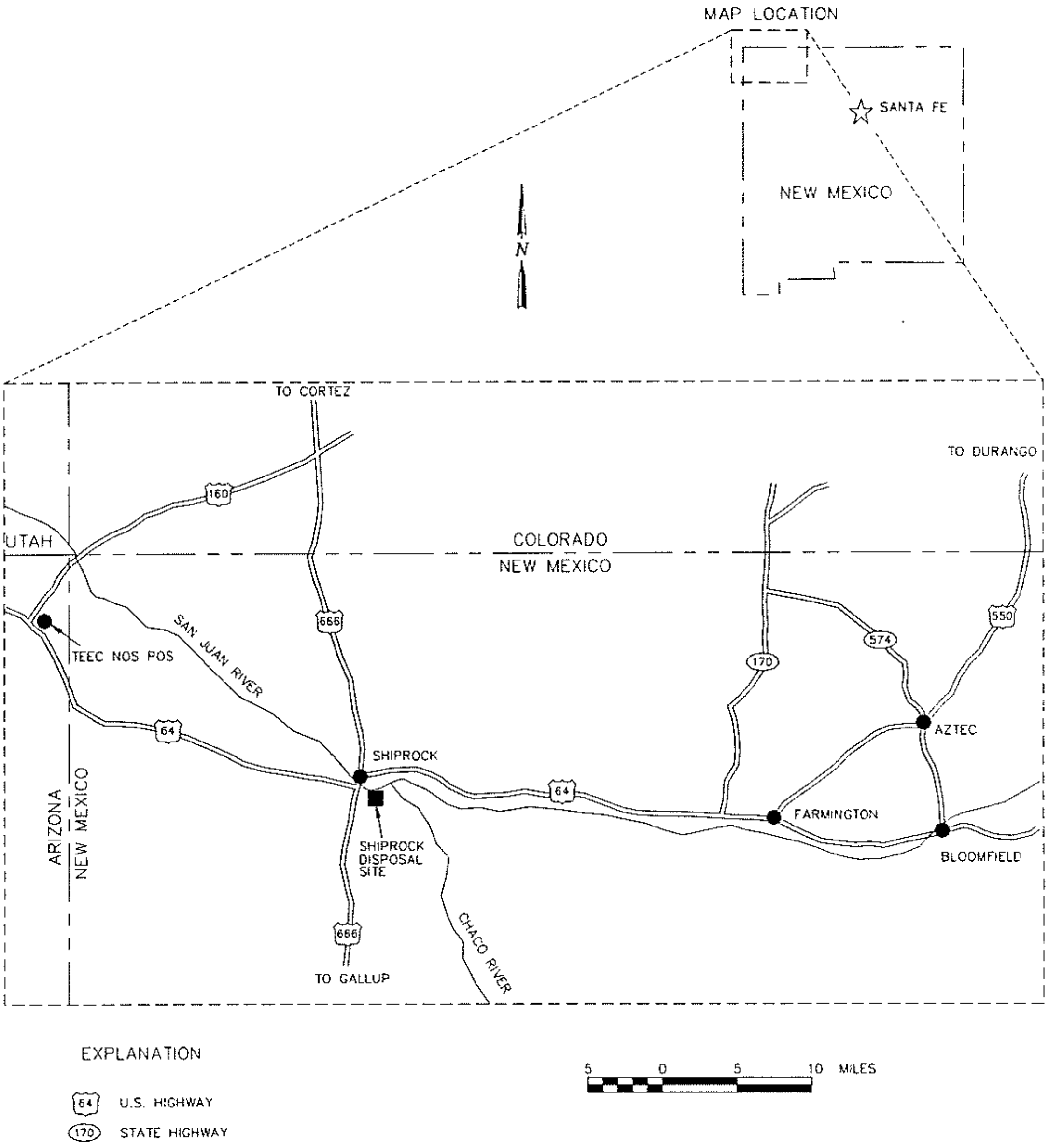

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Figure 1–1. Site Location

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2.0 Regulatory Framework

This section identifies the regulatory framework to be applied to the selected ground water compliance strategy at the former Shiprock millsite to achieve compliance with Subpart B of EPA's Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (40 CFR Part 192) and the final rule to the standards published in 60 Federal Register (FR) 2854.

2.1 Uranium Mill Tailings Radiation Control Act

The United States Congress passed the Uranium Mill Tailings Radiation Control Act (UMTRCA) (42 *United States Code* [U.S.C.] §7901 *et seq.*) in 1978 in response to public concerns about potential health hazards from long-term exposure to uranium mill tailings. UMTRCA authorized DOE to stabilize, dispose of, and control uranium mill tailings and other contaminated materials at inactive uranium-ore processing sites.

Three UMTRCA titles apply to uranium-ore processing sites. Title I designates 24 inactive processing sites for remediation. The Shiprock site is designated under Title I, which directs EPA to promulgate standards, mandates remedial action in accordance with these standards, stipulates that remedial action be selected and performed with the concurrence of the U.S. Nuclear Regulatory Commission (NRC) and in consultation with affected states and Indian tribes, directs NRC to license the disposal sites for long-term care, and directs DOE to enter into cooperative agreements with the affected states and Indian tribes. Title II applies to active uranium mills. Title III applies only to certain uranium mills in New Mexico. The UMTRA Project is responsible for administering only Title I of UMTRCA.

In 1988, Congress passed the Uranium Mill Tailings Remedial Action Amendments Act (42 U.S.C. §7922 *et seq.*), authorizing DOE to extend without limitation the time needed to complete ground water remediation at the processing sites.

2.2 EPA Ground Water Protection Standards

UMTRCA requires EPA to promulgate standards for protecting public health, safety, and the environment from radiological and nonradiological hazards associated with uranium-ore processing and the resulting residual radioactive materials (RRM). On January 5, 1983, EPA published standards (40 CFR Part 192) for RRM disposal and cleanup. The standards were revised and a final rule was published January 11, 1995 (60 FR 2854).

The standards address two ground water contamination scenarios: (1) future ground water contamination that might occur from tailings material after disposal cell construction and (2) the cleanup of residual contamination from the milling process at the processing sites that occurred before disposal of the tailings material (60 FR 2854). The UMTRA Surface Project is designed to control and stabilize tailings and contaminated soil. The UMTRA Ground Water Project addresses ground water contamination at the processing sites and is regulated by Subparts B and C of 40 CFR 192.

2.2.1 Subpart B: Standards for Cleanup of Land and Buildings

Subpart B, "Standards for Cleanup of Land and Buildings Contaminated with Residual Radioactive Materials from Inactive Uranium Processing Sites," requires documentation that action at the former ore-processing sites will ensure that ground water contamination meets any of the following three criteria:

- Background levels, which are concentrations of constituents in nearby ground water not contaminated by ore-processing activities.
- Maximum concentration limits (MCLs), which are limits set by EPA for certain hazardous constituents in ground water and are specific to the UMTRA Project (Table 2–1).
- Alternate concentration limits (ACLs), which are concentration limits for hazardous constituents that do not pose a substantial hazard (present or potential) to human health or the environment as long as the limit is not exceeded.

Table 2–1. Maximum Concentration Limits of Constituents in Ground Water at UMTRA Project Sites

Constituent	Maximum Concentration[a]
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Lead	0.05
Mercury	0.002
Molybdenum	0.1
Nitrate (as N)	10.0[b]
Selenium	0.01
Silver	0.05
Combined radium-226 and radium-228	5 pCi/L
Combined uranium-234 and uranium-238	30 pCi/L[c]
Gross alpha-particle activity (excluding radon and uranium)	15 pCi/L

[a] Concentrations reported in milligrams per liter (mg/L) unless otherwise noted.
[b] Equivalent to 44 mg/L nitrate as NO_3.
[c] Equivalent to 0.044 mg/L, assuming secular equilibrium of uranium-234 and uranium-238.

pCi/L = picocuries per liter.
Reference: 60 FR 2854.

2.3 Natural Flushing Standards

Subpart B also allows for use of natural flushing as a strategy to meet EPA standards. Natural flushing allows natural ground water processes to reduce contaminant concentrations in ground water to acceptable levels (background levels, MCLs, or ACLs). If the natural flushing strategy is used, ground water contaminant concentrations must be within EPA standards within 100 years. In addition, institutional controls and an adequate monitoring program must be established and maintained to protect human health during the period of natural flushing. Institutional controls would prohibit inappropriate uses of the contaminated ground water. The ground water also must not be a current or projected source of drinking water for a public water system during the period of natural flushing, and beneficial uses of ground water must be protected.

2.3.1 Subpart C: Implementation

Subpart C provides guidance for implementing methods and procedures to reasonably ensure that standards of Subpart B are met. Subpart C requires that the standards of Subpart B are met on a site-specific basis using information gathered during site characterization and monitoring. The plan to meet the standards of Subpart B must be stated in a site-specific GCAP. The plan must contain a compliance strategy and a monitoring program, if necessary.

2.4 Supplemental Standards

Under certain conditions, DOE may apply supplemental standards to contaminated ground water in lieu of background levels, MCLs, or ACLs (40 CFR Part 192). Supplemental standards may be applied if any of the following conditions are met:

- Remedial action necessary to implement Subpart A or B would pose a significant risk to workers or the public.
- Remedial action to meet the standards would directly produce environmental harm that is clearly excessive, compared to the health benefits of remediation, to persons living on or near the sites, now or in the future.
- The estimated cost of remedial action is unreasonably high relative to the long-term benefits, and the RRM does not pose a clear present or future hazard.
- There is no known remedial action.
- The restoration of ground water quality at any processing site is technically impractical from an engineering standpoint.
- The ground water is classified as limited use ground water. Subpart B of 40 CFR 192 defines limited use ground water as ground water that is not a current or potential source of drinking water because total dissolved solids (TDS) concentration exceeds 10,000 milligrams per liter (mg/L); there is widespread ambient contamination that cannot be cleaned up using treatment methods reasonably employed in public water systems; or the quantity of water available to a well is less than 150 gallons per day. When limited use ground water applies, supplemental standards ensure that current and reasonably projected uses of the ground water are preserved (40 CFR Part 192).
- Radiation from radionuclides other than radium-226 and its decay products is present in sufficient quantity and concentration to constitute a significant radiation hazard from RRM.

2.5 Cooperative Agreement

UMTRCA requires that remedial action include full participation of the affected states and Indian tribes that own land containing uranium mill tailings. UMTRCA also directs DOE to enter into cooperative agreements with the states and Indian tribes, which has been accomplished. DOE and the Navajo Nation entered into a cooperative agreement with the UMTRA Ground Water Project in February 1999.

2.6 National Environmental Policy Act

UMTRCA is a major federal action that is subject to the requirements of NEPA (42 U.S.C. §4321 *et seq.*). Regulations of the Council on Environmental Quality (to implement NEPA) are codified in 40 CFR Part 1500; these regulations require each federal agency to develop its own implementing procedures (40 CFR §1507.3). DOE-related NEPA regulations are contained in 10 CFR Part 1021, "National Environmental Policy Act Implementing Procedures." DOE guidance is provided in *Recommendations for the Preparation of Environmental Assessments and Environmental Impact Statements* (DOE 1993).

Pursuant to NEPA, DOE drafted a PEIS for the UMTRA Ground Water Project in 1994. The PEIS was made final in October 1996. The purpose of the NEPA document was to analyze the potential effects of implementing four programmatic alternatives for ground water compliance at the designated processing sites. The preferred alternative for the UMTRA Ground Water Project was published in a Record of Decision in 1997 (CFR, V. 62, No. 81). All subsequent action on the UMTRA Ground Water Project will comply with the Record of Decision.

2.7 Other Federal Regulations

In addition to UMTRCA, EPA ground water standards, and NEPA, DOE must also comply with other federal regulations and Executive orders that may be relevant to the UMTRA Project sites. Examples include regulations that require protection of wetlands and floodplains, threatened or endangered species, and cultural resources. Other regulations, for which the State may be delegated authority, include requirements for water discharge and waste management. Executive orders include those related to pollution prevention and environmental justice, floodplains and wetlands, and government-to-government relations with Indian tribes.

2.8 State and Tribal Regulations

State and tribal regulations must also be complied with where federal authority has been delegated to the State or where the Navajo Nation exercised the right of sovereignty. Examples include the right of the Navajo Nation to require water-use permits and permits to drill wells, cultural resources permits, and tribal endangered species issues.

2.9 DOE Orders

Several environmental, health and safety, and administrative DOE orders apply to the work being conducted under the UMTRA Ground Water Project. DOE orders prescribe the manner in which DOE will comply with federal and state laws, regulations, and guidance, and the manner in which DOE will conduct operations that are not prescribed by law. DOE guidance for complying with federal, state, and tribal environmental regulations are contained in the DOE Order 5400.1 series, partially superseded by DOE Order 231.1. DOE Order 5400.5 requires protection of the public from radiation hazards. DOE guidance pertaining to NEPA is contained in DOE Order 451.1, and specific guidance pertaining to environmental assessments (EAs) is provided in *Recommendations for the Preparation of Environmental Assessments and Environmental Impact Statements* (DOE 1993).

3.0 Site Background

The Shiprock UMTRA Project site is on the Navajo Indian Reservation (Navajo Nation) in San Juan County in the northwest corner of New Mexico (Figure 1–1). The UMTRA site is accessible by Uranium Boulevard, which extends from U.S. Highway 666 eastward about 0.5 mi to the Navajo Engineering and Construction Authority (NECA) facility. The site of the former uranium mill, which operated from 1954 to 1968, is on the NECA facility. Immediately east of the NECA facility is the 76-acre UMTRA disposal cell, a stabilization completed in 1986 of two former tailings piles. An overview of the site's physical setting and climate, a history of the former milling operation and other site activities, sources of ground water contamination, and current and future land and water uses is presented in the following sections.

3.1 Physical Setting and Climate

The Shiprock site is in the northwest part of the San Juan Basin on the Four Corners Platform. Bedrock formations in this part of the basin are flat lying or gently dipping. This arid area in the southeast part of the Colorado Plateau has generally low local relief and is characterized by broad, desolate uplands and wide valleys partly covered by vegetation. Ship Rock, the prominent landmark about 10 mi southwest of the site, is a volcanic neck that rises about 1,700 feet (ft) above the upland area.

The disposal cell and adjacent former millsite are on an elevated terrace south of the San Juan River at an elevation of about 5,000 ft. About 50 to 60 ft below the terrace is the San Juan River floodplain that extends 1,500 ft in width north of the millsite and south of the river (Plate 1). An escarpment south of the river forms the boundary between the floodplain and the nearly flat terrace. The floodplain area immediately north of the disposal cell ends at the U.S. Highway 666 bridge to the northwest and ends to the southeast at about 1,500 ft downstream from the confluence of Many Devils Wash with the San Juan River. About 1,000 ft upstream from Many Devils Wash confluence, the floodplain south of the river resumes and continues for about 1.5 mi to the confluence with the Chaco River. A terrace of varying width is present upstream of the disposal cell from Many Devils Wash eastward to the Chaco River area. Bob Lee Wash and Many Devils Wash are two minor north-northeast trending drainages that cut through the terrace south of the river.

Downstream from the U.S. Highway 666 bridge, the floodplain south of the river resumes, but its southern edge is mainly defined by a distributary channel of the river (Plate 1). The terrace area continues westward from the U.S. Highway 666 bridge and is cut by two minor north-trending drainages, 1st and 2nd washes, and a northwest-trending drainage, 3rd wash. About 0.75 mi west of the U.S. Highway 666 bridge, the height of the escarpment at the north edge of the terrace begins decreasing westward and it is not present in the area north of the elementary school. In this area of the site, the main terrace area slopes gently northward north of U.S. Highway 64 to a low terrace where the Sewage Treatment Plant is located (Plate 1).

The Shiprock area along the San Juan River valley has a desert climate, receiving approximately 7 inches (in.) of annual precipitation (Stone and others 1983). Precipitation is heaviest in summer and early fall (July through October) during the Southwest monsoon, in which high intensity, short duration storms produce downpours. Late spring months of May and June are the driest time of the year. Annual snowfall is low, averaging less than 10 in.; it usually occurs during the period from November through March.

The dry climate ensures large diurnal temperature variations of about 35 °F. Summer maximum and minimum temperatures during June through August average in the 90s °F and 50s °F, respectively. Winter maximum and minimum temperatures during December through February average in the 40s °F and teens °F, respectively. Nighttime temperatures fall below freezing generally from November through March. All-time extreme temperatures range from a low of -26 °F to a high of 109 °F.

Surface water evaporation is high owing to the high percentage (about 80 percent) of clear days, the low annual precipitation, and the frequency of strong winds, particularly in the dry spring months of March through May. The annual average pan evaporation rate is approximately 70 in., for a potential evaporation-to-precipitation ratio of about 10:1. Wind direction is most frequently from the southeast; however, stronger winds associated with frontal systems are typically from the southwest, west, and northwest.

Meteorological data for Shiprock (station 298284) has been collected sporadically since 1931, mainly from a location about 1 mi east of the center of the town of Shiprock. Recently (1996 to 1997), the recording station for Shiprock was moved to Diné College about 2 mi north-northwest of the UMTRA site, a location where more continuous and comprehensive data will be available.

3.2 Site History

3.2.1 Pre-Milling Site Conditions

Dry conditions prevailed in the Shiprock area south of the San Juan River in the 1930s and 1940s before the start of irrigated farming, housing developments, business developments, a helium processing plant, and a uranium mill. Only two houses are shown south of the San Juan River in the area of the site (within a mile upstream and downstream of the U.S. Highway 666 bridge) in the U.S. Geological Survey (USGS) topographic map (Chimney Rock SW) surveyed in 1933 and 1934. [**Note**: All figures in Section 3 are presented at the end of the section; they are preceded by an explanation of the aerial photographs in Section 3.4.] Figure 3–1, a 1935 aerial photograph of the site area shows a dry environment with little vegetation, particularly in the floodplain. Sand dunes are prevalent on the floodplain area south of the San Juan River about 1 mi upstream from the site. The floodplain just north of the site is barren except for some vegetation immediately adjacent to the river. Only one small irrigated tract is evident in the photo south of the river; it was watered from a small canal off a distributary channel of the river.

Significant quantities of helium—an important wartime commodity—were found in oil and gas fields in the area in the early 1940s. A helium processing plant was constructed in 1944 by the U.S. Bureau of Mines on the site of the present Shiprock Shopping Center (Plate 1). This plant initially operated only on a trial basis and was on standby status until 1952.

In the early 1950s, the Shiprock area experienced dramatic growth resulting from uranium and oil and gas exploration. In 1952, the helium plant began a high level of production in response to the Korean War. A housing area for plant employees was constructed just south of the plant. Water for the processing plant and housing area was taken from the south bank of the San Juan River at infiltration galleries just west of the U.S. Highway 666 bridge at the head of the distributary channel. Wastewater from the plant and housing area drained to the northwest to a pond (sewage lagoon) in the 3rd wash (Plate 1) off the terrace west of the U.S. Highway 666 bridge (U.S. Public Health Service 1962).

In January 1952, the U.S. Atomic Energy Commission (AEC) established a uranium ore buying station at the Shiprock site. American Smelting and Refining Company, an AEC contractor, operated the station until November 1954 when construction of the uranium mill, built by Kerr-McGee Oil Industries, Inc., was completed just east of the buying station (Albrethsen and McGinley 1982).

3.2.2 Milling-Era History

The uranium mill, known as the Navajo Mill, was operated by Kerr-McGee from November 1954 to March 1963 when it was sold to the Vanadium Corporation of America (VCA). VCA operated the mill until August 1967 when the company merged with Foote Mineral Company, which continued operation until milling ended in August 1968. Before and during the milling operations, the site was leased from the Navajo Nation. In 1973, the lease expired and the site ownership reverted back to the Navajo Nation.

Figure 3–2 is an oblique low-altitude aerial photograph showing the early mill in late 1954 or early 1955. The layout of mill buildings in 1957 is shown in Figure 3–3. An aerial photograph of the mill and surrounding area in August 1962 is shown in Figure 3–4. An oblique low-altitude aerial photograph of the mill and surrounding area in July 1965 is shown in Figure 3–5.

During its life, the mill processed about 1.5 million tons of ore, which contained an average of 0.26 percent uranium oxide (U_3O_8) and 1.16 percent vanadium oxide (V_2O_5). Uranium recovery averaged about 94 percent and vanadium recovery was only about 58 percent, resulting in production of about 7.9 million pounds of U_3O_8 and 35.4 million pounds of V_2O_5 (Albrethsen and McGinley 1982). The mill was initially designed to treat mainly uranium ores containing carnotite and roscoelite from the Salt Wash Member of the Morrison Formation in the Lukachukai Mountains of northeast Arizona. These ores had low lime and high vanadium contents and were initially treated using an acid cure process. However, as the mill capacity increased from about 300 to 500 tons of ore per day and the source of ore changed (because of a decrease in the vanadium market) to a high lime–low vanadium content, the acid cure was converted to a conventional agitation leach in 1955. For several years after 1955, only uranium was recovered and vanadium-rich solutions were placed in the raffinate lagoons for possible later recovery of vanadium. After VCA took over mill operation in 1963, more than half of the ore supplied to the mill was from mines in the Uravan Mineral Belt, 100 to 150 mi to the north.

In 1956, Kerr-McGee added a solvent extraction (SX) circuit for uranium recovery on a trial basis to supplement the agitation leach/ion exchange process circuit. The SX circuit operated successfully and the process was expanded and adapted to include vanadium recovery. By 1957, the mill had converted from the ion exchange process after leaching to a two-stage SX process where uranium was recovered first in a separate SX circuit and vanadium was recovered second in another SX circuit. In this milling process, ore was crushed and ground to less than 35 mesh, then subjected to a strong acid leach in two stages. A high concentration of acid was required in the second stage to improve vanadium recovery. The strong acid solution produced in the second stage was recirculated to the first stage for partial neutralization by the entering ore slurry. In addition to ore, after VCA assumed operation of the mill in March 1963, millfeed also consisted of dried slime concentrates and chemical precipitates produced by the VCA concentrating plants near the Monument No. 2 mine in Monument Valley, Arizona. During the second stage of leaching, old tailings containing vanadium that had not been extracted during uranium processing in the early years of milling were added.

After leaching, the sands and slimes entered a countercurrent washing system in which the sands were washed in classifiers and the slimes were washed in thickeners. Uranium and vanadium were then removed from the pregnant liquors by the two SX circuits. Organic solvents used in the SX process were di(2-ethylhexyl) phosphoric acid (EHPA) and tributyl phosphate (TBP) in a base of high flash point kerosene. Also, alcohol was likely added as a modifying agent (DOE 1997). Both nitrate and ammonium complexes were used as ion exchange strippers to concentrate the uranium, and ammonia was used to adjust the pH of the slurry during milling. Additional details of the leaching and SX processes are in Merritt (1971).

Tailings from the washing circuit were pumped to ponds on the two tailings piles. Raffinate from the SX operation was allowed to evaporate in five to nine unlined raffinate ponds (Figures 3–4 and 3–5), south and southwest of the tailings piles. Water for the milling process was pumped from the San Juan River from an intake about 0.6 mi south-southeast of the mill (Figure 3–4).

During the milling period, the Shiprock area south of the San Juan River and west of the Navajo Mill gained population, and agricultural use increased. These changes required water, and the availability of water changed the character of the terrace area and the area along the San Juan River floodplain. In the mid- to late-1950s, a siphon was constructed west of U.S. Highway 666 to bring irrigation water from the Hogback Canal (diverted from the San Juan River about 8 mi east of Shiprock) southward to the terrace area west of the U.S. Bureau of Mines' helium plant. By 1960, irrigated farming was well established in this area, both north and south of U.S. Highway 64.

In 1961, a well was drilled (presumably an oil and gas test) to a depth of 1,850 ft on the terrace about 0.4 mi northwest of the mill. Known in the UMTRA Program as artesian well 648 (Navajo tribal well 12T–520), the well was not plugged and has since flowed at a rate of approximately 64 gallons per minute (gpm) from a screened zone in the Morrison Formation. For several years after the well was drilled, water from the well is believed to have flowed in a ditch to the northeast and down the escarpment to the floodplain. Evidence for this flow is in an aerial photograph from August 1962 (Figure 3–4) showing a line of vegetation northeast from the well. Flow from the artesian well to the east-southeast toward Bob Lee Wash began sometime between August 1962 and June 1974; an aerial photograph taken in June 1974 shows vegetation along both northeast and east-southeast drainage routes away from the well.

Vegetation increased dramatically on the San Juan River floodplain north of the millsite during the milling period in response to increased availability of water. As early as the summer of 1955, drainage of mill effluent northward onto the floodplain was evident by the presence of a pond at the mouth of a small arroyo incising the terrace and leading north from the mill area. This pond and several smaller ones to the north are present on the floodplain, as shown in the August 1962 aerial photograph in Figure 3–4. By that time, vegetation on the southern part of the floodplain had increased from the pond area westward to the mouth of Bob Lee Wash and to the point farther west where artesian well 648 water drained to the floodplain. This vegetation contrasts with the sparsity of vegetation at the same time in the floodplain south of the San Juan River about 1 mi upstream from the millsite. A similar increase in vegetation is noted in the

August 1962 photo in the floodplain area west of the U.S. Highway 666 bridge along the distributary channel (Figure 3–4). This vegetation is in response to irrigation return flow water and wastewater draining from the helium processing plant.

In 1963 the Navajo Dam was completed on the San Juan River, forming Navajo Lake about 75 mi upstream and east of Shiprock. Before the dam, the river flow fluctuated greatly through the year from extreme low flows in the fall and winter to sometimes extreme high flows in the spring and early summer in response to snowmelt conditions at the headwaters. In most years, the runoff would be high enough to cover the floodplain for periods of several days to weeks. These periodic high flows would scour much of the vegetation off the floodplain and create numerous drainage and distributary channels. After the 1963 control by the dam, fluctuations in river stage have been less extreme. High flows that cover the floodplain are rare and occur only about once every 10 years—the last flood was in June 1995 when water covered the floodplain for only a few days. This control of the river has nearly prevented scouring during flood events and has allowed vegetation to become established along much of the floodplain area upstream and downstream from the site.

During milling, large amounts of mill process water were added to the terrace area in the unlined raffinate ponds and on the tailings piles, as shown in the aerial photograph in July 1965 (Figure 3–5). In August 1960, a large volume of acidic waste effluent was spilled from the west end of the raffinate ponds and flowed down Bob Lee Wash to the floodplain. The effects of this spill and of the long-term conditions resulting from millsite effluent seeping into the San Juan River were evaluated in a report by the U.S. Public Health Service (1962). Several seeps were noted and sampled along the escarpment from upstream of the site just below the mouth of Many Devils Wash to downstream on the first wash (1st wash) west of the U.S. Highway 666 bridge. Also, the presence of a pond was noted that contained piped mill cooling water, which was at times contaminated with overflow of contaminated process waters. This pond discharged northwestward into Bob Lee Wash.

Some of the mill buildings and most of the equipment were dismantled and placed in the west tailings pile from the time that milling ended in 1968 to the expiration of the Foote Mineral Company lease in 1973. During this period, in about 1972, Shiprock Community Development completed several large housing projects on the terrace about 0.75 mi to 1 mi southwest of the millsite. City water and sewer lines to support this development greatly increased the amount of water available to the shallow ground water system south and west of the millsite.

3.2.3 Surface Remedial Action

In 1973 when the millsite and tailings property reverted to control of the Navajo Nation, NECA obtained a lease for the site, occupied the former plant office and shop buildings, and began operating a training school on the site to train Navajo students to operate earth moving equipment. Soon after acquiring the site in 1973, the Navajo Tribal Chairman asked officials from EPA and other federal agencies for assistance in stabilizing the tailings piles (FBDU 1977). In response, EPA conducted radiation surveys around the site in April 1974 to determine the extent of windblown and water-transported tailings. Following this evaluation, EPA recommended decontaminating the site and stabilizing the tailings, and EPA and AEC prepared a work plan to accomplish these objectives (AEC 1974). The decontamination work began in January 1975 and was conducted primarily by NECA trainees under EPA guidance. These activities continued with the trainees until mid-1978, and with other NECA personnel until 1980.

Some moving of the tailings and filling of drainages by the NECA trainees had already occurred by June 1974, as evidenced by a June 1974 aerial photograph that shows reworking of the west (south) tailings pile and partial filling in of the small drainage north of the millsite area. During the early part of the tailings pile stabilization work, a broadcast irrigation system was installed on the south pile to reduce wind erosion; this system was dismantled in 1980. Filling in of the drainages northwest and east of the disposal cell occurred during the significant decommissioning work and recontouring in the mid- to late-1970s. A pond, presumably constructed to hold surface water drainage from the NECA buildings area, was present just northwest of the NECA yard from the mid-1970s to about 1984. This pond, at the site of an earlier pond that had held contaminated mill process waters, was in a small drainage that flowed into the east side of Bob Lee Wash.

By May 1980, the pond on the floodplain just north of the escarpment had been filled in, as had the small drainage to the south from the millsite area that fed the pond. An aerial photograph from August 1980 shows that upper Bob Lee Wash (above the well 648 outflow) was much more vegetated than at present. This presence of vegetation indicates an abundance of water still available at that time in the terrace system from previous milling and processing activities. Also shown in this photograph, water from Bob Lee Wash that entered the floodplain was channeled by ditch northward to an old distributary channel and then westward to the San Juan River; a wetland area was not present.

By 1980 the extensive changes to the site caused by decommissioning activities and the changes in remedial action criteria affected by UMTRCA legislation in 1978 made it necessary to prepare a revised site engineering assessment (FBDU 1981). This was followed by the surface and ground water characterization studies that were conducted prior to the development of the RAP and Site Conceptual Design for Stabilization of the site, completed in June 1985 (DOE 1985). These characterization studies included an aerial radiometric survey conducted in December 1980 (EG&G 1981), a geochemical investigation (DOE 1983), a radiologic characterization (Allen and others 1983), a processing site characterization report (DOE 1984b), and an EA of remedial action (DOE 1984a). Mention was made in the geochemical investigation report (DOE 1983) of the use of contaminated soil from the ore storage area to fill (in the late 1970s) a wash on the river bluff (escarpment). The wash referred to is probably the drainage that went north from the old millsite area to the floodplain. No deep radiologic contamination was identified in this filled area during the radiologic characterization; however, it appears that none of those characterization boreholes (Allen and others 1983) penetrated the filled drainage.

Site remediation occurred during late 1985 and 1986 and consisted of consolidation of the two tailings piles (stabilization in place) into one disposal cell. An excellent photographic record of remediation activities and disposal cell construction during the 1985–1987 period are archived at the DOE Grand Junction Office (DOE–GJO); additional information on construction activities is in the Remedial Action Completion Report for the Shiprock site (MK Ferguson 1987).

September 1985 aerial photos show that the wetlands on the floodplain had not yet formed and that the high school to the west in the irrigated area was under construction. March 1986 aerial photos show the radon cover borrow material (loess) being excavated south of the disposal cell and remediation occurring on the floodplain south of the east-northeast trending fence; three ponds were created in the remediated area on the floodplain for waterfowl. A July 1986 aerial photo (Figure 3–6) shows additional remediation on the floodplain and the waterfowl (duck) ponds, which were filled in about a year later because the ponds contained highly contaminated water; ponded water (which could be the ground water surface or water used to control dust) is shown in the northwest end of the radon cover borrow pit. In July 1986, the floodplain was fenced off to prevent grazing use. Also in 1986, construction started on the shopping center. A summer 1987 aerial photo (Figure 3–7) shows the completed disposal cell, and a white efflorescent (salt) deposit has appeared on the floodplain in the recently disturbed (scraped) and remediated ground surface from Bob Lee Wash southeast along the base of the escarpment. The NECA pond was constructed in about 1987 in the north portion of the NECA yard after completion of the disposal cell. In 1994 a long-term surveillance plan was prepared for the Shiprock disposal site (DOE 1994). Following approval of this plan, NRC issued a license in September 1996 to the DOE-GJO for the long-term care of the site.

3.2.4 Sources of Ground Water Contamination

During active milling, water usage was approximately 270 gpm. Water with tailings from the washing circuit and from yellow-cake filtration was pumped to the disposal area. Although excess solutions were recycled to the plant during winter months, raffinate was also disposed of by evaporation in separate holding ponds (Merritt 1971). Ground water contamination at the site is believed to have resulted from infiltration of these fluids and leaching of ore and uranium mill tailings constituents by mill water and rainwater. An estimate of the amount of ground water contamination that could have resulted from the ore processing is presented in Section 4.3.2.2, "Terrace Ground Water System."

3.3 Present and Anticipated Land and Water Use

The current population of rapidly growing Shiprock is about 12,000. This sprawling unincorporated community is the largest in the Navajo Nation and the largest Native American town in the United States. Several thousand people live south of the San Juan River in the south part of Shiprock. The disposal cell and the floodplain immediately to the north are just east of the south part of Shiprock. Fencing around the disposal cell prevents public access to it, and the gated fence on the road at the mouth of Bob Lee Wash and the natural 50- to 60-ft high escarpment effectively preclude public access to the uninhabited floodplain area.

A variety of land uses occur in the area underlain by contaminated ground water west and south of the disposal cell. Some of these land uses are shown in Plate 1. Immediately west of the disposal cell is the NECA facility (accessed from the west by Uranium Boulevard), which includes offices, equipment repair shops, and equipment and material storage. Also within the fenced NECA facility is an Indian Health Service Office of the U.S. Public Health Service and the Shiprock Field Office of the Navajo Abandoned Mine Lands (AML) Reclamation Department. Several of the NECA facility buildings were former millsite buildings. Southeast of the disposal cell is the fenced NECA gravel pit, which extends nearly to the mouth of Many Devils Wash and includes gravel mining and crushing equipment. South of the disposal cell is the fenced radon cover borrow pit from which loess (silt-sized material) was removed and used for construction of the thick radon barrier in the disposal cell in 1986. West of the fenced NECA facility is the large fairgrounds area north and south of Uranium Boulevard. This is the site of the annual Northern Navajo Shiprock Fair around October 1 attended by approximately 70,000 people.

Commercial and administrative developments line both sides of U.S. Highway 666 south of the San Juan River around the junction of U.S. Highway 64. The largest commercial facility (and in the entire town of Shiprock) is the Tsé Bit' aí (Shiprock) shopping center (Plate 1). Included in the shopping center is the Shiprock Regional Business Development Office that administers business lease tracts. East and northeast of the shopping center are several fast food restaurants and small businesses. South of the shopping center are a few small businesses, a senior citizens center, and a day care center.

Various housing areas are scattered on the terrace and upland areas southwest, west, and northwest of the disposal cell. Most of the housing is in several high density government-funded developments; however, several areas of houses are on individual residential tracts administered by the Navajo Land Department, mainly south and west of the disposal cell, northwest of Bob Lee Wash, and south of the irrigated area (south of Helium Lateral Canal). Two schools, Shiprock High School (and its stadium and athletic fields) and Stokely Elementary School, are in the irrigated area south of U.S. Highway 64.

Irrigated agricultural areas, where mainly alfalfa is grown, are west of U.S. Highway 666, both north and south of U.S. Highway 64. These areas are east of the high school, the Diné College farm area, and the Blueeyes Ranch north of the irrigation return flow ditch (Plate 1). Water for these irrigated areas is supplied by the buried siphon (constructed in the late 1950s) that takes water from the Hogback Canal north of the San Juan River and discharges it into the Helium Lateral Canal. Water flows through this irrigation system during the growing season, generally from April through October.

Grazing (through a system of permits) of mainly sheep and goats and a few cattle occurs in the open lands southeast of NECA gravel pit and in the upland area south of the disposal cell. A grazing permit is held for the floodplain area north of the disposal cell, but grazing has not been allowed there since 1986. Several acres of sewage pits, where septic tanks are drained, are in the grazing area south of the upland along the west fork of Many Devils Wash (Plate 1); these pits are fenced to prevent livestock entry. Cows and horses also graze in the alfalfa fields on the Blueeyes Ranch. A few livestock (cows and horses) also graze around the scattered residences just west of Bob Lee Wash and southwest of the disposal cell.

No ground water from the floodplain aquifer is being used in the site area. The only known use of ground water from the terrace system in the site area is from well 847 at the north edge of the Shiprock High School property. Water from this well is used for irrigating the school grounds. A small amount (several gallons per minute) of ground water from artesian well 648 is piped to the nearby fairgrounds to water stock for a few days each year. Water from the San Juan River is taken by NECA just downstream from the mouth of Many Devils Wash; this water is used at the NECA gravel pit for dust control and gravel processing. The Navajo Tribal Utility Authority (NTUA) provides treated water to most of the residents south of the San Juan River through a municipal water supply system that is piped from the Farmington area. The intake structure on the north bank of the San Juan River just east of the U.S. Highway 666 bridge is operable, but takes water to be treated out of the river only during emergency situations.

Planned land use changes in the Shiprock site area include:

- Movement of the fairgrounds facility by about 2001 to a location about 4 mi to the south.
- Construction of a hotel and several other new businesses in the area of the former fairgrounds.
- Construction of a multipurpose cultural center south of the shopping center and senior citizens center. The center will include a library, welcome center, youth center, small museum, auditorium, amphitheater, gymnasium, and sports fields.
- Construction of a new Diné College facility in the tract east of the Shiprock High School.
- Construction of the Tabaaji Recreation Vehicle Park on the floodplain just north of the San Juan River and west of U.S. Highway 666.
- Return of the floodplain north of the disposal cell to grazing use after remediation is completed.
- Possible expansion of the NECA gravel pit westward to the area of the radon cover borrow pit after remedial action is completed.

Future use of the ground water may include additional use of the terrace ground water west of U.S. Highway 666 where construction of the multipurpose cultural center and the new Diné College facility will result in landscaping that requires irrigation. Ground water for other than irrigation use is not planned or anticipated because of the availability of a municipal water system.

3.4 Explanation of Aerial Photographs (Figures 3–1, 3–2, and 3–4 through 3–7)

Figure 3–1: 1935 Overhead Aerial Photograph of the Shiprock, New Mexico, area. Dry conditions are evident from scant vegetation south of the San Juan River. Sand dunes are present in the floodplain background area (1), vegetation is sparse in the main floodplain area (2), one small irrigated plot (3) is near the distributary channel of the river, and terrace gravel outcrops (4) are distinguishable by their darker color. Only two houses are present south of the river.

Figure 3–2: Winter 1954 to 1955 Oblique Aerial Photograph of the Navajo Mill—View Southeast. The mill had just begun operation in November 1954. The raffinate ponds (1) had just been constructed and many ore piles (2) were present; tailings piles had not yet been generated. Sulfuric acid was stored in the horizontal tanks (3) in the center, and to the right are the change house (4), office (5), control lab (6), and warehouse and shops (7). The main uranium and vanadium mill buildings are just left of the sulfuric acid tanks, and the sampling plant (8) and crusher (9) are farther left.

Figure 3–4: August 1962 Overhead Aerial Photograph of the Navajo Mill area. After nearly 8 years of milling operations, the east (1) and west (2) tailings piles and the raffinate ponds (3) are well established. Vegetation has appeared in Bob Lee Wash and on the floodplain just north of the escarpment. On the floodplain just north of the escarpment, a pond (4) is present at the mouth of a small arroyo draining the area of the mill and east tailings pile. Water from artesian well 648 (5), drilled a year earlier, has drained northeast (from the line of vegetation) to the escarpment. The Helium Plant (6) and the housing area (7) are present and their process water and wastewater were sent to a pond (8) near the escarpment. Water from the Hogback Canal has been siphoned southward and used to create an irrigated farming area (9). Irrigation return flows (10) have supplied water to support vegetation in the floodplain along the distributary channel of the San Juan River.

Figure 3–5: July 1965 Oblique Aerial Photograph of the Navajo Mill area—View Southeast. Abundant milling process water is evident from the full raffinate ponds (1) and ponded water on the east (2) and west (3) tailings piles.

Figure 3–6: July 1986 Oblique Aerial Photograph of Millsite Remediation—View Southeast. Construction of the disposal cell is under way with much of the thick radon barrier material emplaced and some of the cobble blanket cover in place. Loess (silt) material has been excavated from the radon cover borrow pit to construct the radon barrier. The NECA gravel borrow pit in the upper left is in operation. Surface remediation on the floodplain has occurred mainly south of the fence. The duck ponds (1) were created as part of the remediation. The small arroyo (2) that drained the mill area has been filled in. Vegetation is thick along the river bank and has taken over much of the floodplain (outside the remediated area). Water (3) is present in the northwest (low end) of the radon cover borrow pit.

Figure 3–7: Summer 1987 Oblique Aerial Photograph of Completed Disposal Cell—View Northwest. Remediation has been completed. Housing area (1) for the former helium plant is still present, but the plant has been removed and a shopping center (2) has just been completed. To the upper left beyond the irrigated fields, the Shiprock High School (3) is under construction. Much of the floodplain is covered by vegetation north of the fence. Efflorescence, shown by white crust, is evident on the floodplain from the mouth of Bob Lee Wash southeastward along the base of the escarpment.

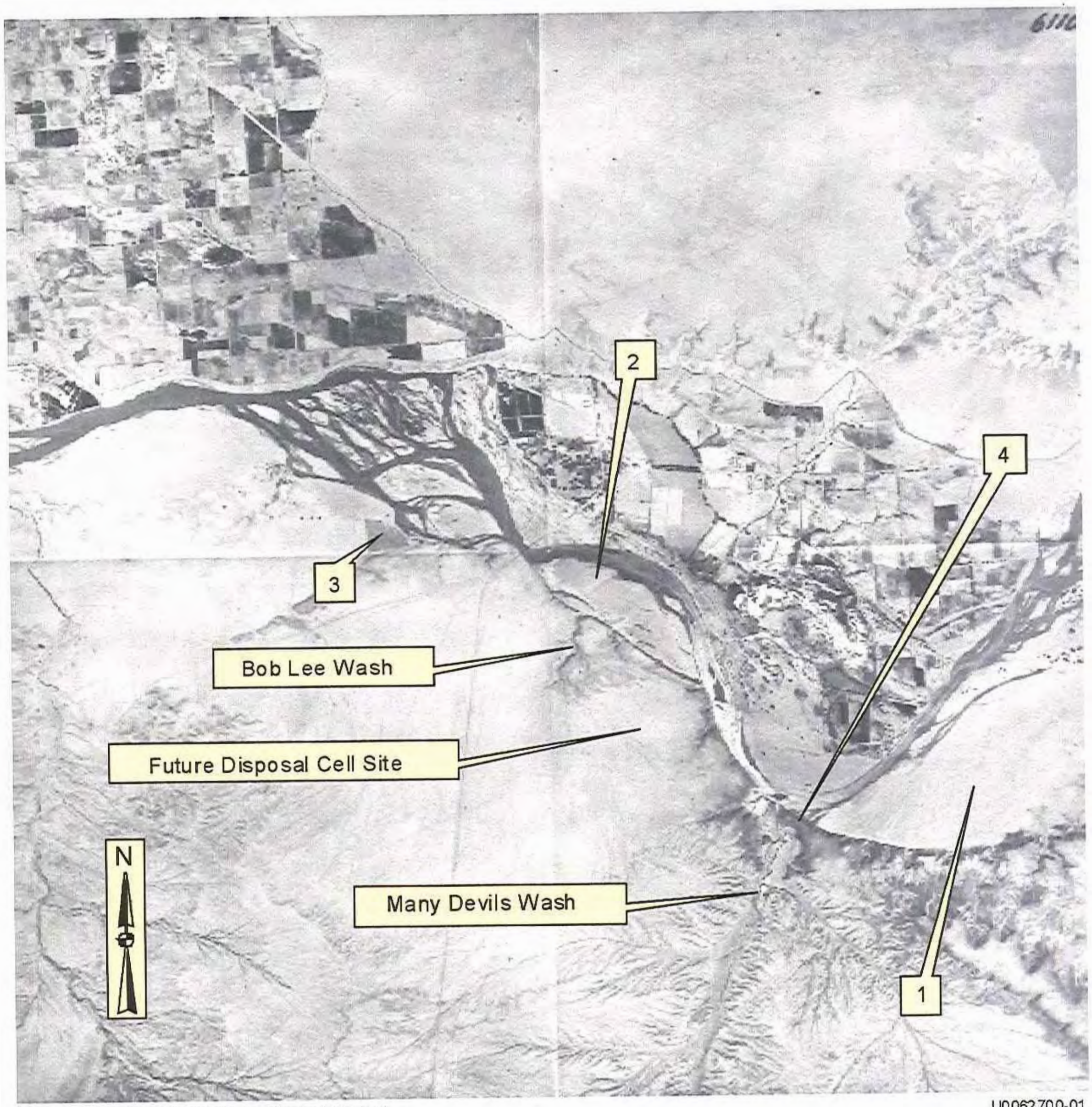

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Figure 3–1. 1935 Aerial View of Shiprock, New Mexico, Area

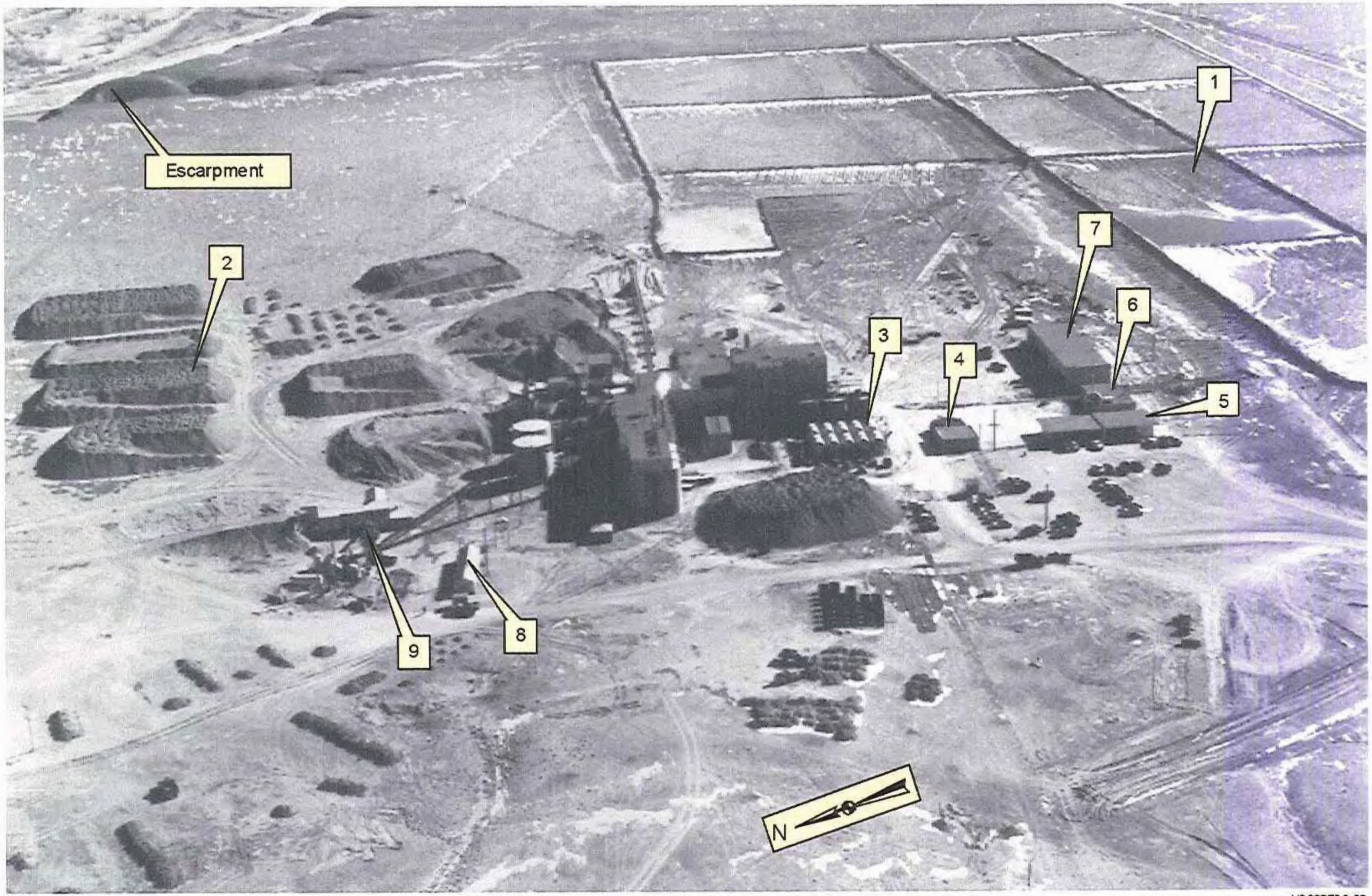

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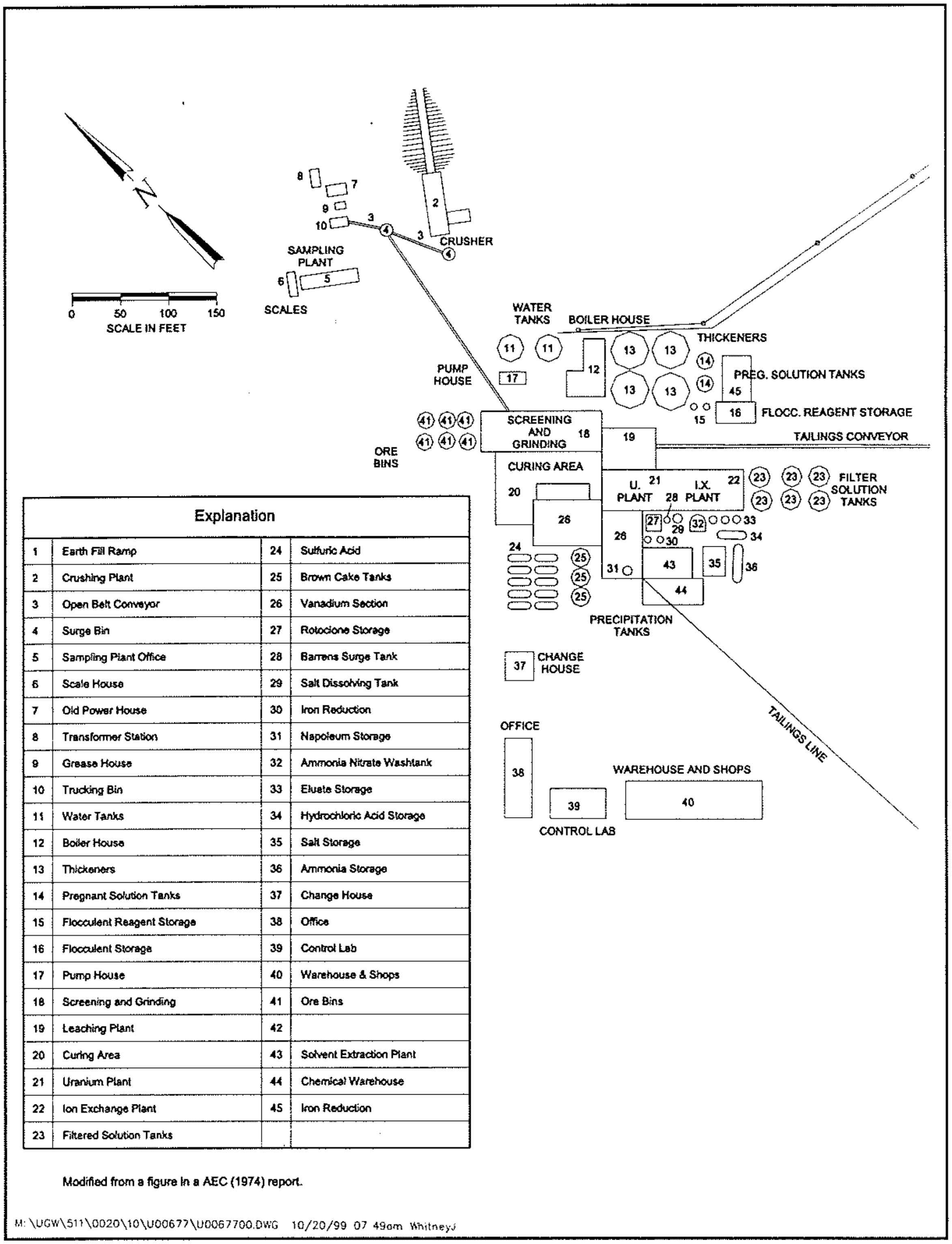
Figure 3–2. Winter 1954 to 1955 View to the Southeast of the Navajo Mill



Explanation

1	Earth Fill Ramp	24	Sulfuric Acid
2	Crushing Plant	25	Brown Cake Tanks
3	Open Belt Conveyor	26	Vanadium Section
4	Surge Bin	27	Rotoclone Storage
5	Sampling Plant Office	28	Barrens Surge Tank
6	Scale House	29	Salt Dissolving Tank
7	Old Power House	30	Iron Reduction
8	Transformer Station	31	Napoleum Storage
9	Grease House	32	Ammonia Nitrate Washtank
10	Trucking Bin	33	Eluate Storage
11	Water Tanks	34	Hydrochloric Acid Storage
12	Boiler House	35	Salt Storage
13	Thickeners	36	Ammonia Storage
14	Pregnant Solution Tanks	37	Change House
15	Flocculent Reagent Storage	38	Office
16	Flocculent Storage	39	Control Lab
17	Pump House	40	Warehouse & Shops
18	Screening and Grinding	41	Ore Bins
19	Leaching Plant	42	
20	Curing Area	43	Solvent Extraction Plant
21	Uranium Plant	44	Chemical Warehouse
22	Ion Exchange Plant	45	Iron Reduction
23	Filtered Solution Tanks		

Modified from a figure in a AEC (1974) report.

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Figure 3–3. Schematic of Navajo Mill Buildings in 1957

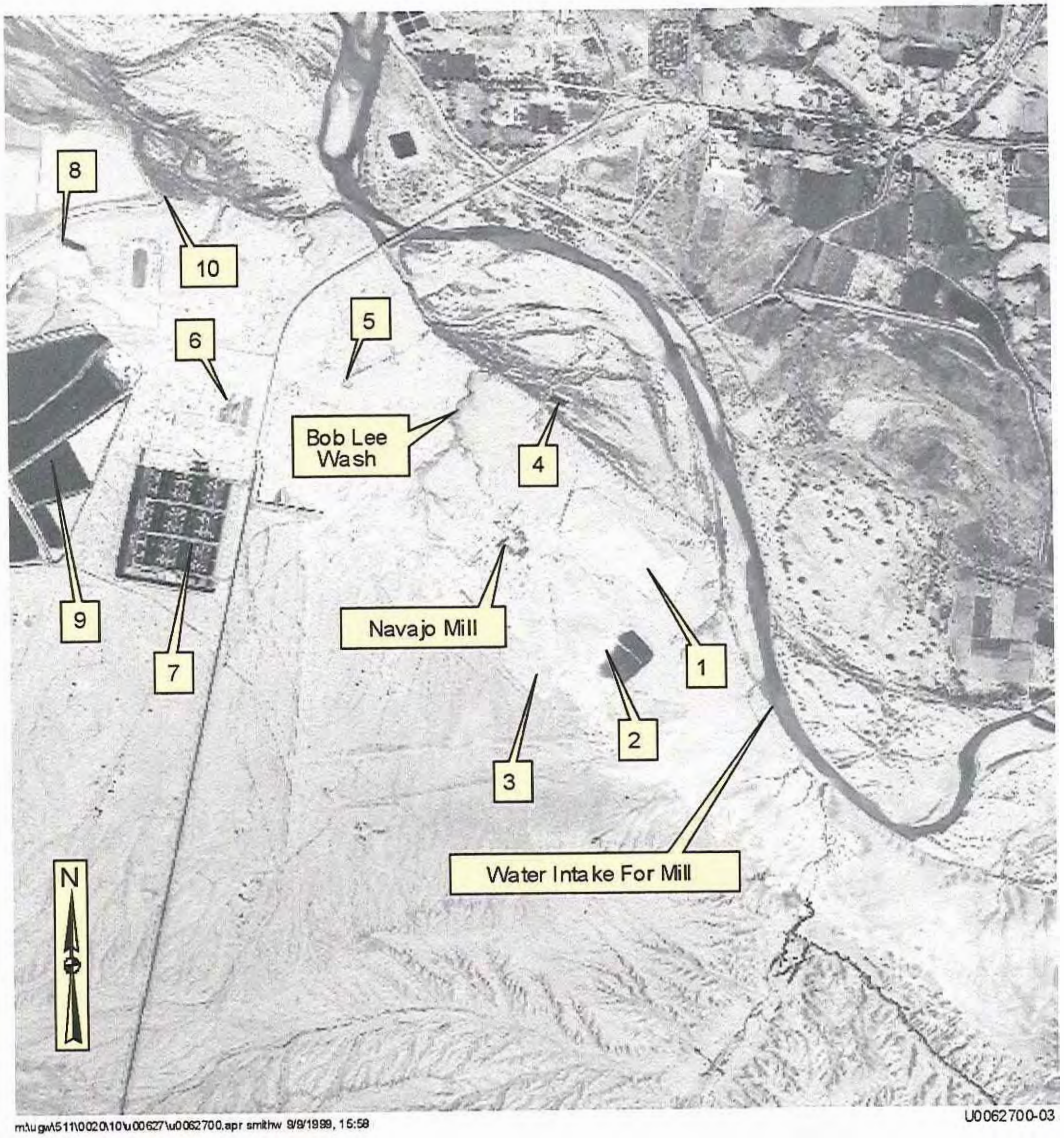

Figure 3–4. August 1962 View of Navajo Mill

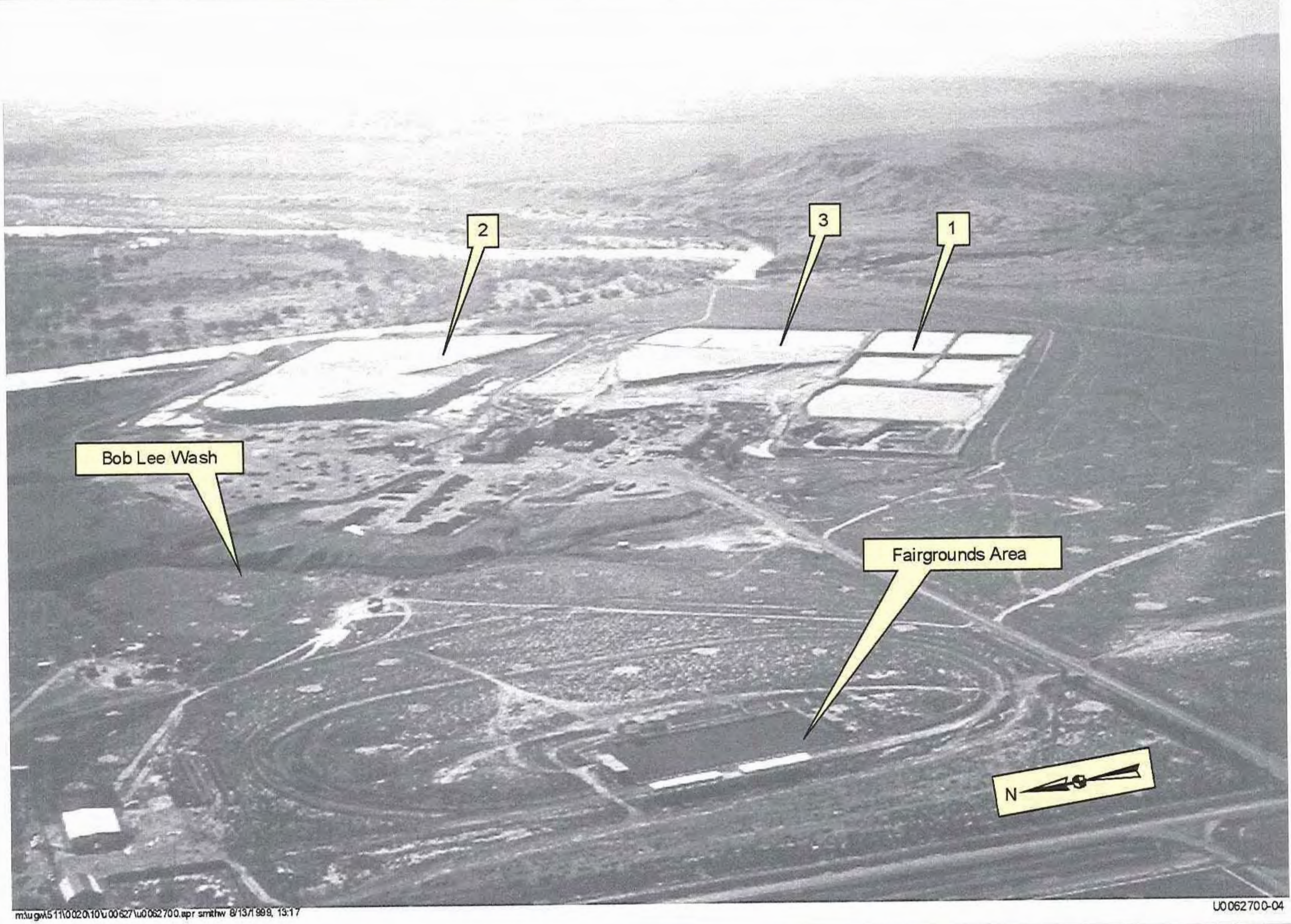

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Figure 3–5. July 1965 View Southeast of Navajo Mill Area

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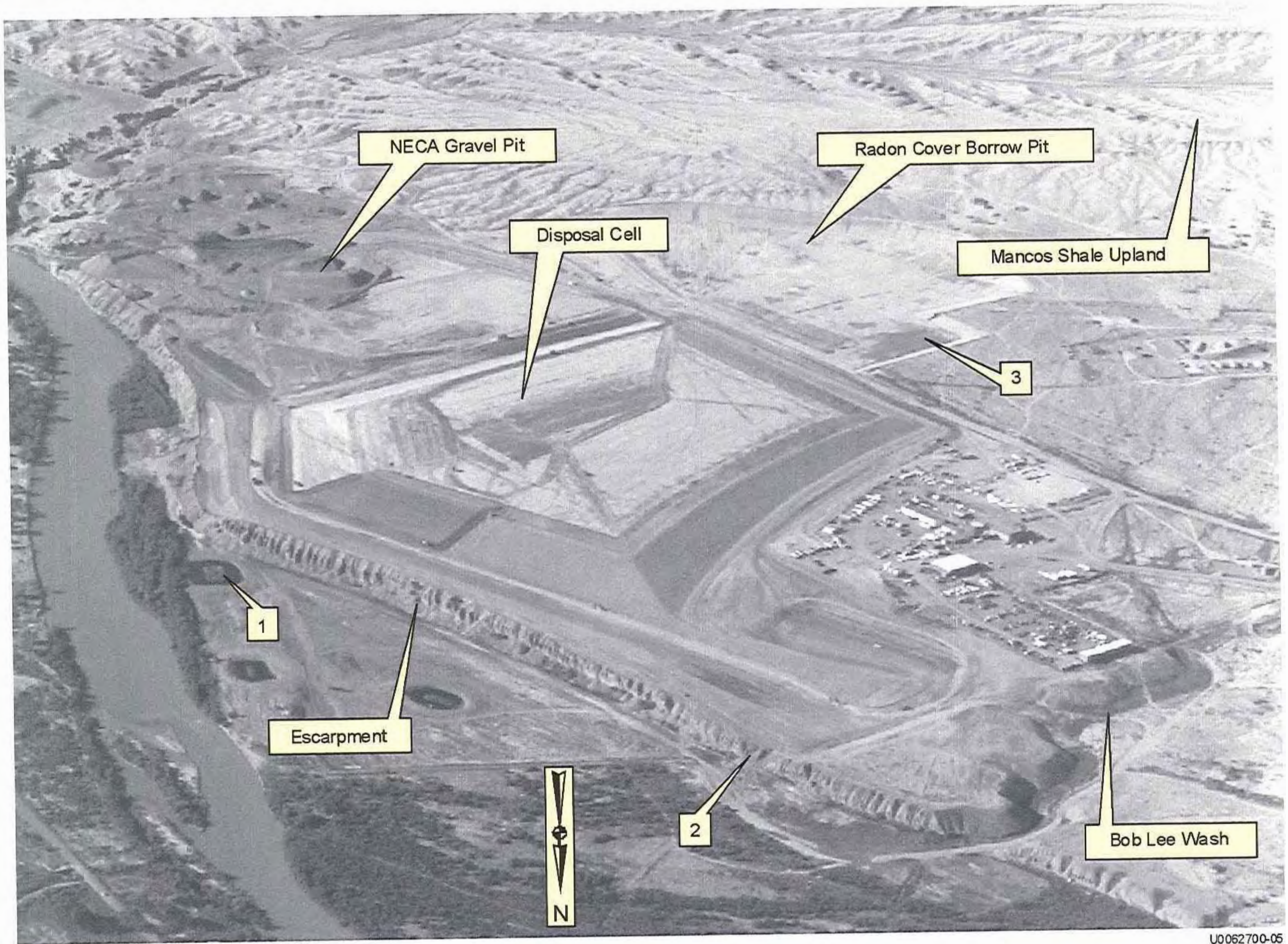

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Figure 3–6. July 1986 View Southeast of Millsite Remediation

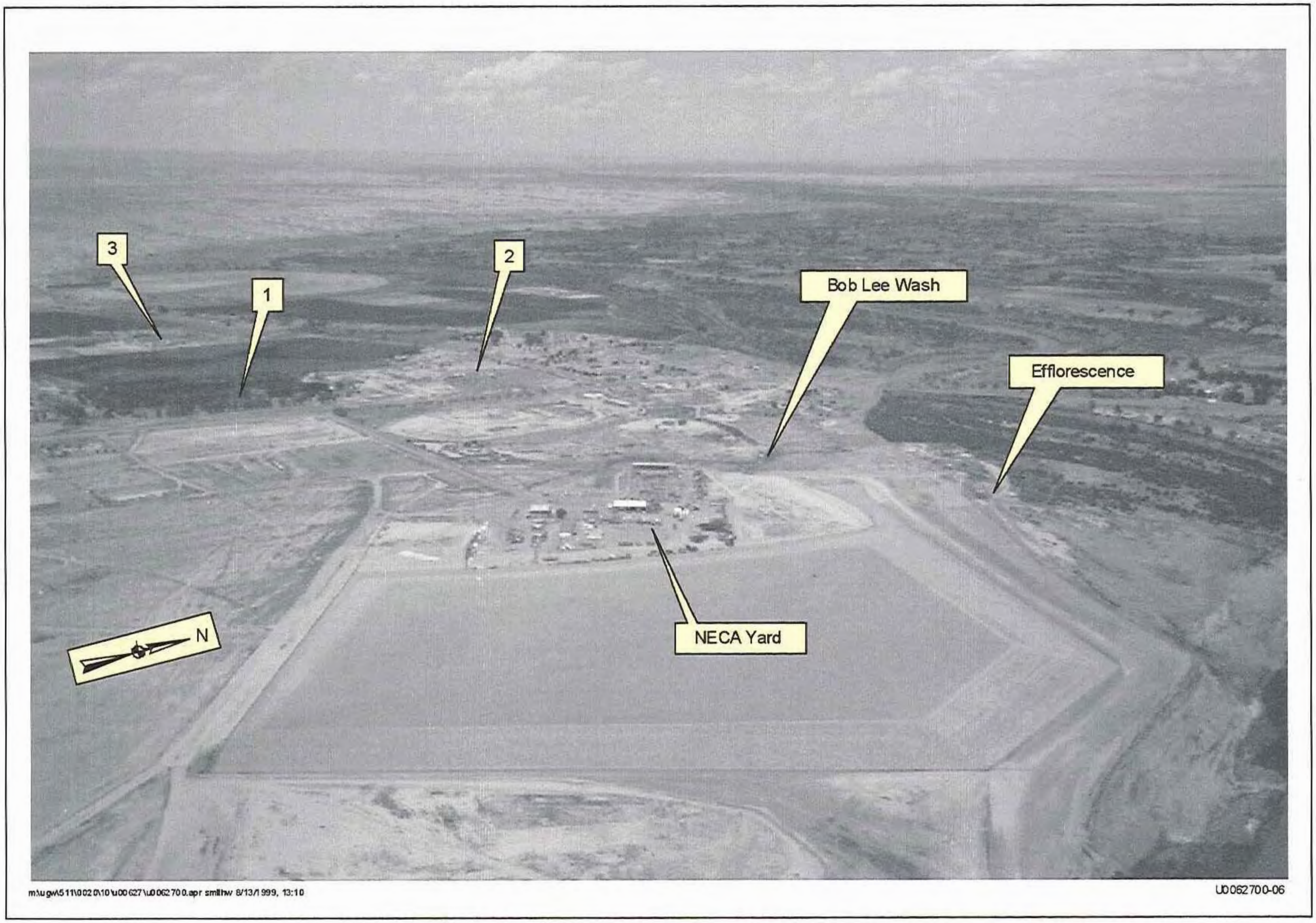

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Figure 3–7. Summer 1987 Oblique Aerial Photograph of Completed Disposal Cell—View Northwest

4.0 Site Characterization Results

The SOWP, Rev. 0 (DOE 1995), provided a summary of site conditions based on characterization data available at that time, presented a site conceptual model, identified likely compliance strategies, and proposed additional data collection activities to address uncertainties. Several of the proposed data collection activities were conducted at the site in early 1996 under the direction of the DOE Albuquerque Operations Office. Stakeholder review of the SOWP identified significant additional site characterization data needs. After programmatic responsibilities for the UMTRA Ground Water Project were transferred to DOE–GJO in late 1996, existing site characterization data were evaluated along with additional stakeholder concerns. To address the data gaps, additional characterization activities were identified and presented in the *Work Plan for Characterization Activities at the Shiprock UMTRA Project Site* (DOE 1998c). The principal goals of the additional data collection were (1) to investigate the extent of ground water contamination in the terrace system, (2) to evaluate the hydraulic interconnection between the terrace and alluvial ground water systems, (3) to evaluate the hydraulic interconnection between the alluvial ground water and the San Juan River, and (4) to select a corrective action for the site. Associated subjects of data deficiencies that needed to be addressed by additional characterization include (1) hydrogeologic properties of floodplain and terrace ground water systems, (2) further definition of nature and extent of contamination in the floodplain, (3) determination of background water quality in the floodplain and assessment (and quality) of ground water conditions at a terrace background site, (4) contribution of ground water from the upland area south of the site to the terrace system, and (5) evaluation of potential ecological risks.

Field investigations were conducted according to the Work Plan (DOE 1998c) from September 1998 through May 1999. The drilling and well installation part of the investigation extended from September to December 1998. Miscellaneous surface sampling and surveying investigations occurred generally from January to June 1999. The sequence of drilling field activities was approximately as follows: (1) coring and installation of monitor well nests, (2) installation of boreholes in upland Mancos Shale, (3) installation of monitor wells and boreholes to determine the extent of the contaminant plume in the terrace system, and (4) installation of monitor wells in the floodplain aquifer. Information from each of these drilling activities was integrated with existing data to continually revise the site conceptual model and to revise and refine the data collection needs. Surface activities that occurred throughout the span of field work (in no particular sequence) included ecological sampling and mapping; sediment, soil, and crust sampling; surface water sampling; geologic mapping; and land surveys of new and old wells and other features.

Results of additional characterization (and the methods used) conducted since the 1995 SOWP was completed are presented in the following subsections. The subsections include discussion and interpretation of the characterization results. These interpreted characterization results from the major disciplines are integrated and presented in Section 5, "Site Conceptual Model." Included in the following subsections are surveying results (Section 4.1, "Investigation Methods") and additional characterization needs (Section 4.7, "Summary of Additional Data Needs").

4.1 Investigation Methods

Field investigations were performed during 1998 and 1999. Investigation methods included subsurface drilling of test borings and well installation; collection of soil, rock core, soil crust, sediment, ecologic, ground water, and surface water samples; water level measurements; and aquifer testing. Methods used in the investigation are described in this section.

4.1.1 Drilling

The three drilling rigs used during the drilling project were a Schramm T–660W air rotary with casing driver, a CME–75 wireline, and a CME–55 all terrain drill. The Schramm drill was used to penetrate gravel and cobbles both on the terrace and in the floodplain areas, to drill the deep holes for well nests, and to drill deep holes in the upland area and the terrace background area. A casing hammer was used to drive casing through the gravel, and a center bit was advanced through the casing to remove cuttings from the hole. The CME–75 was used primarily for coring the Mancos Shale, and the CME–55 was used for drilling in loose-sand areas and for well development. Table 4–1 presents a summary of the tasks that were completed with each drilling rig. The drilling produced 49 new monitor wells, 3 new production wells, and 10 test borings.

Table 4–1. Summary of Tasks Completed With Each Drilling Rig

Task	Schramm T–660W	CME–75 Wireline	CME–55 All Terrain Drill
Test Borings	✓		
2-in. Monitor Wells	✓	✓	✓
5-in. Production Wells	✓		
Coring		✓	
Reaming	✓		
Packer Tests		✓	
Well Development			✓

4.1.2 Subsurface Sampling

Soil samples were collected during the drilling for lithologic descriptions and for geochemical tests and analyses; core samples were also collected for lithologic information and for selection of packer-test intervals from fracture data. During the air-rotary drilling, bulk samples were lifted to the ground surface with compressed air at 10-ft intervals and placed in plastic bags for archival, testing, and analyses. The CME–75 core samples were cut in 10-ft runs and retrieved using an NX wireline coring system. The core samples were placed in core boxes, labeled, and archived at the DOE-GJO core storage area. Coring was performed at holes 820, 823, 860, 862, and terrace-background holes 800 and 802 (Plates 1 and 3). Coring was attempted for approximately 360 ft of drilling; overall, core recovery was approximately 90 percent. Split samples of the core and soil samples were also retrieved for distribution coefficient (*Kd*) analyses. The coring was accomplished using the guidelines published in ASTM D 2113–83 (reapproved 1993).

4.1.3 Lithologic Logging

Samples of rock and soil material were described as they were collected. Descriptions of the soil and rock material were prepared on the basis of guidelines established in ASTM D 2488–93 and ASTM D 2487. Soil (Quaternary material) color was described on the basis of comparison to the Munsell Soil Color Charts (GretagMacbeth 1994) and color of bedrock and cored material was described using the Rock-Color Chart (GSA 1995). The lithologic logs are in Appendix A of this report.

4.1.4 Well Installation and Development

Well installation consisted of 49 new 2-in. monitor wells and three new 5-in. production wells. Wells in both the terrace alluvium and the floodplain alluvium were normally completed by drilling to the top of bedrock and advancing the borehole slightly into the bedrock. However, several new wells were also drilled without reaching bedrock. In those wells, the screen was installed at the desired depth and the annular space was backfilled while the drill string was extracted from the hole. Flush-joint polyvinyl chloride (PVC) was used for well casings, and well screen with 0.010-in. slots was installed. The only exception was well 819, which has a stainless steel screen to monitor for organic constituents in the ground water. Table 4–2 presents a summary of the pertinent well-completion information for all the wells at the Shiprock site. The well locations are plotted on Plate 1.

For nested wells in the Mancos Shale, nominal 2.5-ft screens were used to obtain discreet head measurements. Other monitor wells had longer screened intervals. Natural formation cave-in material was used as filter pack in wells drilled in the floodplain alluvium, and 20-40 fraction sand was used as the filter sand in most of the other borings. The technical approach to the well installation was based on ASTM D 5092–90 (reapproved 1995). Well completion diagrams are in Appendix A of this report.

Each new monitor well was allowed to sit undisturbed for at least 40 hours after final completion before it was developed. Development was performed according to the Work Plan (DOE 1998c).

4.1.5 Packer Tests

Packer tests are conducted in a borehole after the hole is cored and flushed with clear water. The method consists of lowering the testing apparatus into the borehole, inflating the packers so that they fit snugly against the wall of the borehole, and then injecting water under pressure into the test interval. The flow of water into the test interval is measured with a flow meter; the flow rate is measured as a function of the injection pressure. This test provides an estimate of the hydraulic conductivity of the rock formation.

Packer tests were performed on boreholes 820, 823, 860, and 862 (Plates 1 and 3). The tests began at the deepest part of the borehole and proceeded upward until representative parts of the formation were tested. The test intervals were selected on the basis of visual observations of the rock core retrieved from each borehole. Test intervals were chosen in highly fractured, moderately fractured, and unfractured rock; the test intervals were each 5 ft long. The diameter of the cored borehole was nominally 3 in. A gauge pressure of 40 pounds per square inch was used for the injection tests, and a test duration of 20 minutes was used whenever practicable.

Table 4–2. Construction Details for Monitor Wells at the Shiprock Site

Location Code	Install Date	North Coord. (ft State-Plane)	East Coord. (ft State-Plane)	Ground Elev. (ft NGVD)	Borehole Depth (ft BLS)	Borehole Diameter (in.)	Top of Casing Elevation (ft NGVD)	Well Depth (ft BLS)	Casing Diameter (in.)	Top of Screen Depth (ft BLS)	Screen Length (ft)	Top of Bedrock Depth (ft BLS)	Zone of Completion	Status
Wells Installed in 1998														
Floodplain (SHP01)														
850	10/1998	2098486.21	256685.04	4904.99	20.00	8.00	4907.51	15.60	2.0	5.60	9.80	19.00	AL	Active
851	10/1998	2098473.35	256679.18	4904.63	13.00	8.00	4906.45	12.30	2.0	6.00	5.00	-	AL	Active
852	10/1998	2098472.49	256707.25	4904.61	13.00	8.00	4907.37	12.60	2.0	6.40	5.00	-	AL	Active
853	10/1998	2102501.58	251196.38	4888.81	16.50	8.00	4891.41	15.30	2.0	10.00	5.00	16.00	AL	Active
854	10/1998	2103848.58	250820.77	4888.35	13.00	8.00	4890.75	11.80	2.0	9.10	2.50	-	AL	Active
855	10/1998	2103849.57	249057.21	4885.59	17.80	8.00	4888.18	15.10	2.0	4.90	10.00	17.60	AL	Active
856	10/1998	2104395.65	249110.63	4884.83	24.50	8.00	4887.57	24.10	2.0	18.80	5.00	24.00	AL	Active
857	10/1998	2103029.83	251160.35	4891.61	19.20	8.00	4894.02	18.50	2.0	13.20	5.00	19.00	AL	Active
858	09/1998	2101963.30	251540.03	4891.38	25.30	8.75	4893.50	20.60	5.0	10.20	10.00	21.00	AL	Active
859	09/1998	2101971.57	251528.87	4891.37	24.50	8.75	4893.68	19.90	2.0	14.50	5.00	21.00	AL	Active
860	10/1998	2102538.99	250576.01	4889.50	91.00	5.88	4892.28	87.24	2.0	85.57	1.50	14.00	KM	Active
861	11/1998	2102546.90	250570.59	4889.80	138.50	5.88	4891.32	138.35	2.0	135.50	2.50	14.00	KM	Active
862	11/1998	2101451.27	251713.33	4890.73	91.80	5.88	4893.83	91.57	2.0	88.90	2.50	8.50	KM	Active
863	11/1998	2101459.13	251711.10	4890.85	137.70	5.88	4893.00	137.70	2.0	135.10	2.50	8.50	KM	Active
Terrace (SHP02)														
800	09/1998	2097118.68	261458.17	4993.14	65.00	8.75	4995.76	62.46	2.0	52.30	10.00	14.00	KM	Active
801	11/1998	2096236.35	260359.85	4993.22	68.00	8.25	4995.29	65.00	2.0	54.80	10.00	16.00	KM	Active
802	09/1998	2096472.78	259469.34	4992.80	65.00	8.75	4996.01	61.56	2.0	51.40	10.00	20.00	KM	Active
803	11/1998	2097915.13	261956.47	4992.10	68.00	8.25	4994.40	65.00	2.0	55.00	9.80	15.00	KM	Active
804	10/1998	2098659.62	252260.86	4934.73	70.50	5.88	4936.93	70.00	2.0	59.80	10.00	24.00	KM	Active
805	10/1998	2097803.99	252157.62	4950.34	50.90	5.88	4953.14	49.90	2.0	39.70	10.00	3.50	KM	Active
810	09/1998	2095925.14	247626.49	5050.27	100.00	5.88	5049.58	90.00	2.0	79.90	10.00	28.00	KM	Active
812	10/1998	2098339.51	248308.83	5002.16	61.50	5.88	5004.98	61.50	2.0	51.30	10.00	55.00	AL-KM	Active
813	10/1998	2099346.57	248023.06	4984.52	51.00	5.88	4984.37	51.00	2.0	40.80	10.00	47.00	AL-KM	Active
814	11/1998	2100474.01	247414.84	4968.37	36.50	5.88	4968.12	34.00	2.0	23.80	10.00	29.00	AL-KM	Active
815	11/1998	2101610.39	247426.75	4953.79	36.00	5.88	4953.67	32.50	2.0	22.30	10.00	27.00	AL-KM	Active
816	11/1998	2103511.60	247952.70	4935.37	31.00	5.88	4937.92	25.30	2.0	20.10	5.00	23.00	AL-KM	Active
817	10/1998	2100885.97	249770.34	4957.77	36.00	8.88	4957.34	32.00	5.0	21.60	10.02	12.00	KM	Active
818	10/1998	2098534.26	249199.65	4995.40	64.50	8.88	4998.25	62.00	5.0	52.00	9.50	62.00	AL	Active
819	10/1998	2101176.66	249753.77	4956.42	31.20	5.88	4955.76	26.00	2.0	15.67	10.00	12.00	KM	Active
820	11/1998	2102191.62	250374.05	4954.14	153.00	5.88	4954.95	151.89	2.0	149.00	2.50	12.00	KM	Active
821	11/1998	2102200.62	250370.62	4954.21	104.00	5.88	4955.46	101.89	2.0	99.00	2.50	12.00	KM	Active
822	11/1998	2102192.54	250363.65	4953.85	205.00	5.88	4954.42	201.66	2.0	199.00	2.50	12.00	KM	Active

Table 4-2. (continued). Construction Details for Monitor Wells at the Shiprock Site

Location Code	Install Date	North Coord. (ft State-Plane)	East Coord. (ft State-Plane)	Ground Elev. (ft NGVD)	Borehole Depth (ft BLS)	Borehole Diameter (in.)	Top of Casing Elevation (ft NGVD)	Well Depth (ft BLS)	Casing Diameter (in.)	Top of Screen Depth (ft BLS)	Screen Length (ft)	Top of Bedrock Depth (ft BLS)	Zone of Completion	Status
823	09/1998	2101289.48	251528.73	4956.53	122.00	5.88	4957.65	100.34	2.0	97.45	2.50	26.00	KM	Active
824	10/1998	2101288.61	251538.80	4956.75	201.10	5.88	4958.21	201.10	2.0	198.50	2.50	24.00	KM	Active
825	10/1998	2101298.38	251534.90	4956.94	151.00	5.88	4958.68	150.45	2.0	147.79	2.44	27.00	KM	Active
826	10/1998	2101938.33	249596.17	4948.09	31.00	5.88	4950.73	20.17	2.0	10.00	10.00	12.00	AL-KM	Active
827	11/1998	2102444.90	249873.25	4943.91	31.30	5.88	4946.92	30.03	2.0	19.90	10.00	22.00	AL-KM	Active
828	10/1998	2101524.12	249145.90	4946.67	41.00	5.88	4949.34	15.47	2.0	5.30	10.00	7.00	AL-KM	Active
829	10/1998	2102758.77	249544.67	4939.54	62.00	5.88	4941.94	50.20	2.0	40.00	10.00	16.00	KM	Active
830	11/1998	2099901.80	251233.69	4957.75	23.50	5.88	4960.77	17.80	2.0	7.70	10.00	9.00	KM	Active
832	11/1998	2100815.04	245788.84	4964.91	37.00	5.88	4964.65	31.30	2.0	21.10	10.00	28.00	AL-KM	Active
833	12/1998	2102760.52	245623.02	4938.15	41.00	5.88	4940.52	35.00	2.0	24.90	10.00	35.00	AL	Active
835	12/1998	2104159.66	246020.38	4927.75	35.50	5.88	4930.48	32.00	2.0	21.90	10.00	32.00	AL	Active
836	12/1998	2103969.34	241957.93	4898.74	43.00	5.88	4901.74	36.90	2.0	26.80	10.00	37.00	AL	Active
837	12/1998	2105185.63	243678.55	4886.45	32.00	5.88	4889.54	27.20	2.0	17.00	10.10	27.00	AL	Active
838	12/1998	2102498.85	244738.77	4934.66	39.00	5.88	4937.70	32.00	2.0	21.90	10.00	32.00	AL	Active
839	11/1998	2102521.32	247357.45	4943.46	31.00	5.88	4943.21	28.30	2.0	18.10	10.00	27.00	AL-KM	Active
841	11/1998	2099895.06	246000.03	4981.43	57.00	5.88	4984.05	52.20	2.0	42.00	10.00	50.00	AL	Active
843	12/1998	2105743.99	244999.74	4880.60	30.00	5.88	4883.56	22.00	2.0	11.90	10.00	21.50	AL	Active
844	11/1998	2102036.39	246001.56	4948.66	43.00	5.88	4948.46	40.20	2.0	30.00	10.00	34.00	AL-KM	Active
845	11/1998	2100877.91	245146.72	4965.87	28.50	8.00	4969.20	28.33	2.0	18.17	10.00	-	AL	Active
846	12/1998	2102475.12	242268.43	4931.75	32.00	5.88	4934.57	28.00	2.0	17.90	10.00	25.00	AL-KM	Active
Wells Installed Before 1998														
Floodplain (SHP01)														
601	09/1984	2103195.24	251150.35	4890.00	6.00	-	4890.00	3.58	1.25	0.35	2.92	-	AL	Abandoned
602	09/1984	2102936.86	250749.31	4890.00	7.00	-	4890.00	3.58	1.25	0.35	2.92	-	AL	Abandoned
603	09/1984	2103099.48	250099.96	4888.00	5.00	-	4888.00	3.58	1.25	1.35	1.92	-	AL	Abandoned
604	09/1984	2103521.29	249651.66	4888.00	6.00	-	4888.00	3.58	1.25	0.35	2.92	-	AL	Abandoned
606	10/1984	2103248.20	249451.05	4887.67	5.30	-	4888.57	3.58	1.25	0.93	2.30	-	AL	Abandoned
607	10/1984	2102958.88	250249.39	4888.00	6.60	-	4890.00	3.58	1.25	0.93	2.30	-	AL	Abandoned
608	08/1985	2101434.90	251712.60	4891.67	19.00	8.75	4893.35	17.00	4.0	10.00	5.00	10.00	KM	Active
609	08/1985	2101450.00	251704.90	4890.97	14.00	8.75	4892.46	10.80	4.0	3.80	5.00	8.00	AL	Active
610	09/1985	2101686.70	251334.80	4892.58	15.00	8.75	4895.72	11.00	4.0	4.00	5.00	13.00	AL	Active
611	09/1985	2101693.10	251324.10	4892.51	22.00	8.75	4895.62	16.25	4.0	9.50	5.00	13.00	AL-KM	Active
612	09/1985	2101985.40	251560.90	4891.91	15.00	8.75	4893.35	12.00	4.0	5.00	5.00	14.50	AL	Active
613	09/1985	2101991.70	250943.70	4889.92	15.00	8.75	4893.19	12.00	4.0	5.00	5.00	14.00	AL	Active
614	09/1985	2101985.30	250953.10	4890.30	19.00	8.75	4892.79	17.00	4.0	10.00	5.00	14.00	AL-KM	Active
615	09/1985	2102542.20	250564.50	4890.83	14.00	8.75	4892.23	11.50	4.0	4.50	5.00	13.00	AL	Active
616	09/1985	2103009.00	251039.90	4890.28	14.00	8.75	4891.90	12.00	4.0	5.00	5.00	-	AL	Active

Table 4-2. (continued). Construction Details for Monitor Wells at the Shiprock Site

Location Code	Install Date	North Coord. (ft State-Plane)	East Coord. (ft State-Plane)	Ground Elev. (ft NGVD)	Borehole Depth (ft BLS)	Borehole Diameter (in.)	*Top of* Casing Elevation (ft NGVD)	Well Depth (ft BLS)	Casing Diameter (in.)	*Top of* Screen Depth (ft BLS)	Screen Length (ft)	*Top of* Bedrock Depth (ft BLS)	Zone of Completion	Status
617	09/1985	2102937.10	250761.10	4890.05	20.00	8.75	4891.90	12.00	4.0	5.00	5.00	19.80	AL	Active
618	09/1985	2102934.40	250748.50	4889.87	21.00	8.75	4891.51	18.00	4.0	11.00	5.00	20.00	AL	Active
619	09/1985	2103321.90	250401.90	4890.42	20.00	8.75	4892.19	15.00	4.0	8.00	5.00	18.00	AL	Active
620	08/1985	2102960.70	250243.10	4888.18	23.00	8.75	4889.72	20.00	4.0	13.00	5.00	17.00	AL-KM	Active
621	08/1985	2102960.10	250252.90	4888.33	19.00	8.75	4890.20	17.00	4.0	10.00	5.00	16.50	AL	Active
622	08/1985	2102958.90	250263.60	4888.51	16.00	8.75	4890.06	12.00	4.0	5.00	5.00	-	AL	Active
623	09/1985	2103409.00	250256.70	4889.27	23.00	8.75	4891.19	17.00	4.0	10.00	5.00	17.00	AL	Active
624	09/1985	2103396.90	250252.70	4889.29	24.00	8.75	4891.49	22.00	4.0	15.00	5.00	18.00	AL-KM	Active
625	09/1985	2103384.90	250249.60	4889.28	17.00	8.75	4891.23	11.50	4.0	4.50	5.00	-	AL	Active
626	09/1985	2103324.50	249941.40	4888.48	20.00	8.75	4891.40	16.50	4.0	9.50	5.00	19.00	AL	Active
627	09/1985	2103526.80	249650.70	4887.48	20.00	8.75	4889.41	15.00	4.0	8.00	5.00	17.00	AL	Active
628	09/1985	2103517.40	249660.30	4887.84	15.00	8.75	4889.87	12.00	4.0	6.00	4.00	-	AL	Active
629	09/1985	2103359.80	249378.70	4887.29	20.00	8.75	4887.49	17.00	4.0	10.00	5.00	13.00	AL-KM	Active
630	09/1985	2103349.40	249382.80	4887.65	15.00	8.75	4887.62	12.00	4.0	5.00	5.00	13.00	AL	Active
631	09/1985	2105158.20	249038.60	4888.21	23.00	8.75	4889.95	20.00	4.0	13.00	5.00	20.00	AL	Active
632	09/1985	2105146.80	249045.10	4888.17	20.00	8.75	4890.01	15.00	4.0	8.00	5.00	19.00	AL	Active
634	09/1985	2102727.63	252113.40	4896.20	24.00	-	4896.90	24.00	-	0.00	24.00	-	AL	Active
635	09/1985	2103503.93	251674.62	4893.01	12.00	-	4895.01	12.00	-	0.00	12.00	-	AL	Active
638	03/1987	2104780.10	248983.91	4882.17	5.00	-	4884.37	5.00	2.0	0.00	5.00	-	AL	Abandoned
639	03/1987	2104782.81	249952.79	4889.00	5.00	10.00	4890.07	5.00	8.0	0.00	5.00	-	AL	Active
640	03/1987	2104446.71	248636.45	4881.37	5.00	-	4883.97	5.00	2.0	0.00	5.00	-	AL	Abandoned
641	03/1987	2103910.58	249690.43	4884.21	5.00	-	4887.41	5.00	2.0	0.00	5.00	-	AL	Abandoned
642	03/1987	2104375.10	249931.82	4883.87	5.00	-	4886.37	5.00	2.0	0.00	5.00	-	AL	Abandoned
643	03/1987	2104440.83	249162.13	4882.73	5.00	-	4885.63	5.00	2.0	0.00	5.00	-	AL	Abandoned
644	03/1987	2104136.15	250519.01	4884.97	5.00	-	4886.96	5.00	2.0	0.00	5.00	-	AL	Abandoned
645	03/1987	2100670.51	252104.62	4898.70	5.00	-	4901.30	5.00	2.0	0.00	5.00	-	AL	Abandoned
646	03/1987	2100610.00	252118.00	4898.63	5.00	-	4902.33	5.00	2.0	0.00	5.00	-	AL	Abandoned
647	03/1987	2100547.36	252118.53	4898.02	5.00	-	4902.32	5.00	2.0	0.00	5.00	-	AL	Abandoned
670	01/1988	2104550.07	250560.69	4889.22	11.05	-	4892.67	11.05	2.0	7.05	3.50	-	AL	Active
671	01/1988	2104418.59	250662.29	4889.49	10.90	-	4892.65	10.90	2.0	6.90	3.50	-	AL	Active
672	01/1988	2103823.00	251489.00	4891.50	10.88	-	4894.41	10.88	2.0	6.88	3.50	-	AL	Abandoned
732	03/1993	2099626.90	252632.80	4895.62	19.00	8.00	4897.55	19.00	2.0	7.00	10.00	12.00	AL-KM	Active
733	03/1993	2104885.20	249564.20	4887.78	15.00	6.00	4889.67	13.50	2.0	6.50	5.00	-	AL	Active
734	03/1993	2104505.10	248608.50	4886.00	7.00	2.00	4886.55	7.00	2.0	2.00	2.00	-	AL	Active
735	03/1993	2099904.10	252193.70	4894.53	9.00	6.00	4895.85	9.00	4.0	3.00	5.00	-	AL	Active
736	03/1993	2104420.60	249808.00	4887.20	7.00	2.00	4887.99	7.00	2.0	3.00	2.00	-	AL	Active

Table 4-2. (continued). Construction Details for Monitor Wells at the Shiprock Site

Location Code	Install Date	North Coord. (ft State-Plane)	East Coord. (ft State-Plane)	Ground Elev. (ft NGVD)	Borehole Depth (ft BLS)	Borehole Diameter (in.)	Top of Casing Elevation (ft NGVD)	Well Depth (ft BLS)	Casing Diameter (in.)	Top of Screen Depth (ft BLS)	Screen Length (ft)	Top of Bedrock Depth (ft BLS)	Zone of Completion	Status
Terrace (SHP02)														
600	01/1982	2102012.70	250674.90	4955.45	62.70	6.75	4955.87	48.80	4.0	29.00	19.80	13.80	KM	Active
601	06/1983	2099020.00	250616.00	4981.24	50.00	6.00	-	45.30	2.0	30.30	10.00	37.00	AL-KM	Abandoned
602	12/1981	2100887.60	249786.10	4957.89	96.70	6.75	4956.89	47.00	4.0	27.00	20.00	9.50	KM	Active
603	06/1983	2098739.30	251190.00	4977.61	42.00	6.00	4978.62	40.90	2.0	25.90	10.00	31.00	AL-KM	Active
604	05/1983	2098538.60	249217.00	4995.43	80.00	6.00	4995.87	77.70	2.0	62.70	10.00	58.00	KM	Active
605	10/1984	2102920.00	249219.00	4898.77	3.80	-	4898.77	3.58	1.25	0.93	2.30	-	AL	Abandoned
633	10/1985	2102392.61	249198.00	4915.99	3.42	5.88	4918.24	3.42	2.0	0.00	3.42	-	AL	Abandoned
648	02/1961	2102944.10	248019.40	4940.18	1850.00	12.00	4943.80	1850.00	12.0	1482.00	295.00	30.00	JM	Active
725	03/1993	2103010.20	249192.20	4906.29	20.00	6.00	4908.58	19.50	2.0	7.50	10.00	16.00	AL-KM	Active
726	03/1993	2102452.80	248972.60	4937.97	40.00	6.00	4939.95	39.20	2.0	27.20	10.00	9.00	KM	Active
727	03/1993	2101721.10	248674.50	4938.52	19.00	6.00	4940.65	18.70	2.0	6.70	10.00	6.50	KM	Active
728	03/1993	2100541.90	248356.20	4962.55	30.00	6.00	4964.46	29.00	2.0	17.00	10.00	23.00	AL-KM	Active
730	03/1993	2099429.90	249494.90	4977.81	40.00	6.00	4979.74	39.00	2.0	27.00	10.00	33.00	AL-KM	Active
731	03/1993	2098278.20	251390.40	4970.15	29.00	6.00	4972.15	29.00	2.0	17.00	10.00	23.00	AL-KM	Active
9003	01/1982	2100683.39	251603.22	4955.80	53.70	6.75	-	30.00	4.0	15.00	15.00	4.50	KM	Abandoned
9004	01/1981	2100403.17	250914.08	4970.60	47.60	6.75	-	29.40	4.0	25.40	4.00	27.00	AL-KM	Abandoned
9005	02/1982	2100373.08	250936.96	4970.00	87.40	6.75	-	56.00	4.0	35.00	19.00	29.40	KM	Abandoned
9006	12/1981	2101071.21	250410.78	4968.00	85.30	6.75	--	54.00	4.0	44.00	10.00	19.00	KM	Abandoned
9007	12/1981	2099416.57	250814.10	4973.50	92.50	6.75	-	48.00	4.0	29.00	19.00	24.00	KM-AL	Abandoned
9008	02/1982	2100285.75	249283.60	4966.70	87.60	6.75	-	64.00	4.0	36.00	27.00	31.00	KM	Abandoned
9009	12/1982	2100217.58	249326.32	4966.80	47.70	6.75	-	45.00	2.0	27.00	13.00	23.50	KM-AL	Abandoned
9010	01/1982	2100428.55	250324.17	4985.00	74.25	6.75	-	65.00	4.0	45.00	20.00	33.00	KM	Abandoned
9011	01/1982	2101128.78	251012.01	4986.40	71.30	6.75	-	70.58	4.0	49.08	20.50	45.00	KM	Abandoned
9012	03/1982	2098851.33	249632.81	4989.20	85.00	6.75	-	84.67	4.0	54.33	30.34	44.00	KM	Abandoned
9013	05/1983	2102145.70	250174.21	4943.33	60.00	6.00	-	25.00	2.0	10.00	10.00	0.00	KM	Abandoned
9014	05/1983	2100104.96	251861.59	4962.90	60.00	6.00	-	38.00	2.0	23.00	10.00	18.00	KM	Abandoned
9015	05/1983	2099606.10	248675.35	4977.31	60.00	6.00	-	53.70	2.0	38.70	10.00	41.00	KM-AL	Abandoned
9016	06/1983	2098615.77	250779.82	4983.93	55.00	6.00	-	52.60	2.0	37.60	10.00	42.00	AL-KM	Abandoned
9017	06/1983	2099368.86	251287.21	4971.43	35.00	6.00	-	35.00	2.0	20.00	10.00	25.00	AL-KM	Abandoned
9018	06/1998	2098296.75	250955.20	4983.71	50.00	6.00	-	39.40	2.0	29.40	10.00	41.00	AL-KM	Abandoned
9019	06/1983	2099053.00	251494.48	4972.78	39.00	6.00	-	34.00	2.0	19.00	10.00	24.00	KM-AL	Abandoned
9020	01/1982	2100438.78	250269.22	4985.00	40.70	6.75	-	40.70	2.0	35.30	5.00	40.00	AL	Abandoned
DM7	01/1982	2099645.67	249944.02	4976.50	85.10	5.60	4974.50	54.00	4.0	38.00	15.00	29.00	KM	Active
MW1	-	2101488.51	251338.36	4956.91	-	-	4955.64	-	-	-	-	-	NR	Active

Zones Of Completion:
AL—Alluvium
JM—Morrison Formation, Westwater Canyon Member
KM—Mancos Shale
NR—No Recovery Of Data For Classifying

The depth to water was recorded before each sequence of tests in a borehole. All tests were performed below the water table. Computations of the hydraulic conductivity were made with the appropriate formulas (University of Missouri-Rolla 1981; U.S. Bureau of Reclamation 1974).

Each reported measurement was assumed to represent a constant flow rate averaged over the elapsed time increment. If the flow rate was so low that it could not be measured with the flow meter, the hydraulic conductivity result was assumed to be less than the detection limit, and the detection limit itself was reported. Raw data and computations of the hydraulic conductivity are presented in MACTEC calculation U0054800.

4.1.6 Water Level Measurements

Water level measurements provided information on ground water flow directions, saturated thickness of the aquifer, and temporal changes in water levels. Measurements were made with a commercially available, weighted, electrical measuring tape. All measurements were taken with respect to a fixed point at the top of each PVC well casing. Water level measurements were collected in all wells in December 1998 and March 1999 and are the basis of the water table maps presented in Section 4.3 of this report. Each measurement was made to the nearest 0.01 ft. Measurements of ground water began as early as 1984 for a subset of wells; these wells provide an opportunity to construct time series plots of ground water elevations. Manual measurements of the water levels were conducted using the guidance in the *Environmental Procedures Catalog*, LQ–2(T), "Standard Test Method for the Measurement of Water Levels in Ground Water Monitor Wells" (DOE 1998a).

Electronic data loggers in selected monitor wells provide continuous water level records for the site. The data are collected at 4-hour intervals and are obtained by programming the electronic data loggers and periodically downloading the data files. The data logger measurements began on February 5, 1999, and are collected each time the water sampling crew visits the site, approximately on a quarterly basis.

4.1.7 Ground Water Sampling and Analysis

After the wells were developed, ground water samples were collected from the new monitor well network and selected existing wells and were submitted to the GJO Analytical Chemistry Laboratory for analyses. Figure 4–1 presents the locations where the most recent water samples were collected.

Ground water sampling was performed in accordance with the *Addendum to the Sampling and Analysis Plan for the UMTRA Ground Water Project* (DOE 1996a) and the *Environmental Procedures Catalog* (DOE 1998a). The following specific procedures from the *Environmental Procedures Catalog* were used for ground water sampling:

- GN–8(P), "Standard Practice for Sample Labeling."
- GN–9(P), "Standard Practice for Chain-of-Sample-Custody and Physical Security of Samples."
- GN–13(P), "Standard Practice for Equipment Decontamination."

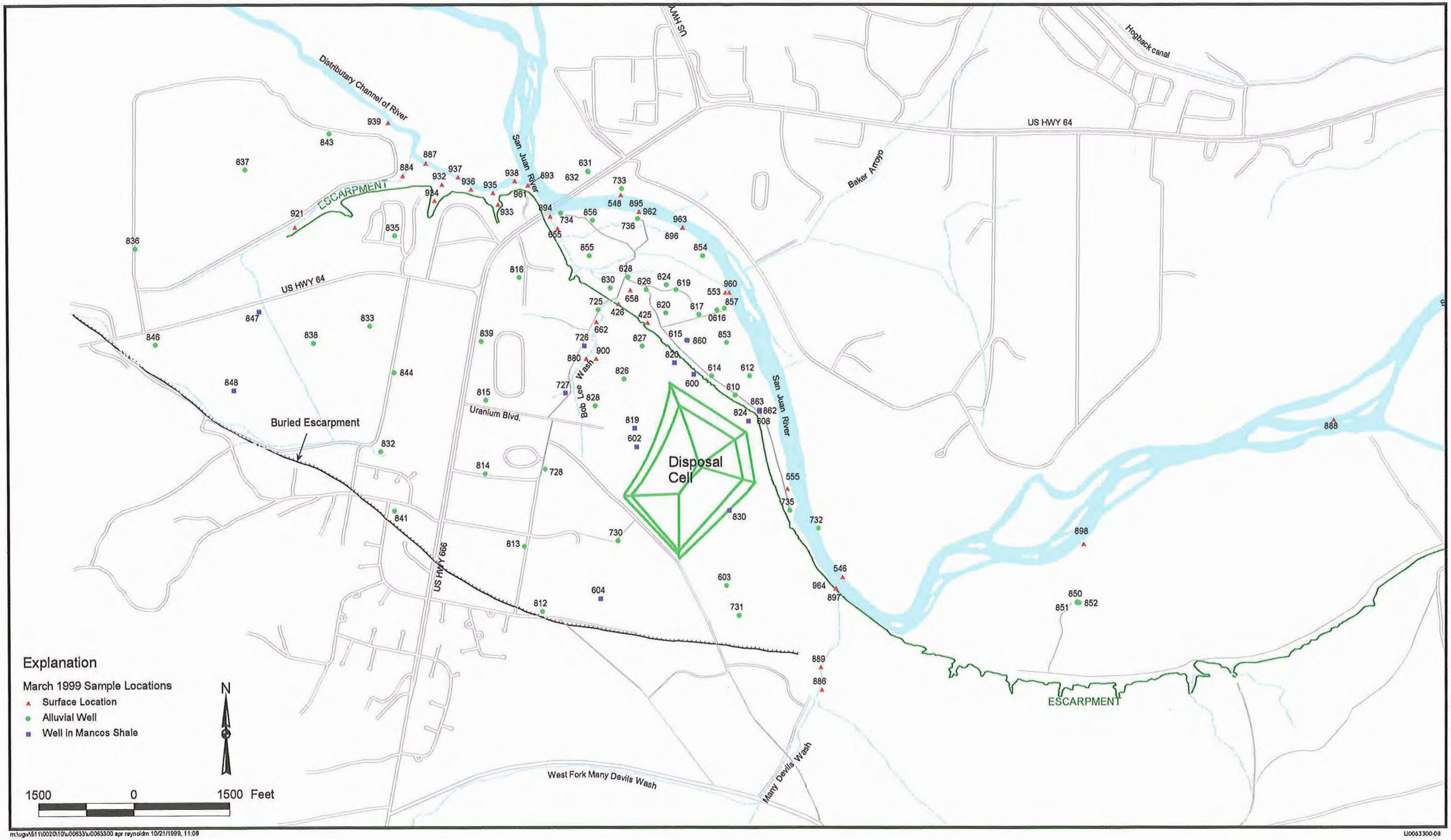

Figure 4–1. Ground Water and Surface Water Sampling Locations for Most Recent Sampling Event, Shiprock, New Mexico, UMTRA Site

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- LQ-3(P), "Standard Practice for Purging Monitor wells."
- LQ-11(P), "Standard Practice for Sampling Liquids."
- LQ-12(P), "Standard Practice for the Collection, Filtration, and Preservation of Liquid Samples."
- LQ-2(T), "Standard Test Method for the Measurement of Water Levels in Ground Water Monitor Wells."
- LQ-4(T), "Standard Test Method for the Field Measurement of pH."
- LQ-5(T), "Standard Test Method for the Field Measurement of Specific Conductance."
- LQ-6(T), "Standard Test Method for the Field Measurement of the Oxidation-Reduction Potential (Eh)."

4.1.8 Aquifer Tests

Aquifer tests were performed in each of the hydrostratigraphic units at the site. One aquifer test was completed in the floodplain alluvium and two tests were completed in the terrace unit. Figures 4–2 and 4–3 show the locations and well configurations, respectively, for the tests. Electronic data loggers were used to capture time and drawdown measurements. The captured data were transferred onto computer files using the software provided by the manufacturer of the data loggers. The data files were copied into Excel 97 spreadsheets and then copied into Aquifer$^{\text{Win32}}$ software (ESI 1999) for analysis and interpretation of the results. Detailed results and interpretation of the pumping test data are presented in MACTEC calculation U0064500. Section 4.3 presents plots of the drawdown-versus-time data for the pumping tests.

The pumping tests were analyzed using Neuman (1972), the Theis unconfined approximation, and the Theis recovery test methods (Theis 1935). These analysis methods are contained in the Aquifer$^{\text{Win32}}$ software package.

4.1.9 Surveying

Location and elevation surveying of key hydrogeologic features were performed in January 1999 and May 1999. All surveying was referenced to USBR BM R–11–L (brass cap, elevation of 4,939.70 ft; local coordinates of North 10,000, East 10,000). Specific hydrogeologic features that were surveyed include all active monitor wells (all monitor wells installed previously by others were resurveyed), surface water and soil sample locations, location and elevation of the San Juan River at various points, location and elevation of a siltstone bed in the Mancos Shale, location and elevation of all test borings drilled in 1998, and location and elevation of seeps and springs along the escarpment. Locations and selected elevations were measured using global positioning system (GPS) methods. Critical elevations, specifically top-of-well casing, were established by running a level loop from the USBR BM R–11–L. All survey locations and elevations were then transferred to the geographic information system (GIS) database at GJO where they are stored.

4.2 Geology

Bedrock underlying all the site area is the Late Cretaceous Mancos Shale that dips gently eastward. Unconsolidated Quaternary deposits consisting of terrace material, loess, and floodplain alluvium cover the bedrock in much of the area within 0.5 mi of the San Juan River. Detailed geologic maps of the site area have not been published; only small-scale geologic mapping by O'Sullivan and Beikman (1963) and Ward (1990) are available.

The Work Plan (DOE 1998c) presents summaries of the stratigraphy and structure of the site area as it was known from previous sources, namely the SOWP, Rev. 0 (DOE 1995), mapping of surficial material by Ward (1990), and geophysical surveys by DOE (1996c). Also identified in the Work Plan were geologic data needs, which, if provided, would improve the site conceptual model and refine the parameters necessary for use in ground water remediation. Data needs defined as tasks were (1) map the surface geology to identify the contact of weathered Mancos Shale bedrock and Quaternary material along the north side of the upland area, (2) measure the orientation and spacing of joints (fractures) in the escarpment where Mancos Shale is well exposed, (3) describe cuttings from proposed boreholes to improve the understanding of bedrock topography and thicknesses of overlying Quaternary geologic units, and (4) describe core from deep boreholes that penetrate into weathered and unweathered Mancos Shale to determine the degree of fracturing and the relative amounts of ground water. The results of these field investigations of 1998 and 1999 are discussed in Sections 4.2.1 through 4.2.4.

4.2.1 Geologic Mapping

The emphasis in geologic mapping of the site was to delineate the contact between the bedrock (Mancos Shale) and Quaternary material. This map, presented as Plate 2, does not distinguish weathered from unweathered Mancos Shale; however, Quaternary material is divided into four units. The location and orientation of joints in Mancos Shale were measured during the geologic mapping; Section 4.2.2 presents descriptions of these features. Also on the geologic map are lines showing the location of seven cross sections that are presented in Plate 3.

Mapping for much of the site area was done on a base map made by enlarging the USGS 7.5 minute (1:24,000 scale) Shiprock topographic map with a contour interval of 20 ft. For the central part of the site, including the millsite/disposal cell and floodplain just to the north, mapping was done on a 2-ft contour topographic base map at a scale of 1:2,400. This map was produced by Morrison-Knudsen Engineers in June 1987 after the disposal cell was completed. A base map covering the site and surrounding area at a scale of 1:2,400 and a contour interval of 2 ft is needed to map detailed geologic characteristics and other pertinent site features.

Descriptions of the surface features noted during mapping of the Mancos Shale and Quaternary units are presented in the following sections. Included are pertinent interpretations of these data as related to ground water hydrology of the site.

4.2.1.1 Mancos Shale

Drab gray to gray-tan exposures of Mancos Shale in the site area represent the upper part of this thick formation, deposited as an open marine mudstone in the Late Cretaceous Western Interior Seaway. Approximately 1,000 ft of the Mancos underlies the site. Most Mancos exposures in the

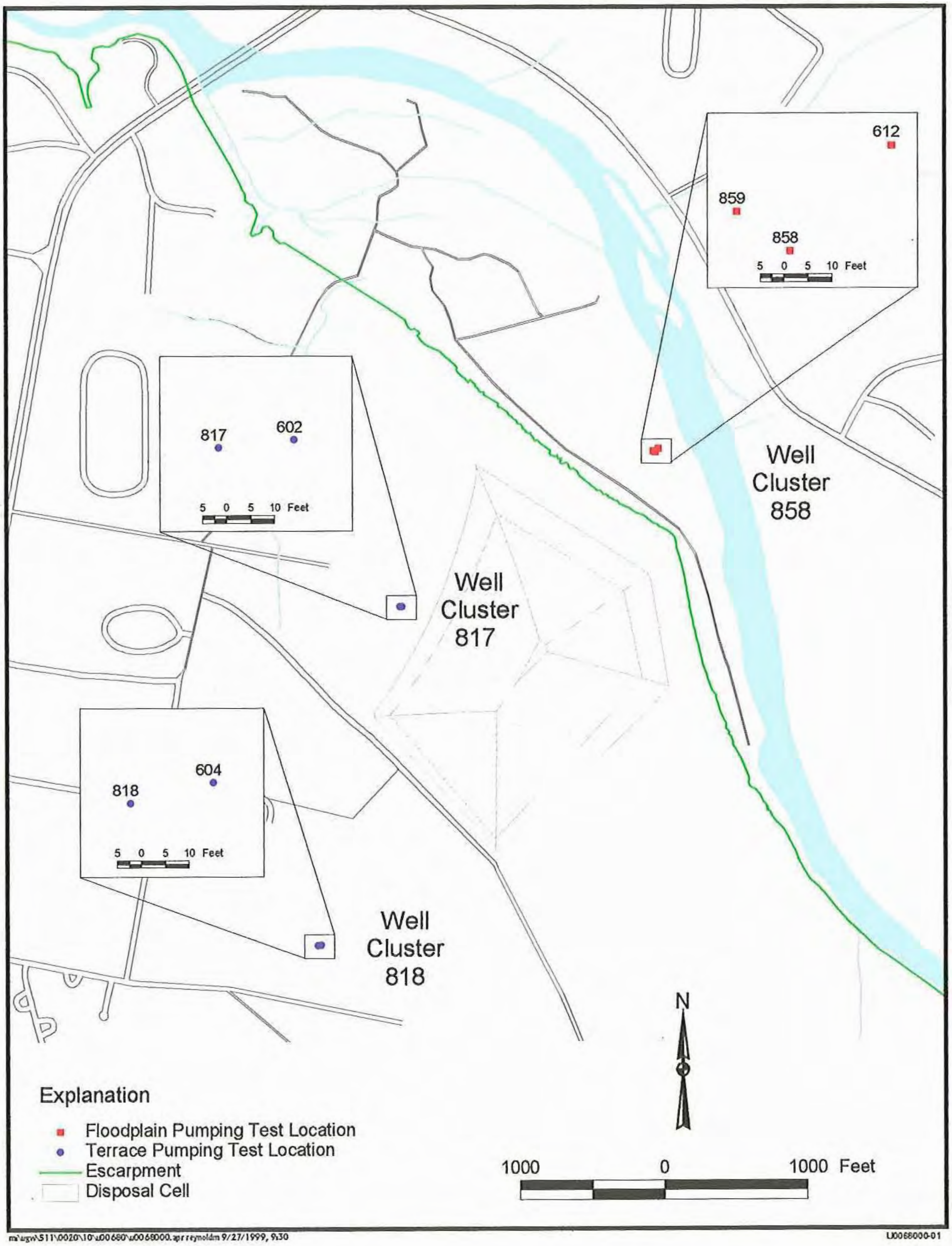

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Figure 4–2. Location Map of Pumping Tests Completed in the Floodplain Alluvial Aquifer and the Terrace Ground Water System, Shiprock, New Mexico, UMTRA Site

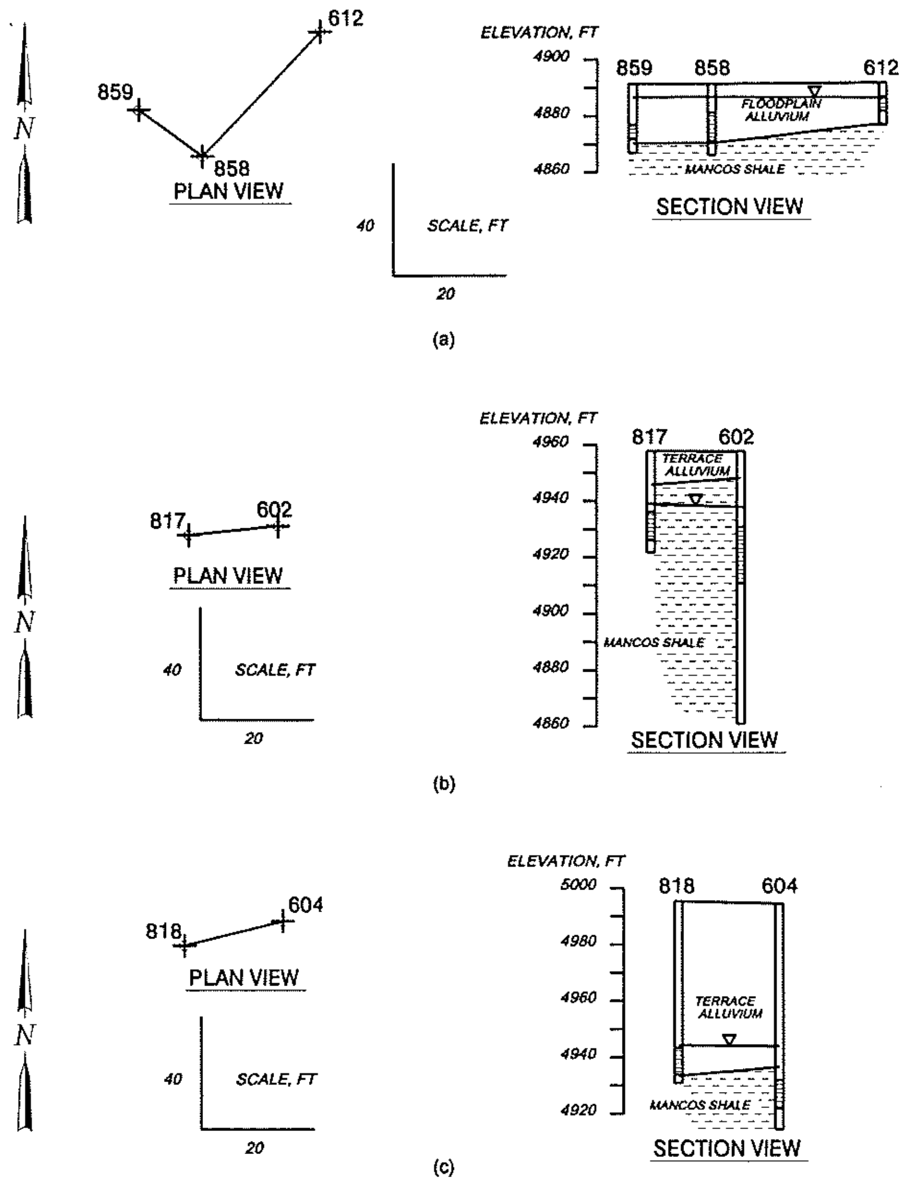

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Figure 4–3. Well Cluster Cross Sections for Pumping Tests at (a) the Floodplain Aquifer, (b) the Weathered Mancos Shale, and (c) the Terrace Alluvium at the Shiprock, New Mexico, UMTRA Site upland area and other areas of low relief are weathered and resemble colluvium. This weathered material is soft and bedding is only poorly to moderately exposed.

The 50- to 60-ft-high escarpment separating the San Juan River floodplain from the adjacent terrace contains the best Mancos Shale exposures in the site area. In several places, such as just upstream and downstream of the Many Devils Wash confluence with the San Juan River and downstream of the south end of the U.S. Highway 666 bridge, the escarpment plunges directly to the San Juan River. The shale exposed in the escarpment is well bedded and only slightly weathered. Another area of well-exposed Mancos Shale is along the lowermost 1,200 ft of Many Devils Wash, where the wash has incised its narrow channel up to 20 ft into the shale.

A continuous, distinctive, thin, tan- to orange-weathered, calcareous siltstone bed about 1 ft thick forms a marker bed in the Mancos Shale in part of the site area. The bed is exposed mainly in the escarpment cliff north and east of the disposal cell, starting from the area of seep 427 and extending southeastward along the San Juan River to about 1,000 ft east of the confluence of Many Devils Wash (Plate 2). The position of the siltstone bed on the escarpment drops in elevation gradually from its westernmost exposure to its easternmost exposure, indicating that the Mancos Shale dips easterly at a low angle. The same siltstone bed is exposed in the lower part of Many Devils Wash where it forms a nickpoint in the wash about 1,200 ft upstream from the confluence with the San Juan River. The determination was made that the siltstone bed in Many Devils Wash was the same as the bed exposed along the escarpment by following semicontinuous outcrops of the siltstone bed from the nickpoint downstream along the walls of the incised wash. Slight undulations and small breaks in the siltstone bed in places along the wash indicate that minor folding and fracturing are present in the wash area; the orientation of these structures may be parallel to the wash. Surveyed elevations of the top of the siltstone bed at various locations indicate by contouring (Figure 4–4) that the strike of the Mancos Shale in the site area is approximately north (varies from an azimuth of 000 to 355). The eastward dip of the Mancos flattens eastward across the site and varies from about 1° just north of the disposal cell to about 0.3° east of Many Devils Wash (Figure 4–4). For the contouring in Figure 4–4, greater certainty was given to the observable, surveyed siltstone bed locations than to the siltstone bed elevations derived from borehole lithologic logs.

Deposits of white salts (efflorescent crusts) of variable thickness are present in places on outcrops of Mancos Shale along the escarpment and in Many Devils Wash. Similar salt deposits are present on the surface in the Mancos Shale upland and other areas of low relief on the shale; however, these deposits occur as thin discontinuous veneers of powder. Thicker salt deposits that occur along the escarpment and in Many Devils Wash often cover the surface, are white with an occasional yellow tinge, and are up to 0.25 in. thick. The deposits form when water of high salt content evaporates and the salts precipitate on the surface. Salt deposits on the escarpment are thickest and most extensive where seeps occur. Salt deposits in Many Devils Wash occur on the wash bottom for several hundred feet above the siltstone bed nickpoint; below the nickpoint, salts are deposited along the wash bottom for most of the distance to the San Juan River and along the sides of the wash below the siltstone for several hundred feet below the nickpoint. The composition of the salt deposits is described in Section 4.3, "Geochemistry." Evangelou and others (1984) describe the efflorescence (salt deposits) that commonly occur naturally in the Mancos Shale as containing a mixture of calcium, sodium, and magnesium sulfate evaporite mineral species.

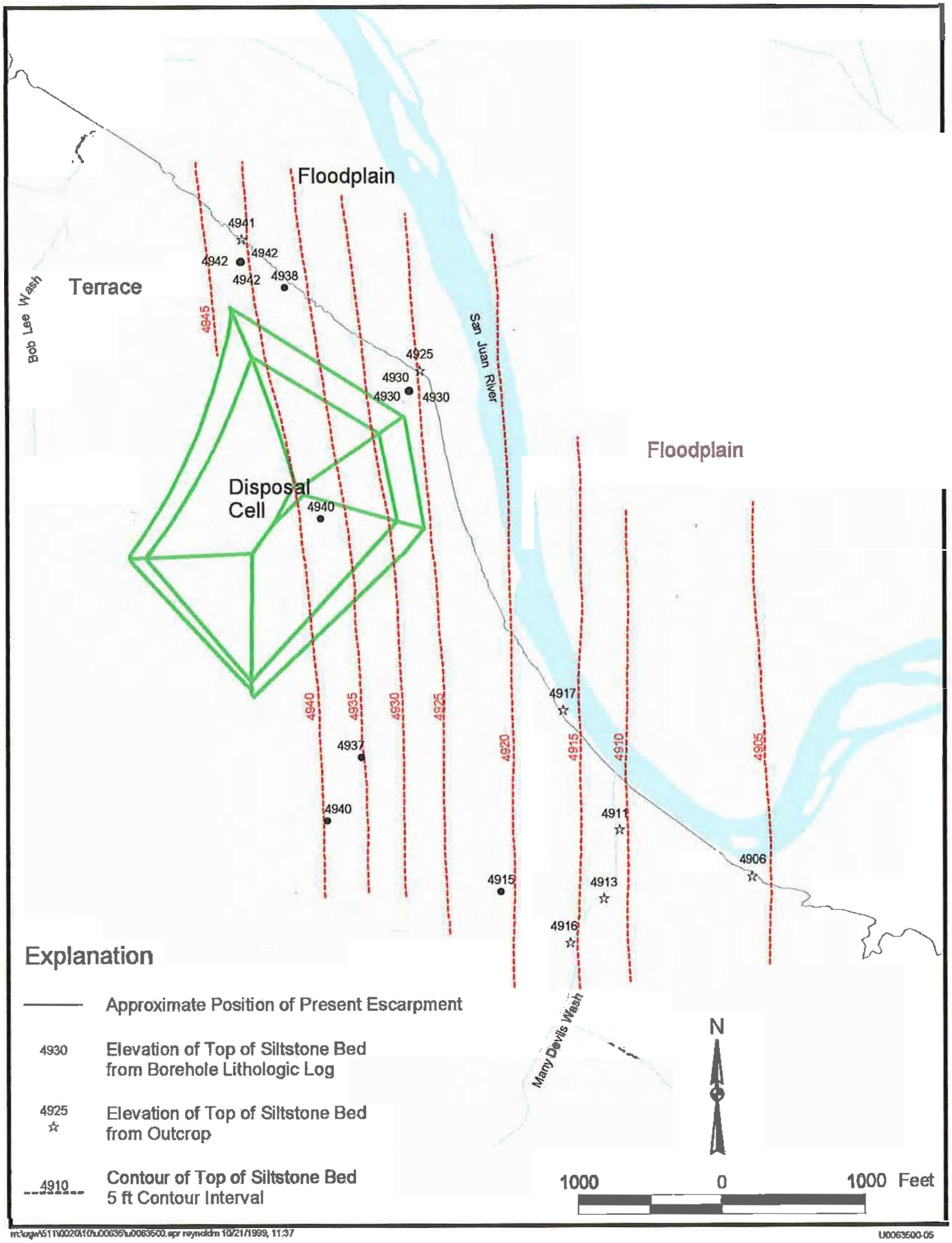


Figure 4–4. Contour Map of Top of Siltstone Bed in Mancos Shale

4.2.1.2 Quaternary Material

Unconsolidated Quaternary material was divided into four units for mapping: (1) terrace material deposited by the ancestral San Juan River about 240 ft above the present San Juan River, designated Qt2; (2) terrace material deposited by the ancestral San Juan River about 50 to 60 ft above the present San Juan River floodplain, designated Qt1; (3) sand deposited in the present San Juan River floodplain, designated Qfps; and (4) loess deposited mainly by wind over terrace material, Mancos Shale, and possibly floodplain material, designated Ql.

Older terrace material (Qt2) caps only one small mesa in the site area (Plate 2). This material, about 20 ft thick capping the mesa crossed by Navajo Road N5072, is outwash from a Pleistocene glacial episode in the San Juan Mountains. Ward (1990) mapped the material as Q5.

Terrace material mapped as Qt1 is extensive and forms a prominent surface approximately 50 to 60 ft above the present floodplain of the San Juan River. The terrace is continuous south of the river from the NECA gravel pit westward to the Shiprock High School area (Plate 2). Most of the town of Shiprock south of the San Juan River sits on this terrace, including the disposal cell, NECA yard/old millsite, and NECA gravel pit. Remnants of the terrace occur in the area of the mouth of Many Devils Wash where incision has removed most of the terrace. About 1 mi east of the mouth of Many Devils Wash, the terrace resumes and extends about 1 mi eastward to the escarpment above the Chaco River. The Qt1 terrace is also present north of the San Juan River on top of an escarpment about 1 mi northeast of the disposal cell (Plate 2).

The Qt1 terrace material is typically 10 to 20 ft thick where exposed along the top of the escarpment and is generally mapped by Ward (1990) as Q6. The Qt1 material was deposited as glacial outwash during a period estimated by Tsosie (1997) from 88,000 to 150,000 (late-middle Pleistocene) years ago. The material was deposited during aggradation in a former San Juan River valley; later erosion and downcutting have left remnants of these deposits preserved as strath terraces. Clast-supported deposits of well-rounded gravel, cobbles, and boulders with a silty and sandy matrix compose much of the terrace material. The coarsest part of the deposit is typically at the base, where cobbles 1 ft in diameter are common, and the largest noted were 2.5 ft in diameter. The resistant cobbles and boulders typically consist of metamorphic rocks (quartzite and metaconglomerate) eroded from the San Juan Mountains. Locally mixed with these far-traveled deposits on the terrace are less coarse and more angular debris derived from nearby tributaries.

Alluvial deposits in the present San Juan River floodplain were mapped as Qfps. This designation identifies sand because it is the most common grain size of the material on the floodplain surface. Where undisturbed, the 10- to 20-ft-thick deposits typically consist of at least 5 ft of sand on the surface, underlain by coarser material composed mainly of gravel and cobbles. In some places on the floodplain where flood-scouring (as on the "island" area downstream from the U.S. Highway 666 bridge) or remedial action activities (as on the floodplain just north of the disposal cell) have occurred, the sand has been removed and gravel material is exposed. These areas are generally small and scattered and were not mapped separately. The surface of the floodplain area south of the San Juan River starting about 0.7 mi upstream from the disposal cell is covered largely by sand in stabilized to semistabilized dunes. The coarser material, generally in the basal part of the floodplain deposits, is shown in the cross sections in Plate 3 as Qfpg.

The floodplain deposits are at an elevation of 5 to 10 ft or less above the San Juan River. With one exception, the base of the escarpment forms the south edge of the floodplain deposits south of the river on the site. The exception is in the northwest part of the site just west of the distributary channel of the river (Plate 2) where a subtle rise of 3 to 4 ft defines the boundary of the floodplain. West and southwest of the rise, the area of cultivated fields on the Blueeyes Ranch is designated as a low terrace and is covered by loess. However, it is believed that the floodplain material underlies the loess and extends southward to the vicinity of the irrigation return flow ditch.

The coarse part of the floodplain alluvial material represents glacial outwash deposited during the most recent glaciation in the San Juan Mountains. This late Pleistocene deposition was estimated by Tsosie (1997) as occurring from 16,000 to 70,000 years ago.

Eolian deposits, mapped as loess (Ql), have draped over and covered some of the landforms in the site area. The loess material occurs in a band from Many Devils Wash westward and northwestward to the elementary and high school area and to the irrigated farm lands on the low terrace (Plate 2). Except in the Many Devils Wash area, the loess generally contacts (indistinctly) weathered Mancos Shale that forms low uplands to the south. The Mancos Shale uplands become more pronounced as hills in the area just west of the elementary school. The color of the loess is typically gray-tan on the surface, and it forms a flat surface that slopes gently northward in the area west of the radon cover borrow pit. To the north, the loess-covered sloping surface indistinctly contacts the terrace material (Qt1). West of the radon cover borrow pit where most of the loess material was removed, the terrace material is present in the subsurface and is covered by a north-thinning wedge of loess.

In the Many Devils Wash area, the tan-colored loess occurs on top of Mancos Shale and consists mainly of silt and very fine grained sand. In places, some thin layers of coarse-grained sand and small pebbles occur, indicating episodes of fluvial deposition. Erosion in the lower part of the wash is actively incising through the loess, leaving distinctive vertically standing remnants (towers) of loess up to 25 ft in height and creating extensive piping structures up to 25 ft in depth. The piping has facilitated gully-head recession southward in Many Devils Wash, where the southernmost incision point is several hundred feet beyond the remains of concrete-and-rock walls constructed across the wash in the early 1930s to control erosion.

The distinctive piping and towers in the loess produce a pseudokarst topography, as described by Parker and Higgins (1990). The piping that causes this topography develops in material that has high contents of smectite clay and salts. Wetting and drying of the smectite clay causes swelling and shrinking, leading to the formation of desiccation cracks that are infiltrated and enlarged by runoff water. High salt content, especially high exchangeable sodium in the soils, also causes swelling when wetted. Mancos Shale, from which much of the loess is derived, has a high salt content and contains large amounts of smectite and illitic clays.

Loess accumulated in low areas along ancestral drainages in locations on the north (or leeward) side of topographic features, sheltered from prevailing southerly winds. In the site area, this occurred primarily north of the Mancos Shale upland, where loess filled the south part of the ancestral San Juan River floodplain (on top of the Qt1 gravel and cobble deposits) after the river had downcut into the area of the present floodplain. Loess also filled in low areas along Many Devils Wash, which at that time had incised through the Qt1 deposits to allow it to drain into the San Juan River. Most of the loess was probably deposited during dry periods in late Pleistocene time, after the Qtl material was deposited, and as late as the mid-Holocene dry period of 2,800 to 6,000 years ago (Love and Gillam 1991).

Fill material and the covered tailings pile, or disposal cell, have also been mapped in Plate 2. The fill material is mapped along the bottom of Bob Lee Wash, in four locations along the escarpment north and east of the disposal cell where small drainages have been filled, and in one area adjacent to the southwest corner of the disposal cell. Bob Lee Wash fill material was emplaced during and after milling operations; fill in the drainages was emplaced after milling from the mid-1970s to the 1985–1986 period of remediation, escarpment stabilization, and disposal cell construction. Grading and leveling of part of the old raffinate pond area in the 1970s and 1980s created the fill southwest of the disposal cell. Fill material, which may be up to 25 ft thick in the filled drainages, is probably uncompacted and probably does not consist of tailings according to the site completion report (MK–Ferguson 1987) and the radiologic characterization report (Allen and others 1983). However, another report on the geochemical investigation (DOE 1983) of the site indicated that contaminated soil from the ore storage area was used to fill a drainage that went north from the old millsite.

4.2.2 Joint Measurements

Joints (fractures) were investigated to evaluate what effect they might have on movement of ground water through the Mancos Shale and on location of seeps. The investigation focused on the escarpment where Mancos Shale is well exposed between the corner of the escarpment near wells 862 and 863 northwestward to the mouth of Bob Lee Wash. This escarpment area is immediately north of the disposal cell and is the site of seeps 425 through 427. Twenty-four joint orientation measurements were made with a Brunton compass. These measurements of joint strike are shown on Figure 4–5. The dip of all the joints measured was vertical, or within a few degrees of vertical. A rose diagram of joint orientation frequency is presented on Figure 4–6. This diagram shows that the principal joint strike direction is northeast. Tsosie (1997) noted the northeast direction of fracturing and indicated that most of the gullies cutting the escarpment edge were fracture induced.

Joints along the escarpment from seeps 425 to 427 and southeastward to the escarpment corner did not appear to be a significant factor in ground water movement. Instead, particularly at seeps 425 and 426, water appears in a less resistant horizontal layer that may represent a more permeable lithology within the Mancos Shale, or the layer may contain numerous bedding plane fractures that promote water movement. Also, seeps in Mancos Shale just west of the U.S. Highway 666 bridge emerge in a less resistant horizontal layer, and water movement along vertical fractures is not apparent.

Joint measurements were made at two other locations along the escarpment; one was east of the NECA gravel pit and the other was west of the U.S. Highway 666 bridge. Joints are vertical in both locations. At the location east of the gravel pit, near sample location 922, the joint orientation is 035; west of the highway bridge, near sample location 935, joints have orientations of 000, 010, and 035. Ground water expressed as seeps in both of these locations appears to flow along horizontal bedding in the Mancos Shale, probably along a slightly more permeable layer similar to the occurrence at seeps 425 and 426.

4.2.3 Borehole Stratigraphic and Structural Results

Boreholes drilled from September to December 1998 were for the purposes of monitor well installation and collection of stratigraphic and structural information. Depending on the drilling method and objectives for drilling each borehole, samples of material penetrated were brought to the surface by coring, split-barrel sampling, drill cuttings, and auger returns. Lithologic logs prepared in the field during drilling of each of the 62 boreholes were placed into gINT, a computer-generated borehole log system. The gINT logs for all 1998 boreholes are presented in Appendix A. Also included in Appendix A are gINT logs for earlier boreholes and monitor wells (active and abandoned) for which lithologic logs are available. Information from the new as well as old boreholes was used in this geologic site characterization.

Borehole lithologic information was used to prepare the geologic cross sections (Plate 3), the contour map of the top of the siltstone bed in the Mancos Shale (Figure 4–4), and the bedrock contour map (Figure 4–7). Subsurface characteristics of the Mancos Shale, the Mancos Shale bedrock surface, and overlying units noted as a result of drilling are described in this section.

Mancos Shale has been separated into upper and lower parts by the Gallup Sandstone in this part of New Mexico (Ward 1990). The Gallup Sandstone, present in part of the San Juan Basin to the west and south of the site area, pinches out several miles southwest of the town of Shiprock (Molenaar and others 1996). Northeast of the pinchout, a sporadic extension of this sandy interval has been called the "Stray" sandstone; more recently, this interval was named the Tocito Sandstone Lentil. The Tocito crops out about 4 mi west of the site along the San Juan River, and the unit is present in the subsurface of the site area. No boreholes drilled during site characterization were deep enough to penetrate the Tocito, but its presence and depth are known generally from the lithologic log of artesian well 648 (Appendix A), which was drilled as an oil and gas test to a depth of 1,850 ft from October 1960 to February 1961. The well produces water from the Morrison Formation of Late Jurassic age through a perforated zone from 1,482 to 1,777 ft in depth. Well 648 penetrated the Gallup Sandstone (now termed the Tocito Sandstone Lentil in this area) from depths of 248 to 330 ft. A projection of the east-dipping (about 1°) Mancos Shale westward to the west edge of the site around well 846 would place the depth of the top of the Tocito at about 150 ft. As shown on cross section E–E' or Plate 3, the depth to the Tocito in the western part of the site is several tens of feet deeper than the approximate 150 ft total depth of well 848. Penetration of the Tocito Sandstone should be avoided, because ground water that may be present in the sandstone would be under artesian conditions.

During the 1998 characterization, depth to bedrock (Mancos Shale) was recorded in all the boreholes drilled to sufficient depth on the terrace and floodplain. In addition to the 1998 data, bedrock depths from earlier boreholes were also used to prepare the contour map of the bedrock surface shown on Figure 4–7. In cases where bedrock elevations from earlier boreholes differed greatly from 1998 borehole bedrock elevations, preference (or weighting) was given to the more recent data in preparation of the bedrock surface map. The bedrock surface was considered as the top of the weathered Mancos Shale. The weathered Mancos Shale is typically 5 to 10 ft thick, but may be up to 30 ft thick in places. Tan-orange limonitic staining that typically occurs on bedding plane surfaces within the uppermost few feet of the Mancos is a distinguishing feature of the soft, weathered shale.

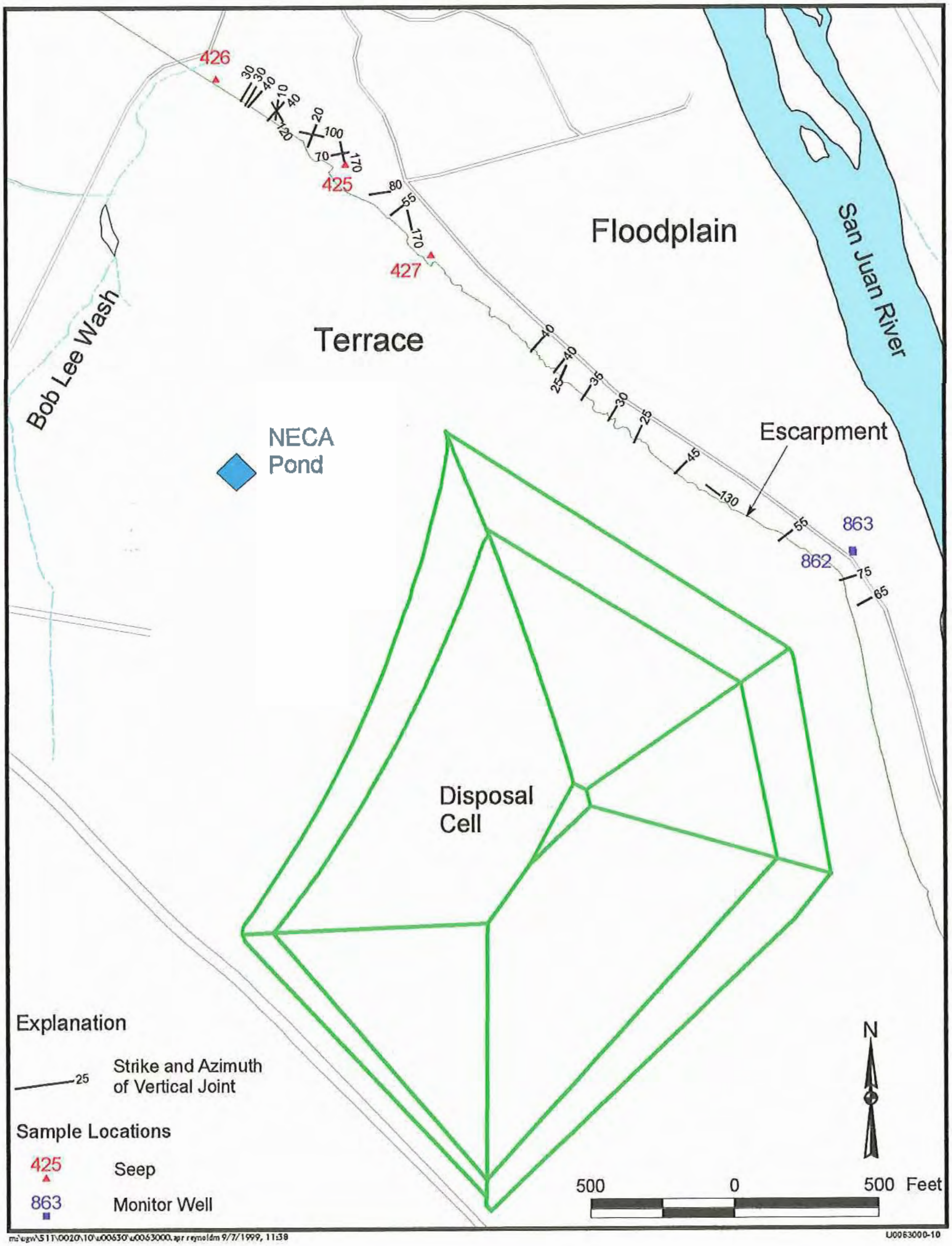


Figure 4–5. Orientation of Vertical Joints Along Escarpment

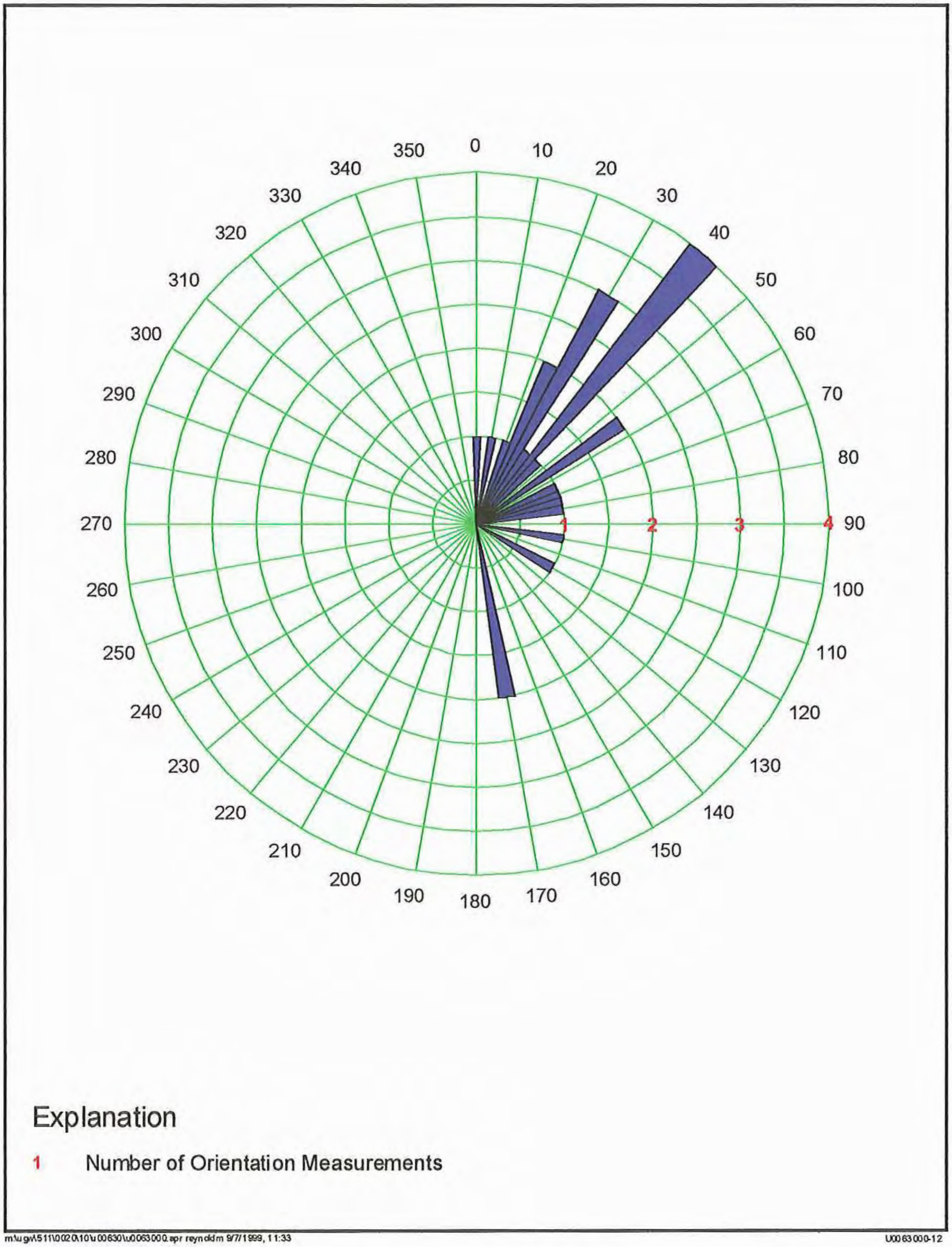


Figure 4–6. Rose Diagram of Joint Orientations (azimuths) for Locations shown on Figure 4–5

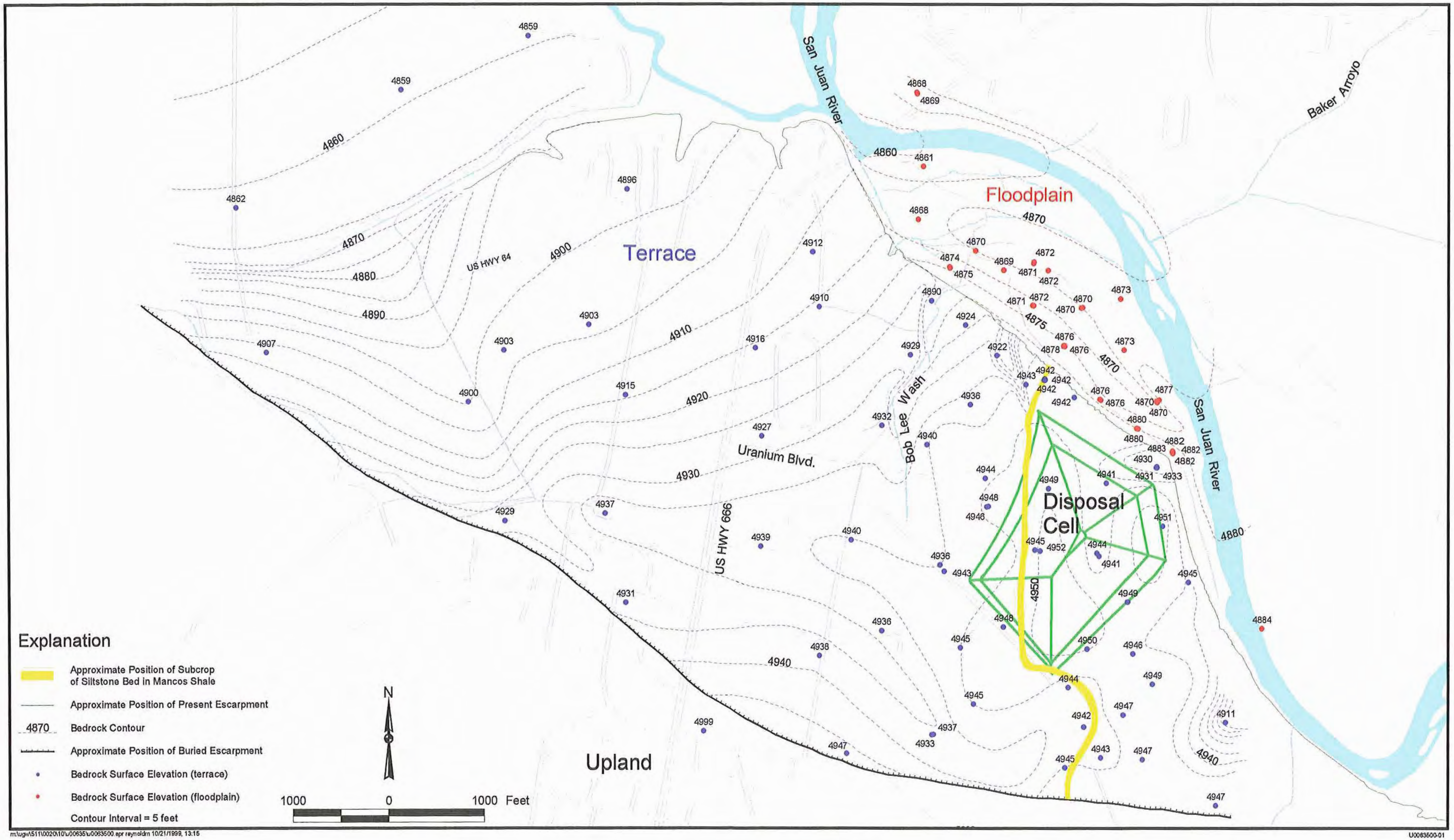


Figure 4–7. Contour Map of the Mancos Shale Bedrock Surface

Additional depth-to-bedrock data from the 1998 boreholes have provided a different and more complete understanding of the terrace bedrock surface than what was presented in the SOWP, Rev. 0 (DOE 1995). The approximately northwest to southeast 2.3-mi extent of the terrace bedrock surface is shown on Figure 4–7. The map, using a 5-ft contour interval, was developed based on bedrock data from old and new boreholes. The bedrock surface gradually drops about 90 ft northwestward across the 2.3-mi distance. A buried escarpment bounds the bedrock surface to the south and west and forms the north boundary of the upland area. The approximate location of the buried escarpment is shown on Figure 4–7. The presence of this feature is evident by noting the difference in bedrock elevations between boreholes 808 and 812 or 806 and 807. This buried escarpment, about 50 to 60 ft high, is similar to the present escarpment to the north that separates the terrace from the present floodplain. An unusual stratigraphic sequence in well 841 indicates that the escarpment may be vertical to overhanging in places. This borehole penetrated 10 ft of loess, then 16.5 ft of Mancos Shale, below which 23.5 ft of coarse sand, gravel, and cobbles were followed by more Mancos Shale bedrock at 50 ft. The Mancos Shale initially penetrated by the borehole could represent an overhanging cliff at the edge of the buried escarpment, or the shale could be a block of bedrock that fell from the nearby escarpment onto the outwash material in the former San Juan River channel.

Characteristics of the terrace bedrock surface, or strath terrace formed by the ancestral floodplain of the San Juan River, affect ground water movement. The disposal cell sits on an elevated and nearly flat bedrock surface. This low-relief surface extends south-southeast from the disposal cell to the buried escarpment. Wells 603 and 731 are on this surface, which forms a low divide that separates steeply sloping surfaces to the east from gently sloping surfaces to the west. Also, extending westward from the disposal cell area is a low ridge about 1 mi long that is defined by wells 728, 814, and 832. North of this ridge, the bedrock surface drops gradually to the northwest, and south of the ridge is a shallow valley that slopes gently to the west and northwest (Figure 4–7). The south edge of this shallow valley is the buried escarpment. Wells 604, 818, 812, 813, and 841 are situated in the shallow valley. Borehole 834 is at the west end of the shallow valley; north of this point, the bedrock slope abruptly steepens and the valley appears to extend northwestward to the area of borehole 831.

Ground water laden with raffinate pond effluent during milling (and for years afterward) likely moved south and southwest into the shallow bedrock valley. The flat to gently sloping valley promoted only slow westward movement of this water. A large area of contaminated water is still present in this low bedrock valley area between wells 818 and 841. Ground water from the east end of the raffinate ponds could also have moved southward along the nearly flat bedrock divide. There, in the area of wells 731 and 603, movement of ground water also could be slow.

Another feature shown on the bedrock surface contour map (Figure 4–7) that affects ground water movement is the approximate position of the subcrop of the 1-ft-thick siltstone bed in the Mancos Shale. This bed dips about 1° eastward, and its subcrop extends across the mostly low relief bedrock surface from the north end of the disposal cell southward to the buried escarpment south of borehole 807. The position of this resistant siltstone bed may be the reason that the relatively flat bedrock surface is present. The orientations of the siltstone subcrop and the high, flat bedrock area are roughly coincident. In addition to providing a resistant lithology to "hold up" the high bedrock area, the siltstone bed provided a relatively low permeability barrier to ground water movement east of its subcrop. Ground water east of the siltstone subcrop could percolate down through weathered Mancos Shale until it reached the siltstone bed, then move downdip eastward along this perched layer to seeps along the escarpment (such as expressed at sample location 922) and along Many Devils Wash.

Several narrow drainages have incised into the bedrock surface north and east of the nearly flat bedrock surface in the disposal cell area. The most prominent of these is Bob Lee Wash; less noticeable are several short, narrow drainages that were filled during remediation in the 1970s and 1980s. The general position of these small drainages cut into bedrock is shown on Figure 4–7 and also on the site geologic map on Plate 2, where they are shown as filled drainages. The three bedrock drainages north and east of the disposal cell provided potential pathways for effluent-laden ground water in areas of the millsite and tailings piles to move down to the floodplain. The first drainage drained the north part of the mill area, and its mouth cuts through the escarpment between seeps 425 and 427. No boreholes have probed this drainage and its incised depth is estimated; however, its location is known from old aerial photographs (Figures 3–1 and 3–4) and a 1960 topographic map. A second drainage is at the corner of the escarpment just north of the northeast corner of the disposal cell. This drainage was probed by wells 823, 824, and 825 (the east terrace nest). The third drainage is just south of the southeast corner of the disposal cell and enters the floodplain just north and west of well 735. Its head is near the former raffinate ponds. No boreholes have probed this filled drainage, but its location is known from a 1960 topographic map.

Ten of the 13 additional boreholes drilled in 1998 on the floodplain north of the disposal cell penetrated the alluvial material and contacted the top of the Mancos Shale bedrock. These boreholes provided a more complete understanding of the floodplain bedrock surface; however, data points are still sparse in the north part of the floodplain because few boreholes have been deep enough to contact bedrock. The floodplain bedrock surface map shown on Figure 4–7 is different from the bedrock surface map presented in the SOWP, Rev. 0 (DOE 1995). The present interpretation on Figure 4–7 is simplified and shows a shallow swale that parallels the escarpment (about 500 ft north of it). The swale, which represents an ancestral channel of the San Juan River, is bounded on the north by a low ridge. The edge of the ridge may have as much as 10 ft of topographic relief in places, as shown in the area of the cluster of wells 858, 859, and 612. From the bedrock surface map presented on Figure 4–7, the mainly subtle bedrock topography does not appear to present barriers to a normal northwestward movement of ground water through the floodplain.

Terrace material (Qt1) overlying the Mancos Shale is typically about 20 ft thick. As shown in Plate 3, the terrace material thickness in various parts of the site varies from less than 10 ft at wells 831, 844, and 846 to about 35 ft at well 818. Terrace material appears to be the thickest along the ancestral channel of the San Juan River just north of the buried escarpment (Plate 3, cross section A–A'). Thickness of the terrace material around well 835 is about 30 ft. This area may be the site of another ancestral river channel. Near the escarpment and in the millsite area, the terrace material is only about 10 to 15 ft thick. This lesser thickness is probably the result of removal of some material during remedial action.

Sandy material, shown in the cross sections on Plate 3 as terrace sand (Qts), overlies the terrace material in several places in the subsurface in the south and west parts of the site. This sandy material, not exposed on the surface, occurs east and west of U.S. Highway 666 in different hydrogeologic settings. East of the highway, it occurs in wells 812 and 813 and in borehole 807. At these eastern locations the sand is brown, fine to medium grained, and about 5 ft thick. This sandy layer was not found in wells 818 and 604, so it is uncertain if the sand present at borehole

807 extends as a continuous layer westward to the area of the wells 812 and 813. The sand in these eastern locations is dry and is about 20 ft above the ground water surface in the terrace material or weathered Mancos Shale.

West of U.S. Highway 666 sandy material occurs in wells 833, 838, and 844 and in borehole 831. At these western locations, the sand is yellowish brown to grayish brown and is from 4 to 11 ft thick. The sand in this western area around the Diné College construction tract is probably continuous, and the ground water surface is either in the lower part of the sand or just below in the terrace gravel material. The sand in both locations east and west of the highway overlies the coarser grained terrace material and was deposited during a low-energy regimen of the ancestral San Juan River before the river abandoned its terrace location and established its course in the present floodplain area.

Loess covering much of the terrace area typically overlies either the terrace gravel material or sandy material. The loess overlies Mancos Shale in the Many Devils Wash area and along the north edge of the upland area. In the low terrace area at the far northwest part of the site, loess covers floodplain gravel. The loess material is composed mainly of silt, with minor amounts of very fine-grained sand, clayey silt, and sandy clay. A finer grained variant of the loess occurs in the lower terrace area where wells 831, 836, and 843 penetrated about 5 ft of sandy clay or clayey silt in the lower part of the loess sequence. The silt is mottled in places, calcareous, and contains a few thin, white layers of caliche (?). Light yellowish brown is the most common color of the loess and brown and light brownish gray also occur.

Thickest loess occurrences are in the south part of the terrace area just north of the buried escarpment. Well 812 is in such a setting and penetrated 34 ft of loess. Similar thicknesses likely occur to the northwest in the high school area, and at least 25 ft of loess was removed from parts of the radon cover borrow pit. Loess is thinner in the terrace background area where wells 800 through 803 penetrated only about 5 to 10 ft of it. The ground water surface is below the loess in all terrace locations, except the low terrace area, where the lower part of the loess is saturated (wells 836, 837, and 843).

Alluvium in the San Juan River floodplain north of the disposal cell consists mainly of two types of material: (1) a lower, coarse-grained unit composed of sand, gravel, and cobble-sized material representing glacial outwash overlain by (2) a finer-grained unit consisting of silt, sand, and minor gravel. The coarse-grained unit is shown in cross sections (Plate 3) as Qfpg, and the finer-grained unit is shown on the geologic map (Plate 2) and cross sections as Qfps. The coarse-grained unit is thicker, and in some places in the eastern part of the floodplain (wells 853, 854, 858, 862, and 863) it is the sole alluvial unit present. The absence of the finer-grained unit in some of the eastern part of the floodplain may be a result of removal during surface remediation.

Thirteen additional boreholes were drilled into the floodplain alluvial material north of the disposal cell in 1998. Ten of these boreholes reached bedrock. Grab samples of the alluvial material were taken, typically at 5-ft intervals, during drilling of the boreholes. Lithologic description of this material and sampled intervals are in the gINT logs for each borehole in Appendix A. The alluvial material in the floodplain north of the disposal cell reaches as much as 24 ft thick; the typical thickness was 15 to 20 ft. Alluvial material of similar composition and thickness was found in boreholes for the three wells (850 through 852) installed in the floodplain background area, where 16 ft of sandy gravel was overlain by 4 ft of sand.

Four boreholes completed as terrace monitor wells in 1998 penetrated fill material. The fill at these locations was placed in small drainages near the terrace edge in the mid- to late-1970s. Wells 823 through 825 in the east terrace cluster penetrated about 26 ft of fill in an east-trending drainage (Plate 2 and cross section G–G' on Plate 3). Approximately 22 ft of fill was penetrated at well 827 (cross section B–B' on Plate 3), which was drilled along the west side of a northwest-trending drainage (Plate 2) that drained millsite effluent to a pond on the floodplain. During borehole drilling it became apparent that filled drainages had been penetrated at both borehole locations because the expected depth to bedrock was greatly exceeded. The existence and location of the drainages was later confirmed by their positions shown on a 1960 topographic map. The composition of the fill material in both drainages was similar to that of the terrace material (Qt1) adjacent to the drainages.

Core (NX size) was recovered from Mancos Shale in six boreholes during the 1998 drilling. Four of the boreholes cored were from each of the terrace and floodplain well nests (wells 820 and 823 and wells 860 and 862). The other two boreholes cored were in the terrace background area (wells 800 and 802). Detailed description of the rock core is included in the gINT lithologic log (Appendix A) of each cored borehole. The labeled core is boxed by borehole and stored at the DOE–GJO facility.

Coring in both the well nest and terrace background boreholes was conducted in weathered and unweathered Mancos Shale to evaluate the presence of ground water and its relation to fracturing and stratigraphic features. The amount of fracturing in the core, recorded in the core log, was the basis for selecting intervals to be packer tested for hydraulic conductivity in the terrace and floodplain well nest boreholes. A summary of the results of coring from a hydrogeologic perspective follow.

The Mancos Shale is generally light gray to dark gray and is calcareous throughout, but especially so in the lighter-colored, coarser-grained (silty) layers. Thin claystone layers (up to several inches thick) are common and are the darkest (dark gray); they swell when brought to the surface and appear to be excellent aquicludes. Traces of carbonaceous material and finely disseminated pyrite were identified. Contorted bedding caused by bioturbation is common in these shales deposited in a shallow shelf environment. Wavy and planar bedding is also common. Fossils occur sporadically; the largest are flattened pelecypod shells preserved as white, fibrous, aragonite layers. Weathered Mancos Shale in the shallowest parts of the cored intervals is dark yellowish brown to light olive gray, contains some limonite staining, and white calcite and gypsum fracture fillings. Fracturing decreases with depth, and bedding plane fractures are the most common. Only a few inclined or vertical fractures were identified; all were closed with no evidence of ground water movement along them.

The 1-ft-thick calcareous siltstone bed penetrated by coring in terrace background well 803 (Appendix A) is believed to be the same siltstone that crops out in Many Devils Wash and along the escarpment north and east of the disposal cell. The presence of this siltstone bed at an elevation of 4,937 ft indicates that the dip of the siltstone (and the Mancos Shale) is at a low angle westward at well 803. This occurrence of the siltstone bed infers that a shallow, synclinal axis is present west of well 803 and east of Many Devils Wash. From the terrace background area, the Mancos Shale rises eastward on the flank of the Hogback anticline.

4.2.4 Geophysical Survey Results

Geophysical surveys were conducted in February 1996 by Geraghty and Miller, Inc. (DOE 1996c) on the floodplain north of the disposal cell and on the terrace in areas adjacent to the disposal cell. These surveys were conducted to address data needs identified in the SOWP, Rev. 0 (DOE 1995). Four other geophysical surveys were conducted from mid-1995 to mid-1996 on the floodplain north of the disposal cell. These surveys were conducted with EM 31 and EM 38 instrumentation, and the results show different configurations of the contaminant plume corresponding to different levels of the San Juan River (Tsosie 1997).

The Geraghty and Miller work consisted of electrical conductivity surveys with EM 31 instrumentation on the floodplain and EM 34 instrumentation on the terrace; seismic refraction surveys were also conducted in the floodplain. The floodplain EM 31 survey was intended to locate sulfate and nitrate contamination. Results of this survey showing areas of high conductivity (DOE 1996c, Figure 3) on the floodplain correspond closely to the present understanding of the configuration of the contaminant plume. The siting of well 854 was based on the position of the high-conductivity area shown in this EM 31 survey (DOE 1998c). Analyses of ground water samples from this well and from backhoe trenches in the nearby area verified that the contaminant plume extends northward across the floodplain to the San Juan River in the well 854 area. The EM 34 survey on the terrace was conducted to identify contaminant concentrations and bedrock fractures that might act as conduits for ground water movement. Results of this survey indicated that few fractures were present and none were of importance. Areas of high conductivity were identified adjacent to the disposal cell and NECA yard and extended southeast through the NECA gravel pit; a low conductivity area identified south of the disposal cell is probably the result of a thick layer of loess and terrace material covering the contaminant plume.

The refraction surveys were conducted to determine bedrock topography and its relationship to areas of high conductivity (high contaminant concentrations). Results indicated that bedrock depressions generally coincided with areas of high conductivity (DOE 1996c). However, present interpretation of bedrock topography based on additional borehole data does not indicate a correlation of high levels of contaminants with bedrock depressions.

4.3 Hydrologic Characterization

This section presents the hydrologic characterization of the UMTRA Shiprock disposal cell. The surface water part of this section presents an overview of the San Juan River and its importance as a water supply in the region, as well as a description of surface water that comes from flowing well 648, seeps and springs that emerge from the escarpment, irrigation return flow, 1st and 2nd washes, and wetlands on the floodplain at the mouth of Bob Lee Wash.

The ground water portion of the section describes the floodplain alluvium, the terrace alluvium, and the weathered bedrock systems. The floodplain alluvium is a potentially significant ground water resource. However, the floodplain alluvium north of the disposal cell is affected by surface water that enters at the mouth of Bob Lee Wash. This location creates a local wetland, and the ground water mounding in the area of the wetland significantly alters the natural ground water flow system. Although flow modeling of the floodplain was performed under the UMTRA Surface Project (DOE 1995), there has been no measurement of hydrologic parameters of the floodplain alluvium. During this investigation, an aquifer pumping test was performed in the floodplain to obtain an estimate of the transmissivity of the system, and a water balance was developed for the floodplain as a whole. Numerical flow-and-transport modeling of the alluvial aquifer was also performed to evaluate compliance strategies for the system.

The terrace alluvium was described previously as a limited use ground water system (*Federal Register* January 11, 1995, p. 2863). The assumption of limited use was the basis for the site conceptual model for a number of years, and no concerted effort was made to test its validity. The 1998 investigation was geared toward (1) evaluating if the terrace alluvium does constitute a limited use aquifer; (2) assessing if water is present in background areas near the disposal cell; (3) evaluating the upland areas south of the disposal cell to determine if they contain water, and, if not, then delineating the boundary between the upland areas and the terrace alluvium; (4) delineating the discharge boundaries of the terrace alluvial flow system; and (5) evaluating the hydrologic interaction between the terrace alluvium and the floodplain alluvial aquifer.

4.3.1 Surface Water

This section presents descriptions of the various surface water bodies and estimates of discharge and water use for those systems.

4.3.1.1 San Juan River

The San Juan River has a drainage area of approximately 12,900 square miles (mi^2) upstream from the town of Shiprock. Discharge records for the San Juan River at Shiprock are nearly continuous since February 1927. A river stage recorder (09368000) operated by the United States Geological Survey (USGS) is located on Shiprock's alternate-water-source intake structure about 300 ft east (upstream) of the U.S. Highway 666 bridge along the north side of the river (Plate 1). The river gauge was established at this location in 1995; formerly, the gauge was located about 3 mi west (downstream) of Shiprock. Data from the river gauge indicate that extreme low and high flows before 1963 ranged from less than 8 cubic feet per second (cfs) to about 80,000 cfs, respectively. After construction of the Navajo Reservoir (located 78 river mi upstream of Shiprock) was completed in 1963, the extreme low and high flows moderated to about 80 cfs and 15,000 cfs, respectively. Average flow in the San Juan River at Shiprock is 2,175 cfs (Stone and others 1983). Figure 4–8 presents a hydrograph of the San Juan River at Shiprock. A stilling well has also been established (location 899), but not enough data have been collected at this time to report.

The Chaco River drains more than 4,000 mi^2 and empties into the San Juan River upstream about 2 mi east of the Shiprock site. It drains many areas in the San Juan Basin that contain coal and uranium (Stone and others 1983). Flow in the lower reach of the Chaco River ranges from 10 to 30 cfs during nonstorm-flow periods. Much of the flow is reported to be effluent from the Four Corners Power Plant, about 12 mi southeast of the Shiprock site (Stone and others 1983). Water quality standards have been promulgated by the Navajo Nation for surface waters within the reservation. The San Juan River is classified as a domestic water supply suitable for primary and secondary human contact, for livestock and wildlife watering (including migratory birds), for irrigation, and for a cold-water fishery. Consequently, stringent water quality standards are applicable to the San Juan River at Shiprock. These standards are described in terms of their significance to the Shiprock UMTRA site in Section 7.0, "Ground Water Compliance Strategy." Water quality is monitored by USGS at river gauge 09368000, the location of which is now shared with Shiprock's water intake structure. The water is also monitored by NTUA in

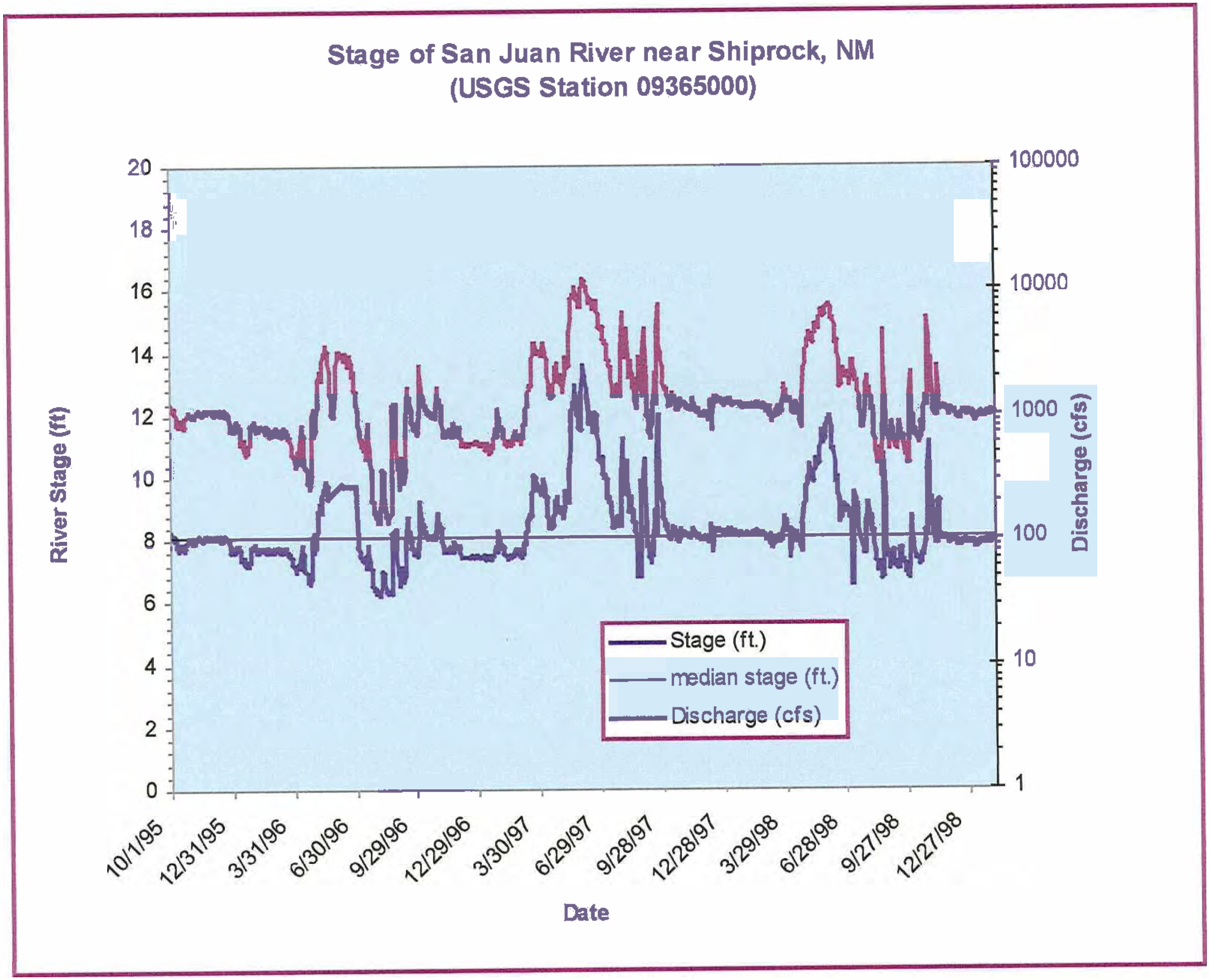


Figure 4–8. Hydrograph of the San Juan River Near Shiprock, New Mexico

conjunction with requirements of the Safe Drinking Water Act (SDWA). DOE monitors the San Juan River both upstream and downstream of the Shiprock millsite under the auspices of the UMTRA Project.

Table 4–3 presents results of quarterly water quality monitoring performed by USGS. These results indicate that for the varied flow rates reported, concentrations of the selected analytes are below the water quality standards for domestic and primary human-contact designated uses in the proposed water quality standards of the Navajo Nation (Navajo Nation 1998). In conjunction with the analytical results of DOE monitoring, the results also indicate that millsite-related contaminants do not pose an immediate threat to the quality of the alternate water supply (see Section 4.3.1.2) at Shiprock. DOE's analytical results are discussed in Section 4.4.

Table 4–3. Surface Water Quality Parameters for Selected Analytes Monitored at U.S. Geological Survey Gauge 09368000 at Shiprock[a]

Date	Discharge (cfs)	Sulfate (mg/L)	TDS (mg/L)	Nitrogen as NO_2+NO_3 (mg/L)	Arsenic Total (µg/L)	Selenium Total (µg/L)	Uranium (µg/L)
Nov 17, 1994	996	170	410	0.410	2	1	2.2
Mar 02, 1995	1,460	170	392	0.390	Not Analyzed	Not Analyzed	Not Analyzed
May 03, 1995	4,210	65	199	0.090	2	<1	0.68
Aug 08, 1995	1,280	100	260	<0.050	Not Analyzed	Not Analyzed	Not Analyzed

[a] mg/L = milligrams per liter
µg/L = micrograms per liter

4.3.1.2 Water Supply

The town of Shiprock's water supply is maintained by NTUA. NTUA has several potential sources of water available, all of which rely on the San Juan River. From Shiprock upstream toward Navajo Reservoir Dam, these sources are:

- **San Juan River at Shiprock (alternate water source)**: The Shiprock alternate water source consists of an octagonal (in plan view) intake structure set in the river channel next to the north bank of the river (Plate 1). The structure has four slide gates, each at a different elevation to allow operators to adjust intake elevation in response to changes in river stage. The capacity of the intake structure is calculated to be 2.6 million gallons per day (MGD). The 1997 maximum projected peak production for Shiprock was 2.6 MGD, and 3.1 MGD is projected by the year 2013 (Molzen-Corbin & Associates 1993). Therefore, the capacity of the intake structure is projected to be insufficient to supply the entire peak demand. The single biggest operation and maintenance problem with the Shiprock water intake is inadequate facilities to remove the suspended river sand (Molzen-Corbin & Associates 1993).

- **Navajo Irrigation Authority (NIA) Canal**: Hogback Ditch is an irrigation canal designed to deliver 143 MGD to various tribal agricultural users in the San Juan River Valley; the canal is operated and maintained by NIA. The intake for the canal is located 11 mi upstream from Shiprock on the north bank of the San Juan River. Canal deliveries usually occur between April and September. Chemical water quality in the canal is assumed to be similar to water pumped from the water intake structure; however, the suspended load is probably much lower. Hogback Ditch is projected to be capable of meeting all municipal requirements through the year 2013 with only a 3 percent loss of carrying capacity (Molzen-Corbin & Associates 1993) .

- **City of Farmington:** The City of Farmington has been selling water to NTUA through a purchase agreement that began in 1967. This is the principal source of municipal water for the town of Shiprock. The original purchase agreement had a 10-year term with options to renew for additional 10-year periods. The terms of the original purchase agreement were that NTUA would purchase at least 0.7 MGD and that the maximum quantity delivered on any day would be 3.0 MGD. The cost of the water is adjusted annually to reflect changes in the City of Farmington's actual cost basis. As of 1993, the City of Farmington believed that the contract with NTUA had expired but that there was enough surplus treatment capacity to enter into another long-term agreement. The 1993 cost of treated water was $0.98 per 1,000 gallons (Molzen-Corbin & Associates 1993).
- Other potential San Juan River diversions include the Navajo Agricultural Products Industries (NAPI) Irrigation Canal and the Proposed Navajo-Gallup Pipeline Project (Molzen-Corbin & Associates 1993). Both of these are additional potential sources of water supply for the town of Shiprock.

4.3.1.3 Bob Lee Wash

Discharge from flowing-well 648 accounts for almost the entire surface water flow in Bob Lee Wash. The flow at the mouth of the wash has not been measured with a weir, but during the winter of 1999, discharge from well 648 was measured with a flow meter at approximately 64 gpm. It is reasonable to assume that discharge at the mouth of the wash is equal to well discharge during the winter. During the summer, evapotranspiration may reduce the flow slightly en route to its discharge point at the mouth of the wash. Upstream of the confluence with well 648 discharge, seeps in Bob Lee Wash support salt grass vegetation but no stream flow, even in winter. These seeps are contaminated with millsite effluent and issue forth from weathered Mancos Shale and terrace alluvial gravel, as described in Section 4.3.2, "Ground Water."

A wetland about 5 acres in size is present on the floodplain near the mouth of Bob Lee Wash. Discharge from the wetland flows slowly west to northwest along an abandoned distributary channel on the floodplain. Ultimately, the discharge from the wetland, and any intercepted ground water discharge, emerges from the floodplain near surface sampling location 894.

4.3.1.4 Many Devils Wash

Surface water in Many Devils Wash is confined largely to the northernmost 1,400 ft of the channel. The southernmost, or first, occurrence of water in the channel appears to be spring flow that is controlled by a 1-ft thick siltstone marker bed in the Mancos Shale. In the vicinity of sample locations 889 and 916, where the marker bed is exposed in Many Devils Wash (Plate 1), the soil and shale bedrock are covered with a whitish efflorescence that occurs along both east and west banks of the wash. However, as described in Section 4.3.2.2, "Terrace Alluvium," the source of water in the wash is quite likely derived from the saturated terrace alluvium to the west. The siltstone marker bed is also believed to subcrop beneath the saturated terrace alluvium south and southeast of the disposal cell, as described in Section 4.2.3, "Borehole Stratigraphic and Structural Results," and shown on Figure 4–7. Discharge at the mouth of Many Devils Wash measured in March 1999 was 0.3 gpm; consequently, the total spring fed discharge into Many Devils Wash is also approximately 0.3 gpm. This discharge empties directly into the San Juan River.

4.3.1.5 Additional Washes

Three additional washes drain the terrace area west of the U.S. Highway 666 bridge. These washes have no formal name and are designated 1st, 2nd, and 3rd Washes (Plate 1). The 1st and 2nd Washes each support minor surface water discharge that appears as spring flow near the base of the terrace alluvium. Water from these washes discharges to the distributary channel of the San Juan River west of the U.S. Highway 666 bridge. In winter 1999, the baseflow was estimated to be approximately 1.5 gpm in 1st Wash and about 0.2 gpm in 2nd Wash.

4.3.1.6 Escarpment Seeps and Springs

The escarpment west of Many Devils Wash and east of 1st Wash contains numerous active seeps and springs that issue from the Mancos Shale. The seepage flux is minor and normally manifests itself as damp zones along the cliff face. White efflorescent crust at other locations, that are now dry, suggest that seepage along the cliff face has been more common in the past.

Spring-fed flow is also apparent at several other locations, particularly at 425 and 426 where discharges totaling approximately 1 gpm have been measured by bucket and stop watch. Minor seeps (that have not been measured) flow at locations 427, 922, and 936. A spring near the mouth of 1st wash has a flow estimated at about 1.5 gpm.

4.3.2 Ground Water

This section provides information about the occurrence and general characteristics of ground water near the UMTRA Shiprock site, such as sources, flow rates, flow directions, and volumes stored in the ground water systems, and the results of tests performed on the aquifers.

4.3.2.1 Floodplain Alluvium

The floodplain alluvial aquifer is north of the disposal cell in the floodplain area between the San Juan River and the base of the escarpment. It consists of unconsolidated medium- to coarse-grain sand, gravel, and cobbles that are in direct hydrologic communication with the San Juan River. The gravel and cobble fraction is composed of detrital material that was transported as glacial outwash derived from the San Juan Mountains. Borehole evidence indicates that the sandy gravel unit is overlain by a layer of silty sand several feet thick. Both the sandy gravel and silty sand layers appear to be laterally continuous.

A simple depositional facies model provides a description of the hydrostratigraphy of the floodplain alluvial aquifer. The basal gravel (or channel gravel) was deposited as the river migrated northward from the base of the escarpment to its present position. During its migration, older alluvial sediments to the north were eroded and a new layer of coarse sediment was deposited. These processes resulted in a continuous layer of channel gravel, sand, and silt that was deposited on a scoured bedrock surface. Periodic flood events later deposited sand and silt on top of the gravels, resulting in the present alluvial stratigraphy. This depositional model is similar to the fluvial-floodplain facies model of Mackin (1937), which was later described in Leopold and others (1964). According to this model, the unstratified channel gravel is the coarsest material that moved along the stream channel. Because the channel material is uniformly coarse grained, directional and spatial contrasts in hydraulic conductivity are expected to be relatively minor.

Plate 1 shows the locations of monitor wells and well points in the floodplain alluvial aquifer. Borehole logs of the 26 wells completed in the alluvium indicate that the average thickness of the alluvium is 14.7 ± 3.3 ft, and the average saturated thickness of the alluvium is 12.4 ± 3.8 ft. The hydraulic gradient in the floodplain aquifer ranges from approximately 0.002 to 0.004. Figure 4–9 is a contour map of the water table for the terrace system and the floodplain alluvial aquifer.

Monitor wells in the floodplain alluvium were installed in three time periods: 1984, 1993, and 1998. Consequently, the longest record of water levels dates back to 1984. Figure 4–10 presents the hydrographs of the wells with water level records dating back to 1984. It also presents (in the bottom figure) the hydrograph for well 735 that was installed in 1993. The hydrographs contain a partial-duration plot of river stage and show that the aquifer responds to fluctuations in San Juan River levels.

Boundaries of the ground water flow system may be described as time-varying head where the alluvium contacts the San Juan River and as limited flux to no flux where the alluvium contacts the base of the escarpment. Surface water, originating as well 648 discharge, enters the floodplain alluvial aquifer at the mouth of Bob Lee Wash. The contribution from well 648 is the major source of water to the floodplain and dominates the hydrodynamics of the floodplain. The floodplain is also recharged with San Juan River water and infiltration of precipitation and runoff. Discharge from the floodplain alluvial aquifer enters the San Juan River along its northern edge.
Ground water in the floodplain alluvium presently supports the growth of phreatophytic vegetation. Before the drilling of well 648 and before milling operations, the floodplain alluvial aquifer might have been entirely recharged by the San Juan River and may have discharged entirely to the river. The floodplain itself was sparsely vegetated because overbank flows scoured the land surface annually during spring runoff (see the 1935 aerial photograph, Figure 3–1).

Pumping Test Results

Figures 4–2 and 4–3 show the location and generalized cross sections for the aquifer pumping tests performed in the floodplain alluvium. Well 858 was the pumping well for the test. It was pumped at a rate of 60 gpm for 18 hours. Observation wells 859 and 612 located 13.8 ft and 30.4 ft from well 858, respectively, were monitored with electronic pressure transducers during the test. A vapor lock in the fuel line interrupted the test prematurely; the test was originally planned to run for 24 hours. A recovery test was begun immediately after the pumping stopped.

Figure 4–11 presents the drawdown-in-relation-to-time records for the aquifer tests in the floodplain alluvium. The transmissivity measured during the pumping phase was between 1,100 and 1,400 square feet per day (ft^2/day); during the recovery test it ranged from 2,100 to 2,400 ft^2/day. The average of these data is approximately 1,800 ft^2/day. Saturated thickness in the area of the test is approximately 16 ft. Therefore, the hydraulic conductivity, defined as the transmissivity divided by initial saturated thickness, is computed to be 110 feet per day (ft/day).

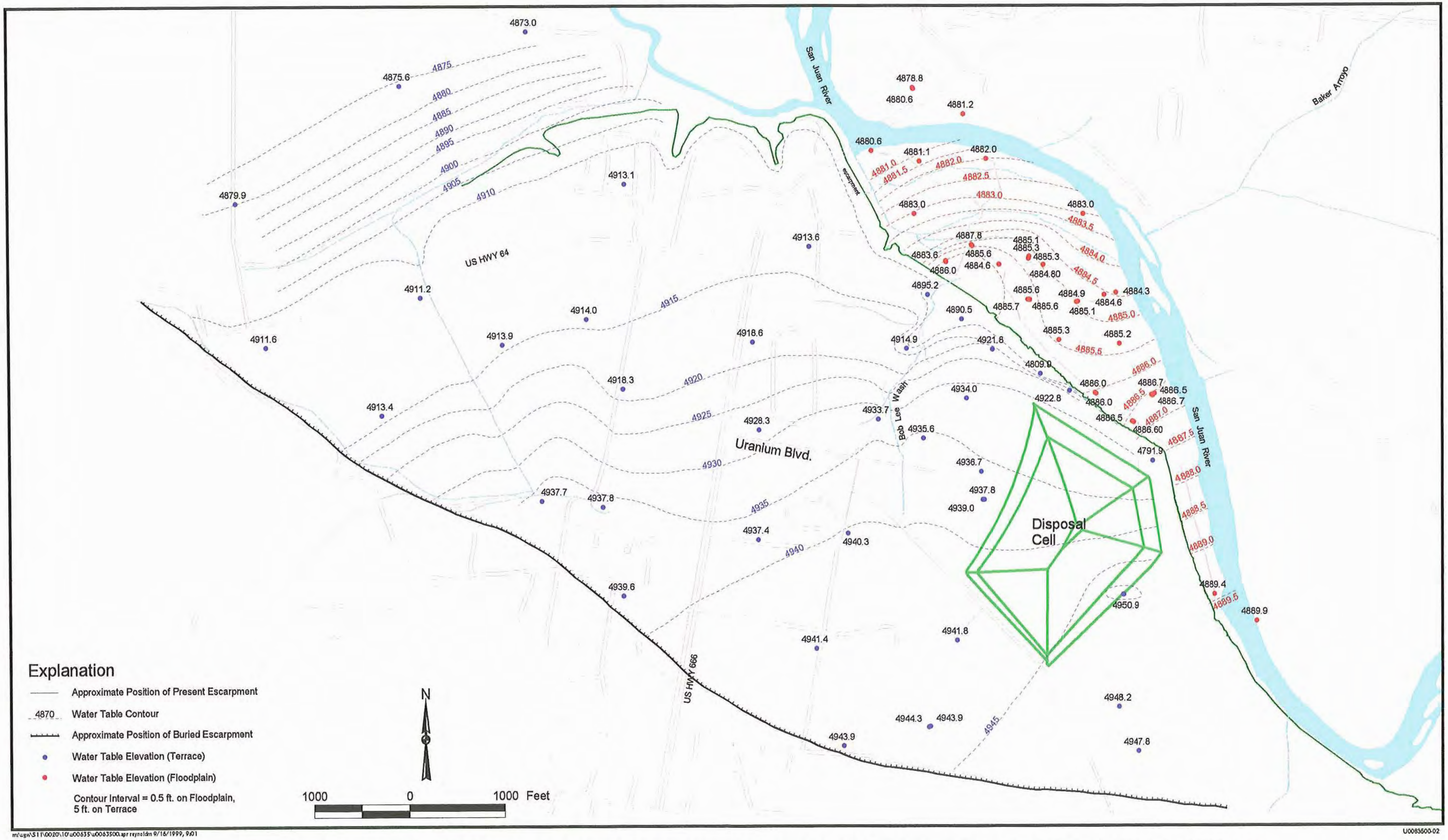


Figure 4–9. Approximate March 1999 Contours of Equipotential Surface for Both Floodplain Alluvial Aquifer and the Terrace Ground Water System, Shiprock, New Mexico, UMTRA Site

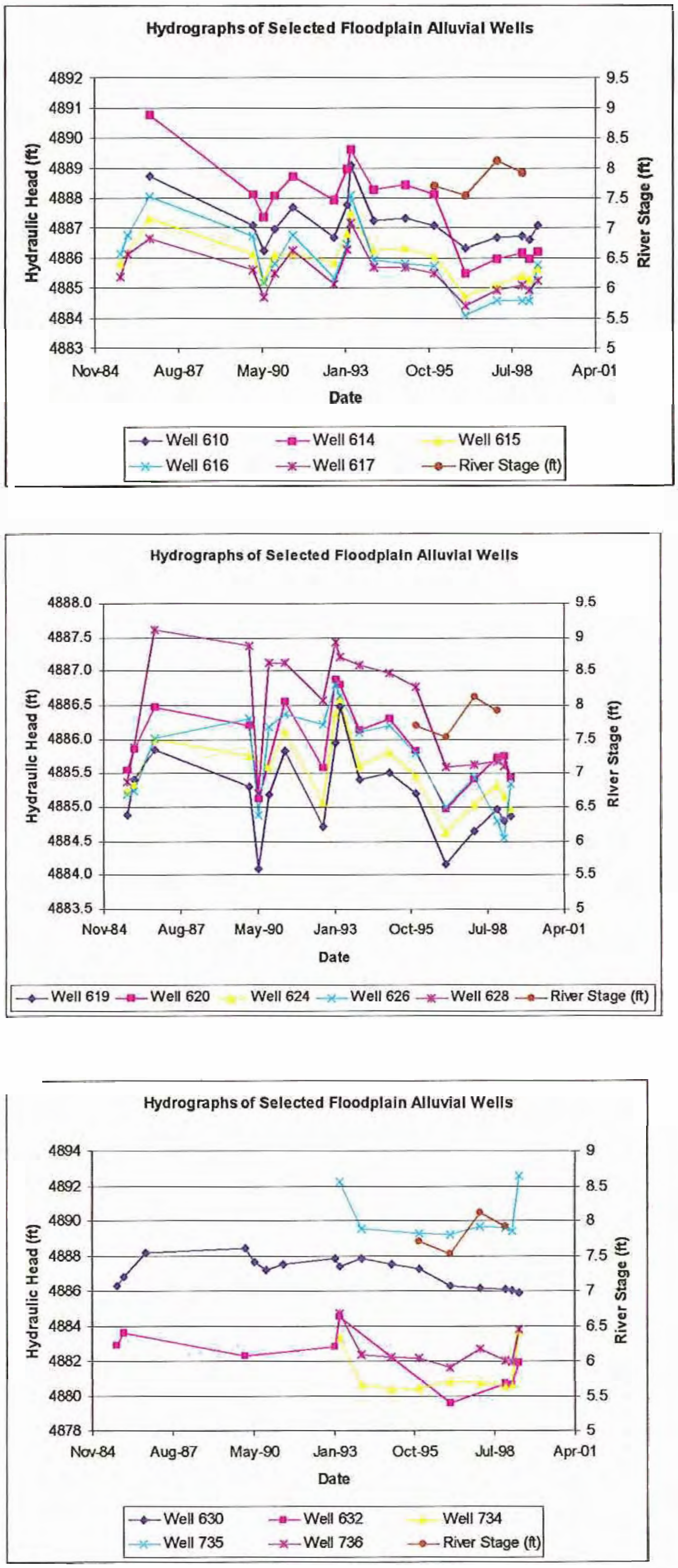


Figure 4–10. Hydrographs of Selected Floodplain Wells, Shiprock, New Mexico, UMTRA Site

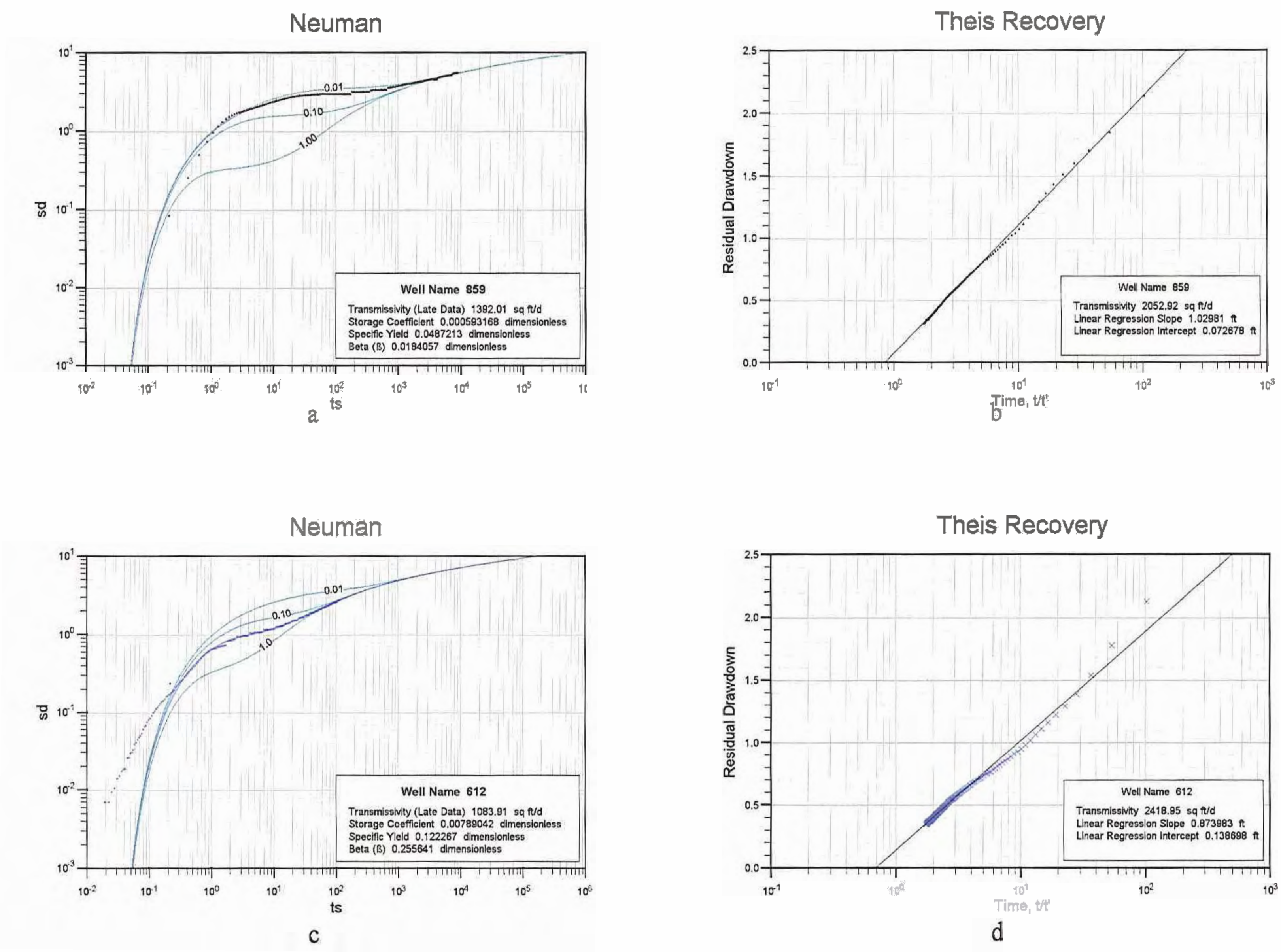


Figure 4-11. Aquifer Test Data Collected While Pumping From Well 858 at 60 gpm: (a) Drawdown in Relation to Time for Observation Well 859, (b) Residual Drawdown in Relation to Dimensionless Time for Observation Well 859, (c) Drawdown in Relation to Time for Observation Well 612, and (d) Residual Drawdown in Relation to Dimensionless Time for Observation Well 612, Shiprock, New Mexico, UMTRA Site

Water Balance

The water balance for the floodplain comprises the following components: (1) inflow from the San Juan River, (2) inflow that is due to recharge of precipitation and runoff, (3) inflow from well 648, and (4) outflow to the San Juan River. Table 4–4 presents a summary of the water balance for the floodplain alluvial aquifer. The approximately 5-percent difference between estimated inflows and outflows is probably equivalent to the potential error in the water balance components. The water balance indicates that about 70 percent of the ground water in the floodplain alluvial aquifer originates as flow from artesian well 648. Discharge from well 648 is routed to and enters the floodplain at the mouth of Bob Lee Wash. Inflow from the San Juan River accounts for approximately 20 percent of the water in the aquifer, and recharge from precipitation accounts for approximately 10 percent. Outflow from the aquifer is mainly due to discharge to the San Juan River. Figure 4–12 illustrates the locations of the various flow components of the water balance.

Table 4–4. Water Balance for the Floodplain Alluvial Aquifer, Shiprock New Mexico UMTRA Site

Flow Component	Inflow (ft^3/day)	Outflow (ft^3/day)
Inflow from San Juan River	3,600	0
Inflow of Recharge	2,600	0
Inflow from Well 648	12,320	0
Outflow to San Juan River	0	19,400
Total	18,500	19,400

Evapotranspiration is probably a minor component, as evidenced by the wetland area near the mouth of Bob Lee Wash and the abundant, phreatophytic, salt cedar vegetation. This component exists during the growing season (April through October) and is virtually absent during the remainder of the year. Evapotranspiration is not quantified in the water balance but the remaining components are.

Component 1: Inflow from the San Juan River

Inflow from the San Juan River is estimated graphically using the water table contour map (Figure 4–12) in conjunction with Darcy's law. The map shows that the easternmost section of the aquifer is dominated by inflow from the San Juan River. At its widest point, the southern section of the aquifer is approximately 900 ft wide. The transmissivity (T) of the alluvial aquifer is approximately 2,000 ft^2/day (MACTEC calculation U0064500). The water table map indicates that the hydraulic gradient is approximately 0.002.

Volumetric inflow (Q_{in}) from the San Juan River is

$$Q_{\text{in}} = (2{,}000\ \text{ft}^2/\text{day}) \times (900\ \text{ft}) \times (0.002) = 3{,}600 \text{ cubic feet per day } (\text{ft}^3/\text{day}).$$

Component 2: Inflow that is Due to Recharge of Precipitation and Runoff

Annual precipitation in the Shiprock area is approximately 7 in. It is assumed that inflow that is due to precipitation and runoff accounts for approximately 30 percent of the total. The surface area of the floodplain alluvial aquifer is 124 acres (5,401,440 square feet [ft^2]). Therefore, the volumetric recharge to the aquifer is 2,600 ft^3/day. However, no explicit measurements of natural recharge are available for the site.

Component 3: Inflow from Well 648

Discharge from well 648 was measured as 64 gpm (12,320 ft^3/day). It is assumed that transit losses are negligible and that essentially all the flow from well 648 is discharged to the floodplain at the mouth of Bob Lee Wash.

Component 4: Outflow to the San Juan River

Outflow to the San Juan River is the primary mode of discharge from the floodplain alluvial aquifer. Outflow is estimated graphically from the water table map in combination with Darcy's law. A schematic depiction of flow components for the alluvial aquifer illustrates the discharge to the San Juan River (Figure 4–12). By summing up the individual discharge components from the aquifer, the total discharge to the San Juan River is estimated to be 19,400 ft^3/day.

Volume of Water in Floodplain Alluvial Aquifer

The volume of water stored in the alluvial aquifer is estimated by multiplying the average saturated thickness (12.4 ft) by the surface area of the aquifer (5,401,440 ft^2) and by the assumed porosity of the alluvium (0.30). The result, expressed to three significant figures is 20.1 million ft^3 (150 million gallons).

4.3.2.2 Terrace Ground Water System

Aerial photography from 1935 (Figure 3–1) of the Shiprock millsite area prior to existence of the mill reveals that the terrace region was extremely arid. There were no visible sources of natural recharge and no evidence of seepage along the escarpment. Because the photos were taken before the existence of flowing well 648, no perennial surface water was evident in Bob Lee Wash. The irrigation canal south of the San Juan River was also absent; consequently, there was no source of water for a terrace aquifer south of the San Juan River. For all practical purposes, the terrace gravels received little to no recharge or discharge and were essentially dry.

In contrast to the 1935 observation, more recent aerial photographs and field observations indicate that during the time of milling operations at the site, large quantities of water were being pumped onto the terrace to process the uranium ore. Evaporation and raffinate ponds near the mill were full of water, flowing well 648 was discharging ground water from the Morrison Formation, irrigation water was being conveyed to the south side of the San Juan River, and discharge was visible in seeps along the escarpment and in the ephemeral washes. Figure 3–4 indicates that human activities along the terrace by 1962 had in large measure created the sources of water that are now part of the terrace ground water system.

To further evaluate the theory that the terrace alluvium is ground water system anthropogenic in origin, an analog site with comparable geologic and hydrologic features was located on an adjacent terrace about 1 to 2 mi east southeast of the disposal cell (see Plate 1). Test wells 800 through 803 were drilled on the analog terrace site. There is no water either in the terrace gravel section nor in the upper part of the Mancos Shale in these wells at the terrace analog site. This

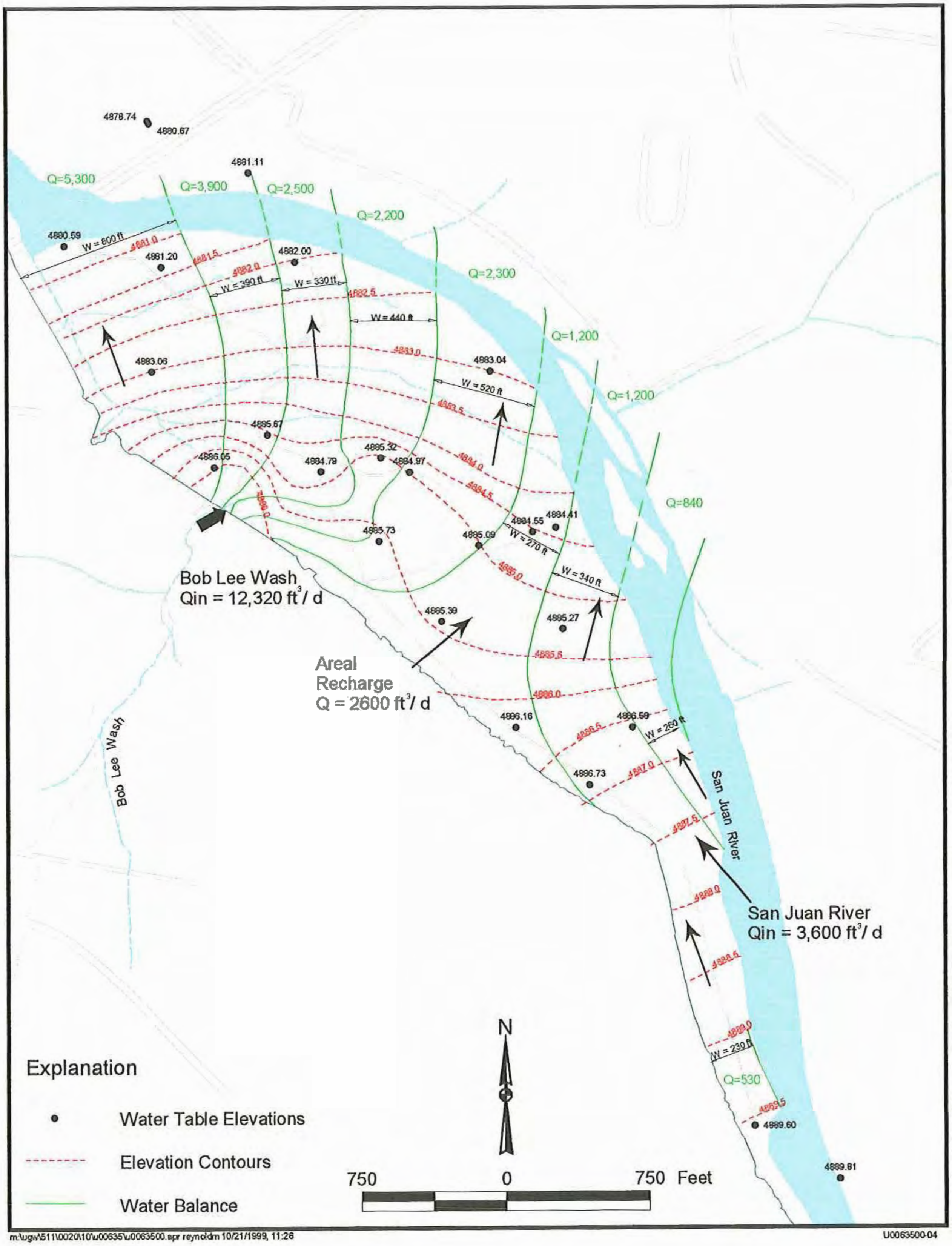


Figure 4–12. Generalized Depiction of Flow Components for Alluvial Aquifer, Shiprock, New Mexico, UMTRA Site

evidence supports, but does not prove, the hypothesis that the terrace near the disposal cell was dry prior to milling, irrigation, and other anthropogenic activities.

Water-Level Measurements

As mentioned in Section 4.1, some water wells were installed at the site in 1984 and some in 1993. Figure 4–13 presents the hydrographs for the terrace alluvium wells that span the longest interval in time. Wells 602 and 600 have the longest period of record for wells installed in the terrace. Uranium milling at the site began in 1954 and ended in 1968. Because the mill was only in operation for 14 years, and 20 years elapsed before ground water measurements began, the decline in the assumed ground water mound was not captured with the ground water measurements performed for the UMTRA Surface Project. The hydrographs reveal small-scale perturbations but do not represent any noteworthy trends.

Figure 4–9 presents a water table map for the terrace ground water system based on the most recent (March 1999) water-level measurements at the site. Discharge from the disposal cell appears to be directed toward Bob Lee Wash and toward the escarpment. Water stored in the terrace system south of the disposal cell appears to occupy a buried channel carved into the Mancos Shale and flows toward the northwest along the orientation of the channel. The gentle hydraulic gradient in the area south of the disposal cell may be a reflection of the gentle slope of the bedrock surface (see Figure 4–7). Figure 4–14 presents a map of the saturated thickness in the terrace ground water system. The map shows that the thickest portions of the system are located along the axis of the buried channel south of the disposal cell. Outside the buried channel zone, the system either consists of a thin veneer of saturation, less than 2 ft thick, or it resides within the weathered portion of the Mancos Shale.

Source and Volume of Mill-Related Ground Water

No records were found that indicate the exact water usage during milling. The only reference that was found indicates that in the uranium circuit "approximately 270 gpm of pregnant solution are contacted with an average of 27 gpm of organic" (Merritt 1971). This reference suggests that water usage was at least 270 gpm. Merritt further states (p. 422) that the treatment rate was about 300 tons of ore per day.

The approximate water balance for the terrace system during the time of milling can be reconstructed to estimate the volume of mill-related water that may be present in the terrace ground water flow system.

The RAP for the Shiprock site (DOE 1985) indicates that the surface area of evaporation ponds at the site was about 20 acres.

From these data it is possible to estimate a water balance for the disposal cell during milling as follows: The infiltration rate into the ground = (feed rate to the ponds) – (evaporation rate) – (runoff rate to floodplain alluvium). Data required to complete this estimate are

- Water flow to evaporation ponds = 270 gpm
- Approximate pan evaporation rate for the area is 70 in. per year (Stone and others 1983)

- Surface area of evaporation ponds = 20 acres (DOE 1985)

The feed rate to the ponds can be estimated to be 270 gpm × (1,440 minutes per day) × (365 days per year) = 142 × 10^6 gallons per year

The evaporation rate can be estimated to be 70 in. per year × (1 ft per 12 in.) × (43,560 square feet per acre) × (20 acres) × (7.48 gallons per cubic feet) = 38.0 × 10^6 gallons per year

Runoff to the floodplain alluvium is assumed to be equal to the sum of all discharge components from the terrace alluvium. In November 1960, these were measured to be 177.7 gpm (U.S. Dept Health Education and Welfare 1962). Therefore, the runoff rate to the floodplain alluvium is estimated to be 177.7 gpm × (1,440 minutes per day) × (365 days per year) = 93.4 × 10^6 gallons per year.

Thus, the annual infiltration rate into the terrace ground water from milling activities is estimated to be (142 × 10^6 gallons per year) – (38.0 × 10^6 gallons per year) – (93.4 × 10^6 gallons per year) = 10.6 × 10^6 gallons per year.

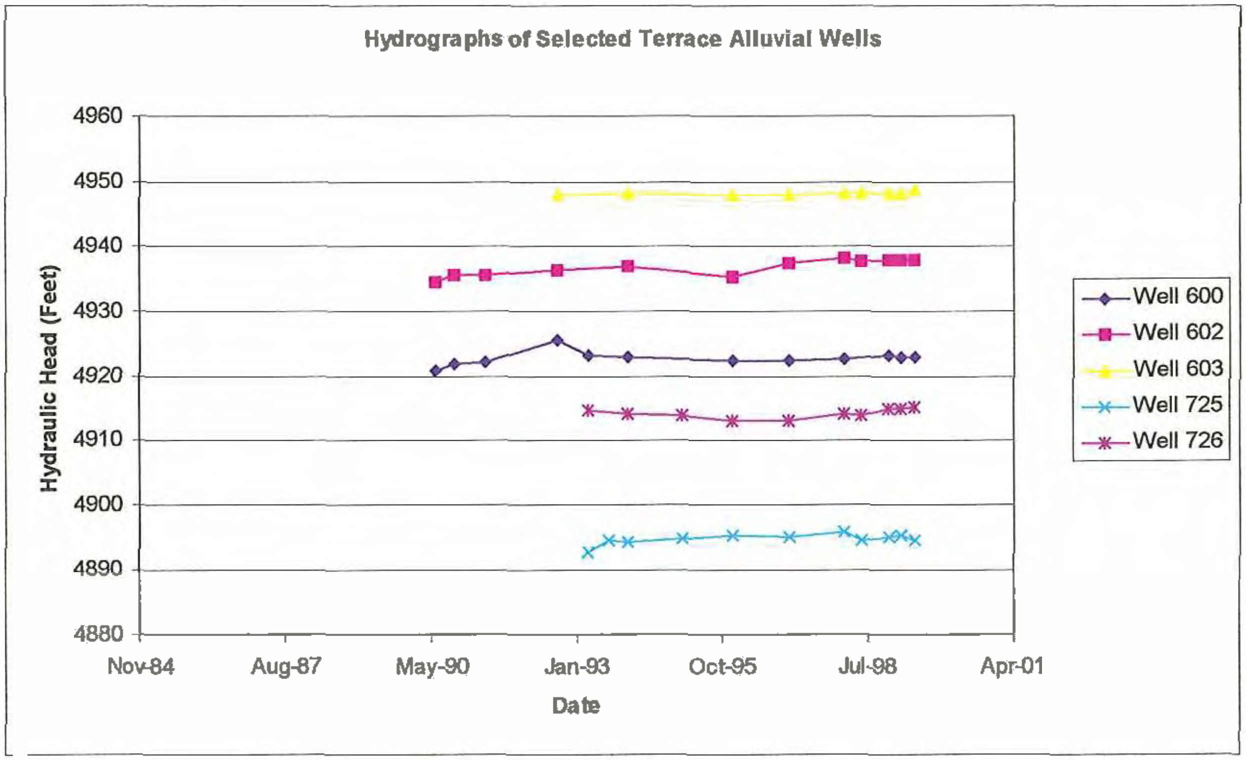
Because milling at the Shiprock site occurred for a period of 14 years, the cumulative volume of water infiltrated into the terrace alluvium could have been approximately 150 × 10^6 gallons.

Aquifer Volume

The contour map of saturated thickness (Figure 4–14) was used to estimate the volume of water stored in the terrace ground water system south of the disposal cell. Table 4–5 presents a summary of the estimated volume of ground water in the buried channel south of the disposal cell. The estimate is computed on the basis of the assumption that the porosity of the terrace alluvium is 0.30. On the basis of this assumption, the minimum volume of ground water south of the disposal cell is approximately 50 × 10^6 gallons.

Table 4–5. Estimate of the Minimum Volume of Ground Water in the Buried Channel Section of the Terrace Ground Water System South of the Disposal Cell

Contour	Surface Area (ft^2)	Volume of Solid (ft^3)	Volume of Liquid (ft^3)	Volume of Liquid (gal)
2	5,518,619	11,037,238	3,311,171	24,767,559
4	3,421,020	6,842,040	2,052,612	15,353,538
6	1,668,512	3,337,024	1,001,107	7,488,280
8	524,297	1,048,594	314,578	2,353,043
10	84,927	169,854	50,956	381,150
Total	11,217,375	22,434,750	6,730,424	50,343,570



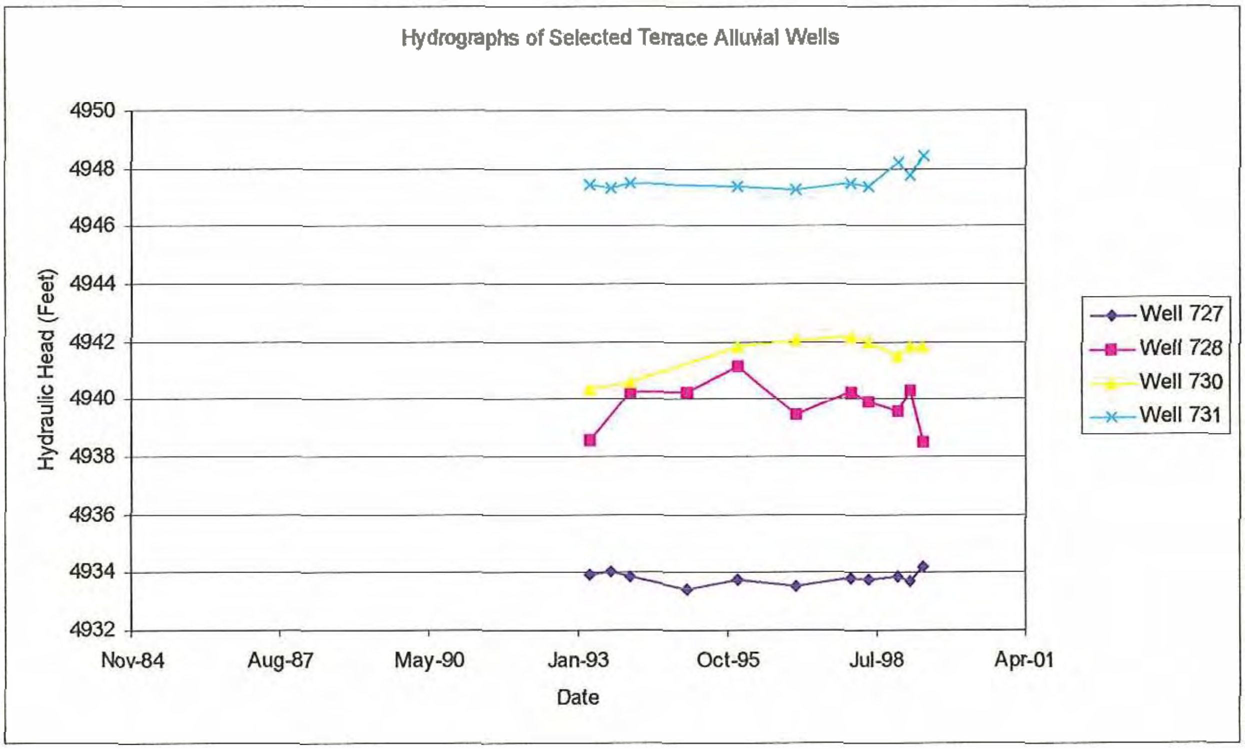


Figure 4–13. Hydrographs of Selected Terrace Alluvial Wells at the Shiprock, New Mexico, UMTRA Site

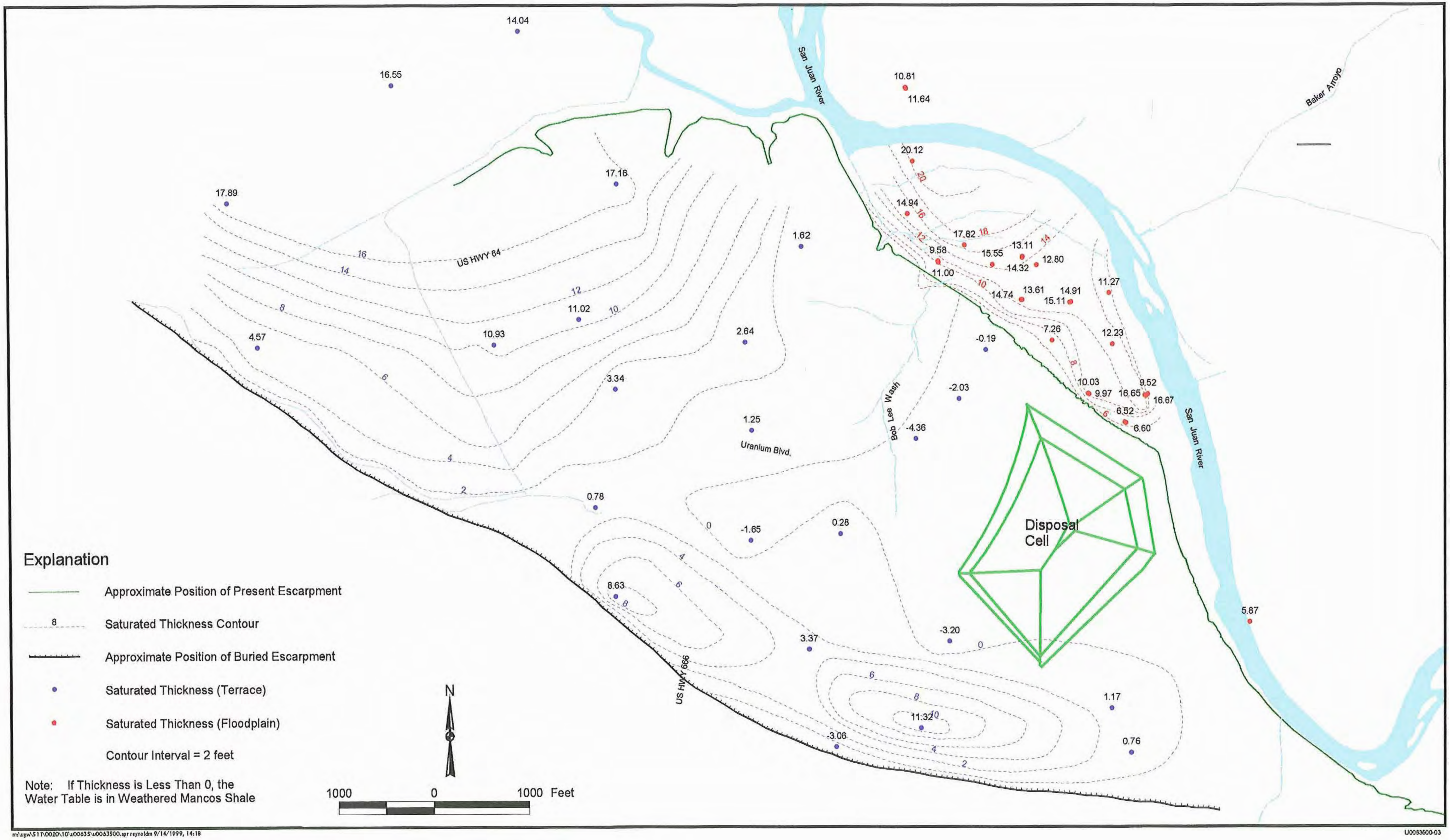


Figure 4–14. Saturated Thickness for Floodplain Alluvial Aquifer and Terrace Ground Water System, Shiprock, New Mexico

Packer Test Results

Table 4–6 presents a summary of the packer test results. The results indicate that the hydraulic conductivity of the bedrock is low, but the bedrock appears to be stratified in terms of its hydraulic conductivity. The upper 10 to 30 ft of the bedrock are weathered.

Table 4–6. Summary of Packer Test Results, Shiprock UMTRA Site

Borehole	Depth Interval (feet below land surface)	Hydraulic Conductivity[a] (cm/s)
820	45–50	J 2.6×10^{-7}
	55–60	J 2.5×10^{-7}
	70–75	J 2.6×10^{-7}
	80–85	J 1.2×10^{-7}
	85–90	J 2.6×10^{-7}
	95–100	J 2.6×10^{-7}
	110–115	J 1.4×10^{-7}
	120–125	J 2.6×10^{-7}
823	55–60	J 2.6×10^{-7}
	65–70	J 2.6×10^{-7}
	77–82	5.8×10^{-7}
	95–100	4.1×10^{-6}
	104–109	J 1.8×10^{-7}
	114–119	J 7.3×10^{-8}
860	30–35	6.0×10^{-4}
	35–40	J 5.2×10^{-7}
	45–50	J 7.7×10^{-7}
	55–60	J 5.2×10^{-7}
	60–65	J 3.9×10^{-7}
862	20–25	1.9×10^{-3}
	34–39	4.7×10^{-6}
	41–46	6.2×10^{-6}
	50–55	3.8×10^{-5}
	55–60	J 1.6×10^{-7}

[a] J represents the quantitation limit for the test.

The weathered section of the formation has hydraulic conductivities in the range of 1×10^{-4} to 1×10^{-6} centimeters per second (cm/s); consequently, it is capable of storing and transmitting limited quantities of ground water. The bedrock below the uppermost section appears to be much less weathered, even though field observations of the core samples indicate significant subhorizontal bedding-plane partings at depth. Perhaps the release of the overburden pressure during core recovery make these partings appear more pronounced. Hydraulic conductivity of the unweathered shale appears to be less than 1×10^{-7} cm/s.

Aquifer Pumping Test Results

The pumping tests performed in the terrace ground water system were designed to test the two different stratigraphic sections of the flow system: the terrace alluvial gravel and the weathered Mancos Shale bedrock. Two tests were conducted: the first was at control well 818 and the second was at well 817.

The pumping rate at control well 818 was 1.86 gpm for 24 hours. A recovery test was initiated immediately after the withdrawal test. The observation well for this test was well 604; it is located 18.9 ft from well 818. Figures 4–2 and 4–3 show the location of these wells and a general cross section of the test site. Observation well 604 is screened mostly in the upper part of the Mancos Shale. However, the sand filter extends into the overlying terrace alluvium, and the well responds to pumping at well 818. The transmissivity determined for well 604 is about 220 ft^2/day. Because the saturated thickness of the terrace alluvium is about 10 ft near well 604, the hydraulic conductivity of the terrace alluvium at that location is about 22 ft/day. The recovery test in control well 818 indicated a transmissivity of approximately 85 ft^2/day, and, on the basis of a 10-ft saturated thickness, a corresponding hydraulic conductivity of 8.5 ft/day. The average of the hydraulic conductivity measurements is approximately 15 ft/day. Perhaps a more representative transmissivity could be obtained if the observation wells were better coupled to the aquifer. Figure 4–15 presents the results of the pumping test for well 818. Test details are presented in MACTEC calculation U0064500.

The pumping rate at control well 817 was 0.25 gpm for 24 hours. A recovery test began immediately after the conclusion of the withdrawal test. The observation well for this test was well 602; it is located 15.8 ft from well 817. Figures 4–2 and 4–3 show the location of these wells and a general cross section at the test site. Observation well 602 was instrumented during the initial step tests, but there was no measurable drawdown. Consequently, the only useful data provided from this test were the recovery data from pumping well 817. These data indicate that the transmissivity at this location is about 3.5 ft^2/day. The low transmissivity at well 817 is not surprising considering that the well is entirely screened within the Mancos Shale. On the basis of a minimum of 10 ft of saturated thickness in this section of weathered Mancos Shale, the hydraulic conductivity is computed to be 0.35 ft/day. This value agrees with the highest hydraulic conductivities obtained with packer tests during the core drilling on this project. Figure 4–15 presents the results of the pumping test for well 817. Additional test details are presented in MACTEC calculation U0064500.

The terrace alluvium near the 818/604 well pair is sufficiently conductive that water can flow readily to a well. Similarly, the weathered Mancos Shale near well pair 817/602 yields small quantities of water to a well. Because the well yields at both locations exceed 150 gallons per day, the terrace alluvium is sufficiently permeable to be classified as an aquifer by UMTRA standards (40 CFR 192.11).

Hydrostratigraphic Controls

The terrace alluvial ground water system is topographically elevated above the floodplain alluvial aquifer. The primary control on the separation of these two flow systems is hydrostratigraphic or the low hydraulic conductivity of the Mancos Shale that underlies both gravel systems. Ground water in the terrace ground water system flows to the northwest along the buried alluvial channel and to the north in the weathered Mancos Shale. A minor component of ground water flow may also exist toward the southeast, along the top of the siltstone bed in the Mancos Shale. The dip of the siltstone bed is approximately 1° to the east, and it may exist in subcrop beneath the extreme eastern head of the buried channel south of the disposal cell (see Figure 4–7). As presented in Section 4.4, "Geochemistry," similar water chemistry in the terrace

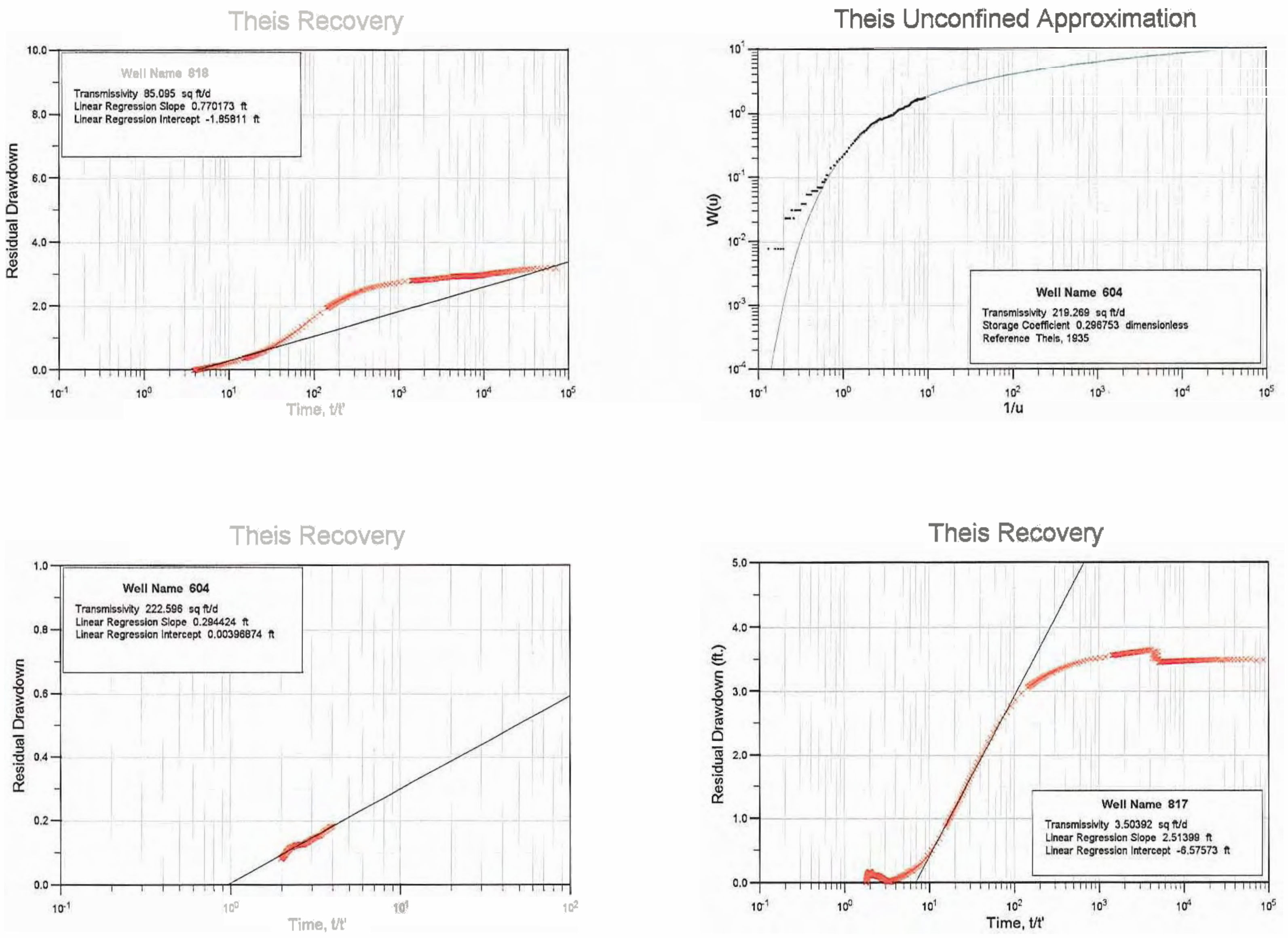


Figure 4–15. Aquifer Pumping Test Data for Pumping Well 818 Discharge of 1.86 gpm and Pumping Well 817 Discharge of 0.25 gpm: (a) Residual Drawdown in Relation to Dimensionless Time at Pumping Well 818, (b) Drawdown in Relation to Time at Observation Well 604, (c) Residual Drawdown in Relation to Dimensionless Time for Observation Well 604, and (d) Residual Drawdown in Relation to Dimensionless Time at Pumping Well 817 at the Shiprock, New Mexico, UMTRA Site

ground water south of the disposal cell and in the surface water in Many Devils Wash suggests that a flow pathway exists between these two locations. The ground water discharge into Many Devils Wash is approximately 0.3 gpm.

Additional details of the hydrogeologic relationships of this pathway remain to be resolved and will be investigated in fall 1999. But in theory, the hydraulic conductivity of the weathered Mancos Shale can be estimated from the following factors: (1) the dip of the marker bed, (2) the measured amount of flow in Many Devils Wash, and (3) the length of the wash that receives seepage from the west. As mentioned, the flow is 0.3 gpm and the dip of the bed is about 1°. The length of the wash where the discharge occurs is about 700 ft. The average thickness of the wet zone is not known precisely but is probably between 1 and 3 ft, so assume 2 ft. From Darcy's law we have

$$K = (Q) / (dh/dl)\, A = [(0.3 \text{ gal/min})\, (1440 \text{ min/day})\, (\text{ft}^3/7.48 \text{ gal})]/[\tan(1°)\, (700 \text{ ft})\, (2 \text{ ft})]$$
$$K = 2 \text{ ft/day } (7 \times 10^{-4} \text{ cm/s})$$

This estimated hydraulic conductivity value is computed rather crudely, but it is not unreasonable for the weathered Mancos Shale. It also compares favorably with the range of hydraulic conductivity values of 6.0×10^{-4} and 1.9×10^{-3} cm/s obtained from packer tests of the weathered Mancos Shale.

Terrace and Floodplain Alluvium Interactions

Four new well nests—820 through 822, 860 and 861, 823 through 825, and 862 and 863—were drilled to evaluate the hydraulic interconnection between the terrace system and the floodplain alluvium. These nests are illustrated in cross sections F–F' and G–G' on Plate 3. Measurements of hydraulic head at these well nests indicate that the hydraulic gradient is predominantly vertical, and the horizontal components of gradient are practically absent. These findings suggest that transfer of water from terrace system to the floodplain alluvium, if it exists, occurs in localized zones of preferred flow rather than as a large-scale phenomenon.

As described in Section 4.4, "Geochemistry," elevated concentrations of contaminants in the floodplain alluvium near the base of the escarpment strongly suggest that a contaminant source feeds the floodplain alluvium from the terrace. The exact manner in which the ground water is transferred to the floodplain is unknown. However, several hypotheses may apply: (1) the water is transported through localized zones of higher conductivity and are hidden from view because they enter the floodplain below the ground surface; (2) the water is transported along the axes of gulches and washes that were filled in during the remediation and are also hidden from view; or (3) the water is transported along vertical fractures or joints in the Mancos Shale that are difficult to intersect with vertical boreholes.

Any combination of these factors may also be present. Section 4.7, "Summary of Additional Data Needs," presents additional characterization planned to further evaluate the nature of the interaction between the terrace and the floodplain.

Terrace Water Balance

The water balance for the terrace comprises the following components: (1) infiltration of precipitation and runoff, (2) infiltration of water from the NECA gravel pit, (3) infiltration of drainage from the disposal cell, (4) infiltration of irrigation water, (5) leakage from the water supply and sewer lines, (6) discharge to the escarpment, (7) discharge to Many Devils Wash, (8) discharge to the irrigation return-flow system, and (9) discharge to the San Juan River. Table 4–7 lists the locations of the various flow components of the water balance.

Table 4–7. Preliminary Water Balance for the Terrace Ground Water System at the Shiprock, New Mexico, UMTRA Site

Flow Component	Inflow (ft^3/yr)	Outflow (ft^3/yr)
1: Infiltration of Precipitation and Runoff	227,500	
2: Infiltration of Water from the NECA Gravel Pit	<< 39,000	
3: Infiltration of Drainage from the Disposal Cell	10,500	
4: Infiltration of Irrigation Water	53,600,000	
5: Leakage from the Water Supply and Sewer Lines	Unknown	
6: Discharge to the Escarpment		562,000
7: Discharge to Many Devils Wash		21,000
8: Discharge to the Irrigation Return-Flow System		15,768,000
9: Discharge to the San Juan River		37,529,000
Total (rounded)	**53,880,000**	**53,880,000**

Component 1: Infiltration of Precipitation and Runoff

Infiltration of precipitation and runoff occurs throughout the area where the terrace exists. However, its effect is most pronounced south of the disposal cell because a large catchment was created in 1986 during remediation when the radon cover borrow pit was excavated for disposal cell construction. Most of the silty loess material that naturally mantled the terrace gravel deposit was removed, leaving only a thin veneer of silt overlying the terrace gravel. Under natural conditions, the thick silt layer protected the terrace gravel from direct infiltration. Under natural conditions, such as those that existed before 1935, the terrace gravel was mantled with a gently sloping silt layer and a drainage pattern that channeled the runoff to the ephemeral washes, such as Bob Lee Wash. Consequently, the terrace gravel received little to no recharge.

Today, the radon cover borrow pit functions as a rainwater runoff-collection feature. Runoff is channeled into it, and the pit is graded and has a sump along its northwestern margin. Because much of the natural silt cover has been removed, the gravel is near the land surface and acts as a conduit to recharge the terrace alluvial system. Runoff from the upland area south of the disposal cell collects in the cell cover borrow area via the rock-armored channels constructed at intervals around the perimeter of the borrow pit. This greatly increases the amount of water available for infiltration.

It is assumed that infiltration of runoff accounts for at least 10 percent of precipitation. The total area of both the radon cover borrow pit and the region tributary to it is 3.9×10^6 ft^2. When multiplied by the infiltration rate, the volume is estimated to be at least 227,500 cubic feet per year (ft^3/yr).

Component 2: Infiltration of Water from the NECA Gravel Pit

Water is drawn from the San Juan River and used in the NECA gravel pit primarily for dust control. It is applied at the crusher and results in about 1-percent moisture content by weight. During the past year, the gravel pit created approximately 121,000 tons of aggregate and used 290,000 gallons (1,210 tons) of water (Jonathan James, 1999 personal communication) according to the following schedule:

October 1998	85,000 gallons
November 1998	35,000 gallons
December 1998	35,000 gallons
January 1999	20,000 gallons
February 1999	60,000 gallons
March 1999	55,000 gallons

It is assumed that a small percentage of the water applied to the aggregate leaked into the terrace gravel material. However, it is not believed to constitute an important fraction of the terrace water balance because the volume of water is low (less than 39,000 ft^3/yr).

Component 3: Infiltration of Drainage from the Disposal Cell

The rate of disposal cell drainage was estimated during the preparation of the RAP (DOE 1985), and no additional investigation of the disposal cell or numerical modeling of infiltration through the cover was performed. The numbers provided at that time were assumed to represent an upper limit of drainage through the cell. The calculation presented in the RAP states that the infiltration through the cover is 0.04 in. per year. It also states that the area of the disposal cell is 72 acres ($3.14 \times 10^6 \text{ ft}^2$). The annual flow through the cover is estimated as

$$0.04 \text{ in./yr } (3.14 \times 10^6 \text{ ft}^2)(1 \text{ ft}/12 \text{ in.}) = 10{,}500 \text{ ft}^3/\text{yr}$$

Because leachate from the disposal cell would contain significantly higher chemical concentrations than other sources of recharge, it may function as an important source of chemical contamination in the terrace alluvial unit.

Component 4: Infiltration of Irrigation Water

During the months of April through October, water may be present in the irrigation canal system west of the disposal site and west of U.S. Highway 666. The water is conveyed to the Helium Lateral Canal through a siphon that originates along the Hogback Canal near the water treatment plant. Total flow through the siphon to the high point of the canal is 7 to 10 cfs, (Marlin Saggboy, personal communication, August 1999) depending upon the head at the siphon inlet; therefore, the average flow is assumed to be 8.5 cfs. Almost all the flow in the canal is used along its 5-mi length. Canal losses through the system are unknown and detailed measurements along the canal system are not taken. It is assumed that irrigation accounts for almost all the water used. The surface area of irrigated land both north and south of U.S. Highway 64 is approximately 370 acres. Diversions taken north of U.S. Highway 64 account for approximately 50 percent of the total flow in the canal (Marlin Saggboy, personal communication, August 1999). As a rule of thumb, irrigation losses are typically adjudicated to be 20 percent of the application rate. Therefore, the volume of water that passes through the irrigated fields and returns to the San Juan River as irrigation return flow is approximately 3.4 cfs during the 6-month irrigation season or approximately 53,600,000 ft^3/yr. This volume of irrigation water is an estimate of the amount that passes through the system. Because measurements are not taken along the canal, it is difficult to apportion a percentage to ground water and a percentage as pass-through surface water. Because the amount of irrigation water entering the terrace aquifer is critical to modeling simulation, this number will be refined as described in Section 4.7, "Summary of Additional Data Needs."

Component 5: Leakage from the Water Supply and Sewer Lines

Water supply lines and sewer lines are another source of water to the terrace alluvium that probably exists but cannot be accounted for precisely. The locations of these potential sources are unknown and cannot be determined at this time.

Component 6: Discharge to the Escarpment

Discharge to the escarpment includes ground water discharge to Bob Lee Wash, to the seeps and springs along the escarpment, and to the other washes and gulches west of the U.S. Highway 666 Bridge. Table 4–8 lists the visible discharges from the various seeps. Cumulatively, they amount to about 8 gpm. On an annual basis this seepage flux may be 562,000 cubic feet (ft^3) or more. Other locations of discharge are likely present below the ground surface of the floodplain and, judging from ground water contamination, may be present near wells 735, 613, and 614. These locations will be investigated in more detail as described in Section 4.7, "Summary of Additional Data Needs."

Table 4–8. Visible Ground Water Discharge Along the Escarpment

Seepage Location	Estimated Flow (gpm)
Seep 425	0.5
Seep 426	1.0
Seep 922	<0.5
1st Wash	1.5
2nd Wash	0.2
Bob Lee Wash	1
Seeps near 936 area	2
Seeps 200 to 400 ft west of U.S. Highway 666 Bridge	1
Total	8

Component 7: Discharge to Many Devils Wash

This component of discharge is listed separately because it is a terrace-flow component that is believed to flow toward Many Devils Wash. As described in the "Hydrostratigraphic Controls" section, ground water is believed to flow along the top of the siltstone bed in the Mancos Shale. The wintertime discharge at the mouth of Many Devils Wash is assumed to equal the ground water discharge along the wash. The measured discharge was 0.3 gpm (21,000 ft^3/yr).

Component 8: Discharge to the Irrigation Return-Flow System

This component is not monitored by NIA but is assumed to be about 1 cfs over the course of the 6-month irrigation period or 0.5 cfs on an annual basis. This flow rate may also be expressed as 15,770,000 ft^3/yr. This value will be measured during fall 1999 field work.

Component 9: Discharge to the San Juan River

This final component cannot be measured with a flow meter; therefore, it is estimated by difference from the other components. Regardless of what the true value may be, its relative magnitude overwhelms the other discharge components. It is solved to 37,830,000 ft^3/yr. As described in Section 4.7, "Summary of Additional Data Needs," a better estimate of this component will be developed during further characterization of the terrace.

4.4 Geochemistry

DOE collected ground water, surface water, soil, and sediment data from the floodplain and the terrace from September 1985 to early June 1999.

Data from analyses of these samples is extensive; for convenience in interpreting the present water quality, a summary of recent surface and ground water sample analyses from the period of 1997 to March 1999 is presented in Appendix B. The more extensive and comprehensive data from analyses of all samples is presented in CD-ROM format in Appendices C through E. Data used to assess the current surface and ground water quality were mainly from the most recent routine sampling round in March 1999.

4.4.1 Surface Water Chemistry

4.4.1.1 Floodplain

Surface water from the floodplain drains into the adjacent San Juan River. Two locations upgradient of the floodplain (898 and 888) were sampled to provide river-water quality data representing background. Location 888 is downgradient of the confluence with the Chaco River. A summary of background water quality data from the March 1999 sampling is presented in Table 4–9. Higher nitrate, sulfate, chloride, and sodium concentrations in samples from sampling location 888 were probably due to the influence of the Chaco River entering the San Juan River. Uranium concentrations were also higher in samples from location 888 than at location 898 but were close to the analytical detection limit. Location 898 is used to represent San Juan River water quality immediately upgradient of the millsite floodplain.

Table 4–9. Background Concentrations in the San Juan River (upgradient)[a]

Location	pH	EC (µS/cm)	Ca (mg/L)	Cd (mg/L)	Cl (mg/L)	Fe (mg/L)	K (mg/L)	Mn (mg/L)	Mg (mg/L)	Na (mg/L)	NH_4 (mg/L)	NO_3 (mg/L)	Ra-226 (pCi/L)	Ra-228 (pCi/L)	Sb (mg/L)	Se (mg/L)	SO_4 (mg/L)	Sr (mg/L)	TDS (mg/L)	U (mg/L)
888	8.41	1050	85.1	< 0.001	31.8	0.005	4.2	0.017	32.3	99.5	0.044	3.63	0.14	0.81	< 0.001	0.002	369	1.29	730	0.004
898	8.42	583	57.7	< 0.001	15.1	0.014	2.43	0.008	12.2	42.3	0.01	0.891	0.14	0.8	< 0.001	< 0.001	165	0.786	378	0.002

[a] EC = Electrical conductivity; µs/cm = microsiemens per centimeter; pCi/L = picocuries per liter; and TDS = Total dissolved solids

Figure 4–16 shows a Piper diagram for samples (March 1999 data) of San Juan River water. The chemical signature of location 888 is different from that of the other locations, indicating that the quality of river water at that location may be influenced by the Chaco River. Data from each of the last two sampling events (December 1998 and March 1999), omitting location 888, indicate that uranium concentrations are slightly higher in samples from the San Juan River on site and downgradient than in samples collected upgradient of the millsite floodplain (Figure 4–17). All uranium concentrations, however, are near the instrument detection limit where analytical uncertainty is greatest. Therefore, it is inconclusive if uranium concentrations increase in the San Juan River because of contamination at the millsite. Uranium concentrations in samples collected at or downgradient of the millsite are less than 0.0032 mg/L.

TDS concentration is also high in samples collected at location 888 near the Chaco River. On average, the pH of the San Juan River is 8.4. Uranium concentrations in samples collected at sampling locations 553, 896, and 895 were slightly higher than in samples collected at background location 898 for both the December 1998 and March 1999 sampling. This is the part of the millsite floodplain where much of the ground water discharges. It correlates with the plume configuration shown on Figure 4-18 and supports the possibility of millsite influence. Concentrations in samples from these locations on the millsite floodplain, however, are lower than samples collected at upgradient location 888 near the Chaco River inflow, Figures 4-18, 4-21, and 4-22.

Concentrations of some constituents vary seasonally. Sulfate, uranium, nitrate, chloride, ammonium, and TDS concentrations were higher in samples from the December sampling than the March 1999 sampling, whereas the pH was slightly lower in December 1998 (Figure 4-17). This variation may be due to different flow regimes of the river and different influxes from the floodplain. Ammonium concentrations in samples from sampling locations 553, 896, and 895 are 3 times higher in December 1998 than in March 1999, perhaps because of the flushing action from a heavy precipitation event in late October 1998; however, chloride and nitrate concentrations did not vary with the seasons.

Table 4–10 provides a summary of surface water data for selected constituents for the floodplain and the terrace. The background concentrations are an average of available (December 1998 and March 1999) data at sampling location 898 for San Juan River water.

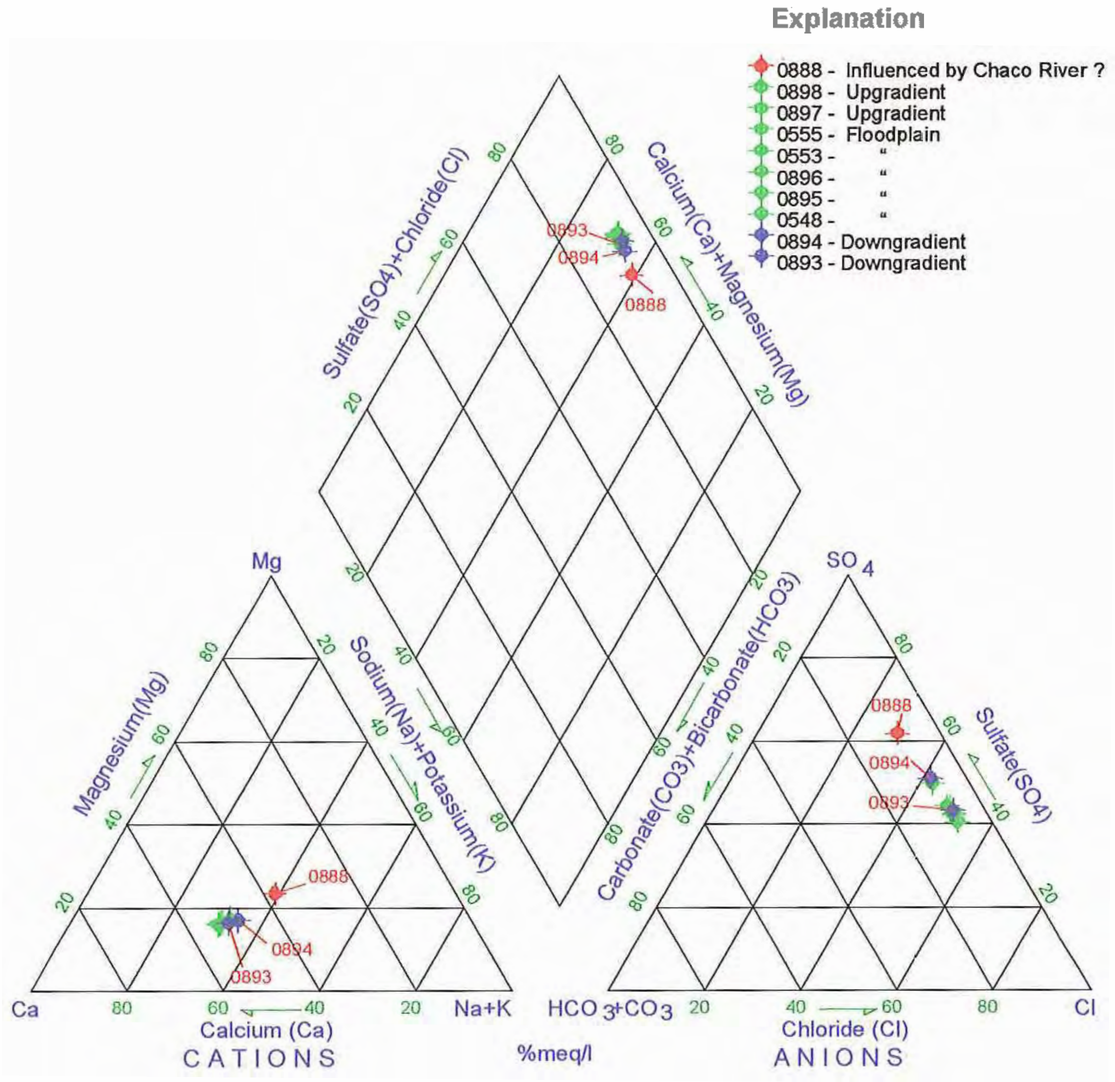
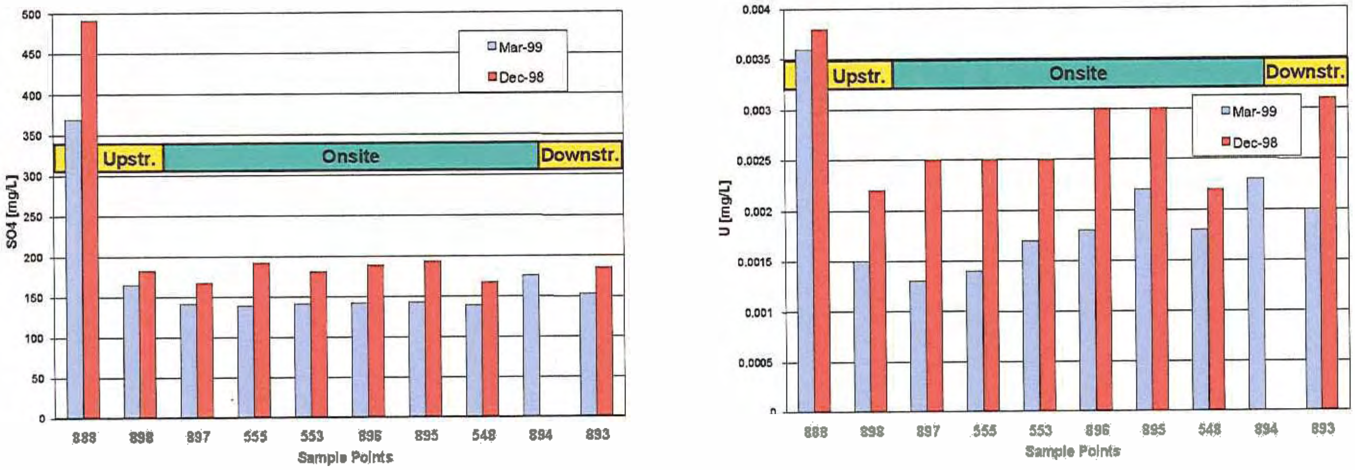
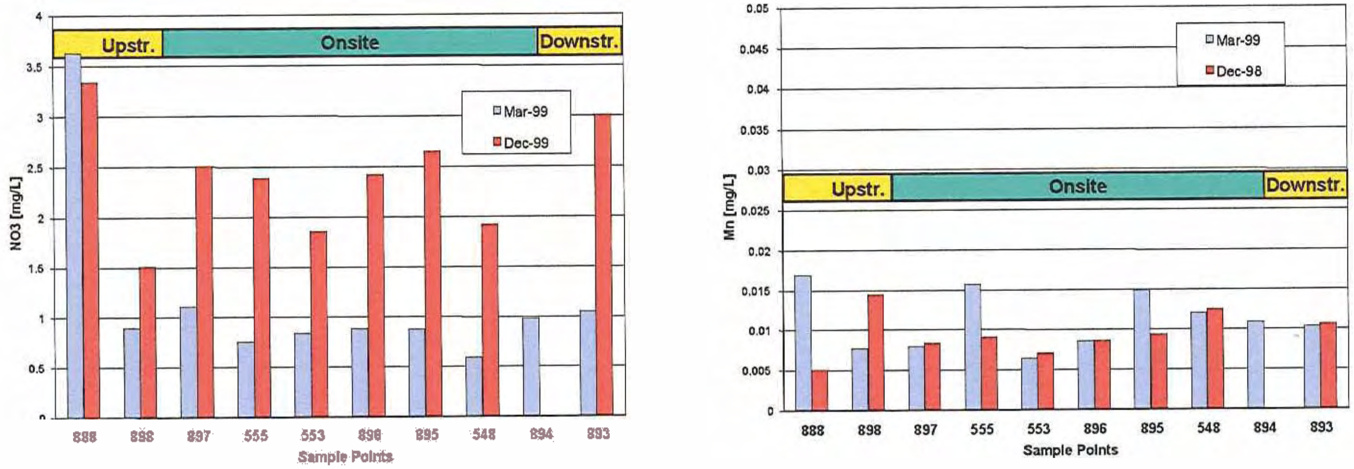


Figure 4–16. Piper Diagram of San Juan River Water



Sulfate

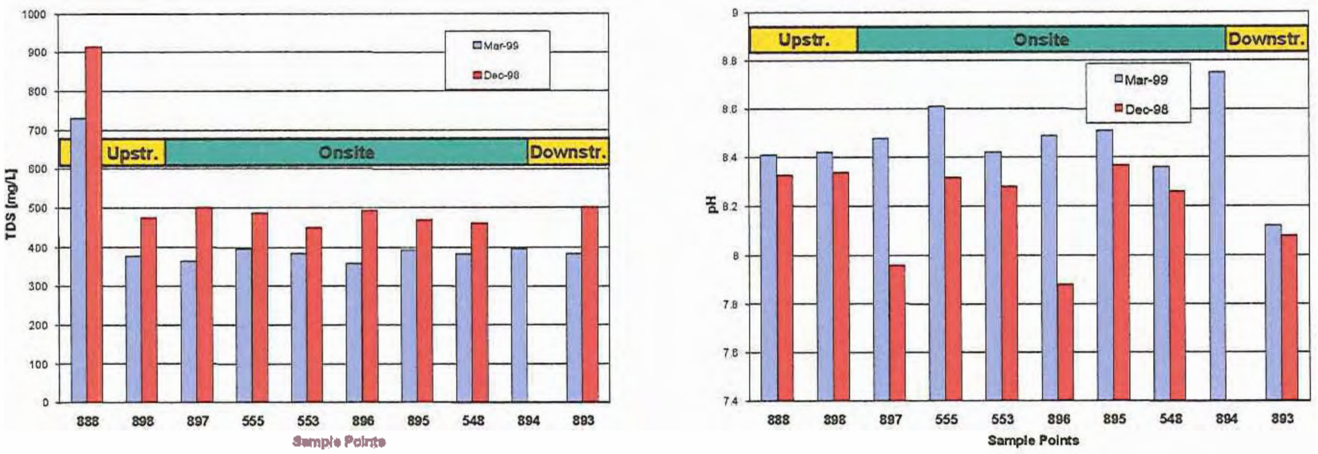
Uranium



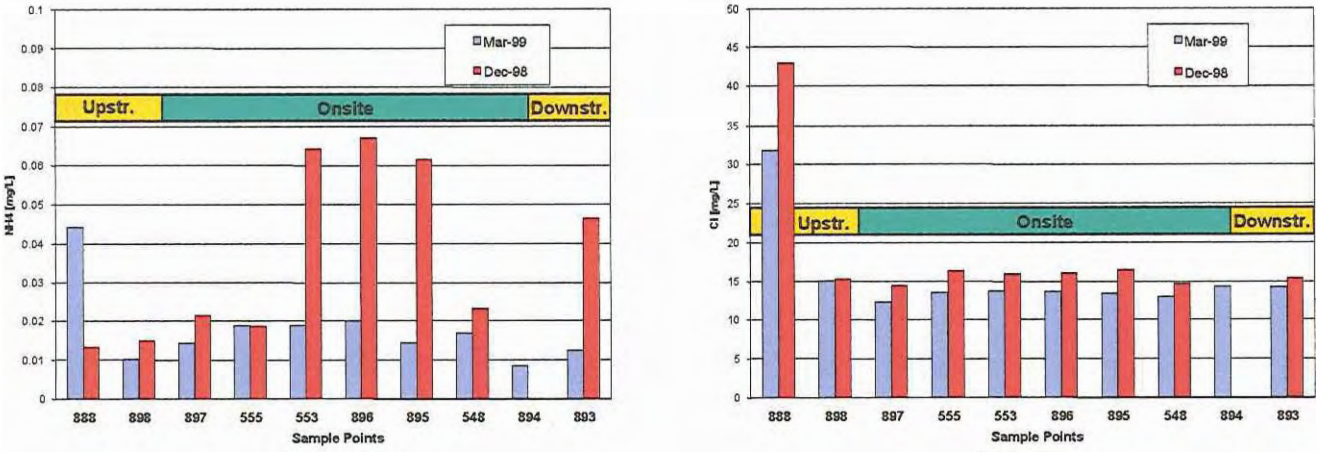
Nitrate

Manganese

Figure 4-17. Spatial Distribution of Concentrations in San Juan River Water (Data: December 1998, March 1999



TDS pH



Ammonium Chloride

Figure 4–17 (continued). Spatial Distribution of Concentrations in San Juan River Water (Data: December 1998, March 1999)

Table 4–10. Concentrations of Selected Constituents in Surface Water Samples[a]

Constituent	UMTRA MCL	Location	Background[b]	Range	FOD	Location (max. conc.)
Ammonium (mg/L)	no MCL	Floodplain	0.013	0.009 – 0.164	19/19	963
		Terrace		0.014 – 0.299	6/6	425
Antimony (mg/L)	no MCL	Floodplain	< 0.001	< 0.001	0/19	
		Terrace		< 0.001	0/6	
Arsenic (mg/L)	0.05	Floodplain	< 0.001	< 0.001	0/19	
		Terrace		< 0.001	0/6	
Cadmium (mg/L)	0.01	Floodplain	< 0.001	< 0.001	0/19	
		Terrace		< 0.001	0/6	
Magnesium (mg/L)	no MCL	Floodplain	13.6	10.3 – 265	19/19	887
		Terrace		14.5 – 1,440	6/6	886
Manganese (mg/L)	no MCL	Floodplain	0.011	0.006 – 0.36	19/19	887
		Terrace		0.002 – 0.145	6/6	425
Nitrate	44	Floodplain	1.2	0.461 – 165	19/19	887
		Terrace		1.36 – 3,800	15/15	886
^{226}Ra + ^{228}Ra (pCi/L)	5	Floodplain	0.85	0.69 – 1.34	19/19	658
		Terrace		0.86 – 1.73	6/6	889
Selenium (mg/L)	0.01	Floodplain	< 0.001	< 0.001	3/19	887
		Terrace		< 0.001 – 2.78	5/6	886
Sodium (mg/L)	no MCL	Floodplain	43.7	37.3 – 1,030	19/19	655
		Terrace		215 – 10,500	6/6	886
Strontium (mg/L)	no MCL	Floodplain	0.844	0.711 – 11.6	19/19	658
		Terrace		5.28 – 11.7	6/6	662
Sulfate (mg/L)	no MCL	Floodplain	173	134 – 2,540	19/19	655
		Terrace		760 – 23,400	15/15	886
Uranium (mg/L)	0.044	Floodplain	0.002	0.001 – 0.05	19/19	887
		Terrace		< 0.001 – 1.59	14/15	900

Data: March 1999

[a] MCL: maximum concentration limit; FOD: frequency of detection.

[b] Background concentrations are an average of concentrations of samples collected in December 1998 and March 1999 at location 898.

4.4.1.2 Terrace

Surface water on the terrace includes water from artesian well 648 that drains into Bob Lee Wash, water in Bob Lee Wash above the well 648 outflow, water in Many Devils Wash, and water in the NECA pond. The high nitrate concentrations in samples from Many Devils Wash (up to 3,800 mg/L) and the high uranium concentrations in samples from Bob Lee Wash (up to 1.59 mg/L) indicate millsite contamination. Further hydrochemical details are discussed in Section 4.4.2.2,"Terrace".

Concentrations of contaminants of potential concern (COPCs) in samples from the NECA pond (sampling location 849) on the terrace were below background. Uranium and nitrate concentrations in samples from the pond were below their detection limits.

4.4.2 Ground Water Chemistry

4.4.2.1 Floodplain

The background concentration is defined as the concentration in portions of the aquifer that are unaffected by milling activity. The background quality of ground water in the floodplain was determined from analyses of samples from three monitor wells (850, 851, 852) at an upstream floodplain location that is lithologically similar to the millsite floodplain. The average concentrations in samples collected from these three wells in the last two samplings (December 1998 and March 1999) were used to represent background water quality (Table 4-11). Table 4–11 also provides the concentration ranges, the frequency of detection (FOD), and the wells that had samples with the highest concentrations.

Areal Extent of Contamination

The spatial distribution of contamination in the floodplain is shown on plume maps for uranium, nitrate, and sulfate (Figures 4–18 through 4-23). The most recent data (March 1999) were used to prepare the maps. The river and the escarpment were used as geochemical boundaries. During the drilling program, ground water chemical data were collected and analyzed in a mobile laboratory to help identify plume areas. These data were used to guide the drilling program according to the principles of Expedited Site Characterization (ESC). In certain parts of the floodplain, data from samples from monitor wells were supplemented by data from samples from trenches dug by backhoe and analyzed using the ESC process (ASTM 1996).

To demonstrate the movement of the uranium, nitrate, and sulfate plume in the central portion of the floodplain during the last 12 years, data from samples from selected wells with long sampling histories were used to create contour maps (Figures 4–24 through 4-26). The two sets of plume maps are based on different data and cannot be compared in detail. In addition to the plume maps shown in this section, graduated symbol maps based on constituent concentrations in samples from shallow wells on the terrace and the floodplain are presented in Appendix F.

Flushing of uranium, nitrate, and sulfate concentrations in the floodplain occurs in the southeast portion by the San Juan River and in the northwest portion by Bob Lee Wash (Figures 4–24 through 4-26). After the surface reclamation was completed in 1986, the plume centroids for these three contaminants migrated from the central portion of the floodplain to an area near the escarpment. Since 1993, the centroids have stagnated at this position. However, the highest uranium and sulfate concentrations (3.43 and 22,400 mg/L, respectively) in March 1999 were identified in samples from well 854 that is located close to the San Juan River (Figures 4-18 and 4-23).

Time series for uranium, nitrate, sulfate, and TDS concentrations in samples from three wells selected to represent the southern, central, and northern portions of the floodplain are shown on Figure 4–27. The uranium concentration in samples from the central portion of the floodplain (well 619) decreased from 3.0 mg/L in 1985 to 0.9 mg/L in 1992 and then increased again to 1.6 mg/L in 1999. In samples from the same well, sulfate concentrations decreased from about 19,000 mg/L in 1985 to about 12,000 mg/L in March 1999. Nitrate concentrations in samples from well 619 are currently as high as 200 mg/L but have remained below 400 mg/L for the past 9 years.

Table 4–11. Background and Concentration Range of Selected Constituents in Ground Water[a]

Constituents	UMTRA MCL	Location	Background[b]	Range	FOD	Well No. (max. conc.)
Ammonium (mg/L)	no MCL	Floodplain	0.06	0.0174 – 602	31/31	608
		Terrace		0.0036 – 2,160	35/35	603
Antimony (mg/L)	no MCL	Floodplain	< 0.001	< 0.001 – 0.0047	2/30	860
		Terrace		< 0.001 – 0.0049	2/35	820
Arsenic (mg/L)	0.05	Floodplain	< 0.001	< 0.001 – 0.0035	4/30	733
		Terrace		< 0.001	0/35	
Cadmium (mg/L)	0.01	Floodplain	< 0.001	< 0.001	0/30	
		Terrace		< 0.001 –0.0479	4/35	730
Magnesium (mg/L)	no MCL	Floodplain	40	7.37 – 3,540	30/30	854
		Terrace		40 – 3,070	35/35	811
Manganese (mg/L)	no MCL	Floodplain	1.63	0.0151 – 12.8	30/30	854
		Terrace		< 0.001 – 34.5	34/35	603
Nitrate (mg/L)	44	Floodplain	0.28	0.011 – 3,480	31/31	614
		Terrace		0.0408–7,240	35/35	813
$^{226}Ra + ^{228}Ra$ (mg/L)	5	Floodplain	0.860	0.69 – 4.95	29/29	734
		Terrace		0.73 – 15.28	30/30	602
Selenium (mg/L)	0.01	Floodplain	< 0.001	< 0.001 – 1.1	20/30	615
		Terrace		< 0.001 – 6.9	33/35	812
Sodium (mg/L)	no MCL	Floodplain	570	92.1 – 6,040	30/30	854
		Terrace		114 – 6,360	35/35	812
Strontium (mg/L)	no MCL	Floodplain	2.73	0.566 – 16.2	30/30	854
		Terrace		0.166 – 17.6	35/35	813
Sulfate (mg/L)	no MCL	Floodplain	1,485	134 – 22,400	31/31	854
		Terrace		882 – 16,800	35/35	602
Uranium (mg/L)	0.044	Floodplain	0.015	0.0034 – 3.43	30/30	854
		Terrace		0.0025 – 3.04	35/35	826

Data: March 1999

[a] MCL: maximum concentration limit; FOD: frequency of detection.

[b] Background concentrations SHP01: well no. 850, 851, 852; average of concentrations of December 98 and March 99 sampling

The uranium concentrations in samples from the northern portion of the floodplain (well 736) decreased from 1.3 mg/L in 1993 to 0.4 mg/L in 1999. Sulfate concentrations in samples from the same well varied between 10,000 and 15,000 mg/L within the last 5 years but seem to have decreased since 1998. Nitrate concentrations in samples from well 736 are low, ranging from 0.3 to 2 mg/L.

High concentrations of uranium, nitrate, and sulfate were measured in samples from wells located close to the escarpment (southern floodplain) in 1999. Uranium concentrations in samples from well 608 (near the escarpment) were as high as 3.7 mg/L after the surface remediation was completed in 1986 but decreased within the last 10 years. Uranium concentrations in samples from well 608 average 2 mg/L at the present time.

Chemical data for samples collected at the escarpment below the disposal cell were evaluated to determine if a continuing source exists. Time series for selected wells along the escarpment are presented in Figure 4–28. Uranium concentrations in ground water samples from the Mancos Shale in the terrace at the north corner of the disposal cell (well 600) have been relatively constant since 1988, ranging from 1.0 to 1.5 mg/L. Well 614 is located on the floodplain close to the escarpment just north of well 600. In the same period of time, the uranium concentrations in samples from well 614 increased from 0.8 mg/L to 2.2 mg/L. Increases in contaminant concentration in samples from well 614 are also observed for nitrate, sulfate, and TDS. Samples from the four wells (608, 610, 614, and 615) completed in the floodplain alluvium had similar concentrations (Figure 4–28). The increase in uranium concentrations in samples from well 614 suggest that there is a contribution from the terrace. Alternatively, the source of contamination could be soils on the floodplain.

In June 1999, water was discovered in two neutron hydroprobe ports in the disposal cell. The ports are plugged at the bottom, so they should not be in contact with tailings water unless they are corroded. Recent analyses of water samples (Table 4–12) from the two hydroprobes showed low nitrate and uranium concentrations. One sample had high sulfate concentration. The low concentrations of uranium indicate that the water in the ports was not in contact with tailings material. The elevated sulfate concentrations could result from seepage water through the cover.

Table 4–12. Analysis of Water Found in the Neutron Hydroprobe Ports in the Disposal Cell

Sample ID	Nitrate (mg/L)	Sulfate (mg/L)	Uranium (mg/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
NDF401	2.67	14,800	0.0417	<264.8	376.7
NDF402	47.2	2,650	0.031	637.2	1,445

The composition of ground water from the terrace and the floodplain is illustrated in a Piper diagram on Figure 4–29. Wells 600 and 824 represent terrace ground water from the Mancos Shale. Ground water samples from wells 600 and 824 were collected from depths of 60 ft and 200 ft, respectively. The last two samplings of well 824 are displayed in the figure because of the unusual composition of the water. The wells marked with a blue symbol represent ground water from the floodplain close to the escarpment. The yellow symbols show the signature of ground water in the southeast portion of the floodplain, which is flushed by the San Juan River. Deep ground water from the Mancos in well 824 has a different signature in all three diagrams than the other ground waters. It contains relatively higher concentrations of bicarbonate, sodium, and potassium, whereas the water from the floodplain contains relatively higher concentrations of sulfate, calcium, and magnesium. Low permeability of the Mancos Shale causes a long residence time for deep ground water. The water in well 824 seems to be influenced by interaction with the Mancos. The saturation index for calcite is 0.01 in water from well 600 and 0.29 in water from well 824, suggesting that these waters are oversaturated with calcite. For gypsum, the water in well 600 has a saturation index of –0.02, and the water from well 824 has a saturation index of –0.37.

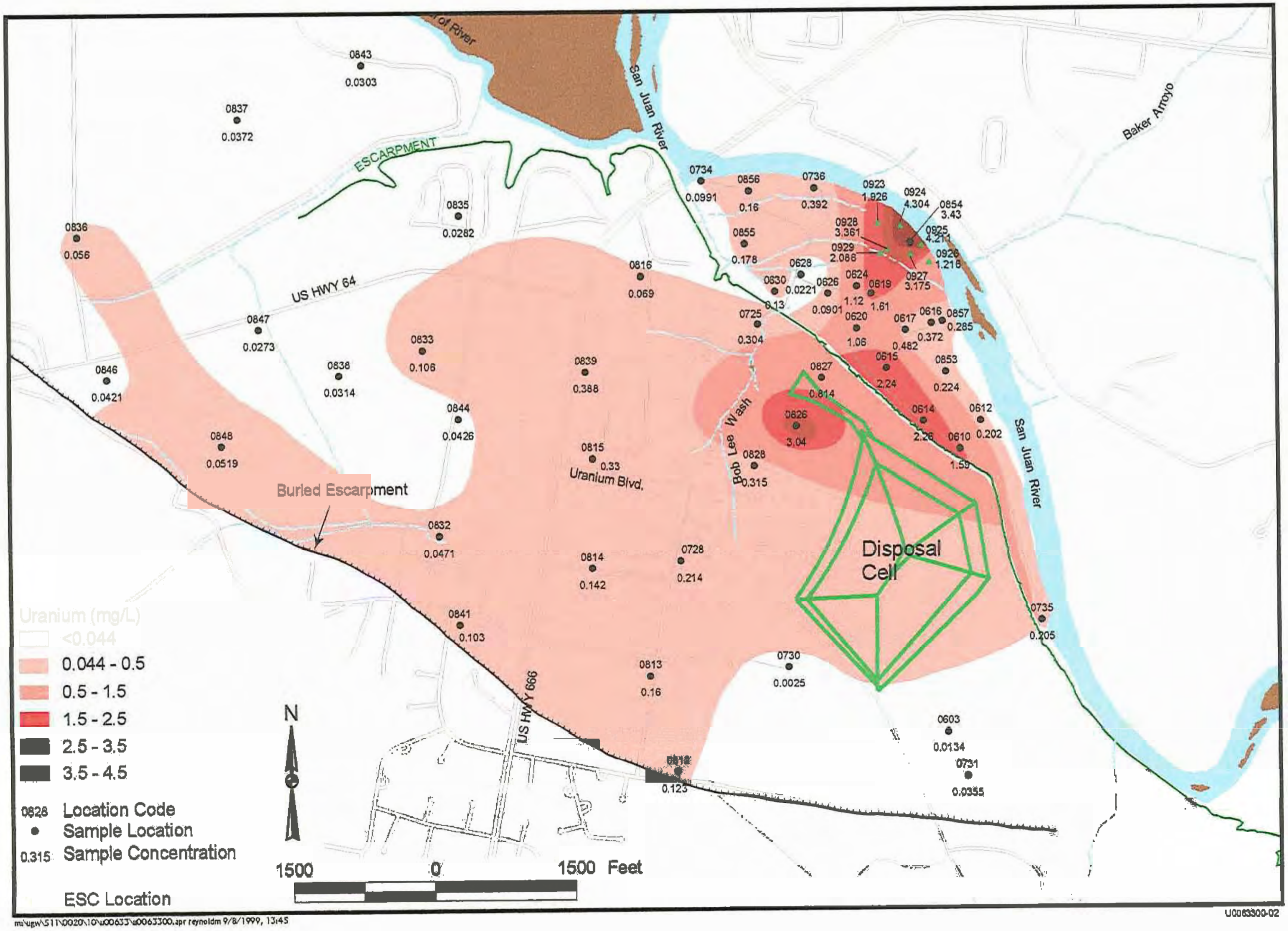


Figure 4–18. Uranium Plume in Alluvial Ground Water (data: March 1999)

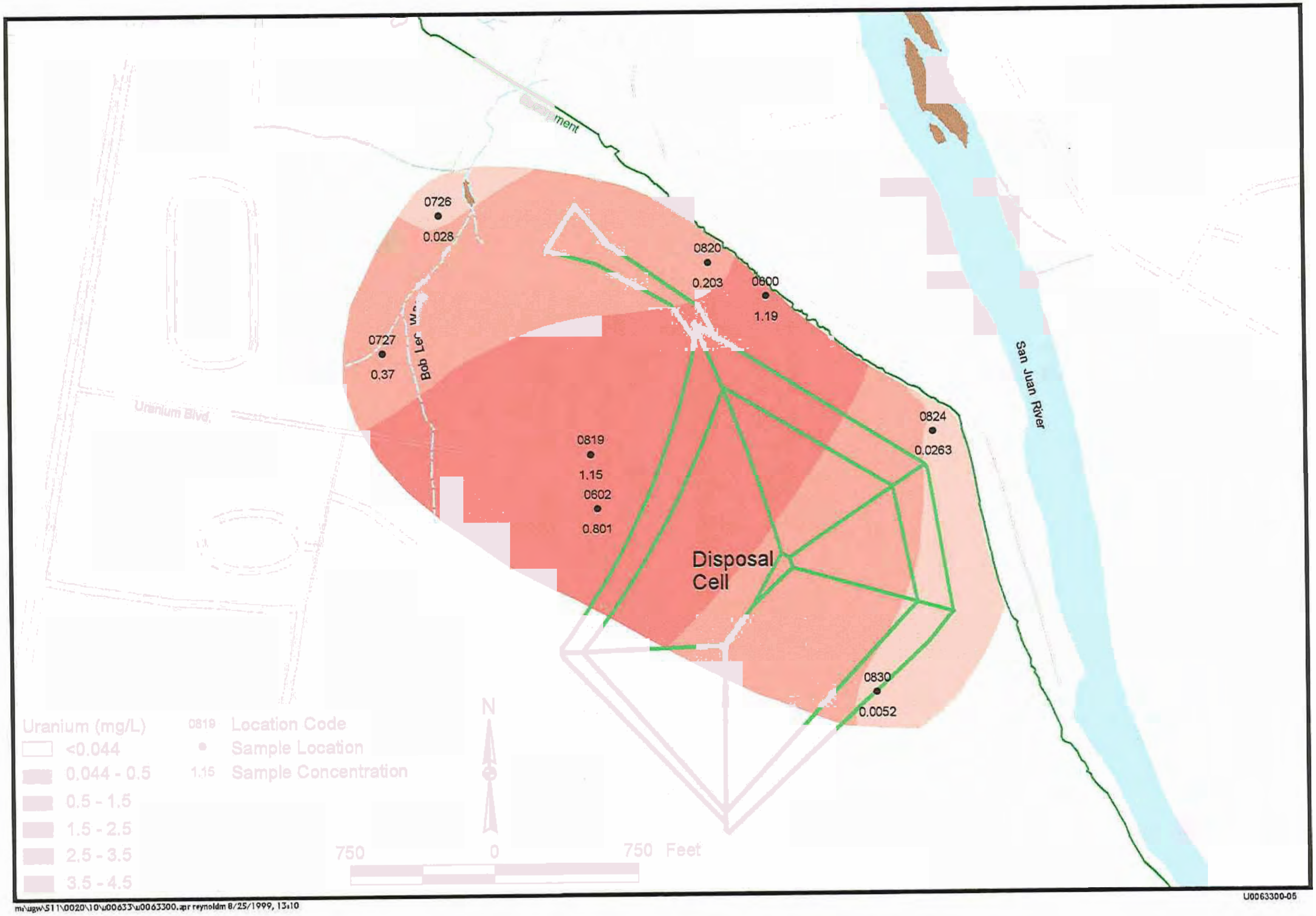


Figure 4–19. Uranium Plume in Mancos Shale (data: March 1999)

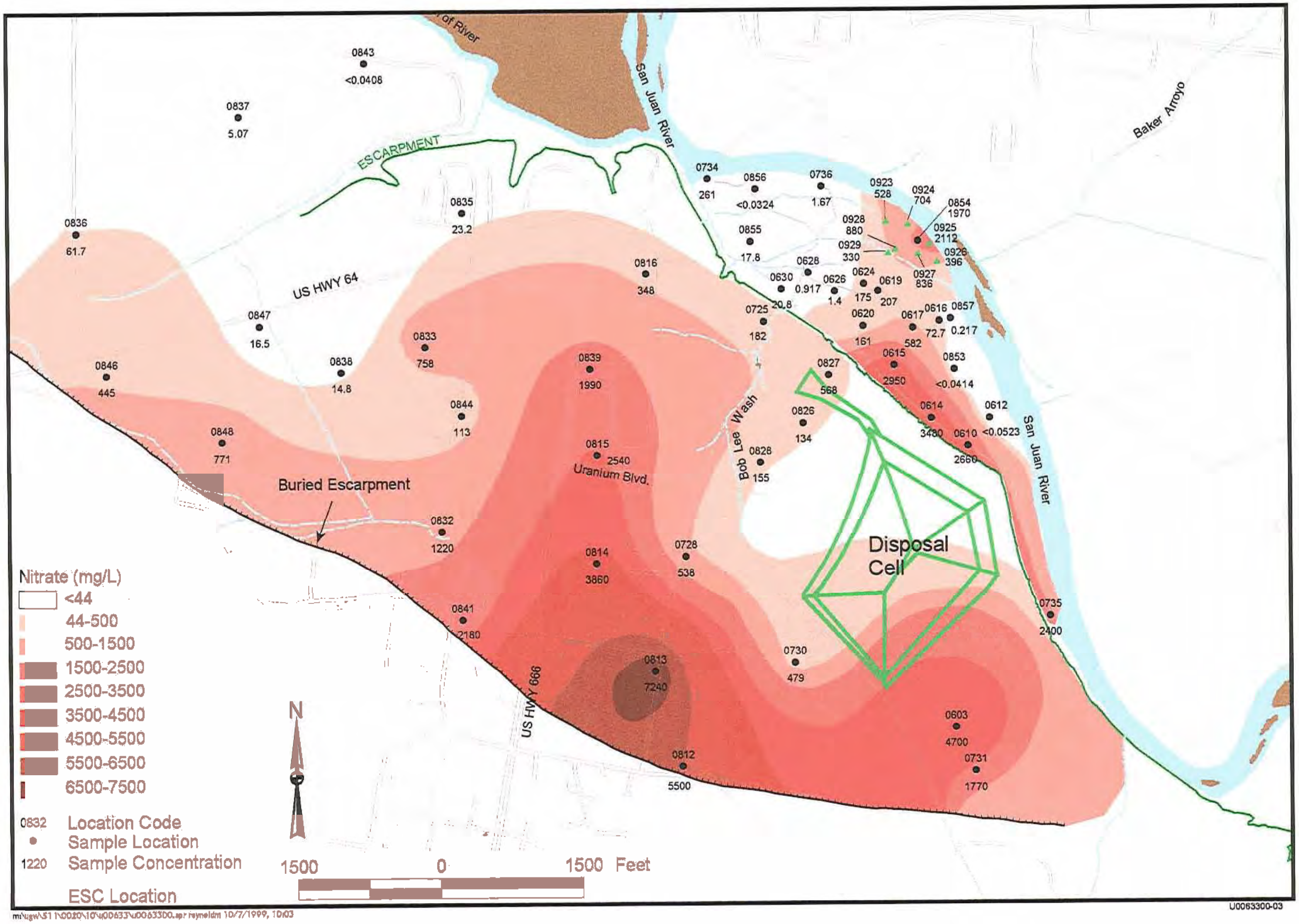


Figure 4–20. Nitrate Plume in Alluvial Ground Water (data: March 1999)

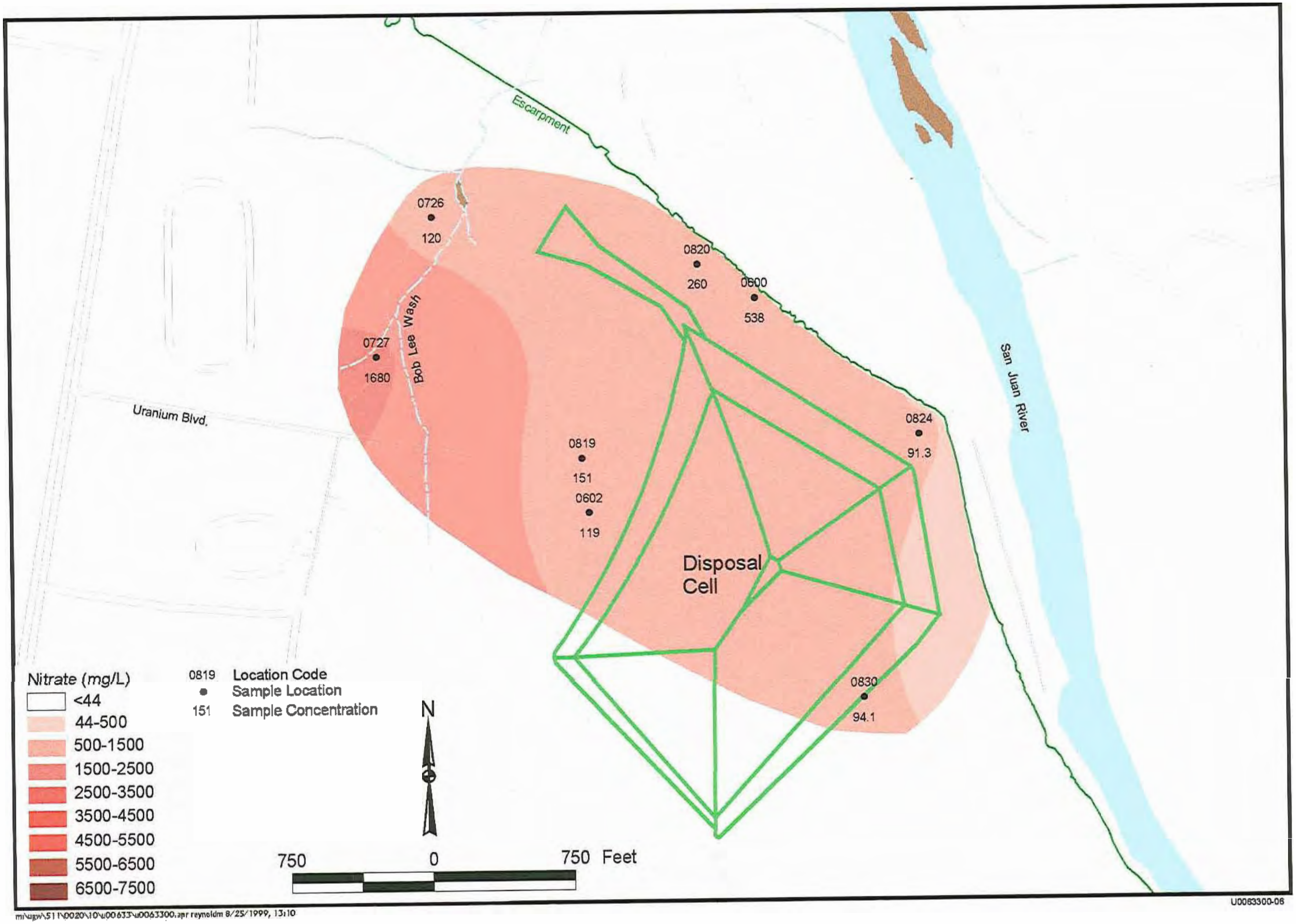


Figure 4–21. Nitrate Plume in Mancos Shale (data: March 1999)

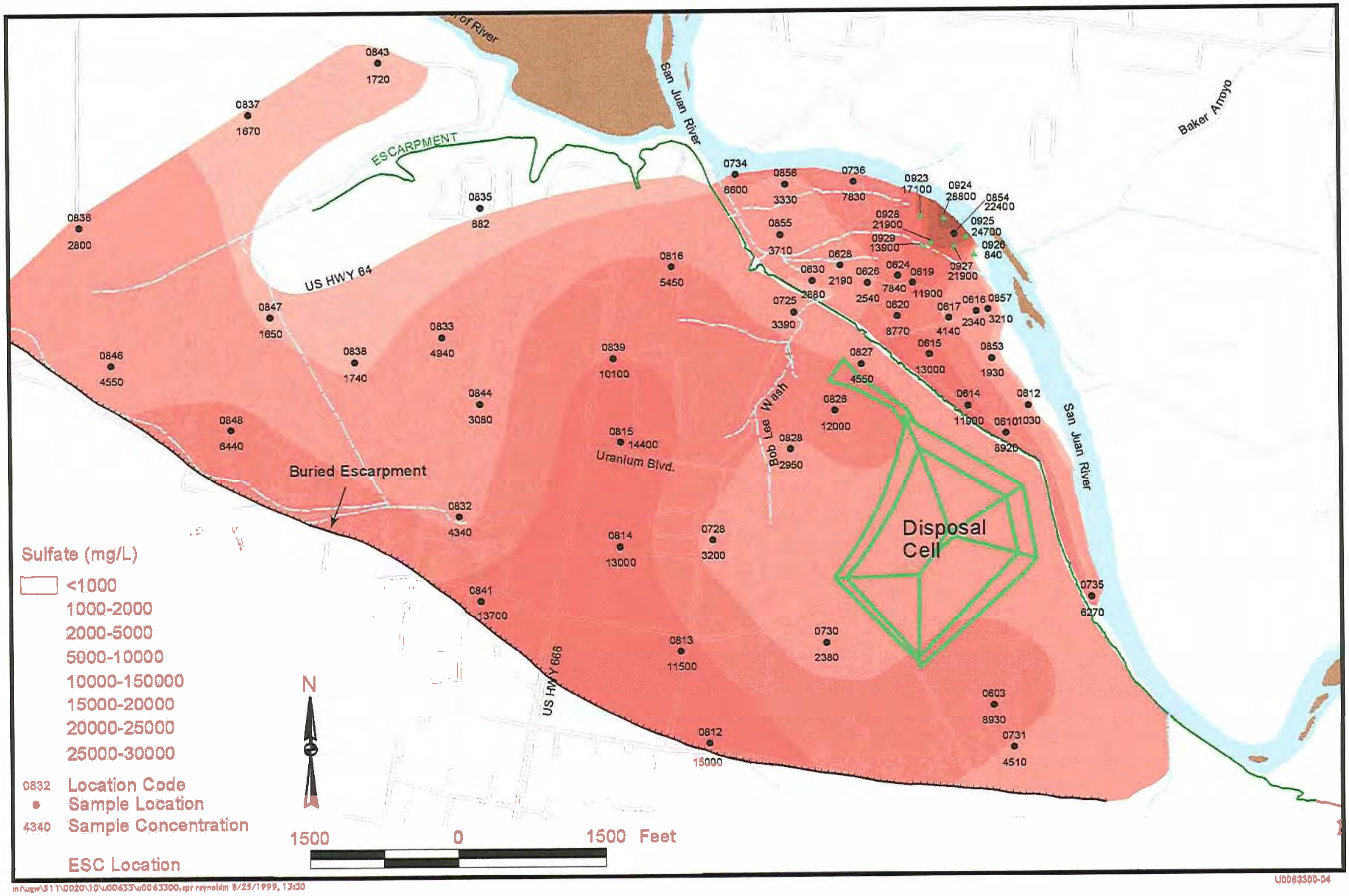


Figure 4–22. Sulfate Plume in Alluvial Ground Water (data: March 1999)

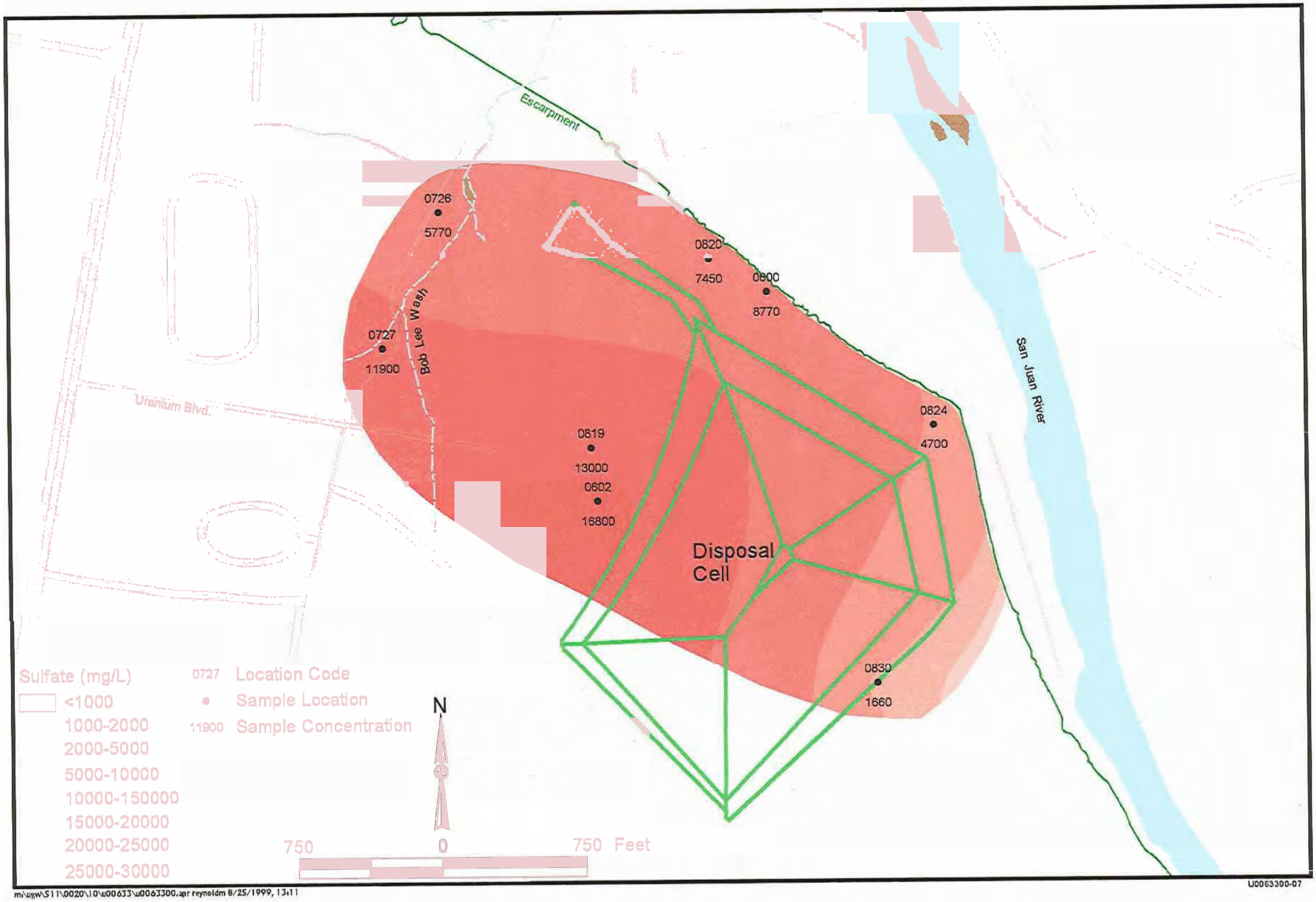


Figure 4–23. Sulfate Plume in Mancos Shale (data: March 1999)

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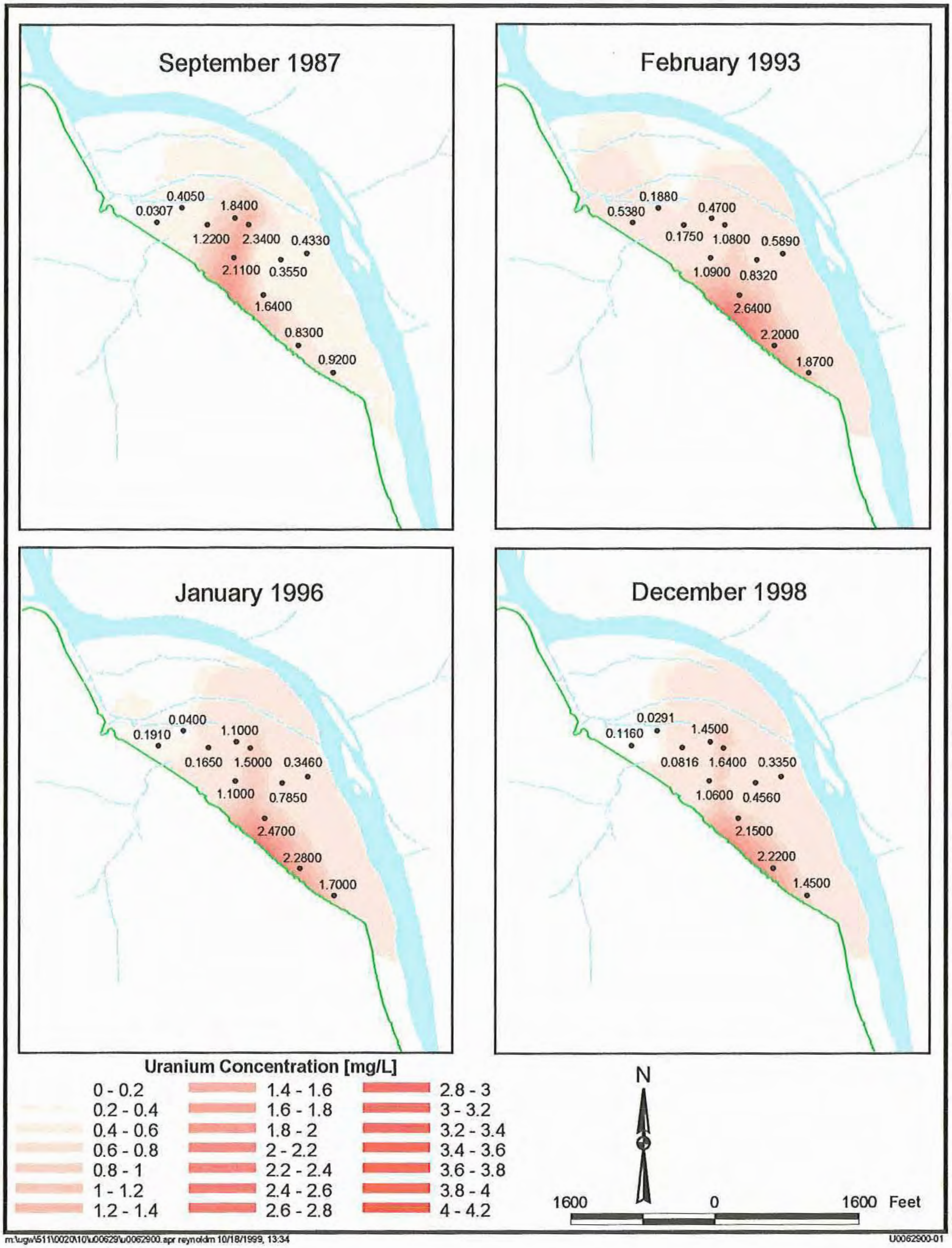

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Figure 4–24. Uranium Concentrations Over Time in the Floodplain Alluvium

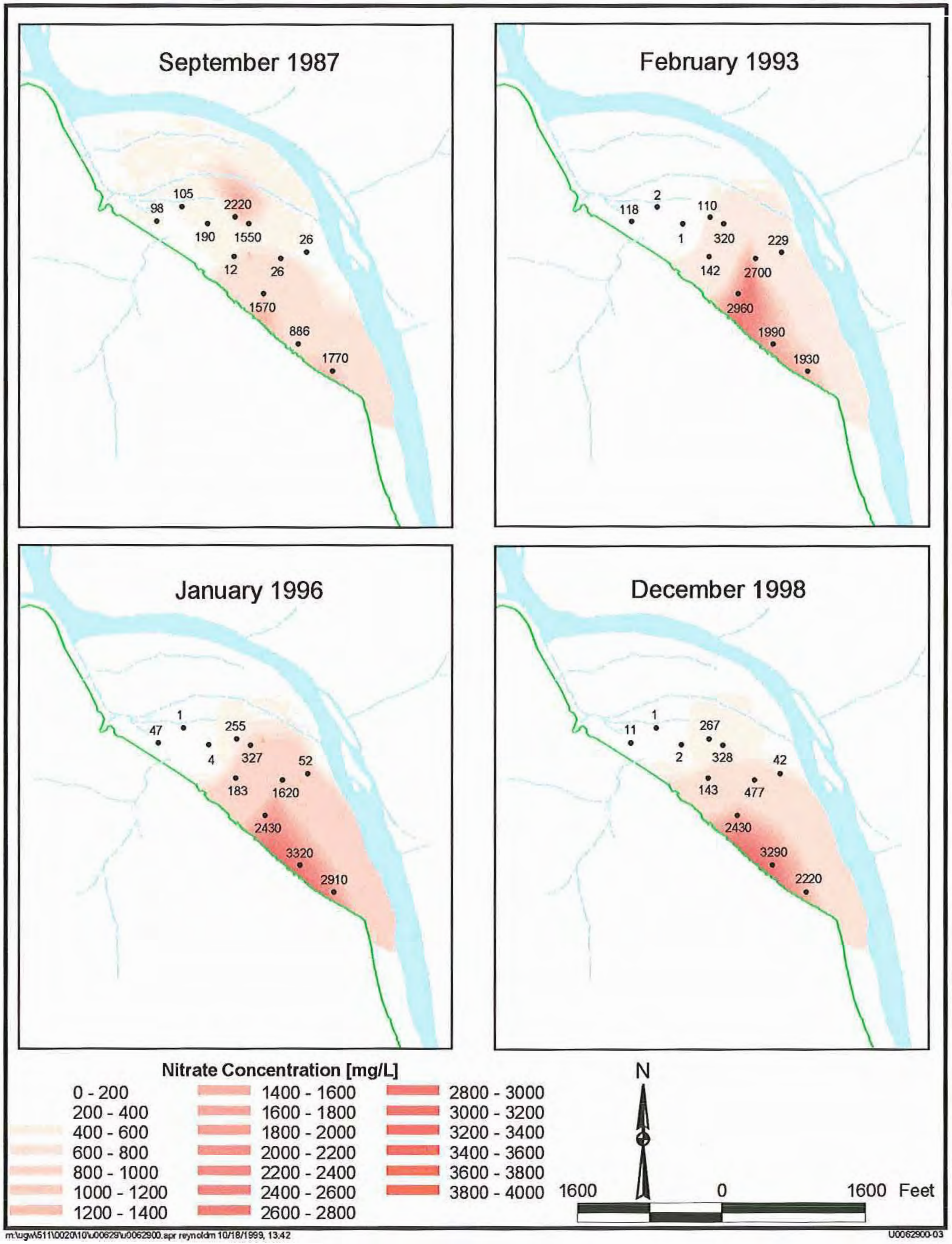

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Figure 4–25. Nitrate Concentrations Over Time in the Floodplain Alluvium

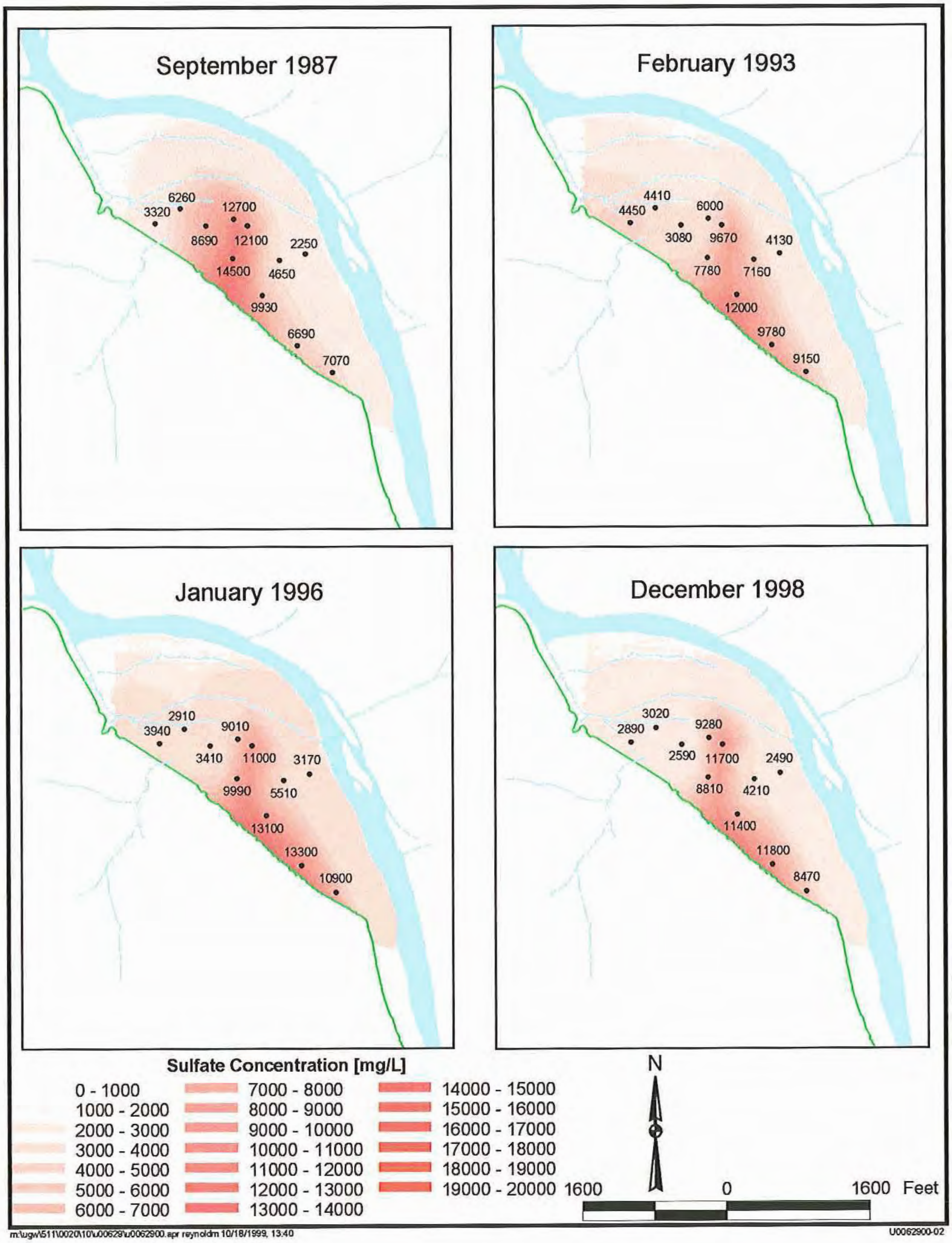

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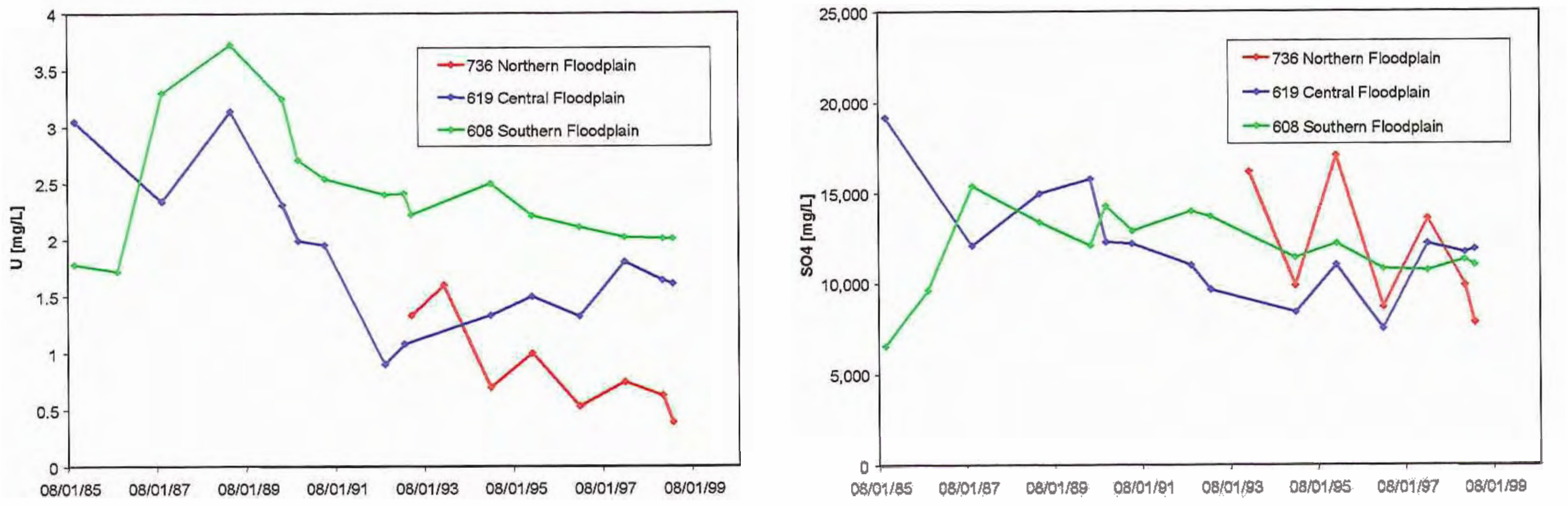
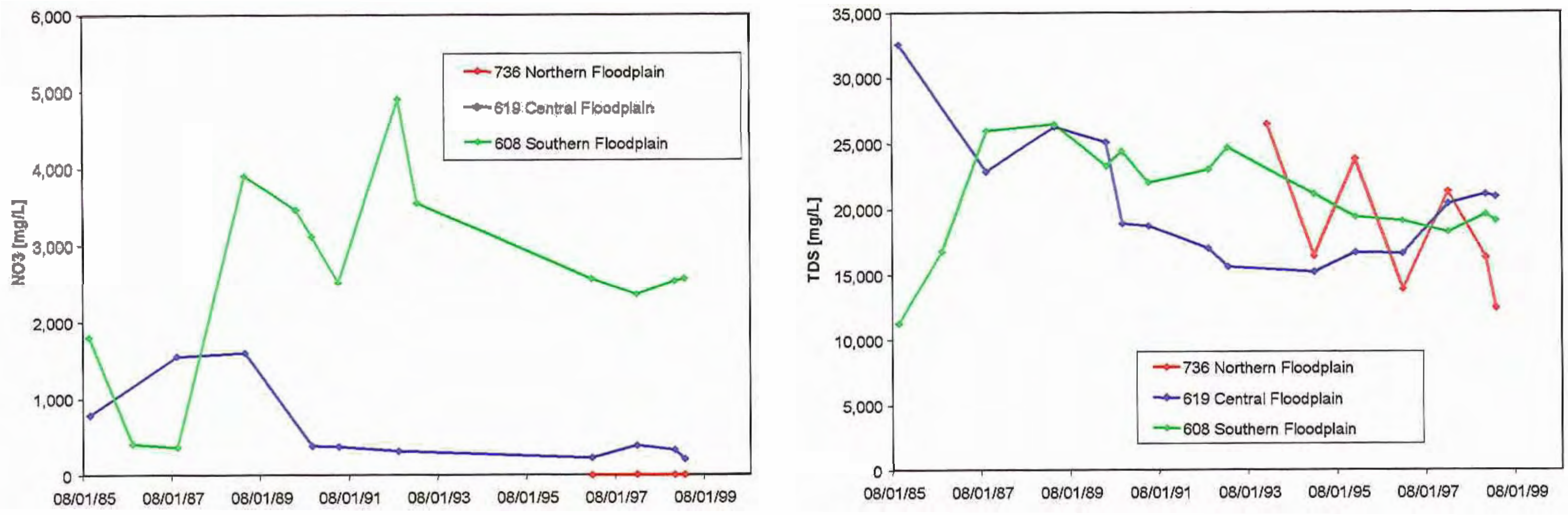
Figure 4–26. Sulfate Concentrations Over Time in the Floodplain Alluvium



Uranium

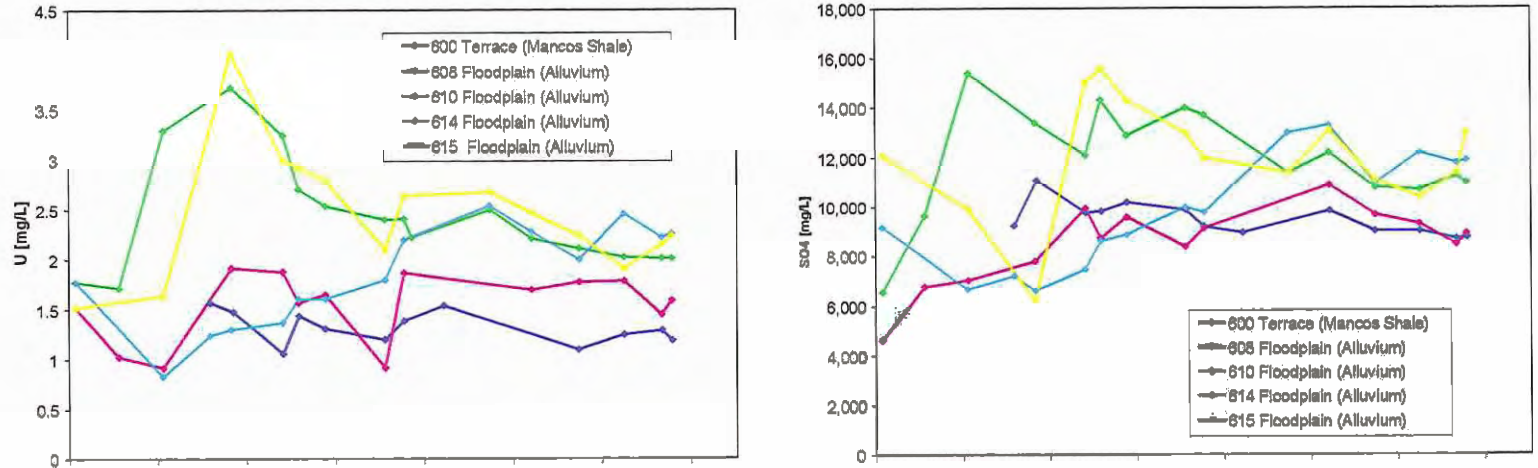
Sulfate



Nitrate

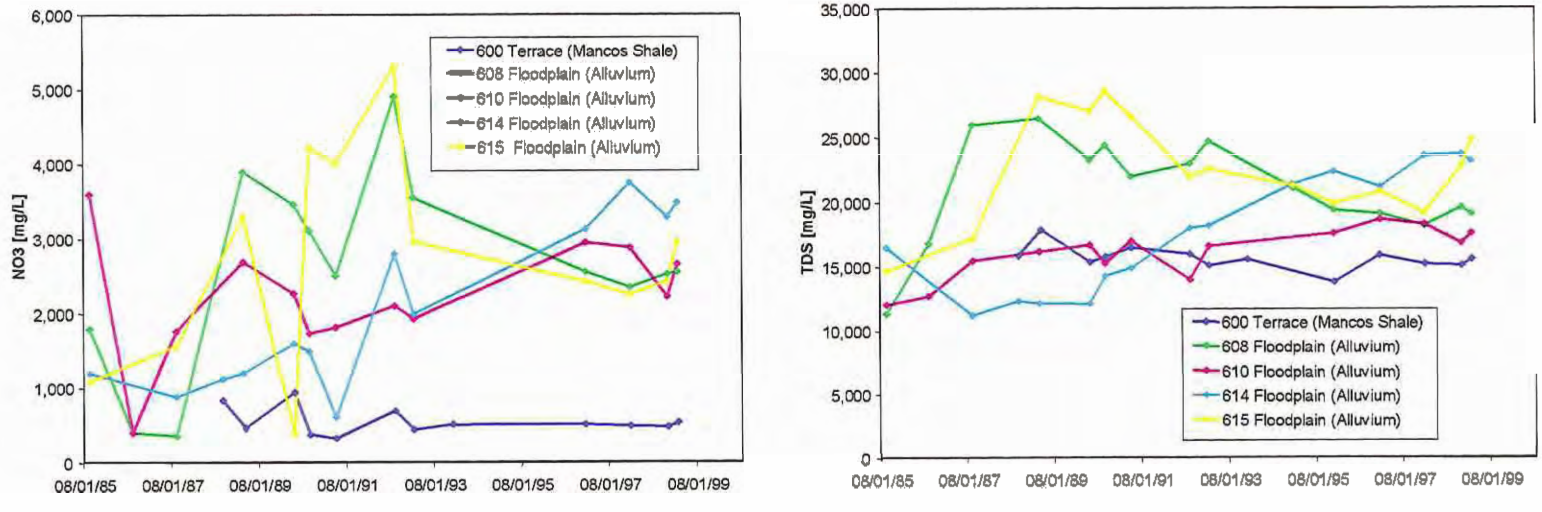
TDS

Figure 4–27. Ground Water Contaminant Concentrations Over Time in Samples from the Floodplain Alluvium



Uranium

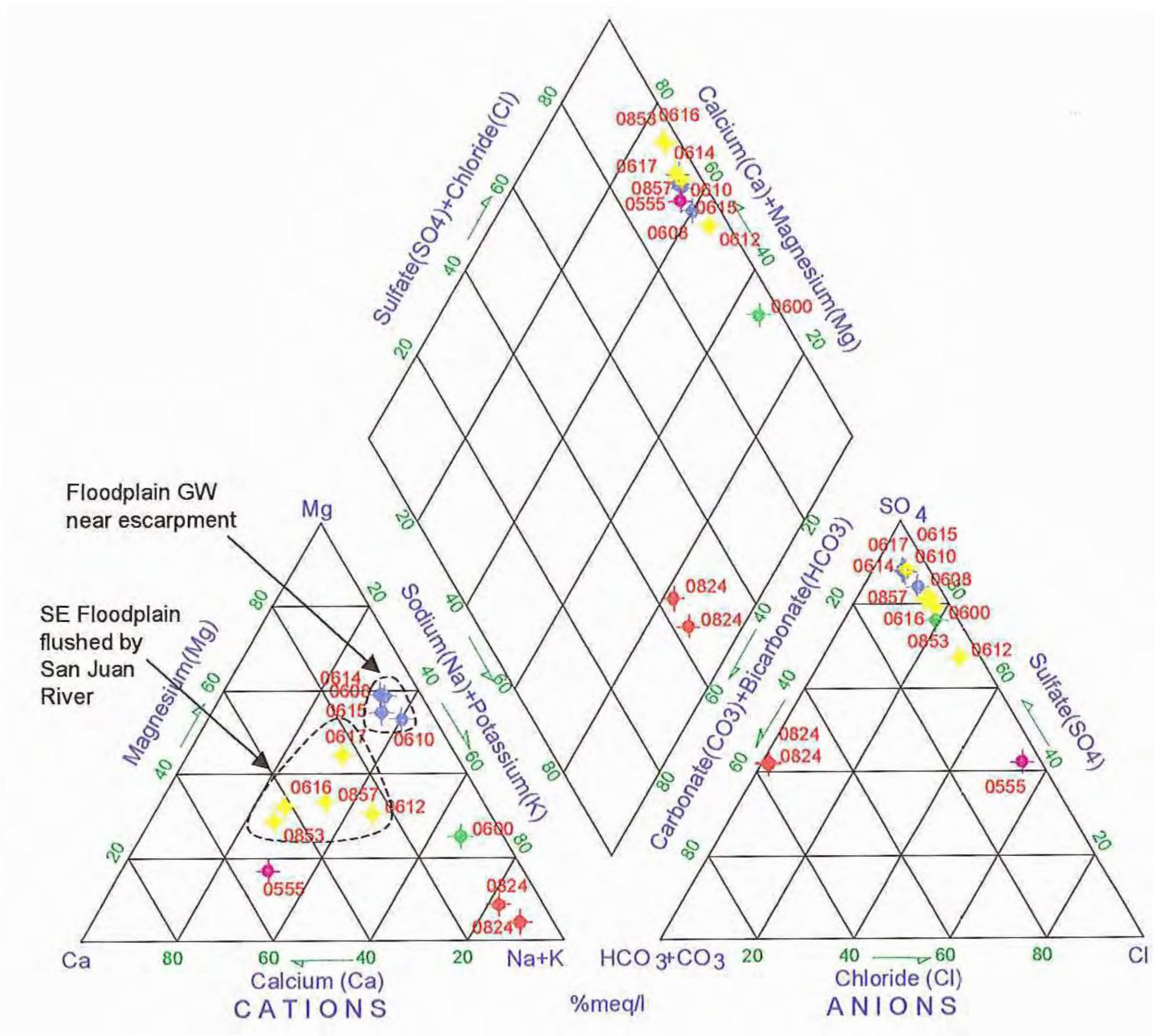
Sulfate



Nitrate

TDS

Figure 4–28. Ground Water Contaminant Concentrations Over Time in Samples from Wells Close to the Disposal Cell and Escarpment



Explanation

- ◆ 0608 - Floodplain GW
- ◆ 0610 - Floodplain GW
- ◆ 0614 - Floodplain GW close to the escarpment
- ◆ 0615 - Floodplain GW close to the escarpment

- ◆ 0600 - Terrace GW (Mancos) - 60 ft. depth
- ◆ 0824 - Terrace GW (Mancos) - 200 ft. depth

- ◆ 0612 - SE Floodplain flushed by San Juan River
- ◆ 0616 - SE Floodplain flushed by San Juan River
- ◆ 0617 - SE Floodplain flushed by San Juan River
- ◆ 0853 - SE Floodplain flushed by San Juan River
- ◆ 0857 - SE Floodplain flushed by San Juan River

- ◆ 0555 - San Juan River

Figure 4–29. Piper Diagram of Terrace and Floodplain Ground Water Quality

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shows that the ground water from the upper portion of the Mancos (well 600) could be a mixture of alluvial ground water from the floodplain near the escarpment (blue symbols) and the deep ground water from the Mancos (well 824). Nitrate and uranium concentrations in the ground water in well 600 are lower than in the floodplain, whereas sulfate and TDS concentrations are almost as high as in the floodplain.

Some of the highest floodplain contaminant concentrations occur close to the escarpment, suggesting that a continuing source is present in the terrace or the floodplain. Major-ion chemistry in the deep Mancos Shale close to the escarpment is different from that in the floodplain sediments, suggesting that the deep Mancos is not a pathway to the floodplain alluvium. Additional monitor wells in the upper Mancos close to the escarpment are planned to determine if the shallower pathways exist. The high concentrations in samples from well 614 (Figure 4–28) could also be caused by a slug of stagnant water within the floodplain.

Vertical Extent of Contamination

The vertical extent of contamination was monitored in samples from nested wells 820, 821, 822, and 615, 860, 861 shown on cross section F–F' and wells 823, 824, 825, and 608, 862, 863 shown on cross section G–G' on Figure 4–30. Plate 2 shows the location of cross sections F–F' and G–G'. In most cases, concentrations of uranium, sulfate, and nitrate in samples decrease with depth. The pH values of samples increase as a function of depth, which may be caused by buffering of the Mancos Shale. Although samples from wells in cross sections F–F' and G–G' had similar ground water concentrations of uranium, sulfate, and nitrate at shallow depths, samples from well 861 had higher concentrations at 138 ft than samples from well 863. It is possible that cross section F–F' is located closer to a potential pathway in the Mancos Shale than section G–G'. The ammonium concentration (220 mg/L) in samples from well 861 is higher than in samples from the shallower wells 615 and 860 at the same location. The more reducing conditions in deep ground water may have preserved the ammonium from oxidation.

Flushing of the Floodplain

Water from artesian well 648, drilled in 1961, flows down Bob Lee Wash. For approximately the last 10 to 15 years, this flow has created a wetland area where Bob Lee Wash drains into the floodplain. The continuous flow of water has flushed the northwest portion of the floodplain. An analysis of water sampled from well 648 is shown in Table 4–13. Figure 4–31 shows a Piper diagram for the water of the artesian well, Bob Lee Wash, and the ground water of the northwest and southeast parts of the floodplain. Ground water in the southeast portion of the floodplain is influenced by San Juan River water, as discussed previously. It contains relatively more calcium and magnesium, whereas water from the artesian well contains relatively more sodium (and potassium). Much of the ground water in the northwest portion of the floodplain is derived from the water flowing down Bob Lee Wash, as indicated by the similarity of chemistry on the Piper diagram.

Table 4–13. Water Quality of Samples from Artesian Well 648 (June 1998 sampling)

Alkalinity (mg/L) $CaCO_3$	Ca (mg/L)	Cd (mg/L)	Cl (mg/L)	Fe (mg/L)	K (mg/L)	Mg (mg/L)	Mn (mg/L)	Na (mg/L)
59	110	0.001	52.2	0.106	7.82	13.5	0.0886	836

NH_4 (mg/L)	NO_3 (mg/L)	pH (mg/L)	Ra-226 (pCi/L)	Ra-228 (pCi/L)	SO_4 (pCi/L)	Sr (mg/L)	TDS (mg/L)	U (mg/L)
0.569	0.0285	7.8	0.58	0.83	2000	12.1	3100	0.001

Figure 4–32 presents a time series for the water quality of the artesian well, the shallow ground water in Bob Lee Wash, and the northwest part of the floodplain. Uranium, sulfate, and TDS concentrations in the northwest part of the floodplain decrease over time. Concentrations of uranium, sulfate, nitrate, and TDS are lower in the artesian well water samples than in Bob Lee Wash or floodplain ground water samples. Sulfate concentrations in the northwest part of the floodplain will not decrease lower than 2,000 mg/L as long as the artesian well water flushes the floodplain. Although the nitrate concentrations in the artesian well samples are lower than 0.1 mg/L, the samples of the shallow ground water in Bob Lee Wash show slightly increasing concentrations over time, probably because of the addition of nitrate from the millsite.

4.4.2.2 Terrace

Since September 1998, numerous additional wells were drilled on the terrace to better define the areal extent of contamination. Terrace background ground water quality could not be determined because no water was present in any of the wells drilled for background (wells 800, 801, 803, and 810). Separate plume maps for the shallow alluvial (Figures 4–18, 4–20, and 4–22) and Mancos (Figures 4–19, 4–21, and 4–23) wells are presented. Time series for uranium, nitrate, sulfate and the sum of ammonium and nitrate (calculated as nitrate) concentrations for selected wells close to the disposal cell are presented in Figure 4–33.

The highest uranium concentration (3.04 mg/L) in the terrace alluvium was detected in samples from well 826, which is near the former mill buildings and ore storage area (Figure 4–18). Ground water samples from wells 819 and 602, which were completed to depths of 31 ft and 96 ft, respectively, in the Mancos Shale, contained about 1 mg/L uranium (Figure 4–20). Uranium concentrations in samples from well 602 have decreased slightly during the last 11 years, ranging from 0.7 to 1.4 mg/L (Figure 4–33). The southern extent of the uranium plume in the terrace alluvium is at the buried escarpment. Samples from alluvial wells 603 and 731 southeast of the disposal cell have uranium concentrations below the MCL. Uranium concentrations in samples from well 603 have not exceeded the MCL since 1990. A sample from ell 830, which is completed in Mancos Shale, had a uranium concentration of 0.0052 mg/L.

There are no reports of nitrate being used in the milling process. The nitrate in the terrace ground water has probably oxidized from ammonia that was used during the milling process to adjust pH and to precipitate uranium after the solvent extraction. Fluids leaked from the poorly lined waste ponds, as noted by the U.S. Department of Health, Education, and Welfare (1962). Although nitrate and ammonium are target analytes, the analyses do not include nitrite. Some field samples of floodplain and terrace ground water collected by personnel with the Natural and Accelerated Bioremediation Research (NABIR) Program contained nitrite concentrations that were less than

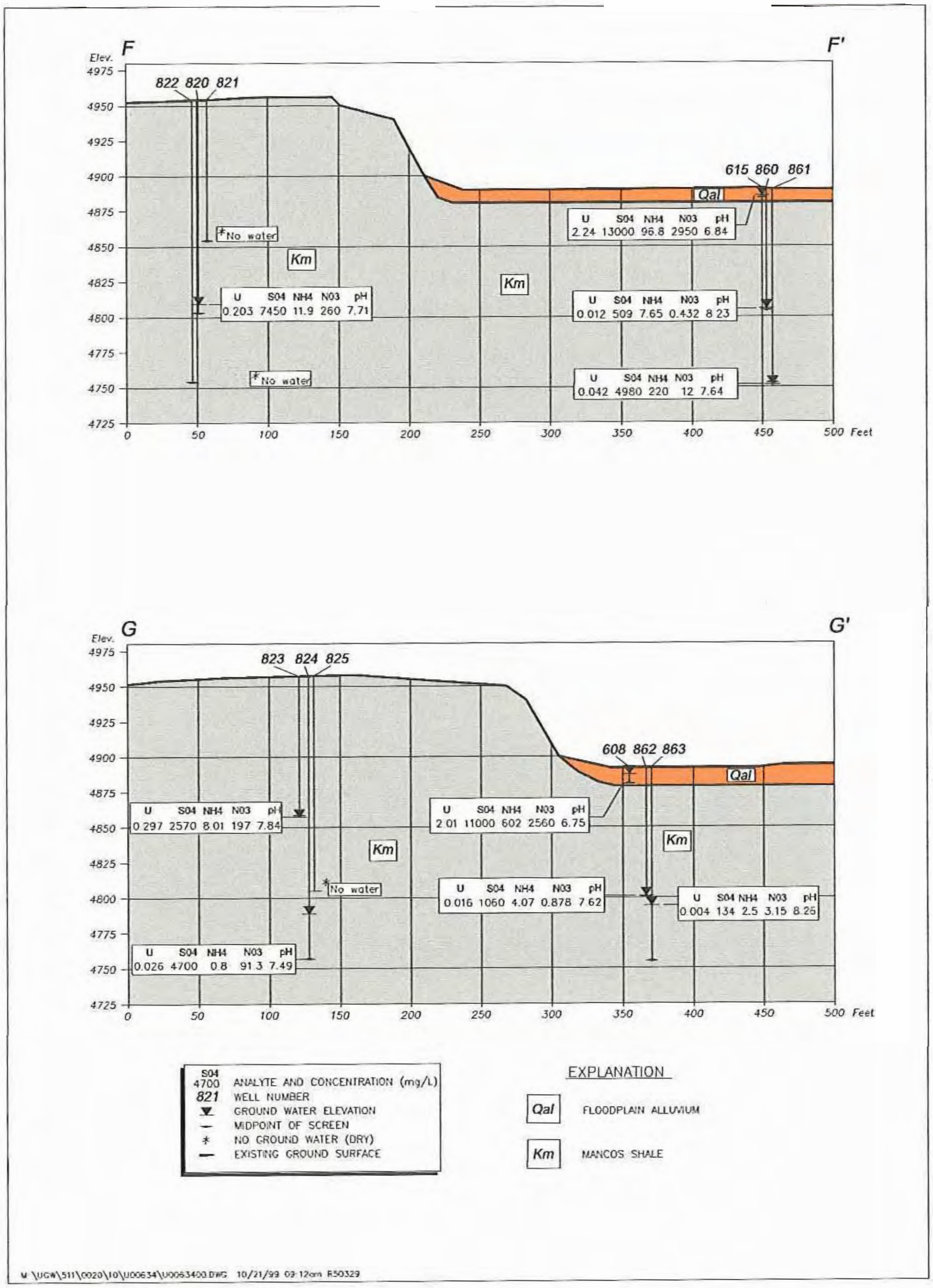


Figure 4–30. Ground Water Concentrations in Cross Sections F–F' and G–G'

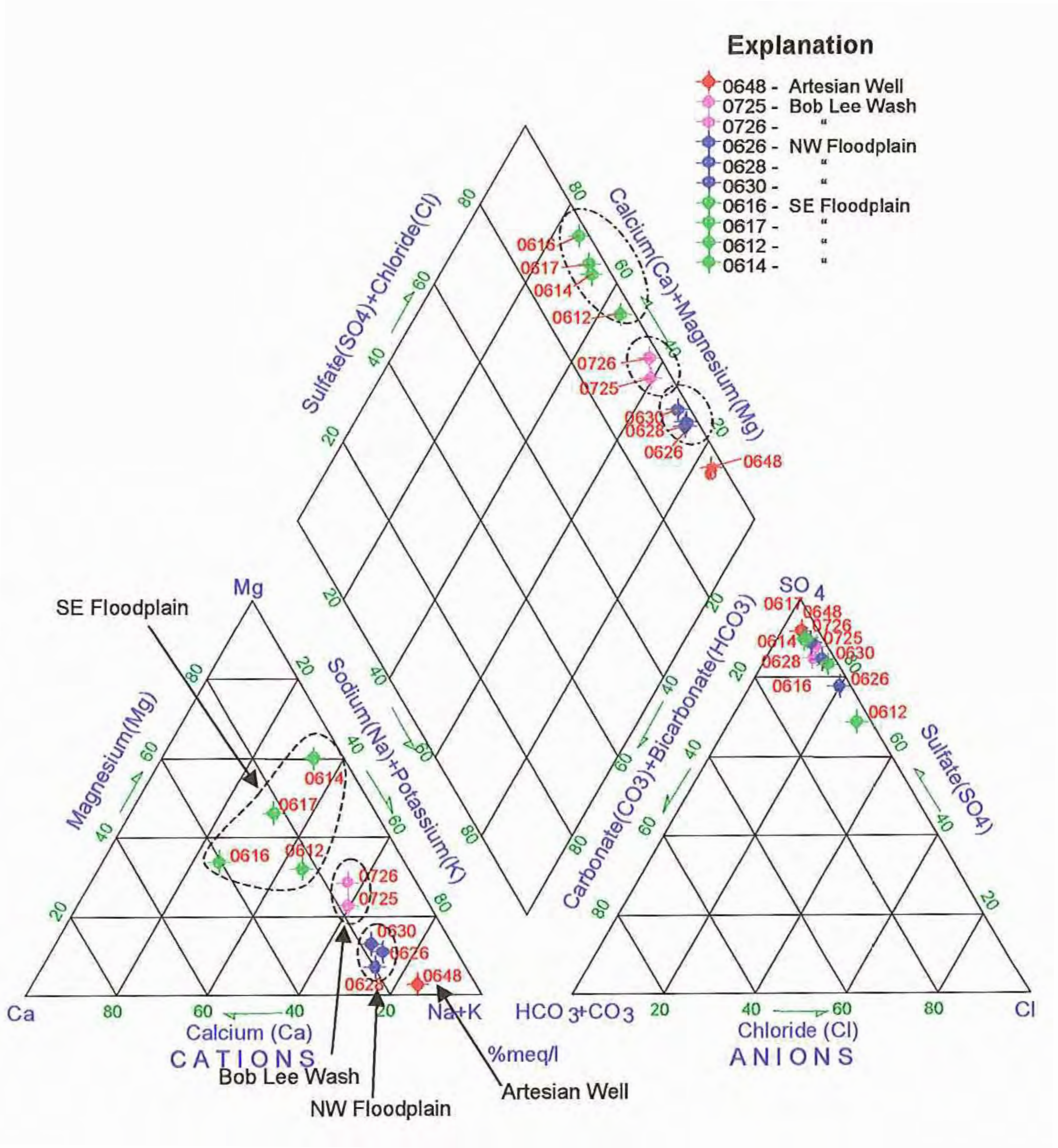
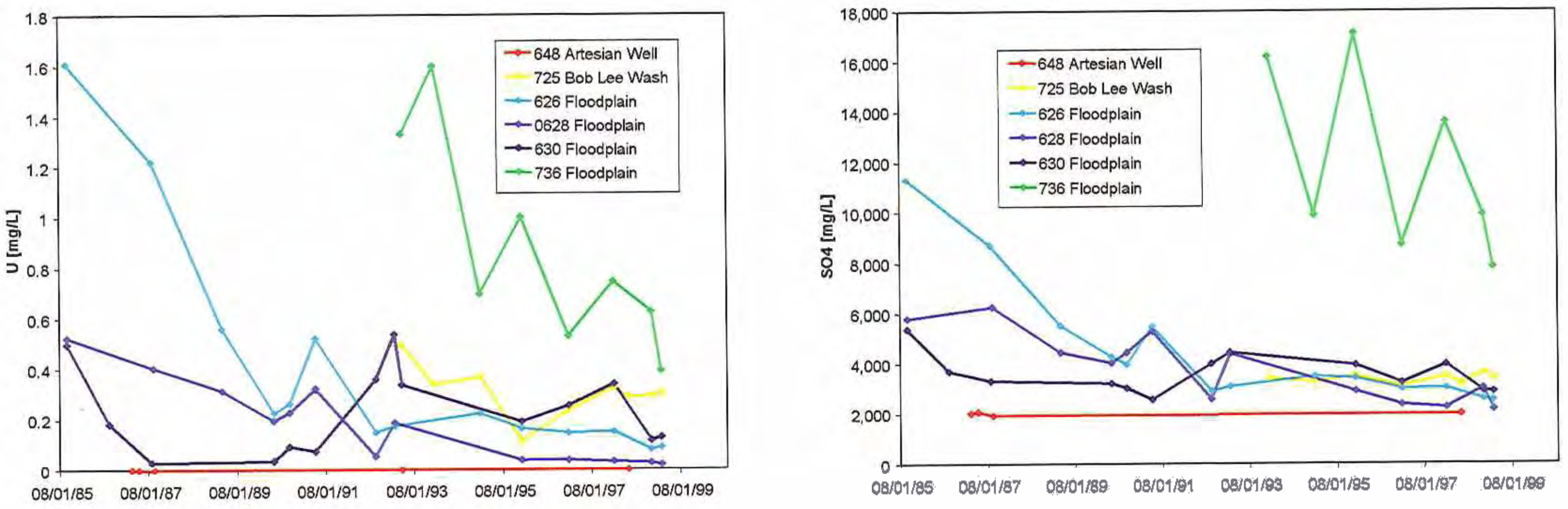
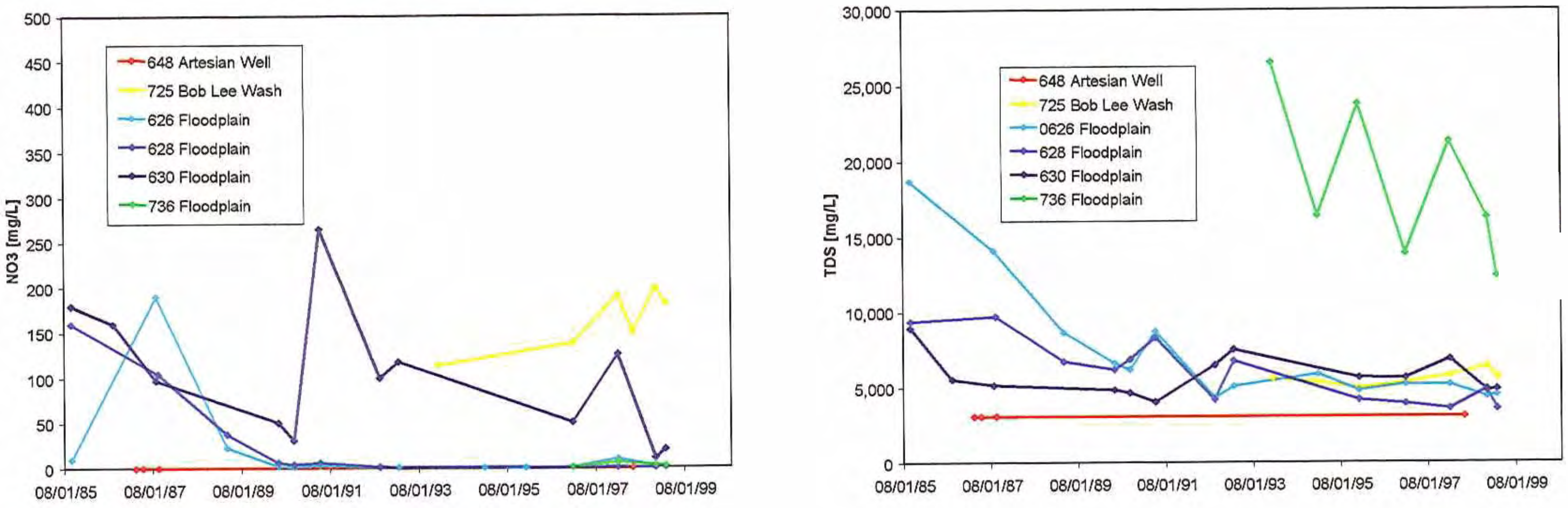


Figure 4–31. Piper Diagram of Artesian Well 648 Water and Floodplain Ground Water



Uranium

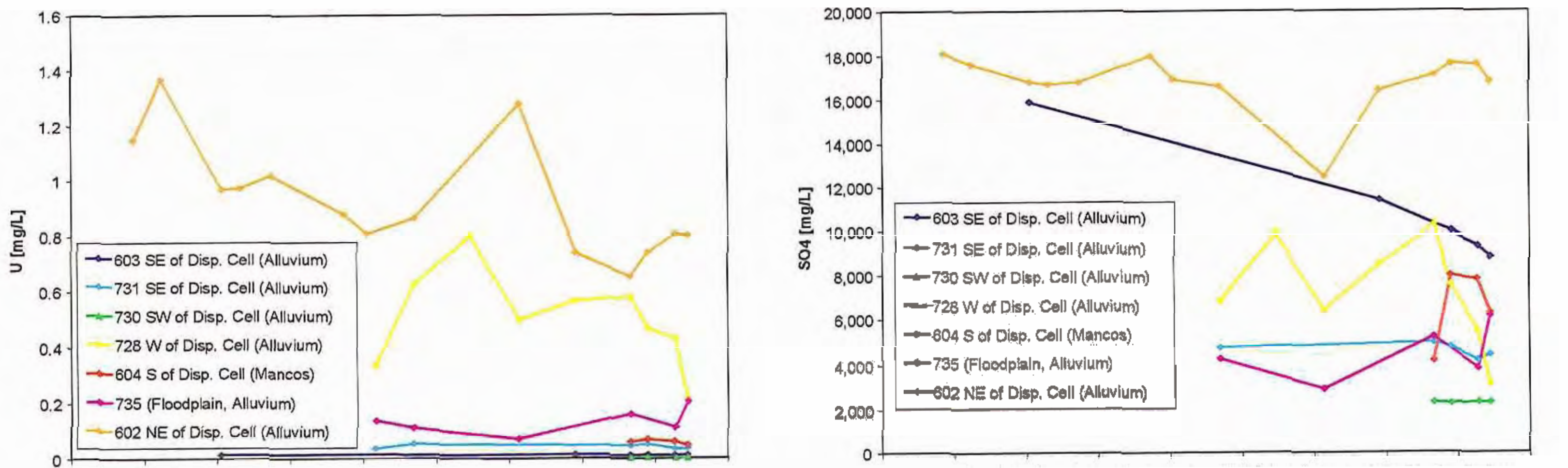
Sulfate



Nitrate

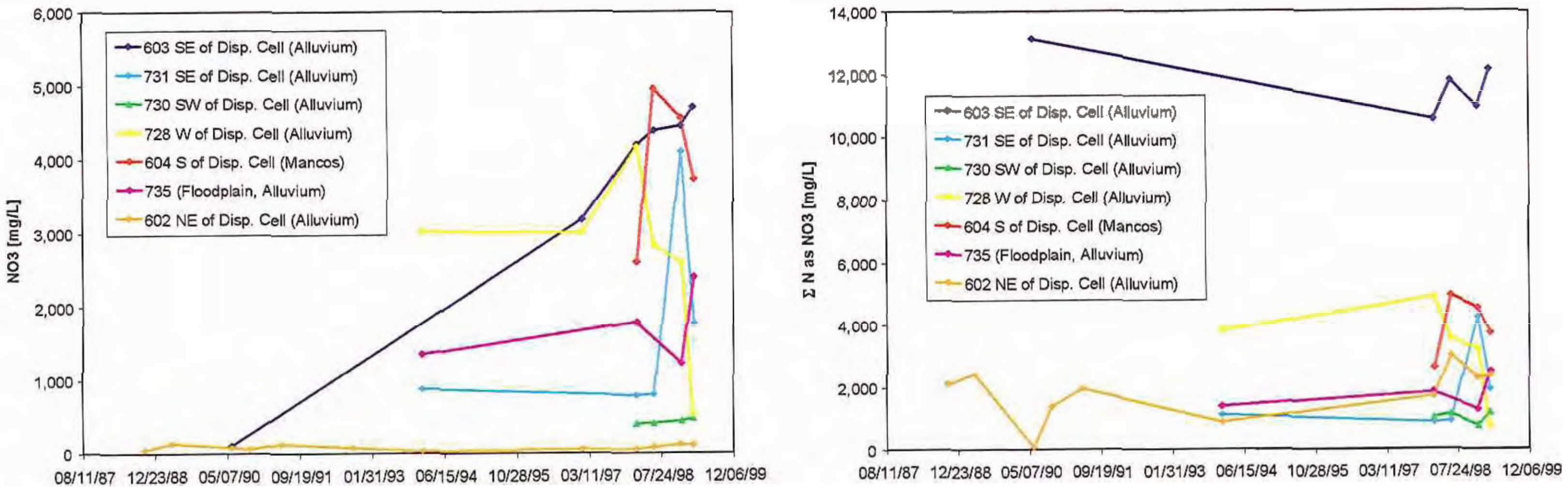
TDS

Figure 4–32. Contaminant Concentrations Over Time in Samples of Floodplain Ground Water and Artesian Well 648 Water



Uranium

Sulfate



Nitrate

Total Nitrogen as Nitrate

Figure 4–33. Terrace Ground Water Contaminant Concentrations Over Time

5 mg/L. One exception was a sample from well 819 that had about 14 mg/L nitrite. Other nitrogen species are not expected to occur in the ground water at the Shiprock site.

Nitrate concentrations exceeded the MCL in all samples of terrace alluvial ground water, except in the far northwest part of the area (Figure 4–20). The highest concentration (7,240 mg/L) in the alluvial aquifer was detected in a sample from well 813, which is located about 1,700 ft southwest of the disposal cell. The highest concentration in the Mancos Shale occurs in a sample from well 604 (Figure 4–33). The concentrations in samples from this well ranged from 2,500 to almost 5,000 mg/L within the last 2 years. The nitrate plume coincides with an ancestral river channel in the terrace alluvium south of the disposal cell. High concentrations continue west of U.S. Highway 666, where a sample of alluvial ground water from well 841 contained 2,180 mg/L. Since 1990, the concentrations of nitrate in samples from well 603, located southeast of the disposal cell, increased significantly and are still increasing. Although well 813 samples had the highest nitrate concentrations (7,240 mg/L), the sum of nitrate and ammonium concentration (12,000 mg/L) is highest in well 603 samples. Thirty-five percent of the nitrogen in well 603 has been oxidized to nitrate. If all the ammonium is oxidized, the nitrate concentrations could increase to 12,000 mg/L at well 603. It is not apparent why the combined ammonium and nitrate concentrations in samples from well 731, which is just south of well 603, were much lower (2,000 mg/L expressed as nitrate). It is possible that activity at the gravel pit (excavating and washing of gravel) has affected the geochemical conditions at well 603 and oxidized the ammonium.

Sulfate was used in the form of sulfuric acid in the milling process. The spatial distribution of sulfate has two maxima (Figures 4–22 and 4–23). One is located in the Mancos at the processing site around wells 602 and 819. These wells are completed at depths of 96 and 31 ft, respectively. The highest concentration in samples from the deep Mancos system is 16,800 mg/L. The second maximum in the terrace is in a sample from the alluvial aquifer. As with the nitrate plume, the sulfate plume coincides with the ancestral river channel south of the disposal cell. The highest concentration is 15,000 mg/L in a sample from well 812. The similarity in the extent of nitrate and sulfate contamination is also observed west of U.S. Highway 666. Sulfate concentrations from samples from wells 844, 832, and 841, located in a north to south trend, are higher than samples from wells to the south.

Samples collected southeast of the disposal cell close to the gravel pit have high concentrations of sulfate and nitrate. The extent of high concentrations farther north toward the escarpment is difficult to determine because most of the terrace alluvium has been removed by operation of the NECA gravel pit. The only two monitor wells in that area are 804 and 805, which were completed to depths of 70 and 50 ft, respectively, in Mancos Shale and are dry. Seepage water has been observed at the escarpment in the area of salt deposit sample 922 but has not been sampled. Contaminated water may migrate through the weathered Mancos beneath the gravel pit. Additional monitor wells screened above the siltstone bed would provide more information about the potential pathway from the terrace to the floodplain.

High nitrate concentrations in samples from locations 886 and 889 (3,800 and 3,500 mg/L, respectively) suggest that the surface water in Many Devils Wash is seeping from the terrace alluvium. A Piper diagram (Figure 4–34) illustrates the composition of seepage water at the escarpment (seeps 425 and 426), the surface water at Many Devils Wash, and selected ground water compositions on the terrace. Water at seep 426 plots approximately in the same area as the ground water from wells 725 and 600. The chemical signature of surface water from Many

Devils Wash (886 and 889) is different from that of the ground water samples. The Many Devils Wash water was expected to be similar to the water from wells 603 and 731, which are located between Many Devils Wash and the disposal cell; instead, a plot of the water from those wells is closer to that of water from well 827 and seep 425. Thus, the seepage into Many Devils Wash may not have flowed along a straight pathway from the millsite to the wash.

Terrace wells 847 and 848, located south of U.S. Highway 64 on the high school property, were drilled for irrigation purposes by a local company to estimated depths of 92.5 ft and 145 ft, respectively. The lengths of the well screens are unknown. The ground water chemistry is much different in these two wells, as indicated by their separation on a Piper diagram (Figure 4–35). Ground water in well 847 has a chemical signature similar to water in well 838. Ground water from wells 836/846 and 844/833 plot in similar locations for the cation composition. Ground water from well 848 has a composition intermediate between water from wells 832 and 841. The high sulfate and nitrate concentrations in well 848 may be due to mixing of ground water. Because the completion information for well 848 is not complete, it may be that the wells are influenced by alluvial ground water, or that ground water in the Mancos Shale at a depth of 145 ft has naturally high concentrations of sulfate and nitrate.

Terrace ground water has two main areas of contamination. Ground water near the former mill buildings and ore storage area has high concentrations of uranium and sulfate. The highest uranium concentrations are in the alluvial aquifer, whereas the sulfate contamination is deeper (about 100 ft) in the Mancos, suggesting that uranium is retained more than sulfate in the shallow aquifer. The extent of the sulfate and nitrate contamination south of the disposal cell suggests that processing water from the former raffinate ponds is the source. Oxidation of ammonium in ground water at well 603 has caused increasing nitrate concentrations.

4.4.2.3 Organic Contamination

Organic compounds were used during the milling process for solvent extraction of uranium. Well 819 was drilled to monitor possible organic contamination in terrace ground water. Samples from monitor wells on the terrace (602, 603, 604, 728, 731, 812, 813, 814, 819, 830, and 841) were analyzed for organic contaminants specific to the milling process in December 1998 and March 1999. Concentrations of possible degradation products of di(2-ethylhexyl) phosphoric acid, tributyl phosphate, kerosene, and alcohol were below or close to the analytical detection limits.

Table 4–14 shows the organic constituents detected in terrace ground water samples. Of these, acetone, chloromethane, and chloroform are common laboratory contaminants and are probably not in the ground water. Benzene, however, is a component of kerosene, which was used in the solvent extraction at the mill. Benzene is the most toxic organic constituent identified at UMTRA Project sites and is the only constituent that is carcinogenic (DOE 1997). Because of microbial processes, benzene rarely persists in the environment for more than 30 years. It is unlikely that organic contamination poses a significant risk.

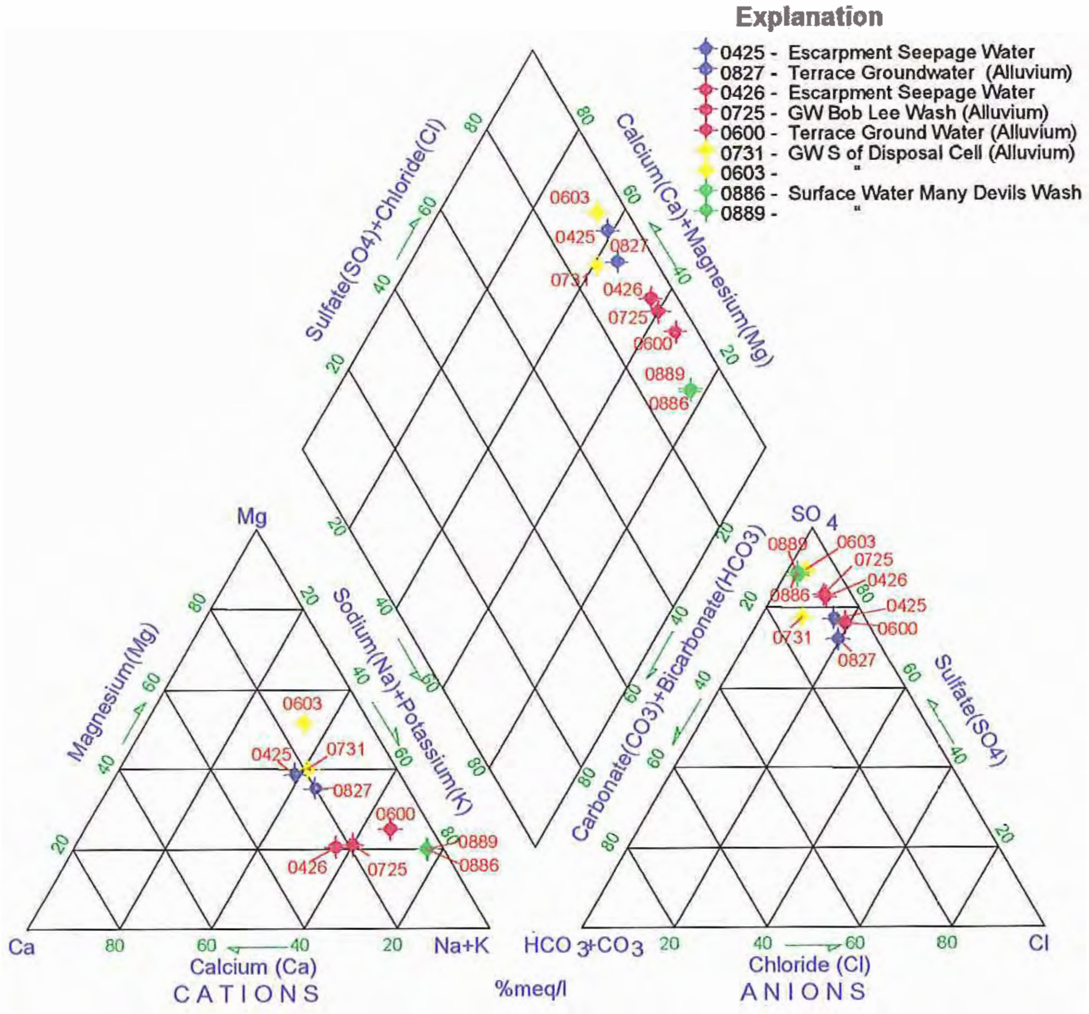


Figure 4–34. Piper Diagram of Terrace Ground Water, Escarpment Seeps, and Surface Water at Many Devils Wash

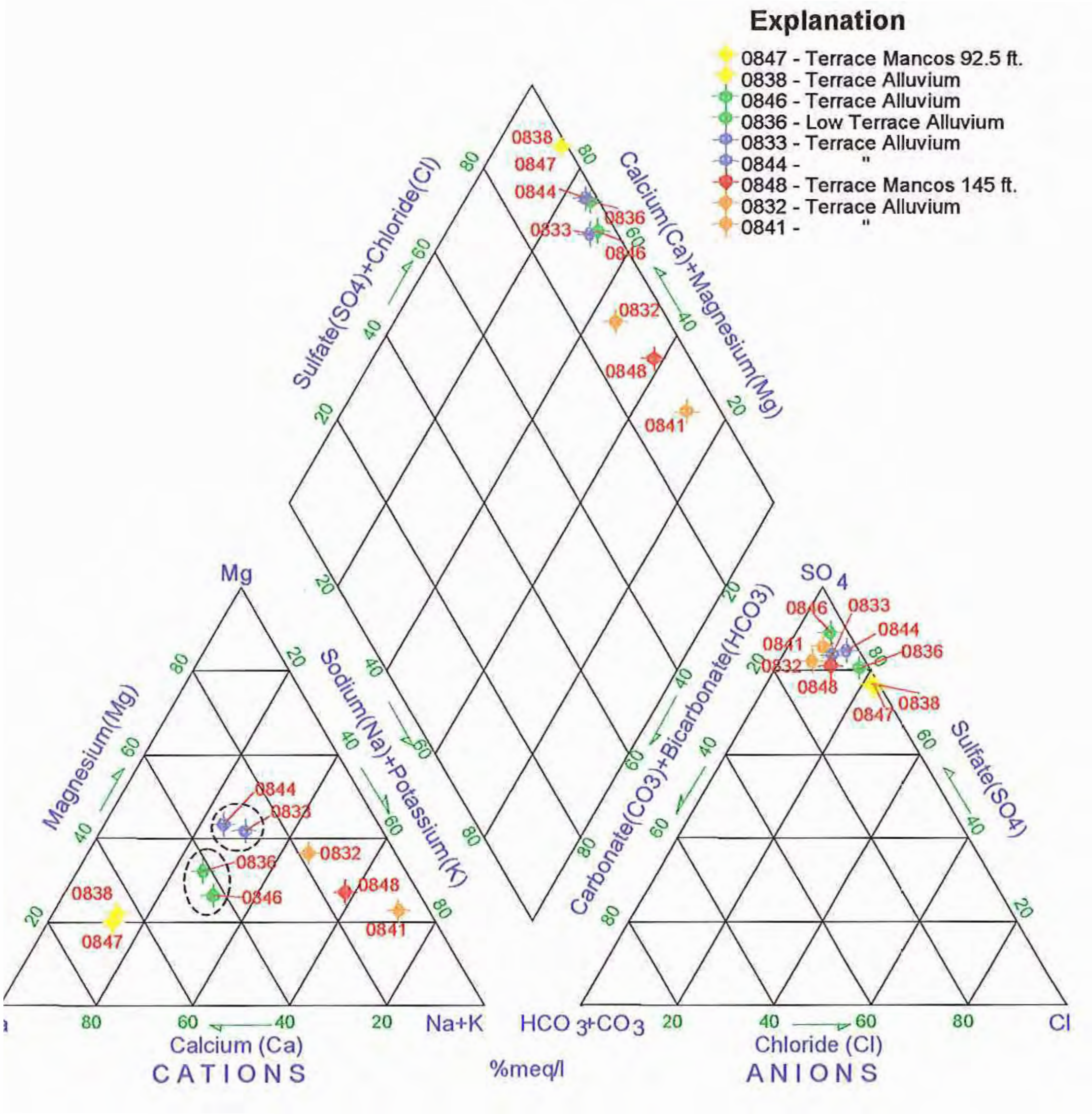


Figure 4–35. Piper Diagram of Terrace Ground Water

Table 4–14. Organic Compounds Detected in Terrace Ground Water

Constituent	Location	Date	Concentration (µg/L)
Acetone	819	03/06/1999	17
	824	03/06/1999	31
	827	03/06/1999	14
	604	07/12/1998	23
Benzene	824	03/06/1999	7
	829	03/08/1999	5
Chloromethane	819	03/06/1999	10
Chloroform	728	12/08/1998	5

4.4.3 Contaminants in Soils and Sediments

The laboratory study presented in this section addresses one of the data quality objectives defined in the Work Plan (DOE 1998c): "Characterize soils as a source of continuing contamination." The results can also be used to help assess the human health and ecological risk of exposure to the soils and sediments. Twenty-six samples were analyzed. This section presents summaries of the methods and results; a more complete description is provided in DOE (1999c).

4.4.3.1 Background

The contaminant chemistry of soils and sediments is needed to determine if the soils will release contamination to ground water. Some of the contaminants are incorporated in recalcitrant mineral grains. An example is the naturally occurring uranium in apatite, zircon, or monazite. Uranium is tightly bound in these minerals and will not be released to ground water. Some portions of the constituents are loosely bound by processes such as adsorption, absorption, chelation, incorporation in soluble minerals, or dissolved in immobile pore fluids. This loosely bound portion is the only portion of interest for environmental work.

The concentration of a constituent in a soil or sediment is determined by digesting the sample, separating the liquid phase by centrifuge or filtration, analyzing constituent concentrations in the liquid phase, and then calculating the concentrations in the solid phase. It is not necessary or desirable to have the tightly bound species digested. The most suitable digestion methods are those that remove only the loosely bound contaminants, because those contaminants have the highest potential for contaminating ground water and for being accessible to biota.

The many liquid media that can be used to digest samples range from deionized water to strong acids combined with hot fluxing agents. Some digestion agents are designed to selectively remove specific mineral phases. For example, a mixture of sodium citrate, sodium dithionite, and sodium bicarbonate is frequently used to selectively remove ferric oxyhydroxide minerals. These types of solutions, however, are not completely selective, in that some forms of contamination, such as adsorbed portions, are also released during digestion. The digestion method of choice may also be specific to the constituent of interest. For example, a low pH solution would be used to desorb cations, whereas a high pH solution would be used to desorb anions.

Numerous digestions with different solutions would be needed for complete characterization of the constituents in a soil or sediment, particularly at the Shiprock site, where a variety of constituents are of interest. This project was intended to provide a screening-level assessment of the accessible contamination in the soils and sediments. For this purpose, a 5-percent solution of

HCl was used. This acidic solution should release the adsorbed cations and dissolve carbonate minerals. Although anions adsorb more strongly at low pH, they should also be released because the acid will dissolve most of the amorphous oxyhydroxide adsorbent phases. Five-percent HCl will not dissolve most silicate minerals (an exception is that it will partially dissolve chlorite), which is desirable because the constituents in silicate minerals are not readily available to ground water. By using HCl instead of nitric or sulfuric acid, the problem of analysis for nitrate and sulfate is avoided. Therefore, while not perfect, the 5-percent HCl digestion was considered a reasonable choice for this project.

All soils and sediments in nature contain some amount of the contaminants used to process ore at the Shiprock mill. In addition, the solid-phase concentrations do not reflect the concentrations that will result in water that passes through the soils or sediments because the aqueous concentrations depend on such factors as flow rate and major-ion chemistry. To help interpret the soil and sediment data, samples were collected from background areas (areas that could not have been affected by the milling operation but that have similar lithology). Comparison of background samples that were digested in the same manner as the on-site samples helped to determine if the on-site samples contained releasable mill-related contaminants.

4.4.3.2 Methods

Soil samples were collected with a shovel or a scoop. Sediment samples from the San Juan River and streams were collected by dipping a container into the bottom sediments near the shoreline. The choice of sampling locations was biased toward those samples that were more likely to contain high levels of contamination, based on sample coloration or high radiometric measurements.

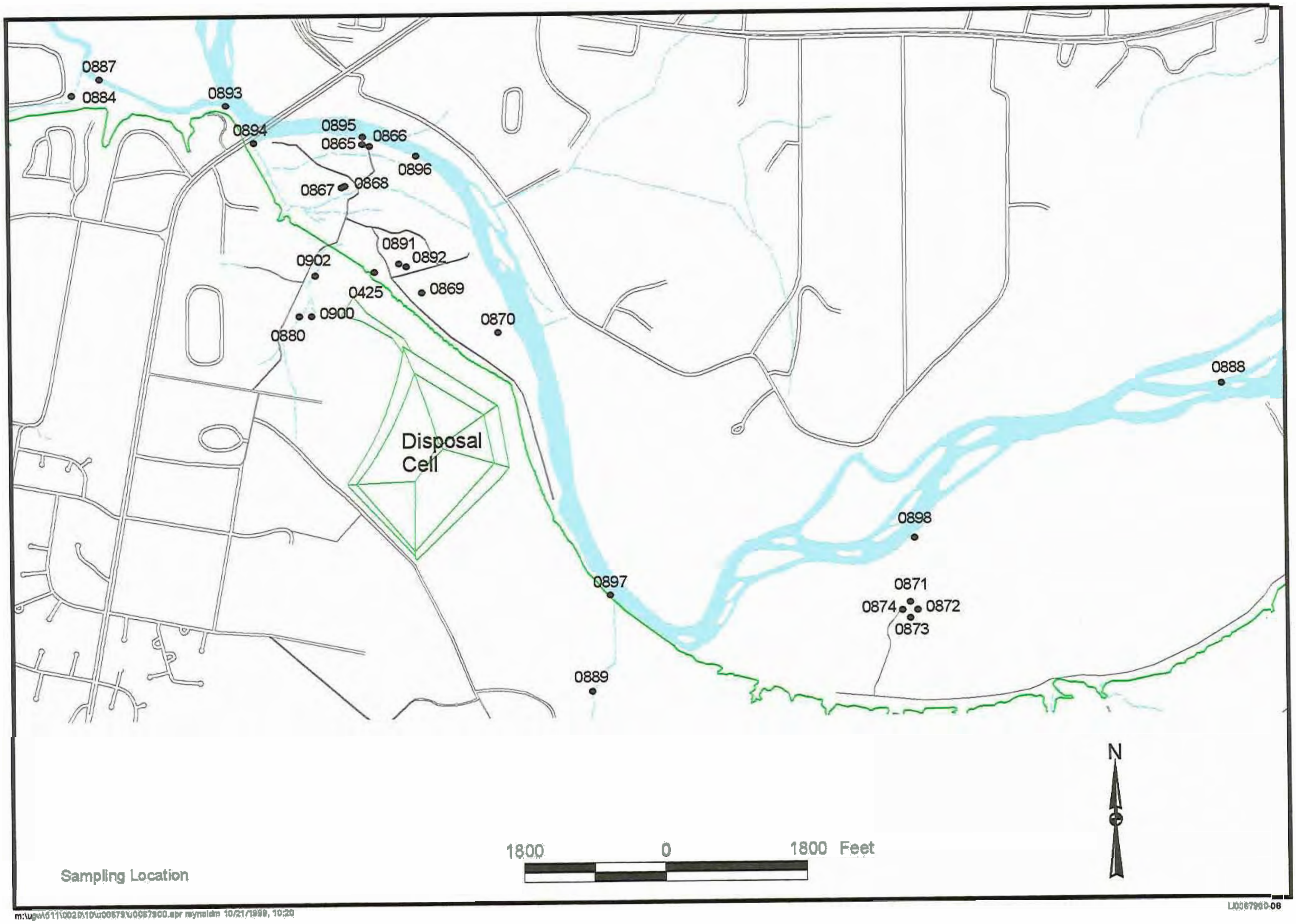
The samples were placed in aluminum pie plates, open to the air, until they were visibly dry (about 5 days). Dried samples were sieved to less than 2 millimeters (mm). The sieving removed only a small portion of the samples. Two grams of each sample was agitated with 100 milliliters (mL) of 5-percent HCl, end-over-end, for 4 hours. The samples were centrifuged, decanted, and leached again with 5-percent HCl. They were then filtered through a 0.45-micrometer (μm) filter and submitted to the GJO Analytical Chemistry Laboratory for analysis of arsenic (As), cadmium (Cd), sodium (Na), magnesium (Mg), manganese (Mn), antimony (Sb), selenium (Se), strontium (Sr), uranium (U), ammonium (NH_4), nitrate (NO_3), and sulfate (SO_4).

4.4.3.3 Results and Discussion

Sampling locations are shown on Figure 4–36. Concentrations of constituents leached from the soils and sediments are provided in Table 4–15. The areal distributions of nitrate, sulfate, and uranium concentrations are shown in Figures 4–37, 4–38, and 4–39, respectively.

Nitrate

Nitrate concentrations in the four floodplain background samples ranged from 10.7 to 23.2 milligrams per kilogram (mg/kg) and averaged 18 mg/kg (Table 4–15; Figure 4–37). Concentrations ranged from 19.7 to 1,010 mg/kg in samples from the millsite floodplain and from 18.6 to 1,120 mg/kg in samples from Bob Lee Wash. These data suggest that these areas



m:\ugw\511\0020\10\u00579\u0057900.apr reynoldm 10/21/1999, 10:20

U0057900-08

Figure 4–36. Soil and River Sediment Sampling Locations

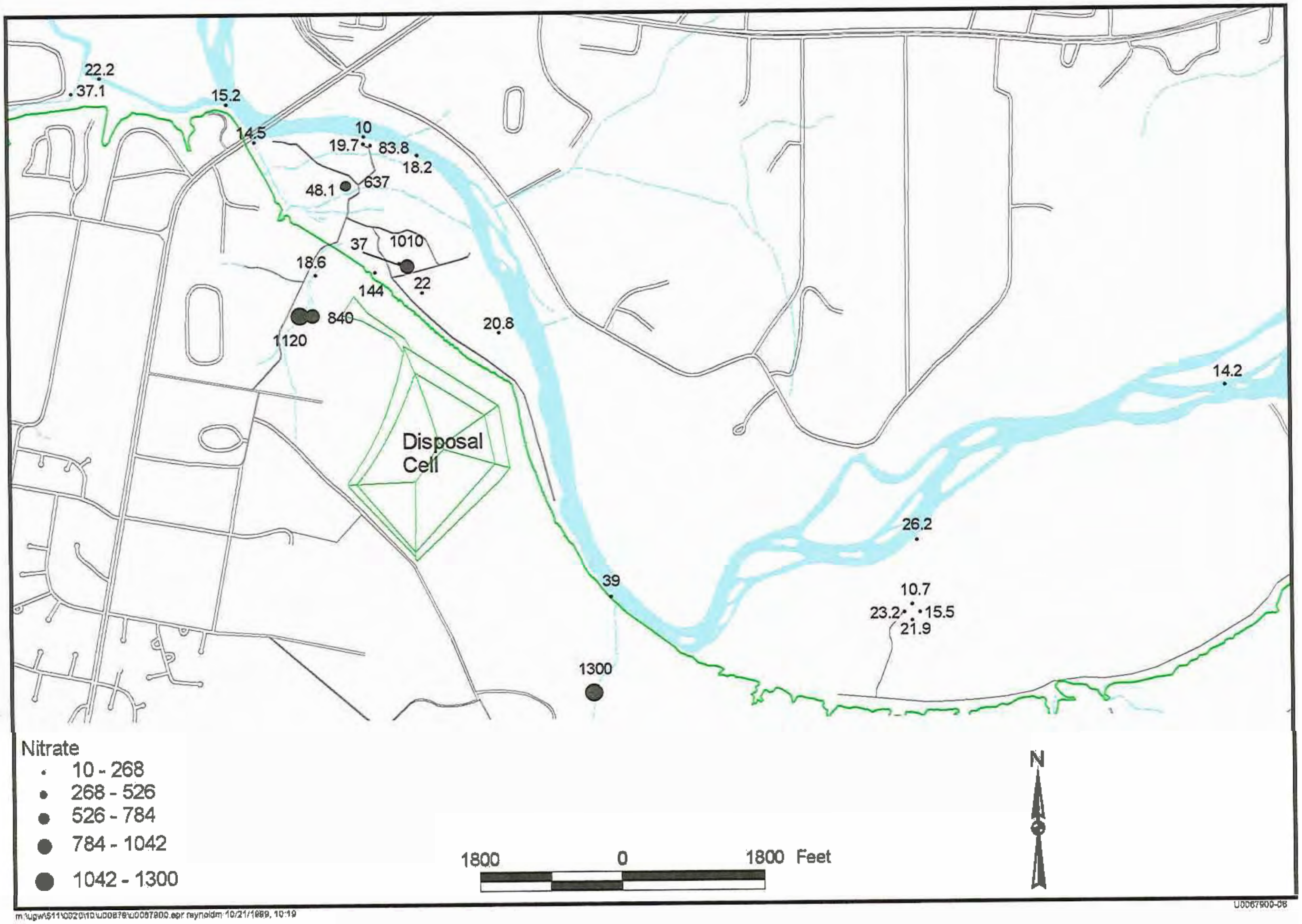


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Figure 4–37. Nitrate [mg/kg] in Soil and River Sediment

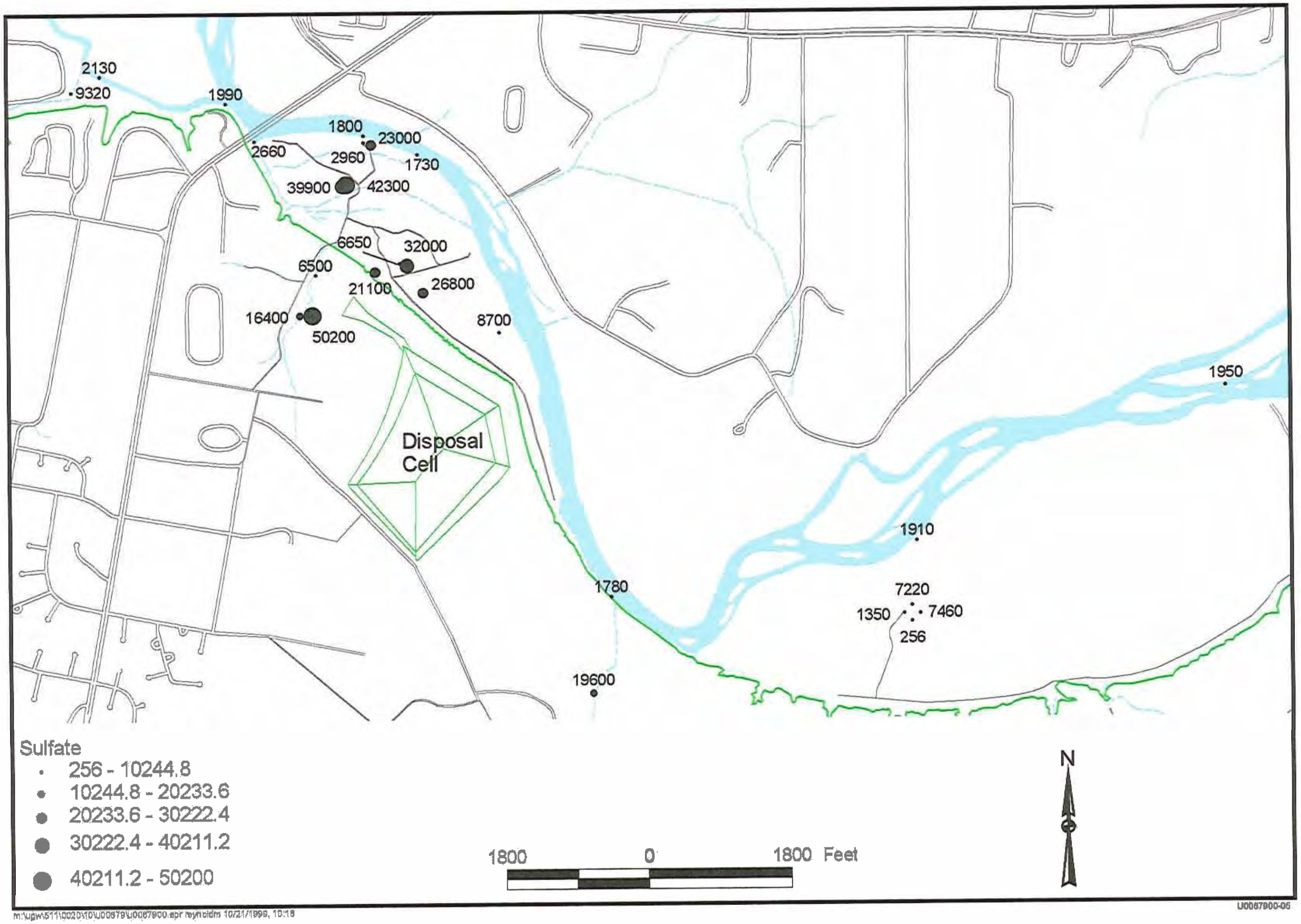

Figure 4–38. Sulfate [mg/kg] in Soil and River Sediment

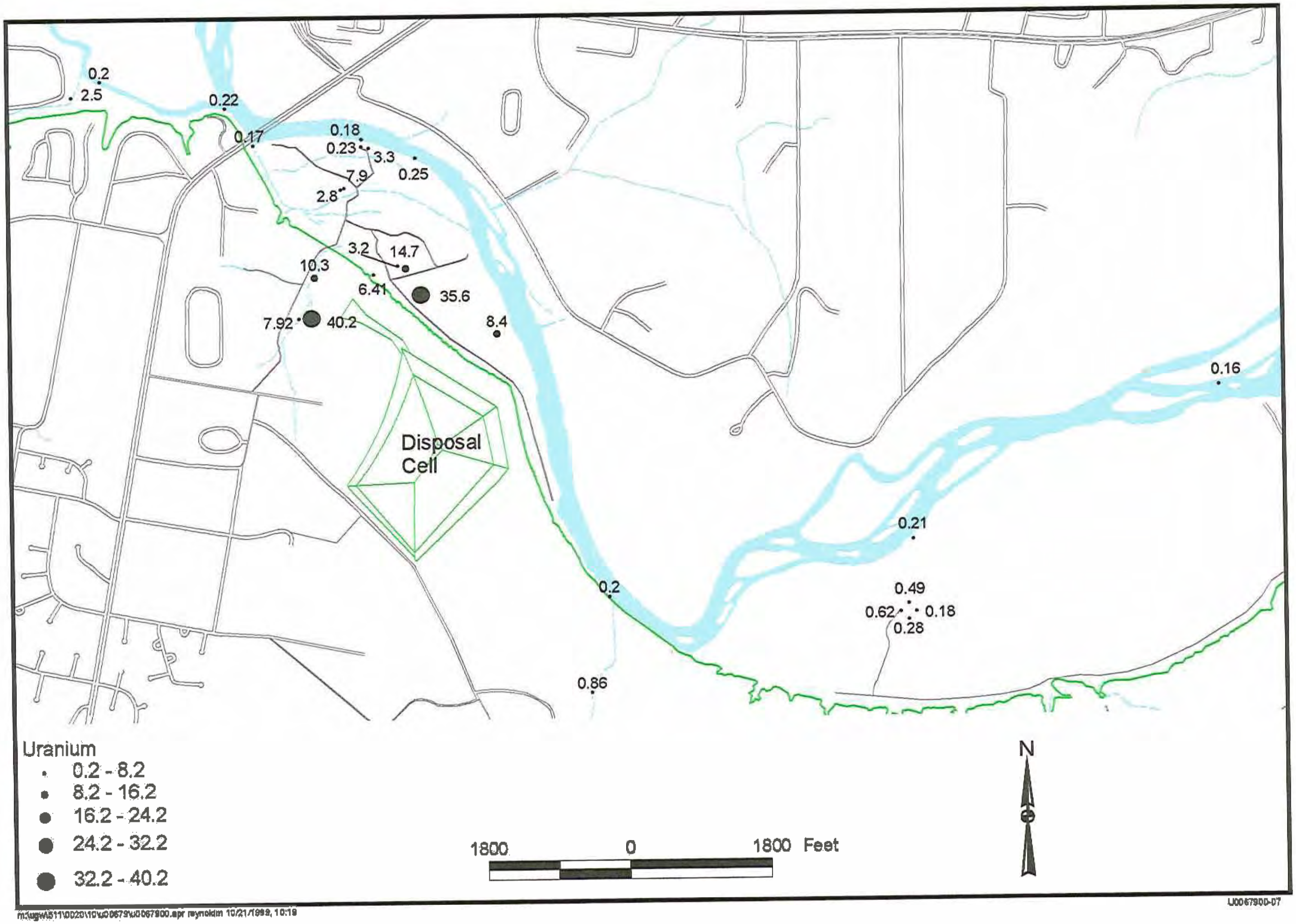

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Figure 4–39. Uranium [mg/kg] in Soil and River Sediment

were contaminated by milling activities. The nitrate concentration in the sample from location 889 in Many Devils Wash was 1,300 mg/kg, which is consistent with the high concentrations of nitrate in the seep water samples.

The nitrate concentration in a sample from the 884 location of sediment in the ditch containing irrigation return flow was 37.1 mg/kg, which is only about twice the average background. The relatively low concentration contrasts with the relatively high ammonium concentration in samples from this location, indicating that nitrate may be converted to ammonium because of the reducing conditions. Nitrate concentrations in the five on-site and downgradient San Juan River sediment samples are similar to those in samples from the two upgradient locations, indicating that the sediments have not been contaminated by millsite effluents (Table 4–15).

Sulfate

Sulfate concentrations in the four floodplain background samples ranged from 256 to 7,460 mg/kg and averaged 4,072 mg/kg (Table 4–15, Figure 4–38). Concentrations in the millsite floodplain samples ranged from 2,960 to 42,300 mg/kg. These data suggest that samples from the millsite floodplain have higher sulfate concentrations that are related to the milling activities. Sulfate concentrations ranged from 6,500 to 50,200 mg/kg in samples from Bob Lee Wash, seep 425, and Many Devils Wash. All areas characterized by high concentrations of sulfate are also characterized by high concentrations of white salt deposits, which is probably the source of most of the sulfate.

Sulfate concentrations in the San Juan River sediment samples from the five on-site and downgradient locations are similar to those in samples from the two upgradient locations, indicating that the sediments have not been contaminated by millsite effluents (Table 4–15).

Uranium

Uranium concentrations in the four floodplain background samples ranged from 0.18 to 0.62 mg/kg and averaged 0.39 mg/kg (Table 4–15; Figure 4–39). Concentrations ranged from 0.23 to 35.6 mg/kg in samples from the floodplain and from 6.41 to 40.2 mg/kg in samples from Bob Lee Wash and seep 425. These data suggest contamination related to the milling activities. The uranium concentration in the sample from location 889 in Many Devils Wash was 0.86 mg/kg, which is only about twice the average background concentration. This relatively low uranium concentration contrasts with the high concentration of nitrate at the same location.

The three floodplain samples that had the highest uranium concentrations (35.6, 8.4, and 14.7 mg/kg) were collected from locations 869, 870, and 892, respectively, and also had elevated gamma activity. The sample with the highest uranium concentration (35.6 mg/kg) was collected from sandy material around monitor well 615. This may be windblown tailings that were not completely removed during the surface remediation.

The sample collected from the sediments in the ditch containing irrigation return flow at location 884 had 2.5 mg/kg of uranium, which is about 6 times the average background. This relatively high value suggests that the reducing environment caused by decaying organic material has accumulated some uranium, which is readily fixed under reducing conditions.

Table 4–15. Concentrations of Constituents (mg/kg) in Soils and Sediments (5-percent HCl leach)[a]

Location No.	Sample Date	Location	As	Cd	Mg	Mn	Na	NH_4	NO_3	Sb	Se	SO_4	Sr	U
0884	12/10/98	AR3-884	2.4	0.81	5510	121	504	49.1	37.1	0.32	1.2	9320	203	2.5
0887	12/10/98	AR3-887	0.69	<0.1	509	171	193	<0.11	22.2	0.11	<0.2	2130	24.4	0.2
0880	3/15/99	BLW-880	1.72	0.35	9260	216	2720	14.7	1120	<0.1	<0.2	16400	136	7.92
0900	3/15/99	BLW-900	1.48	0.47	11000	262	3710	13	840	<0.1	0.57	50200	407	40.2
0902	3/15/99	BLW-902	1.12	0.35	5500	168	1230	9.63	18.6	<0.1	<0.2	6500	75.5	10.3
0425	4/7/99	ESC-425	2.06	1.17	10800	249	989	25.9	144	0.38	<0.2	21100	349	6.41
0865	1/12/99	FP-865	0.75	0.16	328	110	105	9.2	19.7	0.22	<0.2	2960	9.3	0.23
0866	1/12/99	FP-866	2.3	0.42	3940	384	5020	16.1	83.8	0.22	<0.2	23000	113	3.3
0867	1/12/99	FP-867	2.2	0.48	2790	379	11200	8.4	48.1	0.21	<0.2	39900	91.7	2.8
0868	1/12/99	FP-868	4.2	1	4720	723	8630	9.7	637	0.29	<0.2	42300	190	7.9
0869	1/12/99	FP-869	2.2	0.4	3020	149	2970	16.1	22	0.12	0.49	26800	89.8	35.6
0870	1/12/99	FP-870	1.5	0.3	2070	236	119	5.2	20.8	0.12	<0.2	8700	51.6	8.4
0891	1/12/99	FP-891	0.95	<0.1	1480	120	1080	4.1	37	<0.1	0.25	6650	63.1	3.2
0892	1/12/99	FP-892	1.8	0.29	4550	229	8190	7.8	1010	<0.1	1.9	32000	136	14.7
0871	1/13/99	FPBG-871	0.74	0.11	605	146	132	8.7	10.7	<0.1	<0.2	7220	28.6	0.49
0872	1/13/99	FPBG-872	0.47	<0.1	156	94.1	42.5	5	15.5	0.19	<0.2	7460	7.2	0.18
0873	1/13/99	FPBG-873	0.7	<0.1	320	128	64.9	5.7	21.9	<0.1	<0.2	256	14.6	0.28
0874	1/13/99	FPBG-874	0.94	0.12	1010	207	315	8.9	23.2	<0.1	<0.2	1350	40.3	0.62
0889	4/6/99	MDW-889	1.05	0.26	11900	114	3660	11.7	1300	0.18	0.44	19600	184	0.86
0888	12/9/98	SJR-888-U	0.58	<0.1	445	176	170	<0.11	14.2	0.16	<0.2	1950	36.2	0.16
0898	12/9/98	SJR-898-U	0.78	0.21	640	161	241	1	26.2	<0.1	<0.2	1910	30.1	0.21
0893	12/10/98	SJR-893	1	<0.1	646	209	293	1.8	15.2	<0.1	<0.2	1990	44.6	0.22
0894	12/10/98	SJR-894	0.88	<0.1	541	229	581	0.5	14.5	<0.1	<0.2	2660	35.1	0.17
0895	12/10/98	SJR-895	0.79	<0.1	541	176	160	0.22	10	<0.1	<0.2	1800	33.7	0.18
0896	12/10/98	SJR-896	0.92	<0.1	683	214	294	0.76	18.2	<0.1	<0.2	1730	45	0.25
0897	12/9/98	SJR-897	0.99	0.14	654	195	182	1.3	39	0.17	<0.2	1780	41.1	0.2

[a] AR3 = Area 3 distributary channel
BLW = Bob Lee Wash
ESC = Escarpment
FP = Floodplain
FPBG = Floodplain background
MDW = Many Devils Wash
SJR = San Juan River
U (in location number) = upgradient

Uranium concentrations in the San Juan River sediment samples from the five on-site and downgradient locations are similar to those in the samples from the two upgradient locations, indicating that the sediments have not been contaminated by millsite effluents (Table 4–15).

Other Constituents

Ammonium—Ammonium concentrations in the four floodplain background samples averaged 7.1 mg/kg (Table 4–15). Most of the samples collected from the millsite floodplain had concentrations similar to background. Two locations on the floodplain had a concentration of 16.1 mg/kg, which is more than twice the average background but is probably still within the range of natural concentrations. The sample from location 884 had the highest concentration of ammonium. This sample, collected underwater from an irrigation return-flow ditch, contained abundant organic matter. The high ammonium concentration may be a result of fertilizers used in the upstream agricultural fields or may have been released from decaying organic matter. Samples collected in Bob Lee Wash (880, 900, and 902 with ammonium concentrations of 14.7, 13, and 9.63 mg/kg, respectively) are slightly above the average background value of 8 mg/kg but are probably within the range of uncontaminated soils. The concentration in the sample collected at seep 425 was 25.9 mg/kg, which is about 3 times the average background value, indicating the possibility of a small contribution of ammonium from the millsite. Ammonium concentrations in the five on-site and downgradient sediment samples collected in the San Juan River were similar to those in the two upgradient samples, indicating that the sediments have not been contaminated by millsite effluents.

Antimony—Many of the antimony concentrations, both at background and on-site locations, were less than the detection limit of 0.1 mg/kg (Table 4–15). The highest concentration was 0.38 mg/kg in a sediment sample from seep 425. A sediment sample from the irrigation return flow ditch (location 884) had the second highest value of 0.32 mg/kg. These values are about twice that of background location 872 but are probably within the range of natural variation. Antimony concentrations in the five on-site and downgradient samples collected in the San Juan River were similar to those in the two upgradient samples, indicating that the sediments have not been contaminated by millsite effluents.

Arsenic—Arsenic concentrations in the four floodplain background samples averaged 0.71 mg/kg (Table 4–15). Several of the samples collected from the millsite floodplain had concentrations similar to background. However, the sample collected at location 868 on the floodplain had an arsenic concentration of 4.2 mg/kg, which is about 6 times the average background. Several other samples from the floodplain and the sample from seep 425 had concentrations about twice the average background. These values indicate that some mill-related arsenic is present on the floodplain. A sample from location 884, the irrigation return flow ditch, had an arsenic concentration of 2.4 mg/kg, which is about 3 times the average background and suggests a possible contribution from fertilizer or accumulation in the reduced environment caused by decaying organic material. Arsenic concentrations in the five on-site and downgradient samples collected in the San Juan River were similar to those in the two upgradient samples, indicating that the sediments have not been contaminated by millsite effluents.

Cadmium—Cadmium concentrations in all four floodplain background samples were less than 0.12 mg/kg (Table 4–15). Three samples from the floodplain had cadmium concentrations over 0.4 mg/kg, indicating that some mill-related cadmium may be present on the floodplain, but these values could be within the range of natural variation. Samples from Bob Lee Wash and seep 425 ranged from 0.35 to 1.17 mg/kg, indicating the possibility of mill-related contamination in those areas. The sample collected in the irrigation return flow ditch at location 884 had a cadmium concentration of 0.81 mg/kg (about 8 times average background), which suggests a possible contribution from fertilizer or accumulation in the reduced environment caused by decaying organic material. Cadmium concentrations in the five on-site and downgradient samples collected in the San Juan River were similar to those in the two upgradient samples, indicating that the sediments have not been contaminated by millsite effluents.

Magnesium—Magnesium concentrations in the four floodplain background samples ranged from 156 to 1,010 mg/kg and averaged 523 mg/kg (Table 4–15). Concentrations in samples from the floodplain ranged from 328 to 4,720 mg/kg. These data suggest that the floodplain has magnesium concentrations that are related to the milling activities. Alternatively, the higher concentrations could be the result of an increase in the concentration of evaporative salts in the soils. Magnesium concentrations ranged from 5,500 to 11,900 mg/kg in samples from Bob Lee Wash, seep 425, and Many Devils Wash. These areas are characterized by high concentrations of white efflorescent salt deposits, which are probably the source of some of the magnesium. The higher than background concentration of 5,510 mg/kg in a sample from location 884 in the irrigation return flow ditch suggests an influence from fertilizers used upstream or an accumulation of salts. Magnesium concentrations in the five on-site and downgradient samples collected in the San Juan River were similar to those in the two upgradient samples, indicating that the sediments have not been contaminated by millsite effluents.

Manganese—The manganese concentration in the sample from the irrigation return flow ditch at location 884 is only 121 mg/kg, which is lower than the average floodplain background (Table 4–15). In contrast, this sample had anomalously high concentrations of most other COPCs. The low value could be due to the organic-rich and highly reduced conditions at this location. Manganese concentrations in the four floodplain background samples ranged from 94.1 to 207 mg/kg and averaged 144 mg/kg. Concentrations in samples from the millsite floodplain and Bob Lee Wash ranged from 110 to 723 mg/kg. These data suggest that these areas were affected by milling activities. Alternatively, the higher manganese concentration may simply reflect a slightly more oxidized environment. Manganese concentrations in the five on-site and downgradient samples collected in the San Juan River were similar to those in the two upgradient samples, indicating that the sediments have not been contaminated by millsite effluents.

Selenium—Selenium concentrations in all four floodplain background samples were less than 0.2 mg/kg (Table 4–15). Most of the selenium concentrations in samples from the floodplain and Bob Lee Wash area were also less than 0.2 mg/kg. Two samples collected from the floodplain near the escarpment had concentrations of 0.49 and 1.9 mg/kg. One sample from the Bob Lee Wash area had a concentration of 0.57 mg/kg, and the sample from Many Devils Wash had a concentration of 0.44 mg/kg. These higher than background concentrations suggest mill-related contamination but may be within the range of natural variation. The sample collected from the irrigation return flow ditch at location 884 had a selenium concentration of 1.2 mg/kg, which suggests a possible contribution from fertilizer or accumulation in the reduced environment caused by decaying organic material. The selenium concentrations in all San Juan River samples were less than 0.2 mg/kg, indicating that the on-site and downgradient sediments have not been contaminated by millsite effluents.

Sodium—Sodium concentrations in the four floodplain background samples ranged from 42.5 to 315 mg/kg and averaged 139 mg/kg (Table 4–15). Concentrations in samples from the floodplain ranged from 105 to 11,200 mg/kg. These data suggest that the floodplain has sodium concentrations that are related to milling activities. Alternatively, the higher concentrations could be the result of an increase in the concentration of evaporative salts in the soils. Sodium concentrations ranged from 989 to 3,710 mg/kg in samples from Bob Lee Wash, seep 425, and Many Devils Wash. These areas are characterized by high concentrations of white efflorescent salt deposits, which are probably the source of some of the sodium. Except for one sample, the sodium concentrations in the five on-site and downgradient samples are similar to those in the two upgradient samples, indicating that sediments have not been contaminated by millsite effluents. The sample collected near the U.S. Highway 666 bridge at location 894 had a sodium concentration of 581 mg/kg, which is about 3 times the average floodplain background concentration. Because sodium sulfate is the dominant compound in white efflorescent salt deposits that occur throughout the Shiprock region, it is likely that the elevated concentration is due to a small contribution of these salts in the sediment sample.

Strontium—Strontium concentrations in the four floodplain background samples ranged from 7.2 to 40.3 mg/kg and averaged 23 mg/kg (Table 4–15). Concentrations on the floodplain ranged from 9.3 to 190 mg/kg. These data suggest that the floodplain sediments have higher strontium concentrations that could be related to the milling activities. Alternatively, the higher concentrations could be the result of an increase in the concentration of evaporative salts in the soils. Strontium concentrations ranged from 75.5 to 407 mg/kg in samples from Bob Lee Wash, seep 425, and Many Devils Wash. These relatively high concentrations suggest a millsite influence. These areas are characterized by high concentrations of white efflorescent salt deposits, which is probably the source of some of the strontium. The higher than background concentration of 203 mg/kg observed in a sample from location 884 in the irrigation return flow ditch suggests an influence from fertilizers used upstream or an accumulation of salts. Strontium concentrations in the five on-site and downgradient samples collected in the San Juan River were similar to those in the two upgradient samples, indicating that they have not been contaminated by millsite effluents.

4.4.4 Determination of Distribution Ratios

Distribution ratios were determined to address two of the data quality objectives defined in the Work Plan (DOE 1998c): (1) "characterize contaminant sorption in the Mancos Shale below the terrace system" and (2) "characterize contaminant sorption in the floodplain alluvial aquifer." Summaries of the methods and results are presented in the following sections. More complete details of the study are available in DOE (1999d).

The results of this study can be used to help evaluate the performance of ground water remediation methods. For example, a contaminant transport model incorporating a distribution coefficient (*Kd*) can be used to evaluate if natural attenuation or flushing using an enhanced gradient is likely to meet the ground water standards within the regulated 100-year period. The results of this study can also be used to help estimate the volume of ground water that will need to be pumped or passively treated to meet State and Federal ground water standards.

4.4.4.1 Background

As contaminated ground water migrates through soils and rocks, contamination is distributed between the solid and the liquid phases. This phenomenon causes the contamination to travel at a slower rate than the average ground water velocity. Chemical processes that cause this retardation can include adsorption, absorption, precipitation, diffusion into immobile porosity, and transfer to vapor phases. Generally, these processes cannot be differentiated. However, a bulk parameter (the distribution coefficient or *Kd*) has been used with some success to model the retardation of contamination for many aquifer systems. Most numerical ground water models use the *Kd* concept in simulations of contaminant transport. Site-specific *Kd* values are approximated from distribution ratio (*Rd*) values that are empirically determined. A laboratory study was conducted to determine *Rd* values for the terrace and the floodplain systems at the Shiprock site.

Rd is defined as the concentration of a constituent on the solid fraction divided by the concentration in the aqueous phase:

$$Rd = \frac{(\text{mass of solute sorbed per unit mass of solids})}{(\text{mass of solute per volume of solution})} \tag{1}$$

Rd values are calculated from experimental data as

$$Rd = \frac{(A - B)V}{M_s B} \tag{2}$$

where

Rd = distribution ratio in milliliters per gram (mL/g).
A = initial concentration of the constituent in mg/L,
B = final concentration of the constituent (mg/L),
V = volume of solution [100 mL in all cases], and
M_s = mass of soil used in grams (g).

Kd is numerically equivalent to *Rd* if the system is at equilibrium and *Rd* is constant over the range of conditions being considered. If *Rd* is constant over a large range of contaminant concentrations, it is said to be "linear" because a plot of aqueous concentration in relation to solid-phase concentration forms a straight line on an arithmetic plot. *Rd* data are often displayed on log-log concentration plots. A linear *Rd* (referred to as a linear isotherm because temperature is held constant) plots as a line with a slope of 1 on a log-log plot. At elevated concentrations of a constituent, *Rd* often varies with the aqueous concentration. In this case, the isotherm is said to be nonlinear and the migration cannot be accurately predicted using a *Kd* model.

4.4.4.2 Sample Collection and Methods

Sediment or sedimentary rock samples were obtained from two well cores in background locations on the terrace (wells 800 and 802) and from auger cuttings from three wells at background locations on the floodplain (wells 850, 851, and 852). Plate 1 shows the locations of these wells. Background-area cores and cuttings were used instead of material from contaminated areas because of the difficulty in interpreting results from contaminated material.

Two samples of weathered Mancos Shale (well 800 at 21 ft and well 802 at 32 ft), two samples of unweathered Mancos Shale (well 800 at 60 ft and well 802 at 60 ft), and six samples of floodplain alluvium (well 850 at 2 ft, well 850 at 10 ft, well 851 at 2 ft, well 851 at 11 ft, well 852 at 6 ft, and well 852 at 12 ft) were tested. Two of the floodplain alluvial samples (well 850 at 2 ft and well 851 at 2 ft) are from the upper sand unit; all other floodplain alluvial samples are from the lower gravel unit.

Rd data were collected using Environmental Sciences Laboratory (ESL) Procedure CB(BE–3) (DOE 1999d), which follows an American Society for Testing and Materials (ASTM) procedure for batch-type experiments (ASTM 1993). Two synthetic solutions were prepared that simulate the major-ion chemistry and pH of ground water at the site. Contaminants that had ground water concentrations that exceeded 10 times the MCL, or twice background levels, were selected for study. Those contaminants are ammonium, cadmium, selenium, and uranium.

Five-point isotherms were determined for all four constituents for two samples of Mancos Shale (weathered and unweathered) from the terrace and for two samples of alluvial aquifer material from the floodplain. Masses of sampled material varying from 1 to 25 g were used to determine the isotherms.

4.4.4.3 Results and Discussion

Mean values of *Rd* for terrace weathered Mancos Shale, terrace unweathered Mancos Shale, and floodplain alluvial gravel are presented in Table 4–16. Several *Rd* values were significantly different from the mean values. These anomalous values are probably because of sample inhomogenieties or analytical errors. Table 4–17 presents mean *Rd* values with outliers omitted. Values that exceeded 1 standard deviation from the mean are excluded. The mean *Rd* values do not change substantially by omitting the outliers; the *Rd* values for ammonium showed the largest changes.

Table 4–16. Summary of Rd *Determinations*

Constituent	**Description**	**Mean *Rd* (mL/g)**	**Standard Deviation**
Ammonium	Terrace - weathered Km[a]	4.68	6.88
Ammonium	Terrace - unweathered Km	3.16	6.72
Ammonium	Floodplain – Qal[b]	1.39	1.85
Cadmium	Terrace – weathered Km	213.79	86.66
Cadmium	Terrace – unweathered Km	132.04	19.80
Cadmium	Floodplain – Qal	22.55	6.12
Selenium	Terrace – weathered Km	68.09	40.62
Selenium	Terrace – unweathered Km	46.63	18.22
Selenium	Floodplain – Qal	10.51	5.24
Uranium	Terrace – weathered Km	1.13	1.15
Uranium	Terrace – unweathered Km	1.97	0.43
Uranium	Floodplain – Qal	0.64	0.36

[a] Km = Mancos Shale.
[b] Qal = Quaternary alluvium.

Table 4–17. Summary of Rd *Determinations Omitting Outliers*[a]

Constituent	Description	Mean *Rd* (mL/g)	Standard Deviation	Number Omitted
Ammonium	Terrace – weathered Mancos Shale	2.08	2.91	1/6[b]
Ammonium	Terrace – unweathered Mancos Shale	0.59	2.55	1/6
Ammonium	Floodplain – Qal[c]	0.72	0.46	2/14
Cadmium	Terrace – weathered Mancos Shale	180.00	28.76	1/6
Cadmium	Terrace – unweathered Mancos Shale	135.37	8.85	2/6
Cadmium	Floodplain – Qal	21.96	2.92	5/14
Selenium	Terrace – weathered Mancos Shale	54.73	26.90	1/6
Selenium	Terrace – unweathered Mancos Shale	46.60	9.18	2/6
Selenium	Floodplain – Qal	11.44	2.45	6/14
Uranium	Terrace – weathered Mancos Shale	1.59	0.24	1/6
Uranium	Terrace – unweathered Mancos Shale	2.13	0.17	1/6
Uranium	Floodplain – Qal	0.54	0.19	3/14

[a] Outliers are those values that exceeded 1 standard deviation from the mean.
[b] 1/6 = 1 of 6 points were omitted
[c] Qal = Quaternary alluvium.

Ammonium

The final concentrations of ammonium do not correlate well with the amount of solids used in the experiments. For example, the final concentration of ammonium in sample 800 from 21 ft using 25 g of sample was 60,100 micrograms per liter (µg/L), whereas the final concentration with 15 g of sample was 34,100 µg/L. The lack of correlation apparently was due to the instability of the solutions with respect to ammonium. Because ammonium is volatile relative to the other contaminants used in this study, it is possible that some portion was lost during vacuum filtering. Another possibility is that some ammonium has transformed to another nitrogen-bearing species, such as nitrite or nitrate. Additional tests, with careful monitoring of ammonium, nitrate and nitrite concentrations, would be required to confirm the *Rd* values.

Corrected (outliers removed) mean *Rd* values for ammonium concentrations range from 0.59 mL/g for samples from the terrace unweathered Mancos Shale to 2.08 mL/g for samples from the terrace weathered Mancos Shale (Table 4–17). All five isotherm points for each of the two floodplain samples are within 10-percent error bars of the 0.2 to 1 mL/g *Rd* values. Most of the *Rd* values are relatively small (many are less than 1 mL/g), suggesting that ammonium did not partition significantly to the solid phases.

Cadmium

Corrected mean *Rd* values for cadmium concentrations range from 21.96 mL/g for samples from the floodplain to 180 mL/g for samples from the terrace in weathered Mancos Shale (Table 4–17). The *Rd* values for samples from the terrace unweathered Mancos Shale (mean of 135.37 mL/g) are similar to the values from samples from the terrace weathered Mancos Shale. The *Rd* values for cadmium were higher than for other contaminants measured in this study, indicating the tendency for cadmium to be tightly sorbed to the solid fraction of both Mancos Shale and floodplain alluvium. Dissolved cadmium concentrations varied consistently with the amount of sediment. *Rd* values were nearly linear over an order of magnitude range in aqueous concentrations.

Selenium

Corrected mean *Rd* values for selenium range from 11.44 mL/g for samples from the floodplain alluvium to 54.73 mL/g for samples from the terrace in weathered Mancos Shale (Table 4–17). The *Rd* values for samples from the terrace unweathered Mancos Shale (mean of 46.60 mL/g) were similar to samples from the weathered Mancos Shale. The *Rd* values for both Mancos Shale and floodplain alluvium samples were relatively high, indicating the tendency of selenium to sorb to the solid fraction.

Plots of the dissolved concentrations compared with sediment mass for selenium showed somewhat inconsistent results. The plot for weathered Mancos Shale showed, except for the lowest amount of sediment, that the final concentrations are nearly equivalent regardless of sediment mass. This observation suggests that adsorption is not the dominant uptake mechanism. A possible explanation is that the solutions became reducing enough to precipitate a selenide mineral. Other than one point, the five values from one of the floodplain samples are within error bars of an *Rd* of 6 mL/g. Results of the second floodplain sample were within error of an *Rd* of 12 mL/g.

Uranium

Corrected mean *Rd* values for uranium range from 0.54 mL/g for samples from the floodplain alluvium to 2.13 mL/g for samples from the terrace in unweathered Mancos Shale (Table 4–17). Uranium sorption to floodplain sediments was less than to the Mancos Shale. *Rd* values for the floodplain samples were relatively low, indicating the tendency for uranium to remain in the aqueous phase, whereas some retardation is to be expected in the Mancos Shale samples.

Dissolved uranium concentrations decrease consistently with the mass of weathered Mancos Shale; all points are within error bars of *Rd* values ranging from 1.1 to 2.1 mL/g. The unweathered Mancos Shale sample showed a similar trend; all points are within error bars of *Rd* values ranging from 1.5 to 2.8 mL/g. All points for the floodplain samples were within the error bars for *Rd* values ranging from 0 to 0.7 mL/g.

4.4.5 Composition of Salt Deposits

The laboratory study presented in this section addresses one of the data quality objectives defined in the Work Plan (DOE 1998c): "characterize soils as a source of continuing contamination." Analysis of salt deposits was recommended during discussions with stakeholders at a meeting in Tucson, Arizona, on March 4, 1999. The three objectives of this study were (1) to help characterize soils as a source of continuing contamination, (2) to provide data to help evaluate the areal extent of contaminated ground water, and (3) to provide data that will help determine the origin (mill-related or natural) of ground water contamination. This section presents a summary of the methods and results; a more complete description of the study is provided in DOE (1999b). Sample locations are shown on Figure 4–40.

4.4.5.1 Background

Salt deposits are common in arid environments. They appear in various forms such as white powders that coat the ground surface, crystalline deposits on the ground surface, and fracture fillings on outcrops. The deposits are usually white, although some have a yellow tinge. Salts are deposited where ground water evaporates after contacting salt-rich sediments and are most common at locations where water has a high evaporation rate. Salts are found near seeps or in areas where capillary pressure causes ground water to migrate to the ground surface and evaporate. Salts also deposit from evaporation of surface water in closed basins. A wide variety of evaporite minerals are precipitated in the salt deposits.

Salt deposits in Bob Lee Wash, Many Devils Wash, and on the escarpment at the Shiprock site cover large portions of the ground surface. These deposits consist of translucent white or yellow-tinted crystalline minerals that often encrust soil or vegetation. Some salt deposits on the floodplain are crystalline, but many occur as white powders that coat the ground. The crusts and powders are often concentrated in tire tracks (perhaps because the sediment has been compacted, causing an increase in upward capillary water movement). The areal extent of salt deposits in background areas is minor compared with the millsite area. In background areas, the salt deposits were typically observed as thin layers of white powder.

The chemistry of the salt deposits should reflect, in part, the chemistry of the water from which they were formed. This is particularly true if the water completely evaporates and deposits its entire load of dissolved minerals. If only partial evaporation occurs, the salt deposits will be biased by the composition of the most insoluble minerals, which are the first to precipitate.

4.4.5.2 Methods

Samples were air dried for about 5 days. Some of the samples contained large proportions of water-insoluble soil, whereas others were mostly water soluble. For those samples that had large amounts of soils, a larger quantity was used so that results would be within analytical detection limits.

Soluble salts were extracted in deionized water following ESL Procedure CB(BE–4) manual. Five grams of each sample was mixed with 500 mL of deionized water. If the conductivity was less than 2,000 microsiemens per centimeter (µS/cm), additional sample was added. Samples were agitated on an orbital shaker for 24 hours, then centrifuged and decanted. The supernatants were filtered through a 0.45 µm filter. The residues were oven dried at 90 °C and weighed to determine the amount of insoluble soils.

The supernatant solutions were analyzed for pH, alkalinity, and conductivity and for TDS, uranium, nitrate, and sulfate concentrations. TDS were determined by weighing the residue resulting from 100 mL of solution dried at 90 °C. Supernatant solutions from 12 selected samples were analyzed for antimony, arsenic, cadmium, magnesium, manganese, nitrate, selenium, sodium, strontium, sulfate, uranium, ammonium, and major ions (calcium, chloride, potassium, iron, and total inorganic carbon). Concentrations of constituents were normalized to the TDS concentration. Thus, a component with a concentration of 10,000 mg/kg (1 percent) means that this component constitutes 1 percent of the water-soluble portion of the sample.

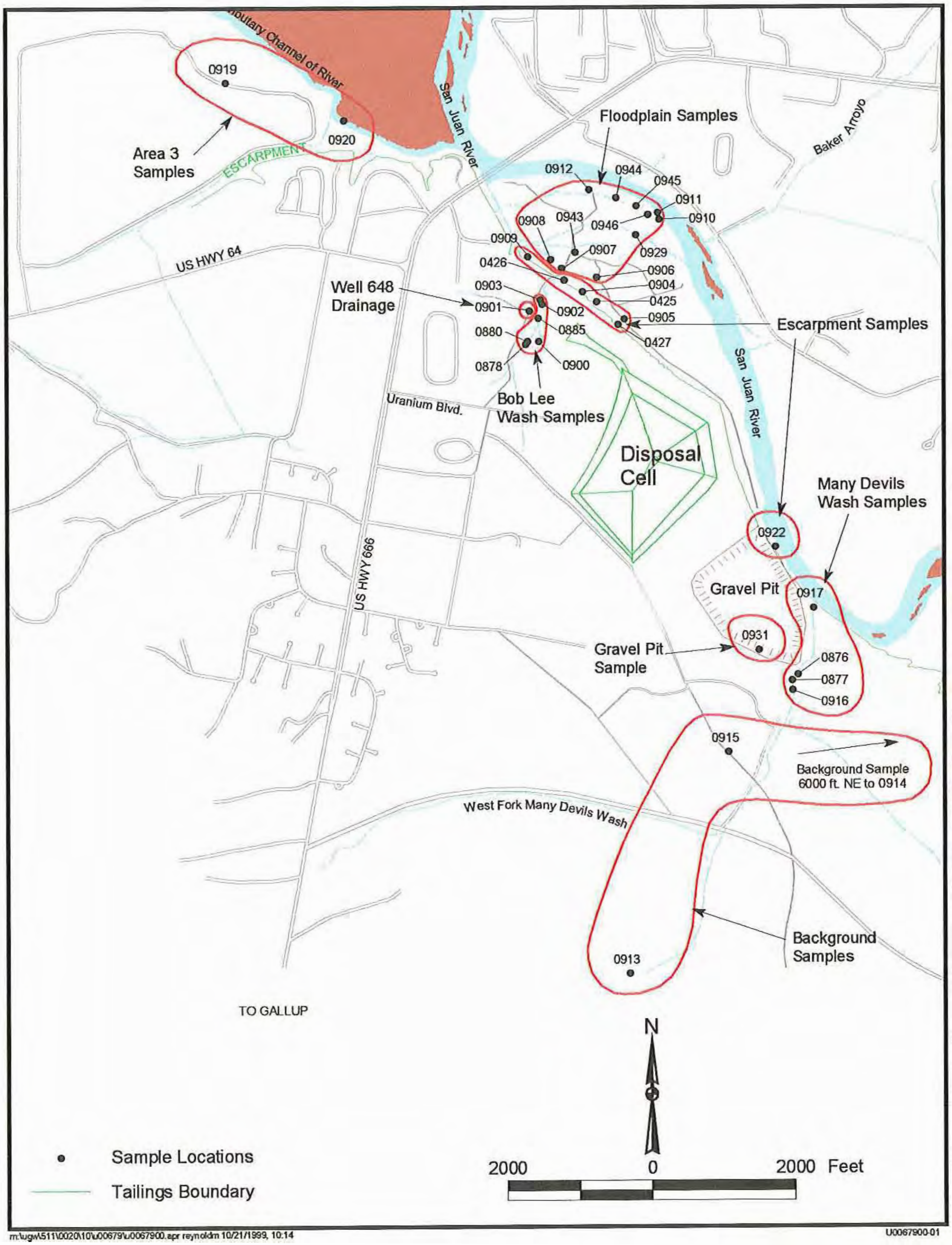

Figure 4–40. Salt Deposit Sample Locations

4.4.5.3 Major Ion Composition of the Salt Deposits

The water soluble salts are dominated by sodium sulfate (Table 4–18). Sodium constitutes 7.31 to 29.99 percent of the TDS. Other cations constituting significant portions of the salt deposits are calcium (to 10.09 percent) and magnesium (to 7.69 percent). Sulfate concentrations ranged from 20.17 percent (201,672 mg/kg) to 73.01 percent (730,114 mg/kg) of the TDS, excluding one sample that was calculated to have 116 percent (1,161,677 mg/kg) sulfate because of an analysis error (Table 4–19). Other anions include chloride with up to 2.18 percent (Table 4–18) and nitrate with up to 14.91 percent (Table 4–19). Trace elements (arsenic, cadmium, iron, manganese, ammonium, antimony, selenium, and uranium) constitute only 0.002 to 0.015 percent of the salts (Table 4–18). Uranium, selenium, and ammonium dominated the trace element compositions (Table 4–20).

Table 4–18. Concentrations (%) of Major Ions in the Salt Deposit Samples (ACL data)[a]

Location	Area	Ca	K	Mg	Na	Sr	SO_4	Cl	NO_3	TIC	Trace[b]	Total
920	AR3	2.10	0.10	7.09	14.07	0.07	60.94	1.16	0.04	0.17	0.002	86
914	BKG	4.08	0.12	4.03	18.18	0.02	61.05	1.36	0.81	0.07	0.009	90
915	BKG	10.09	0.54	0.27	18.15	0.08	64.76	0.10	0.13	0.18	0.008	94
885	BLW	5.52	0.18	4.46	13.75	0.09	57.43	2.18	2.08	0.24	0.015	86
900	BLW	0.96	0.06	1.57	26.81	0.01	62.55	2.01	1.63	0.09	0.008	96
425	ESC	5.89	0.10	7.69	7.31	0.11	57.06	0.60	0.78	0.09	0.003	80
907	FP	2.74	0.10	0.37	27.37	0.07	64.03	0.78	0.12	0.15	0.004	96
910	FP	4.00	0.09	3.44	20.32	0.07	64.00	0.39	0.43	0.14	0.006	93
876	MDW	0.63	0.04	1.39	27.27	0.02	62.50	0.77	2.56	0.08	0.005	95
877	MDW	0.60	0.04	1.72	27.15	0.02	61.14	1.08	3.28	0.05	0.005	95
917	MDW	0.64	0.01	0.39	29.99	0.01	65.73	0.25	0.76	0.04	0.004	98
901	W648	2.46	0.13	0.56	27.11	0.07	67.41	1.01	0.04	0.13	0.002	99

[a] Normalized to TDS.
[b] Total percentage of trace elements from Table 4–20.
TIC = total inorganic carbon.
ACL = GJO Analytical Chemistry Laboratory.
AR3 = Area 3.
BKG = background.
ESC = escarpment.
FP = floodplain.
MDW = Many Devils Wash.
W648 = artesian well 648.

4.4.5.4 Nitrate, Sulfate, and Uranium Concentrations of the Salt Deposits

Nitrate, sulfate, and uranium have high concentrations in ground water at the site. The concentrations of nitrate, sulfate, and uranium are listed in Table 4–19 and their areal distributions are shown on Figures 4–41, 4–42, and 4–43, respectively.

Table 4–19. Concentrations of Nitrate, Sulfate, and Uranium in Salt Deposit Samples (ESL Data)[a]

Location	Area	Recovery (%)	Insoluble Soil (%)	TDS (mg/L)	SO_4 (TDS) (mg/kg)	NO_3 (TDS) (mg/kg)	U (TDS) (mg/kg)
919	AR3	97.09	93	2,580	596,512	8,527	1.09
920	AR3	92.56	56	3,610	673,130	859	4.90
913	BKG	102.32	98	1,680	532,262	24,357	0.60
914	BKG	99.30	95	4,390	669,704	5,412	0.36
915	BKG	98.49	96	2,270	683,700	2,159	0.66
880	BLW	93.86	58	3,610	500,554	81,717	33.10
878	BLW	93.88	64	2,990	201,672	10,702	76.02
885	BLW	94.07	70	4,910	482,485	12,281	70.35
900	BLW	96.36	26	7,050	689,504	9,858	49.74
902	BLW	99.28	91	3,470	635,447	1,902	27.03
903	BLW	98.80	93	2,240	618,750	1,161	12.90
425	ESC	90.01	54	7,150	642,517	6,028	12.74
426	ESC	99.48	75	2,420	556,612	22,562	0.95
427	ESC	98.98	84	2,920	429,452	116,096	3.56
904A	ESC	85.89	79	2,600	569,231	2,692	0.73
904B	ESC	90.44	43	4,720	643,644	3,814	14.41
0922	ESC	88.12	16	7,240	275,552	92,680	1.35
943	FP	99.76	68	3,210	523,053	822	9.72
944	FP	98.26	85	2,570	601,946	20,623	9.14
945	FP	98.78	84	2,880	457,986	1,979	2.33
946	FP	99.10	94	3,310	664,350	2,931	2.54
905	FP	95.67	71	5,020	729,880	12,530	24.84
906	FP	98.97	90	3,520	730,114	750	26.59
907	FP	99.38	72	2,780	657,194	1,424	7.84
908	FP	98.68	91	3,050	661,967	721	53.38
909	FP	96.96	80	3,320	450,602	149,096	0.51
910	FP	99.65	87	2,500	680,800	3,168	8.76
911	FP	92.17	22	4,920	662,602	5,813	13.41
912	FP	99.50	91	3,270	645,260	538	15.23
929	FP	91.56	58	3,340	1,161,677	10,000	5.33
931	GP	95.02	59	3,590	595,543	73,538	0.31
876	MDW	96.92	9	8,800	576,705	25,000	0.69
877	MDW	94.46	8	8,620	614,849	28,886	1.24
916	MDW	94.24	13	8,090	523,239	55,748	1.79
917	MDW	98.04	2	9,570	619,122	6,071	0.39
901	W648	99.68	80	4,020	714,925	871	0.95

[a] (TDS) = Normalized to TDS.

ACL = GJO Analytical Chemistry Laboratory.
AR3 = Area 3.
BKG = background.
ESC = escarpment.
ESL = GJO Environmental Sciences Laboratory.
FP = floodplain.
MDW = Many Devils Wash.
W648 = artesian well 648.

Table 4–20. Concentrations of (mg/kg) Trace Elements in the Salt Deposit Samples (ACL Data)[a]

Sample No.	Area	As	Cd	Fe	Mn	NH_4	Sb	Se	U	Total
920	AR3	<0.55	<0.28	<2.22	<0.28	12.69	<0.28	<0.55	4.74	21.58
914	BKG	<0.46	<0.23	<1.82	0.77	21.57	<0.23	66.74	<0.23	92.05
915	BKG	1.72	<0.44	<3.52	1.01	39.25	<0.44	34.93	0.62	81.94
885	BLW	<0.41	<0.20	<1.63	13.14	42.57	<0.20	12.46	82.08	152.69
900	BLW	0.33	<0.14	<1.13	<0.14	9.16	<0.14	21.13	49.50	81.69
425	ESC	<0.28	<0.14	1.43	<0.14	13.78	<0.14	3.38	11.34	30.63
907	FP	1.01	<0.36	<2.88	<0.36	22.55	<0.36	6.12	7.73	41.37
910	FP	<0.80	<0.40	<3.20	2.08	42.40	<0.40	<0.80	8.56	58.64
876	MDW	0.35	<0.11	2.26	0.16	3.50	<0.11	43.07	0.86	50.43
877	MDW	<0.23	<0.12	<0.93	<0.12	3.57	<0.12	45.13	1.28	51.48
917	MDW	0.68	<0.10	<0.84	<0.10	8.33	<0.10	28.32	0.38	38.85
901	W648	1.12	<0.25	<1.99	2.51	17.01	<0.25	<0.50	1.04	24.68

[a]Normalized to TDS.
ACL = GJO Analytical Chemistry Laboratory.
AR3 = Area 3.
BKG = background.
ESC = escarpment.
FP = floodplain.
MDW = Many Devils Wash.
W648 = artesian well 648.

The maximum nitrate concentration was 14.9 percent (149,096 mg/kg) which was observed in a sample from location 909 on the escarpment west of Bob Lee Wash (Figure 4–41). This sample was collected from a small ravine that drains a residential area of the terrace and may have been affected by a septic leach field in the area. A non-mill related source for the nitrate is supported by the relatively low uranium concentration of 0.51 mg/kg. Nitrate concentrations in excess of 1 percent (10,000 mg/kg) also occur in samples from some locations in the Bob Lee Wash, Many Devils Wash, floodplain, and escarpment areas. The sample collected at the gravel pit (931) and one of the background samples (913) also had nitrate concentrations greater than 1 percent.

The occurrence of high nitrate concentrations with relatively low uranium concentrations in samples from Many Devils Wash suggests either that nitrate has migrated farther from the millsite than uranium or that there are sources of nitrate not related to milling. A high nitrate concentration (24,357 mg/kg) in a background sample from location 913 indicates that other sources of nitrate may be present. This background sample, however, had a low proportion of soluble salts (98 percent of the sample was insoluble soil). A low percentage of soluble salt could cause the normalized value to be biased by constituents leached from the soil. Refuse dumps, septic leach fields, and leaching from Mancos bedrock are possible, non-mill related, sources of nitrate.

Sulfate was a major component in all salt deposit samples. Sulfate in ground water and surface water results from leaching of bedrock and soils in the area. Sulfate also is derived from sulfuric acid used in the uranium milling process. More than 50 percent of the TDS in most samples was sulfate, indicating the ubiquitous presence of this constituent. There were no obvious trends in the areal distribution of sulfate (Figure 4–42).

Uranium concentrations measured in the GJO ESL were as high as 76.02 mg/kg in the salt deposit samples (Table 4–19). Uranium concentrations in samples from Bob Lee Wash, along the escarpment, and on the floodplain are higher than background concentrations (Figure 4–43). The uranium in these deposits is derived from mill effluents. Uranium concentrations in the Many Devils Wash salt deposit samples are close to background concentrations (Figure 4–43).

4.4.5.5 Constituents Other than Nitrate, Sulfate, and Uranium

Cadmium and antimony concentrations were below their detection limits (Table 4–20). Arsenic concentrations were low with most below detection. The highest arsenic concentration was 1.72 mg/kg, which was observed in a background sample from location 915 (Table 4–20). Most of the iron concentrations were less than the detection limit. The highest detectable iron concentration was 2.26 mg/kg (Table 4–20). Ammonium concentrations ranged from 3.50 to 42.57 mg/kg (Table 4–20). While these concentrations are higher than many of the trace elements, they are much lower than nitrate concentrations. Ammonium concentrations in background samples are similar to concentrations in on-site samples. A sample from location 885 in the Bob Lee Wash area had a manganese concentration of 13.14 mg/kg (Table 4–20). All other samples had manganese concentrations of 2.51 mg/kg or less with many below the detection limit. Selenium concentrations ranged from less than 0.50 mg/kg to 66.74 mg/kg; the highest concentration was in a background sample from location 914 (Table 4–20).

The concentrations of these trace constituents (arsenic, cadmium, iron, manganese, ammonium, antimony, and selenium) are probably similar to concentrations in many arid salt deposits and may not be related to milling activities.

4.4.6 Column Leaching of Alluvial Aquifer Sediment

The laboratory study presented in this section addresses one of the data quality objectives defined in the Work Plan: "characterize leachability conditions of alluvial material in several contaminated areas of the floodplain." The study examined the effectiveness of San Juan River water to leach uranium and other constituents from floodplain alluvial sediments. The methods and results are summarized here; a more complete description of the project is provided in DOE (1999a).

4.4.6.1 Background

Column leaching is often used to estimate the concentration of contaminants that will occur when a solution flows through contaminated sediments. Effluent concentration profiles over time can also provide information that indicates how rapidly the concentrations will decrease.

Contaminants can be present in sediment in different forms, including crystalline structure of minerals, adsorbed to mineral surfaces, and immobile pore fluids. Some of the forms of contamination are more easily released than others. Complexing agents in the leach solution enhance the release of some contaminants. Therefore, the choice of leach solution is important. An example is uranium, which desorbs more efficiently in a solution with high concentrations of dissolved carbonate. The pH and oxidation potential of the solution can also affect the leaching process.

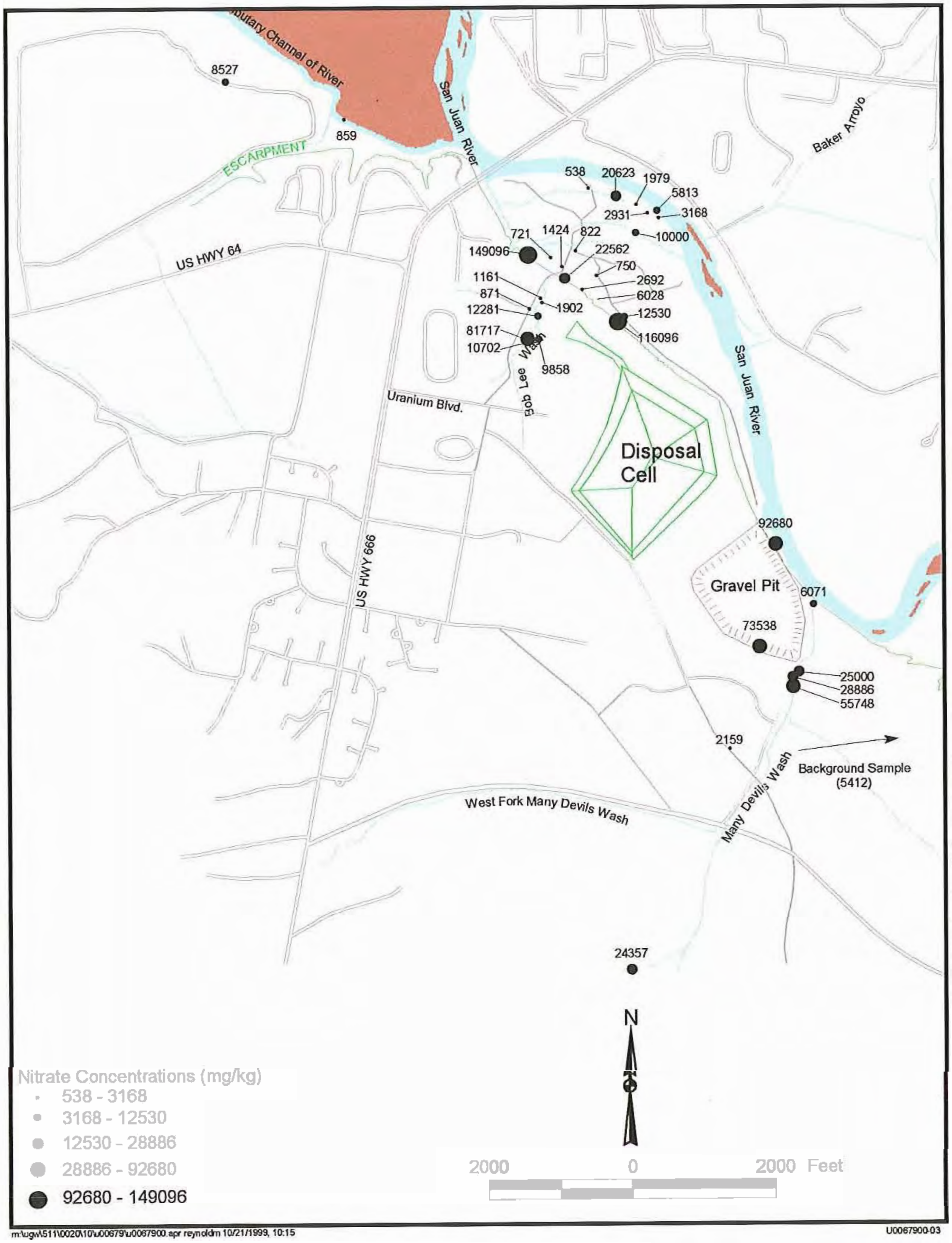

Figure 4–41. Nitrate Concentrations in Salt Deposit Samples

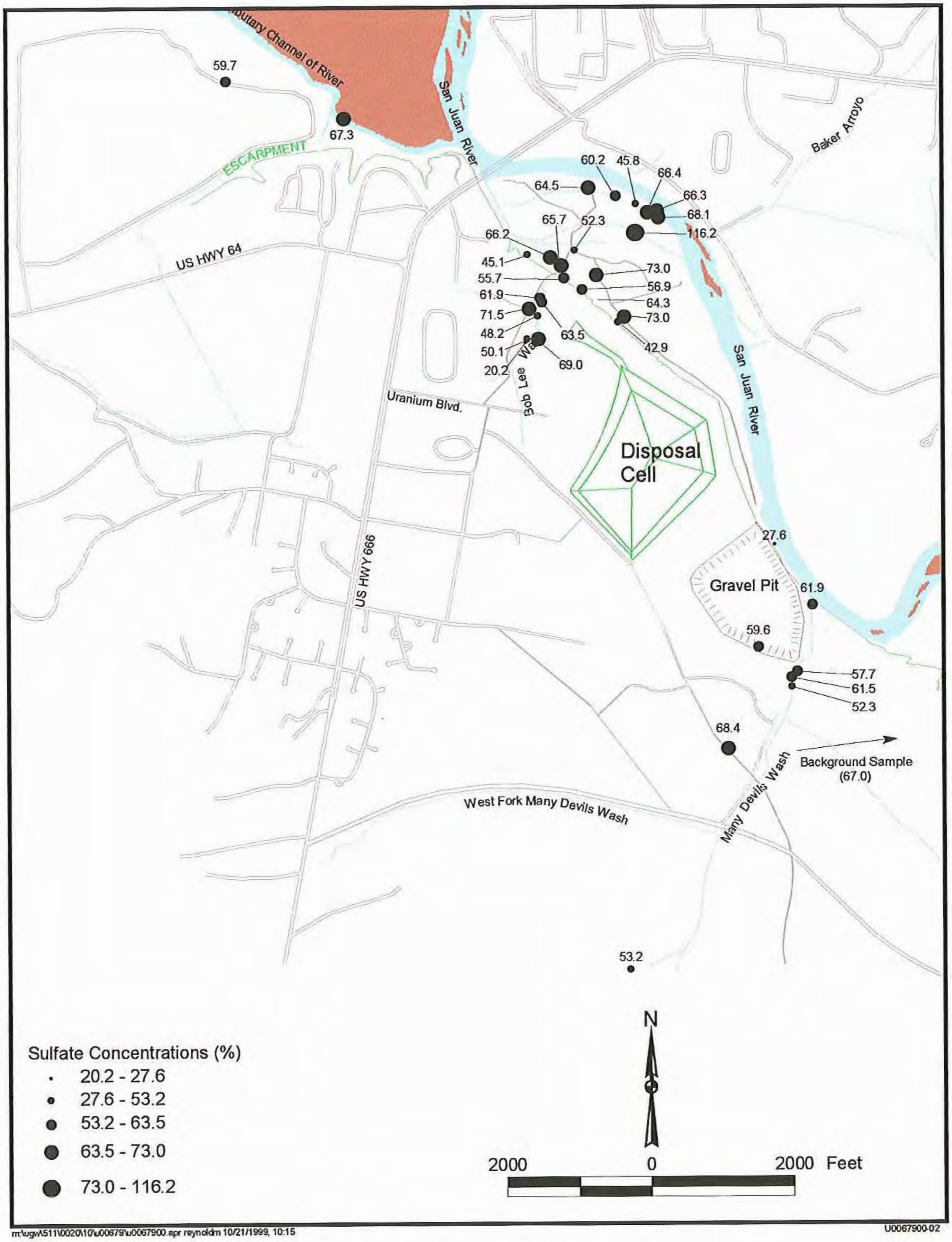

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Figure 4–42. Sulfate Concentrations in Salt Deposit Samples

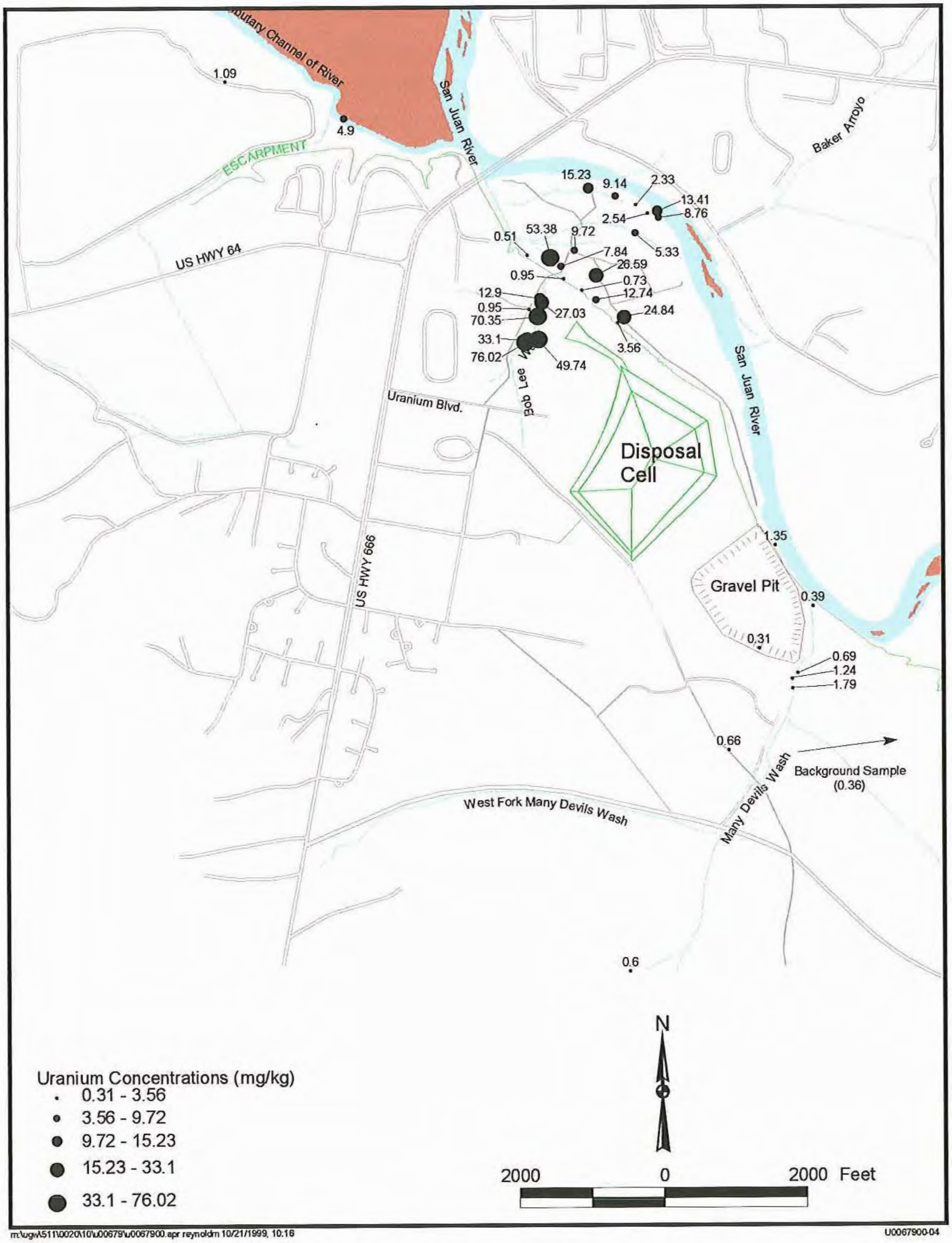

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Figure 4–43. Uranium Concentrations in Salt Deposit Samples

The goal of this study was to determine the concentrations of constituents that are to be expected if San Juan River water were to flow through contaminated alluvial aquifer sediments in the floodplain. Therefore, a leaching solution consisting of the major ions in San Juan River water was used. Leaching with water of a different composition is likely to produce different concentrations in the effluent.

4.4.6.2 Methods

Alluvial aquifer sediment was sampled from six borings. Three borings (locations 854, 856, and 864) are in the contaminated portion of the millsite floodplain, and three (locations 850, 851, and 852) are in the background floodplain. Locations of these borings are shown on Plate 1. The samples were collected by driving a split-spoon tube into the alluvial sediment. In some cases the split-spoon was incapable of retrieving a suitable sample and auger cuttings were used instead. The samples from the millsite floodplain were selected from the most uranium-contaminated portion of the ground water plume. These samples are believed to be representative of those areas that are likely to release the most contamination from the alluvial sediments.

The cores consisted of partially disaggregated floodplain alluvial sediment. Splits of the cores were placed in aluminum pie pans exposed to the air until visibly dry (about 5 days). The sediments were crushed lightly by hand to increase the drying rate. The dried sediment was sieved to less than 3 mesh (6 mm). About 4 in. of the material was placed in the columns at a time and was compacted by lightly tapping the material with a rubber mallet.

This study used a procedure similar to GJO ESL standard column test procedure CB(CT–1) (DOE 1999e). Six columns (2-in. diameter) were constructed from clear acrylic; each column contained sediment from one location. Each sediment column was about 18 in. in height. Synthetic San Juan River solution was pumped with a peristaltic pump set at 0.8 mL/min from bottom to top through the column. The major-ion chemistry of San Juan River water collected at location 546 was synthesized from reagent-grade chemicals.

Effluent samples were collected every 12 hours. Concentrations of uranium and nitrate, pH, electrical conductivity, oxidation-reduction potential, and alkalinity were measured in the GJO Environmental Sciences Laboratory soon after sample collection using the procedures in DOE (1999e). Samples were preserved and submitted to the GJO Analytical Chemistry Laboratory for analysis of arsenic, cadmium, magnesium, manganese, sodium, nitrate, antimony, selenium, sulfate, strontium, uranium, and ammonium.

4.4.6.3 Results and Discussion

Data are plotted as concentration in relation to the number of pore volumes (using midpoints) that have passed through the column. A pore volume was measured as the amount of solution used to fill each sediment column.

Nitrate, Sulfate, and Uranium

Nitrate—The concentrations of nitrate in effluents from the columns that contain floodplain sediments are similar to those from columns that contain background sediments (Figure 4–44). The concentrations are much lower than nitrate concentrations observed in the ground water on the mill floodplain. Apparently, nitrate is strongly partitioned into the aqueous phase and little is contained on the solid particles.

Sulfate—The sulfate concentrations in the first effluent from columns that contain sediment from borings 854, 856, and 864 were 3,200,000 µg/L, 576,000 µg/L, and 485,000 µg/L, respectively (Figure 4–44). These high levels decreased to about 150,000 µg/L after 10 pore volumes. Concentrations of sulfate in the effluents of all three columns containing background sediment were nearly constant at about 100,000 µg/L, which is similar to the influent concentration (121,340 µg/L). The higher concentrations of sulfate from the millsite floodplain were probably due to dissolution of sulfate salts that were deposited from the ground water as the sample was dried.

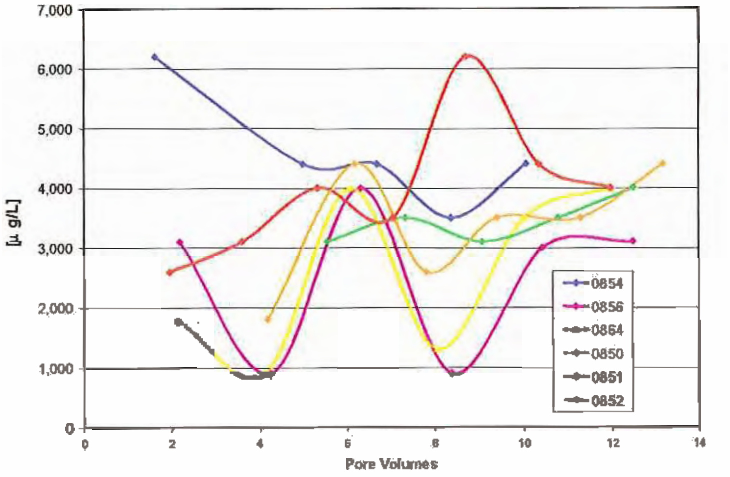
Uranium—Effluents from all three columns that contain sediments from the alluvial aquifer from a boring on the contaminated floodplain had higher uranium concentrations than those from the background borings (Figure 4–44). The first effluent from the column containing sediment from boring 854 had a uranium concentration of 72.9 µg/L. The concentration decreased rapidly and was less than the UMTRA MCL (44 µg/L) after about 4 pore volumes. These results suggest that there is some mill-related uranium contamination in the alluvial sediments. Alternatively, some of the uranium in the samples could have been deposited from contaminated ground water as the sample dried. Uranium released during flushing with San Juan River water is likely to be slightly above the UMTRA MCL initially but should rapidly decrease to relatively low levels.

Constituents Other Than Nitrate, Sulfate, and Uranium

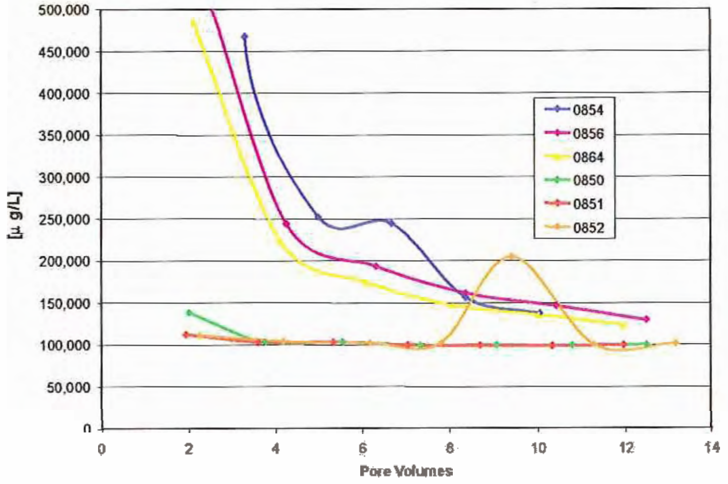
Ammonium—The ammonium concentration in the first sample from the column containing sediment from boring 854 was 1,970 µg/L. The concentration decreased to 287 µg/L after 10 pore volumes. Effluent concentrations of ammonium from all the other columns were much lower with the highest value of 85.5 µg/L from the column containing sediment from background boring 851. The highest concentration of 1,970 µg/L is relatively low compared with ammonium concentrations observed in ground water samples from the site.

Antimony—The highest concentrations of antimony were in leachate from the column containing sediment from background boring 850. These results are consistent with the observation that elevated concentrations of antimony are rare in the floodplain ground water. Antimony will probably not be leached from the floodplain at concentrations above background with San Juan River water.

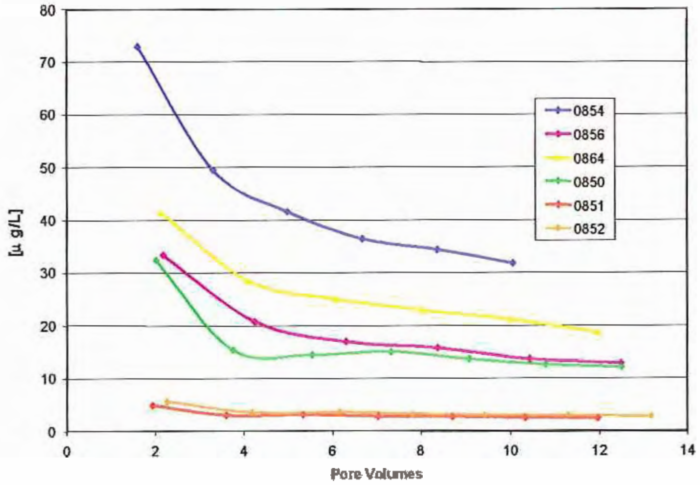
Arsenic—Effluents from all three columns with sediment samples from the contaminated floodplain had higher concentrations of arsenic than the background samples. The highest concentration was 8.3 µg/L from the column containing sediment from boring 856. Although leachate concentrations from the millsite floodplain samples are higher than those in background samples, the concentrations are well below the UMTRA MCL of 50 µg/L. These results suggest that arsenic will not be leached from the floodplain at concentrations above the MCL.



Nitrate



Sulfate



Uranium

Figure 4–44. Column Leaching Results; Concentrations in Effluent

Cadmium—Concentrations of cadmium in all effluents from all columns were less than the detection limit of 1 µg/L. These results are consistent with the relatively rare occurrences of elevated cadmium concentrations in the ground water at the millsite. Cadmium will probably not be leached from the floodplain at concentrations above the MCL (10 µg/L) by San Juan River water.

Magnesium—The magnesium concentrations in effluents from the three columns containing sediment from background borings were about the same as the concentration in the synthetic San Juan River water (2,990 µg/L), indicating that no magnesium was exchanged with the sediment. The first effluent sample from the column containing sediment from boring 854 had a magnesium concentration of 265,000 µg/L. It is likely that the magnesium concentration in this first sample is derived from the dissolution of water-soluble salts in the sample. Effluents from all the other columns had concentrations less than 50,000 µg/L, and most were less than 20,000 µg/L. The three columns with sediments from the millsite floodplain had higher concentrations than the three columns with background location sediments.

To help evaluate the significance of the magnesium concentration in the column effluents, those concentrations can be compared with concentrations in ground water from background wells and with San Juan River water. Samples from wells on the opposite side of the San Juan River from the disposal cell had magnesium concentrations ranging from 40,800 to 318,000 µg/L (DOE 1998a). Samples of river water at upstream locations 888 and 898 had magnesium concentrations of 32,300 and 12,200 µg/L, respectively, in March 1999. The magnesium concentrations in the column leachates are lower than those in background ground water and similar to those in the San Juan River. These results suggest that leaching of floodplain alluvial sediments with San Juan River water will not contribute a significant amount of magnesium.

Manganese—Manganese concentrations in all effluents from two of the columns containing sediments from the contaminated floodplain (borings 856 and 864) were less than 13.5 µg/L and are lower than the concentrations in effluents from the background samples. The manganese concentration in effluent from the other column containing sediment from the floodplain (boring 854) was initially 552 µg/L but decreased rapidly to about 40 µg/L. Effluents from all three columns containing background sediments had manganese concentrations of about 60 µg/L. These results suggest that manganese will not be leached appreciably from the floodplain alluvium by San Juan River water.

Selenium—All three columns containing alluvium from the contaminated floodplain had effluent concentrations of selenium that were less than the detection limit of 2 µg/L. Effluent from all three background columns had selenium concentrations of 7 to 11 µg/L initially, and the concentrations decreased rapidly to between 1.8 to 3 µg/L. The Mancos Shale is known to be a source of selenium, which contaminates ground water. The higher concentrations of selenium in the effluents from the background sediment samples is probably the result of the natural leaching of Mancos Shale.

Sodium—The concentration of sodium in effluent from the column containing floodplain sediments from boring 854 was initially 516,000 µg/L, but the concentration decreased after the first pore volume to 54,900 µg/L. The first effluent is probably affected by the initial dissolution of soluble salts. Sodium concentrations in all other columns was about 30,000 µg/L, which is near the concentration (30,120 µg/L) in the synthetic San Juan River water. These results indicate that the sodium concentration may increase slightly initially, but no sustained increase in sodium concentration of the San Juan River water is likely.

Strontium—Concentrations of strontium in effluents from the three columns containing floodplain sediments (borings 854, 856, and 864) were higher (1,000 to 2,220 µg/L) initially than those in the columns containing background sediments. The concentrations in the columns containing floodplain sediments decreased to about 500 µg/L after several pore volumes. Effluent concentrations of strontium from the columns containing background sediments were about 150 µg/L initially but increased to about 500 µg/L after several pore volumes. These results suggest that a small amount of soluble strontium may be released from the alluvial sediment initially, but that no sustained contribution will occur. Concentrations of strontium in the San Juan River from locations 888 and 898, upgradient of the millsite, are 1,290 and 786 µg/L, respectively. Because strontium concentrations in the leachates are lower than the concentrations in the river, no significant contribution of strontium to San Juan River water flowing through the alluvial aquifer is likely.

4.4.7 Fate and Transport

Some constituents are readily transported by ground water, whereas others are strongly partitioned on immobile solid mineral phases. The rate at which contamination migrates and the concentration in the ground water are controlled by the biogeochemical nature of the aquifer. The biogeochemical factors that typically affect migration of selected constituents are discussed in this section.

4.4.7.1 Ammonium

Under oxidizing conditions, ammonium reacts to form nitrite (NO_2^-), nitrate (NO_3^-), or nitrogen gas (N_2). Some of the transformation reactions are catalyzed by microbiological activity. Ammonium was used during the milling process at the Shiprock site, but there are no reports of the use of nitrate. It is reasonable to assume that the nitrate concentration in the ground water is an oxidation product of ammonium. The MCL for nitrate is 44 mg/L. An equivalent would be a concentration of 12.7 mg/L ammonium.

Ammonium is a strong cation exchanger on clay minerals that are present in most aquifers. At pH values (about 9) above those in San Juan River water, it will transform to ammonia (NH_3) and is volatile. Ammonium is also a nutrient used by plants.

4.4.7.2 Antimony

Antimony is similar, geochemically, to arsenic (Hem 1985). Because of its low abundance in ground water (about one-tenth that of arsenic), it has not been studied in detail and little is known about its chemical mobility. Antimony does not occur in samples of surface water on the terrace or on the floodplain, but its presence was detected in samples of ground water from two wells. The concentrations were below 0.005 mg/L.

4.4.7.3 Arsenic

Arsenic occurs commonly in nature in two oxidation states, As^{+3} and As^{+5}. The arsenate anion ($H_2AsO_4^-$) is the dominant dissolved species under the pH conditions in the Shiprock ground water. Under strongly anaerobic conditions it can also occur with a negative oxidation state and, in the presence of sulfur, form arsenide minerals. Arsenate will form minerals with ferric iron and other metal cations, but these minerals are not likely to precipitate at the low concentrations present in the Shiprock ground water. One form of arsenic (As^{+5}) adsorbs strongly on sediment minerals such as iron oxyhydroxides, whereas As^{+3} is less adsorptive. Most of the arsenic in sediments at Shiprock is probably adsorbed.

The MCL for arsenic is 0.05 mg/L. No arsenic concentrations above the detection limit of 0.001 mg/L were detected in ground water samples from the terrace. It could be detected in only 4 of 30 floodplain ground water samples. The concentrations are close to background and below the MCL.

4.4.7.4 Cadmium

Cadmium is present in ground water as the uncomplexed cation Cd^{2+} or complexed with an anion (e.g., $CdSO_4^0$). Cadmium readily substitutes for Ca^{2+} in carbonate minerals. Coprecipitation with calcite ($[Ca,Cd]CO_3$) is the most likely mechanism for removal of cadmium from the alluvial ground water. Because the aquifer is saturated with calcite, this mechanism is likely to keep cadmium concentrations low. Cadmium can precipitate as greenockite (CdS) under sulfate-reducing conditions. Cadmium will also effectively adsorb to ferric oxyhydroxides.

The MCL for cadmium is 0.01 mg/L. Concentrations above the detection limit of 0.001 mg/L were not detected in ground water samples from the floodplain, but concentrations in samples from two terrace locations exceed the MCL. The occurrence of cadmium at the Shiprock site is localized.

4.4.7.5 Magnesium

Magnesium is present in the dissolved state as Mg^{2+} or as carbonate or hydroxide complexes. It forms minerals with carbonate such as dolomite $[CaMg(CO_3)_2]$ or magnesite ($MgCO_3$) and can substitute for calcium in calcite. Magnesium is a major cation in many minerals and its concentration in ground water at Shiprock is probably controlled largely by the precipitation and dissolution of these minerals.

4.4.7.6 Manganese

Manganese mobility is related to the oxidation-reduction potential of a soil or sediment. Manganese forms oxide minerals under oxidizing conditions and is soluble under more reduced conditions. Therefore, the more oxidized state of a sediment, the more likely it is to have higher concentrations of manganese. Manganese occurs in the 2+ and 4+ oxidation states at the Shiprock site. In the dissolved state, it is present mainly as Mn^{2+} ion. Its redox chemistry is similar to that of iron. Manganese will also partition to sediment by substituting for calcium in calcite.

The average concentration of manganese in ground water samples from the Shiprock floodplain is 1.63 mg/L. Concentrations of manganese in samples from the millsite floodplain are variable, with many less than background. The Mancos Shale may contribute manganese to the ground water.

4.4.7.7 Nitrate

The oxidation state of nitrogen in nitrate (NO_3^-) is +5. It does not complex significantly with other ions under ground water conditions. It is transported without significant interaction with the rock matrix. If appropriate nitrate-reducing microbiota and nutrients are present, nitrate can undergo reduction to nitrogen gas (N_2). Significant denitrification is not expected to occur without a suitable organic nutritional source such as acetate. Therefore, nitrate probably transports nearly conservatively through the aquifer. Concentrations decrease by mixing with other ground water and by dispersion. Under reducing conditions, nitrate can transform to nitrite, elemental nitrogen, or ammonium. The reduction is catalyzed by microbial processes. In high concentrations, such as in salt deposits, nitrate can precipitate in water-soluble minerals. A small amount of nitrate can also adsorb to sediments.

The MCL for nitrate is 44 mg/L. Nitrate concentrations currently are as high as 7,240 mg/L in ground water samples collected at the Shiprock site. Ammonium was used during the milling process at the Shiprock site, but the use of nitrate is not reported. It is reasonable to assume that the nitrate concentration in the ground water is an oxidation product of ammonium.

4.4.7.8 Radium

Two radium isotopes are present in the ground water. Radium-226 is a decay product of uranium-238 and has a half-life of 1,600 years. Radium-228 is a decay product of thorium-232 and has a half-life of 5.7 years. Radium preferentially attaches to particles and dissolved concentrations are typically low. One of the most important reactions to fixate radium is the coprecipitation in $(Ba,Ra)SO_4$. Radium substitutes readily for barium because of its similar ionic radius. Because of the low solubility of barium sulfate, radium has not migrated far from the tailings at most uranium millsites.

The MCL for radium (radium-226 + radium-228) is 5 pCi/L, which is exceeded in ground water samples from five well locations on the terrace (Appendix F). The MCL for radium is not exceeded in ground water samples from locations on the floodplain.

4.4.7.9 Selenium

Aqueous selenium occurs predominantly as selenate $(SeO_4)^{2-}$ or selenite $(SeO_3)^{2-}$; selenate is probably favored under the oxidized conditions of the alluvial aquifer. Concentrations of selenium are not high enough to precipitate selenium minerals at the Shiprock site. Selenium can substitute for sulfur in sulfur-bearing minerals and can precipitate as ferroselite ($FeSe_2$) or coprecipitate with pyrite (FeS_2) under reducing conditions. Selenate adsorbs to ferric oxyhydroxides at moderate to low pH values.

The MCL for selenium is 0.01 mg/L. Selenium concentrations in samples from 14 floodplain wells and 28 terrace wells exceeded the MCL. The Mancos Shale has high concentrations of leachable selenium that are known to contaminate ground water in some areas. High concentrations of selenium in samples of ground water from the terrace area at the Shiprock site are either related to the milling process or are derived from leaching of the Mancos Shale.

4.4.7.10 Sodium

Sodium occurs in ground water as the monovalent cation Na^+ and is a major component of many minerals. It is relatively mobile in ground water but can readily exchange for other cations on clays and oxyhydroxide minerals. In arid areas, it often occurs in relatively high concentrations in ground water because of the dissolution of evaporite minerals.

There is no MCL for sodium. Concentrations are variable in ground water at the Shiprock site because of the variable amounts of dissolution of salt minerals.

4.4.7.11 Strontium

Strontium is present in the dissolved state as Sr^{2+} or as carbonate or hydroxide complexes. Its chemistry is similar to Ca^{2+} and forms minerals with carbonate such as strontianite ($SrCO_3$); strontium can substitute for calcium in calcite. Strontium is a major cation in many minerals and its concentration in ground water at Shiprock is probably controlled by the precipitation and dissolution of these minerals.

4.4.7.12 Sulfate

In alluvial ground water, dissolved sulfur occurs mainly as the unassociated sulfate ion (SO_4^{2-}). The precipitation of gypsum ($CaSO_4$) or sodium sulfate (Na_2SO_4) can partition significant amounts of sulfate into the solid phase. The concentrations of sulfate in solution will remain high even in the presence of these minerals. Much of the concentration gradient in ground water is caused by mixing with other ground water and dispersion. Under reducing conditions brought about by microbial stimulation, sulfate can form sulfide that precipitates heavy metals and arsenic. Investigations by the NABIR Program (McKinley and Long 1999) at the Shiprock site showed low sulfide concentrations in ground water samples from the floodplain and the terrace.

4.4.7.13 Uranium

Most naturally occurring uranium is either in the uranyl (6+) or the uranous (4+) oxidation state. The uranyl form is predominant in oxidized ground water. The uranyl ion forms strong aqueous complexes with carbonate, and uranyl dicarbonate [$UO_2(CO_3)_2^{2-}$] is a dominant mobile species. Uranium adsorbs to ferric oxyhydroxide and clay minerals in soils and rocks. Under reducing conditions, uranium precipitates as uraninite (UO_2), which has a low solubility. The reduction is catalyzed by microbial activity.

The MCL for uranium is 0.044 mg/L. Uranium concentrations in ground water samples from 20 of 30 wells on the floodplain and 22 of 35 wells on the terrace exceed the MCL for uranium.

4.5 Numerical Ground Water Modeling

A calibrated flow-and-transport model was developed for the floodplain aquifer to serve as a screening tool and to evaluate compliance strategies. The MODFLOW code (McDonald and Harbaugh 1988) was used for the flow modeling. Output from the model was used in particle tracking simulations and transport simulations. Particle tracking was accomplished using the code MODPATH (Pollock 1989), while the MT3D code (Zheng 1990) was used in the transport simulations.

4.5.1 Flow Modeling

Calibration of the flow model consisted of (1) developing a site conceptual model on the basis of the site water balance (see Section 4.3, "Hydrologic Characterization"), (2) establishing calibration targets, (3) developing the relationship between the site conceptual model and the numerical model, (4) establishing calibration criteria, (5) performing the model calibration, and (6) conducting a sensitivity analysis.

The floodplain alluvium was simulated as a single layer. The domain of the model includes the area between the San Juan River and the escarpment; however, the model was designed with the capability of being expanded to include the terrace flow system. A uniform grid of 100 ft by 100 ft was used throughout the area of the floodplain.

A uniform hydraulic conductivity of 110 ft/day was used initially for the entire flow field. This value was obtained from the average hydraulic conductivity estimated from pumping tests. The thickness of the alluvium and the top-of-bedrock elevations were obtained from the borehole lithologic logs. External boundaries for the model consist of (1) constant head along the boundary with the San Juan River, (2) no flow along the escarpment, (3) constant flux at the mouth of Bob Lee Wash to simulate the effect of surface water derived from artesian well 648 discharge, and (4) assumed no flow for the bottom of the aquifer that consists of Mancos Shale. The only internal source of water consists of infiltration of precipitation and runoff.

Model calibration was deemed to be adequate when the standard deviation of the residual errors divided by the total range in head fell below 10 percent. This formulation of the error term was eventually reduced to near 5 percent during flow-model calibration. In addition, calibration was performed until the errors, or residuals, were distributed evenly about the mean. This distribution eliminates bias resulting from dominantly negative, or positive, errors. The water balance for the alluvial aquifer was itself a calibration target because the model must be capable of reproducing realistic fluxes as well as precise hydraulic heads.

Figure 4–45 presents a schematic of the output from the flow model, consisting of the simulated water table and a posting of the residuals. The head distribution from this flow model was saved and used for additional simulations of particle tracking and mass transport. One of the striking features of the simulation is the tremendous effect that Bob Lee Wash imparts to the flow system. This effect is increasingly obvious as the model is developed through particle tracking and transport.

Table 4–21 presents a summary of the calibration statistics for the model: a list of the calibration targets, their average hydraulic or measured heads, the model-simulated or computed heads, and the residuals (the difference between the average measured head and the model-calculated head). The summary statistics indicate that the model is calibrated to within 1 ft of the observed head and that the residual standard deviation divided by the head range is 5.6 percent. This value falls within the calibration objective of 10 percent. A plot of the flow-model calibration data is also illustrated in Figure 4–46.

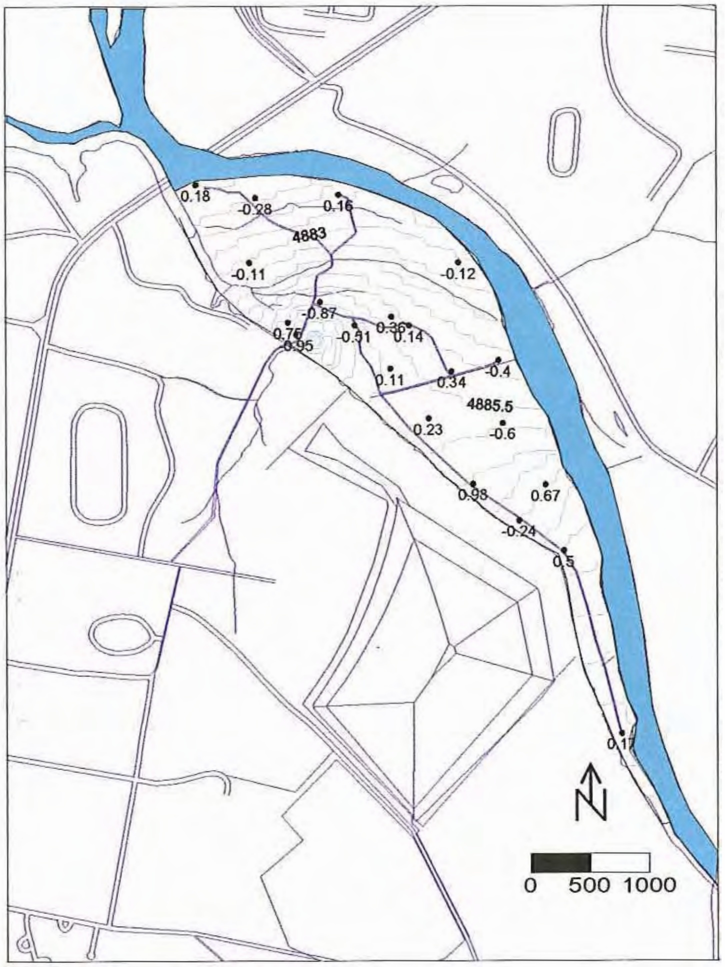


Figure 4–45. Hydraulic Head and Residuals from Calibrated Flow Model of Floodplain Alluvial Aquifer at the Shiprock, New Mexico, UMTRA Site

Table 4–22 presents a comparison of the field-estimated water balance and the model-calculated water balance. The principal difference between the two is that the model-derived values contain a larger proportion of water derived from the San Juan River and from recharge and a smaller amount of water derived from artesian well 648 discharge. The calibrated model uses a hydraulic conductivity value of 100 ft/day, rather than the initial value of 110 ft/day. A calibrated solution to the flow model also exists with a hydraulic conductivity of 110 ft/day; however, the calibration statistics are weaker and, as discussed in the transport modeling section, the remaining components of the water balance are slightly different.

In viewing alternative solutions to the flow system, it appears reasonable to assume that a small transit loss exists between the well head at 648 and the mouth of Bob Lee Wash and that a greater percentage of recharge occurs either from the San Juan River or from precipitation. The assumptions used in the calibrated flow model result in a total flux of 18,600 ft^3/day, which is close to the field-estimated water balance. However, other reasonable and defensible solutions may exist that could impact the total flux, either up or down.

Table 4–21. Calibration Statistics for Flow Model of Floodplain Alluvium, Shiprock, New Mexico, UMTRA Site

Well ID	Average Measured Head (ft)	Computed Head (ft)	Error (ft)
604	4885.05	4885.92	-0.87
606	4886.47	4887.42	-0.95
608	4888.97	4888.46	0.50
610	4887.20	4887.44	-0.24
612	4888.09	4887.42	0.67
613	4887.50	4886.52	0.98
615	4885.99	4885.76	0.23
617	4885.58	4885.24	0.34
619	4885.20	4885.06	0.14
620	4885.94	4885.83	0.11
624	4885.55	4885.19	0.36
626	4885.75	4886.26	-0.51
630	4887.10	4886.35	0.75
734	4880.94	4880.76	0.18
735	4889.86	4889.68	0.17
736	4882.44	4882.28	0.16
853	4885.25	4885.85	-0.60
854	4883.01	4883.13	-0.12
855	4883.00	4883.11	-0.11
856	4881.16	4881.44	-0.28
857	4884.34	4884.74	-0.40

Residual mean = 0.024
Residual standard deviation = 0.50
Sum of squares = 5.23
Absolute residual mean = 0.41
Minimum residual = -0.95
Maximum residual = 0.98
Head range = 8.92
Residual standard deviation/head range = 0.056 (5.6%)

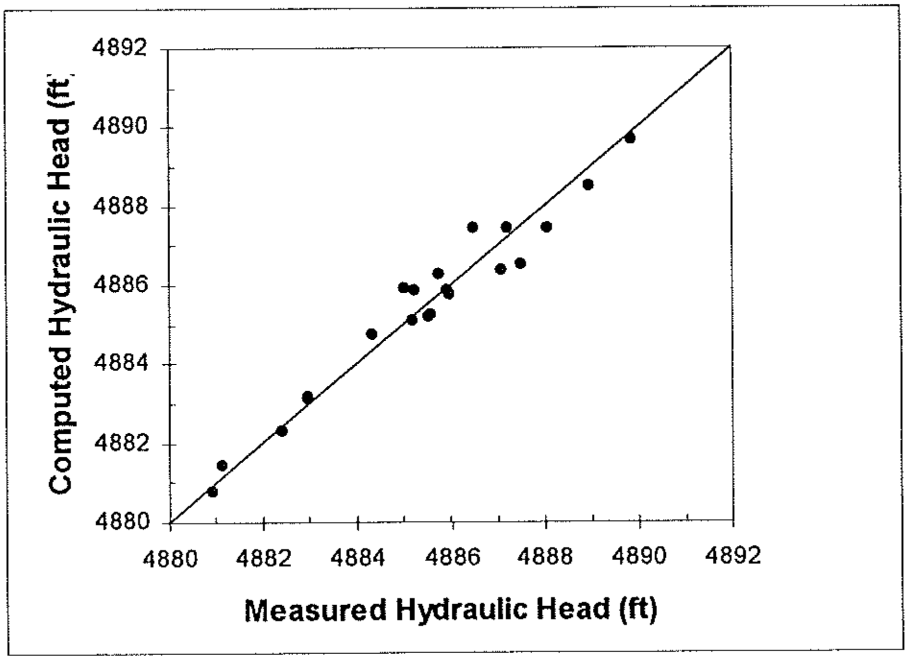


Figure 4–46. Plot of Flow-Model Calibration Data

Table 4–22. Comparison of Model-Calculated Water Balance and Field-Estimated Water Balance[a]

Water-Balance Component	Model-Calculated Inflow	Model-Calculated Outflow	Field-Estimated Inflow	Field-Estimated Outflow
Well (Bob Lee Wash)	10,275	0	12,320	
Constant Head (San Juan River)	5,144	18,587	3,600	19,400
Recharge	3,167	0	2,600	
Total (rounded)	18,600	18,600	18,500	19,400

[a] All values are expressed in ft^3/day.

4.5.2 Particle Tracking

Particle tracking was performed using the "head-save file" from the calibrated flow model as input to the MODPATH model. Particle tracking uses the velocity field from the flow model to plot the direction in which fluid elements and dissolved constituents in the ground water system migrate. Consequently, particle tracking, like any transport model, is sensitive to the selected porosity value. The porosity used in these simulations was 0.30.

Figure 4–47 presents particle-tracking results for the floodplain alluvial aquifer. Interpreted results indicate that Bob Lee Wash supplies at least 60 percent of the water to the alluvial aquifer. These results also indicate that ground water contamination originating north and northeast of the disposal cell may concentrate in the region where the pathlines converge directly north of the disposal cell. This convergence of pathlines might explain why contaminant concentrations are high below the escarpment north of the disposal cell and why a band of high concentrations exist extending northward to well 854 (see Section 4.4, "Geochemistry").

Figure 4–47 also depicts the travel time required for fluid elements to migrate a certain distance. Over the western part of the floodplain, for example, approximately 1,000 days (3 years) are required for water to travel from the mouth of Bob Lee Wash to the San Juan River. In this area, 1 pore volume of the aquifer would flush in approximately 3 years. The water balance further supports this. The volume of water contained in the aquifer is approximately 150 million gallons, while the daily flux is approximately 18,000 to 19,000 ft^3/day. Dividing the volume of water in the aquifer by the daily flux results in 1 pore volume exchanged every 3 years. This potentially rapid rate of flushing in the aquifer is supported by the lower levels of mill-related contamination in the area influenced by artesian well 648 discharge. The main constituent in this region is sulfate, which is present in high concentrations in the Morrison Formation, the source of the water.

Flushing would be slower along the mixing zone where flow converges between water from artesian well 648 and water from the San Juan River. In this region, 1 pore volume of flushing might be expected to require 4,000 days (11 years) or more. High concentrations of contaminants have existed throughout this region since 1984. The presence of these high concentrations in this area for more than 30 years suggests that a continuing source of contamination feeds this area of the floodplain.

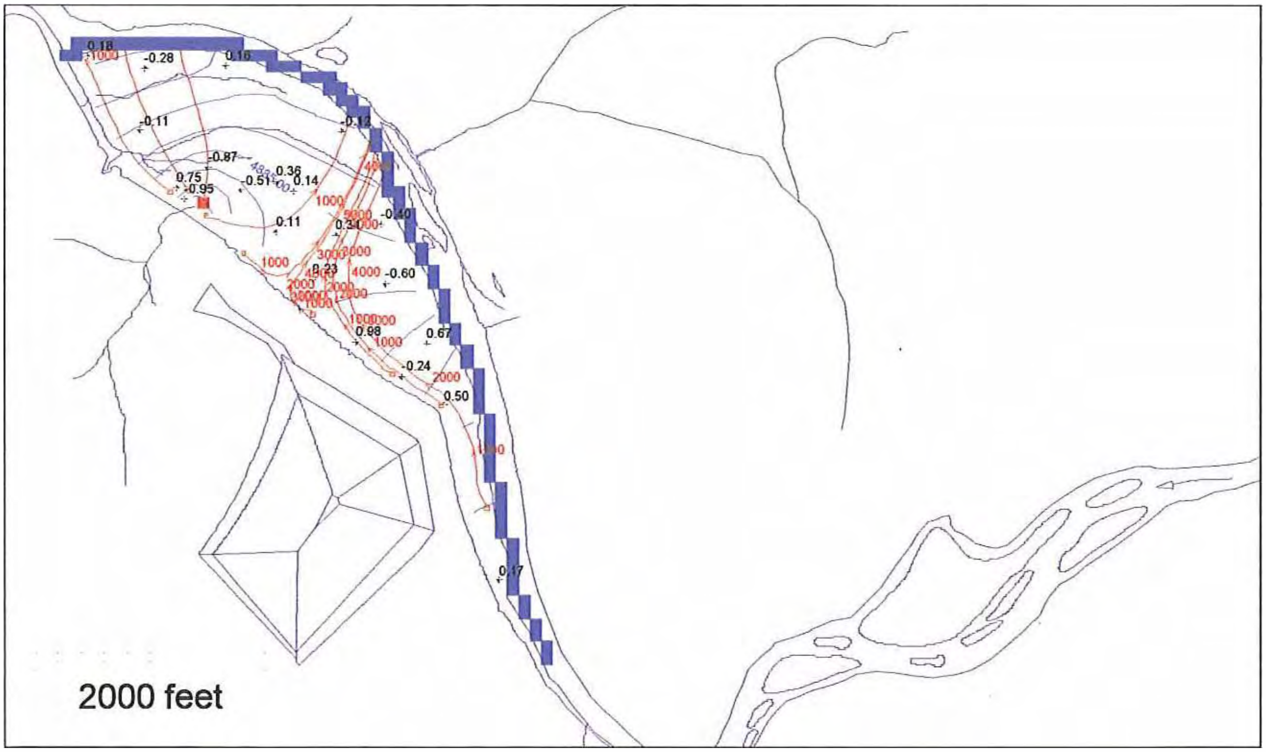


Figure 4–47. Results of Particle Tracking Simulation for Floodplain Alluvial Aquifer, Shiprock, New Mexico, UMTRA Site; Arrowheads Indicate 1,000-Days Travel Time For Fluid Elements

4.5.3 Transport Modeling

Preliminary transport simulations were performed to evaluate the prospects for natural attenuation and flushing in the floodplain alluvial aquifer. Nitrate was simulated as part of this evaluation; it is assumed to be transported without attenuation, or only by advection.

As with flow modeling, transport modeling also requires that boundary nodes be established. The boundary nodes in transport modeling are expressed in terms of concentration. In flow modeling a node can represent constant head, but the analog in transport modeling is constant concentration. Similarly, no-flow boundaries in flow modeling are like no-chemical-flux boundaries in transport modeling; prescribed flux boundaries in flow modeling are analogous to prescribed chemical flux in transport modeling.

Figure 4–48 illustrates the location of prescribed-flux boundary nodes used in the model. These source nodes are located along the base of the escarpment north and northeast of the disposal cell. Because the exact source of the high concentrations in the alluvial aquifer is unknown, the source strength and flux of the source nodes in the model are estimated and used as calibration parameters. If an actual source exists because of leakage from the cell or slow seepage from the terrace, a prescribed flux would be an appropriate type of boundary to use.

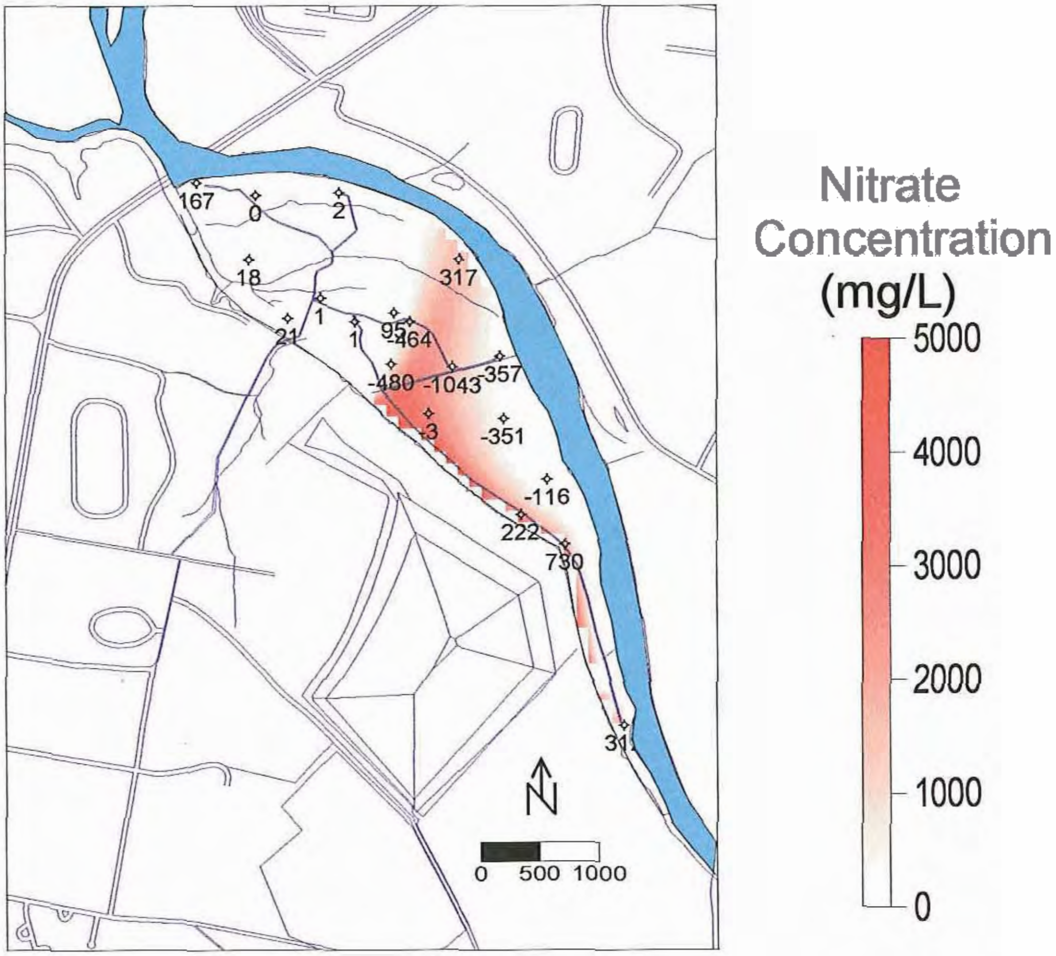


Figure 4–48. Simulated Nitrate Concentrations and Posted Residuals in Milligrams per liter for Floodplain Alluvial Aquifer, Shiprock New Mexico, UMTRA Site (the red cells represent prescribed chemical-flux source nodes at the aquifer boundary)

Calibration of the transport model was accomplished to the point where the mean of the residuals of the nitrate concentration divided by the range in the nitrate concentration was 14 percent. Thus, the transport portion of the calibration failed to reach the 10-percent criterion established for the modeling and, therefore, the calibration is only considered preliminary at this time.

Table 4–23 presents the calibration statistics for the transport model and the calibration data are shown graphically on Figure 4–49. The most difficult wells to bring into transport calibration are 608 and 617. One possible explanation is that calibration was performed relative to the final analytical results, rather than the mean concentrations. In the case of well 608, for example, the mean concentration is more than 400 mg/L greater than the final result. Use of the mean concentration as a calibration target in this case would result in an improved match for this well. In the case of well 617, the total range in the data is about 2,700 mg/L while the final result is 582 mg/L. This well is located at the eastern fringe of the mixing zone between San Juan River water and the plume. It is probable that solute concentrations at this location are particularly sensitive to the San Juan River and its stage. The sensitivity of the transport model to the San Juan River stage has not been explored in detail.

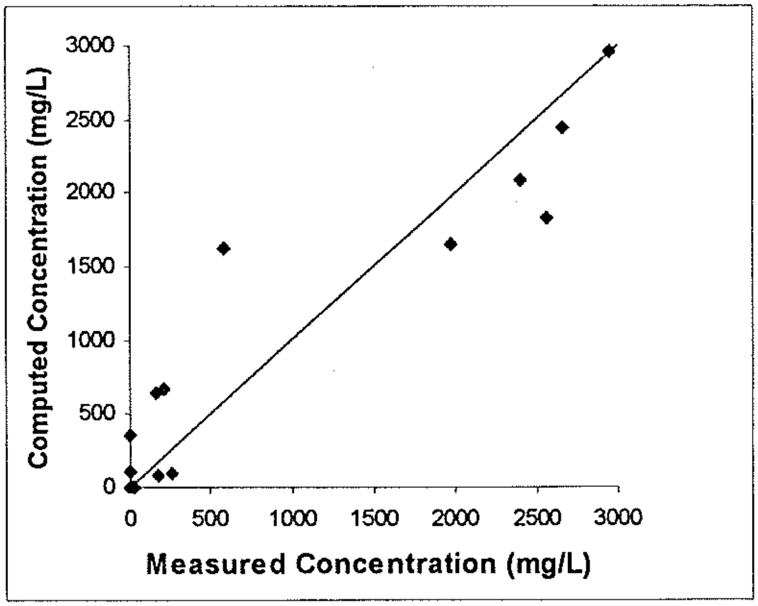


Figure 4–49. Calibration Data

Calibration of the transport model required increasing the hydraulic conductivity to 130 from the 100 ft/d in the flow model, dropping well 648 discharge to 9,000 ft^3/d versus 10,280 ft^3/d used in the flow model, and dropping areal recharge to 1.37×10^{-4} from 5.48×10^{-4} ft/d used in the flow model. These changes increased the total flux to 19,300 ft^3/d versus 18,600 ft^3/d obtained with flow modeling; however, the total flux derived from the transport model practically matches the field-estimated outflow value reported in Tables 4–22 and 4–24. Recalibration of the flow model to obtain the transport model impacted the head calibration. The total range in head divided by the standard deviation increased to 6.3 percent, which is still well within the calibration acceptance criteria.

Table 4–24 presents the water balance results that were achieved following the preliminary calibration of the transport model. In comparison with the field-derived water balance results, the transport-derived water balance indicates that the flux from Bob Lee Wash may be less than originally estimated, while inflow from the San Juan River may be greater.

Flushing of the aquifer was simulated by storing the output from the transport model as an initial condition and restarting the model with the source removed. Concentrations are calculated with the MT3D model for future times and, thus, are an indication of how the aquifer might behave if the source were removed. Figure 4–50 presents the changes in concentration predicted by the model if the source were removed. The results indicate that after a period of 10 years the nitrate concentrations are depleted to low levels and that only a small area of elevated concentration exists along the escarpment near the stagnation point southeast of the mouth of Bob Lee Wash.

Table 4–23. Calibration Statistics for the Transport Model of the Floodplain Alluvial Aquifer, Shiprock, New Mexico, UMTRA Site[a]

Well ID	Measured Nitrate Concentration (mg/L)	Computed Nitrate Concentration (mg/L)	Error (mg/L)
608	2560.00	1829.82	730.18
610	2660.00	2437.80	222.20
612	0.05	115.80	-115.75
615	2950.00	2952.84	-2.84
617	582.00	1624.89	-1042.89
619	207.00	671.01	-464.01
620	161.00	640.55	-479.55
624	175.00	80.12	94.88
626	1.37	0.00	1.37
628	0.92	0.00	0.92
630	20.80	0.00	20.80
734	261.00	94.18	166.82
735	2400.00	2087.72	312.28
736	1.67	0.15	1.52
853	0.04	351.18	-351.14
854	1970.00	1652.94	317.06
855	17.80	0.00	17.80
856	0.03	0.00	0.03
857	0.22	357.33	-357.11

[a] Residual mean: -64.55
Residual standard deviation: 412.14
Sum of squares: 2614547.48
Absolute residual mean: 310.55
Minimum residual: -1042.89
Maximum residual: 730.18
Concentration range: 2949.97
Residual standard deviation/concentration range: 0.14 (14%)

Table 4–24. Comparison of Transport Model-Calculated Water Balance and Field-Estimated Mass Balance[a]

Water-Balance Component	Model-Calculated Inflow	Model-Calculated Outflow	Field-Estimated Inflow	Field-Estimated Outflow
Well 648 (Bob Lee Wash)	9,000	0	12,320	0
Wells (contribution from terrace)	690	0	0	0
Change in Storage	458	0	0	0
Constant Head (San Juan River)	8,379	19,300	3,600	19,400
Areal Recharge	792	0	2,600	0
Totals (rounded)	19,300	19,300	18,500	19,400

[a] *All values are expressed in ft^3/day.*

If the flushing rate were estimated from the flow-model water balance, then approximately 4 percent more time would be required to achieve flushing. This additional time is required because the total flux in the flow model is approximately 4-percent lower than the calculated water balance used in the transport model. In either case, the numerical modeling supports the hypothesis that natural flushing alone could entirely remove the contaminants remaining in the floodplain alluvial aquifer. If the source could be isolated from the floodplain alluvial aquifer, an appropriate compliance strategy could be natural flushing.

4.6 Ecological Field Investigations

The ecology of the former Shiprock millsite and surrounding areas was characterized to further the assessment of ecological risks associated with site-related contaminated ground water and to update the BLRA (DOE 1994). A defensible ecological risk assessment will support the development of a risk-based compliance strategy. In general, the goal of the ecological field investigation was to acquire additional data needed to evaluate potential exposure pathways and receptors at the Shiprock site.

A summary of the BLRA, including discussion of the ecological contaminants of potential concern, potential receptors, and potential adverse effects, is available in Chapter 5 of *Work Plan for Characterization Activities at the Shiprock UMTRA Project Site* (DOE 1998c). The Work Plan also contains a summary of specific ecological data needed to update the BLRA. Sections 4.6.1 and 4.6.2 below present descriptions of ecological field activities conducted in 1998 and 1999. Several remaining ecological data gaps are listed in Section 4.7, "Summary of Additional Data Needs."

The 1998 and 1999 ecological field investigations addressed the following data needs:

- Characterization of the current plant ecology. This activity focused on plant communities containing phreatophytes and wetland species potentially rooted into contaminated ground water and surface water and similar plant communities in reference areas.
- Sampling and chemical analysis of phreatophyte and wetland plant tissues in contaminated areas and in reference areas for comparison. Results of plant tissue analyses were used to calculate hazard indices for toxicity to plants and to animals that might ingest them.
- Sampling and chemical analysis of sediment and surface water in the wetland area at the mouth of Bob Lee Wash and in a reference wetland area for comparison. Results of the surface water and sediment analyses were used to calculate hazard indices for aquatic life and for receptors that may ingest the water or sediment.

4.6.1 Plant Ecology Characterization

Plants that root into sediment contaminated with site water or are irrigated with contaminated site water are potential exposure pathways for humans and ecological receptors. The vegetation also influences recharge and discharge components of the hydrologic system. Current plant ecology of the Shiprock floodplain and associated wetlands were characterized as part of the evaluations of (1) potential human health and ecological risks associated with site-related contaminated ground water and (2) the relative importance of on-site evapotranspiration as a component of the site water balance.

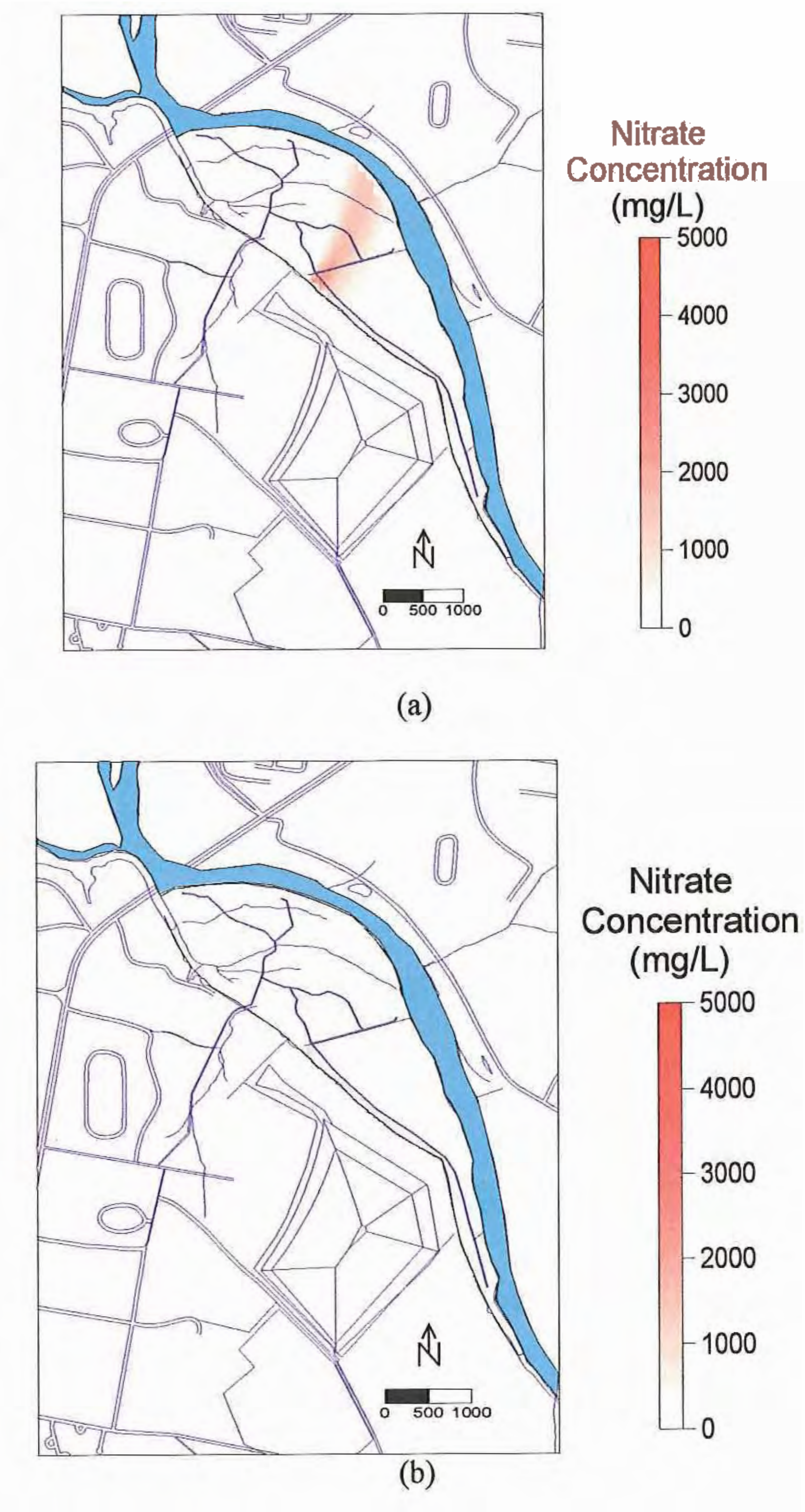


Figure 4–50. Nitrate Concentrations in Milligrams per Liter for the Floodplain Alluvial Aquifer, Shiprock, New Mexico, UMTRA Site, (a) 5 Years After Source Removal and (b) 10 Years After Source Removal

4.6.1.1 Methods

The vegetation of the floodplain and associated wetlands was characterized using the semiquantitative relevé technique (Bonham 1989). This technique was used to characterize the composition and relative abundance of species in plant communities by subjectively selecting representative stands, to compile a list of all species identified while walking through the stands, and then to assign the species to one of six cover classes. Plant cover was not measured precisely. Floodplain and wetland stands were characterized on June 17, 1998.

Vegetation was characterized both in areas influenced by the site-related contaminated ground water, the millsite floodplain and wetlands, and in reference areas. The millsite floodplain is the relatively broad plain between the escarpment north of the disposal cell and the San Juan River (Plate 1). The millsite wetlands is a poorly drained 5-acre area at the mouth of Bob Lee Wash on the floodplain.

Reference areas, or background areas, resemble the site ecologically–landform, soil, and vegetation are similar–but without the influence of site-related ground water contamination. Reference areas were used for baseline chemical data for the ERA (Section 4.6.2), and to help project possible successional pathways. The reference area for the millsite floodplain is a floodplain approximately 1 mi upstream from the disposal cell at the site of wells 850 through 852 (Plate 1). The reference area for the floodplain wetland is a ditch along which outflow water from artesian well 648 flows to Bob Lee Wash and onto the floodplain (Plate 1).

4.6.1.2 Results

Figure 4-51 and Tables 4–25 and 4–26 present the results of the plant ecology characterization. The results confirm the occurrence of phreatophytic and wetland plants (plants that root in ground water) in areas with elevated ground water contamination. Cottonwoods (*Populus fremontii*), saltcedar (*Tamarix ramosissima*), Russian olive (*Eleagnus angustifolia*), and greasewood (*Sarcobatus vermiculatus*) growing in the floodplain are all phreatophytes. Spikerush (*Eleocharis palustris*), common reed (*Phragmites australis*), alkaligrass (*Puccinellia airoides*), bulrushes (*Scirpus* spp.), saltcedar (*Tamarix ramosissima*), and cattails (*Typha latifolia*) growing in the wetland area are also potentially in contact with contaminated water. All these plants may create exposure pathways.

The results of the plant ecology characterization provide input to several other aspects of the field investigation:

- The plant community map and plant characterization data, in combination with ground water data (Section 4.4), were the basis for selecting locations for chemical analysis (Section 4.6.2) as part of the ERA (Section 6.2).
- The plant community data support habitat evaluations for threatened and endangered species (Ecosphere Environmental Services 1998, 1999) and other receptors.

Table 4–25. Relevé Plant Cover for the Shiprock Millsite Floodplain and Floodplain Reference Area[a]

Taxonomic Name	Common Name	Reference Area	Saltcedar Kochia	Saltcedar Barren	Rabbitbrush Kochia	Saltcedar Saltgrass	Giant Dropsee
Atriplex canescens	Four-wing saltbush		+				
Cardaria draba	Whitetop		+				
Chrysothamnus nauseosus	Rubber rabbitbrush						+
Chrysothamnus viscidiflorus	Green rabbitbrush	+	+		2		1
Distichlis spicata	Saltgrass	2	2	3		5	1
Eleagnus angustifolia	Russian olive	2	1				
Guitterezia sarothrae	Broom snakeweed		+				+
Kochia scoparia	Kochia		2				
Kochia sp.	Kochia			2	3	1	
Lactuca serriola	Wild lettuce	+				2	
Machaeranthera canescens	Hoary aster						1
Mentzelia pumila	Blazing star	+	+		1		1
Oenothera albicaulis	Evening primrose		+				
Oryzopsis hymenoides	Indian ricegrass	1	1				2
Populus fremontii	Fremont cottonwood	2	1				
Salix exigua	Sandbar willow	+	+				
Salsola kali	Russian thistle		+		1		+
Sarcobatus vermiculatus	Greasewood		+				
Sitanion hystrix	Squirreltail					2	
Sporobolis airoides	Alkali sacaton	3		+	2		
Sporobolis gigantea	Giant dropseed	+	1		1		4
Tamarix ramosissima	Saltcedar	3	4	3	2	3	+
Xanthium strumarium	Cocklebur	+					

[a] Cover Classes: (+) <1%, (1) 1-5%, (2) 5-25%, (3) 25-50%, (4) 50-75%, and (5) 75-100%.

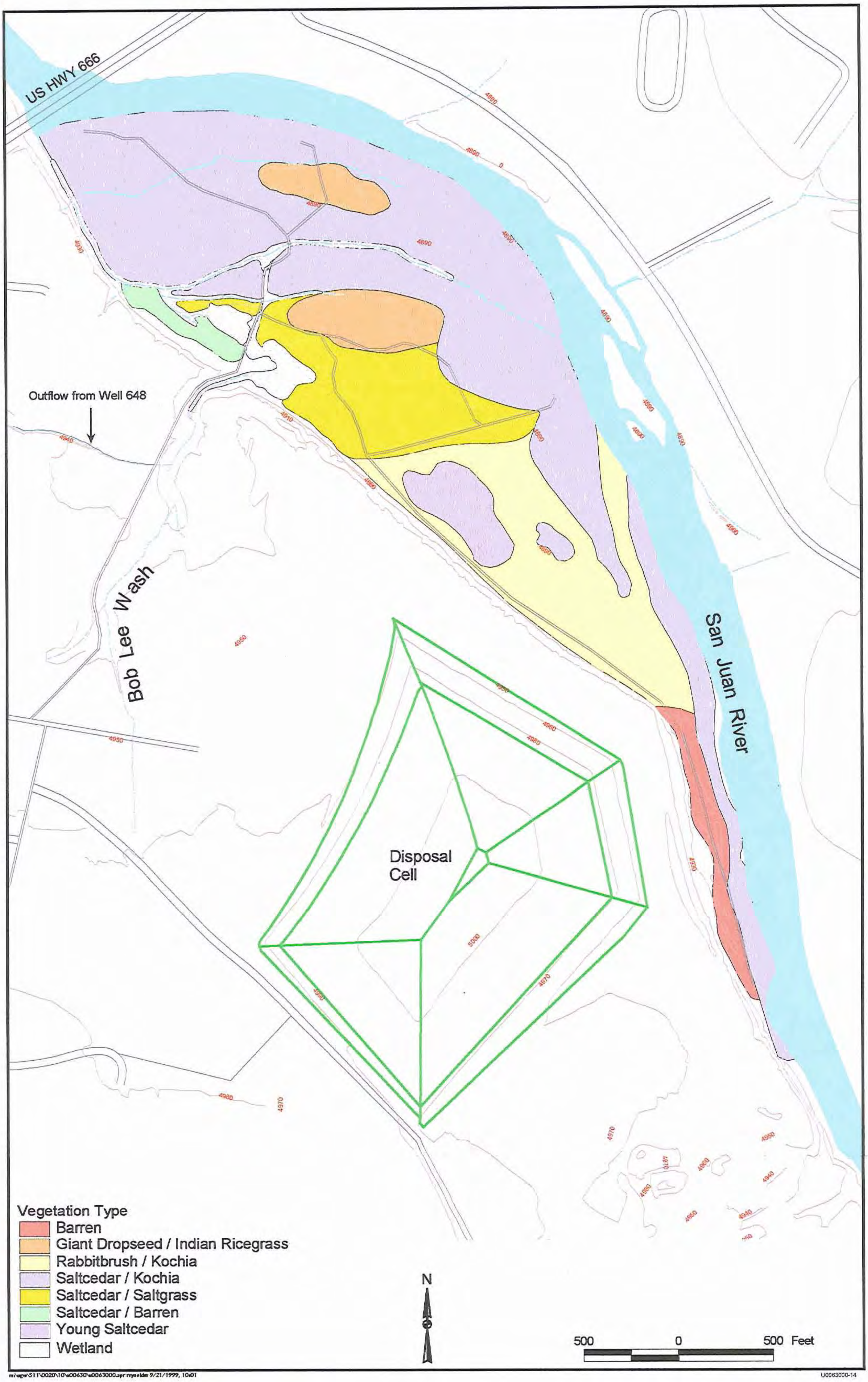


Figure 4–51. Shiprock Floodplain Vegetation Map

Table 4–26. Relevé Plant Cover for the Shiprock Millsite and Reference Wetlands[a]

Taxonomic Name	Common Name	Millsite Wetland	Reference Wetland
Cardaria draba	White top	2	1
Distichlis spicata	Inland saltgrass	2	2
Eleagnus angustifolia	Russian olive		+
Eleocharis palustris	Creeping spikerush	1	
Hordeum jubatum	Foxtail barley	1	
Kochia scoparia	Kochia		3
Lactuca serriola	Wild lettuce		2
Melilotus officionale	Yellow sweet clover	1	
Pascopyron smithii	Western wheat	+	
Polypogon monspeliensis	Rabbitsfoot grass		2
Phragmites australis	Common reed	1	
Puccinellia airoides	Alkaligrass	+	2
Rumex crispus	Curly dock	+	
Salix exigua	Sandbar willow	1	
Salsola kali	Russian thistle		1
Scirpus maritimus	Alkali bulrush	1	1
Scirpus americanus	American 4-square	+	
Scirpus acutus	Hard stem bulrush	3	1
Tamarix ramosissima	Saltcedar	2	2
Typha latifolia	Cattail	3	2

[a]Cover Classes: (+) <1%, (1) 1-5%, (2) 5-25%, (3) 25-50%, (4) 50-75%, and (5) 75-100%.

- The occurrence and relative abundance of certain plant species provide a measure of the magnitude of past ecological impacts, such as grazing, and the current health of the ecosystem.
- The plant community data are needed to estimate evapotransporation as a component of recharge and discharge calculations for site water-balance modeling.
- The plant community data are also needed to evaluate potential effects of remediation alternatives and future land-use alternatives.

The vegetation map for the millsite floodplain and wetlands (Figure 4–51) consists of several different plant associations. A plant association is a unit of classification that defines a particular plant community. An association generally has a consistent floristic composition, a fairly uniform appearance, and a distribution that reflects a certain mix of environmental factors that can be shown to be different from other associations. The relevé data (Tables 4–25 and 4–26) were obtained in plant stands that were considered to be representative of an association. The tables also include relevé results for the references areas. The two-part name of a plant association generally consists of the dominant overstory and understory species.

Brief descriptions of the floodplain and wetland plant associations follow:

Saltcedar/Kochia. This association is the dominant vegetation on the millsite floodplain. It consists primarily of dense stands of saltcedar, an exotic shrub or tree that has taken over most low-elevation riparian areas in the San Juan and Colorado River basins. Only a few native cottonwood and even fewer native willows remain in the millsite floodplain. Grasses and forbs form the understory of the saltcedar thickets. The relatively high abundance of kochia in the understory reflects a history of heavy grazing. This association is divided into two mapping units in Figure 4–51: Saltcedar/Kochia and Young Saltcedar.

Saltcedar/Barren. This association occupies a small area just west of the mouth of Bob Lee Wash on the west part of the floodplain. The structure of the community was different from other saltcedar associations; it consists of widely spaced, mature saltcedar interspersed with large bare patches and some inland saltgrass patches.

Rabbitbrush/Kochia. The large area of green rabbitbrush in the central portion of the millsite floodplain, with an understory dominated by kochia and Russian thistle, reflects a history of disturbance. Some remnants of alkali sacaton and giant dropseed populations were observed. Large bare patches were also observed in the association.

Saltcedar/Saltgrass. This association borders the wetland area at the mouth of Bob Lee Wash. The area is dominated by extensive mats of saltgrass. A few mature saltcedar dot the area. The presence of saltgrass indicates a water table very close to the ground surface.

Giant dropseed/Indian ricegrass. This association is found on sandy soils and often on stabilized dunes. The dominance of giant dropseed suggests a history of moderate grazing. Giant dropseed and its close cousins, sand dropseed and spike dropseed, tend to increase under moderate grazing where more palatable grasses have been killed. The dropseed grasses will also decrease under heavy grazing pressure.

Wetland. The 5-acre wetland on the millsite floodplain is an artifact of drainage from artesian well 648. If the well was not free flowing, the wetland would not occur. The wetland is dominated by cattails and bulrushes.

4.6.2 Sampling for Chemical Analysis

Field sampling for chemical analyses of samples was conducted in September 1998 and June 1999. Data from analyses of these samples is presented in CD-ROM format in Appendix G. This section discusses sampling methods and rationale. The results support and are presented in the ecological risk assessment (Section 6.2). The following is a list of sampling locations, types of media sampled, and sampling dates:

Location	Media	Dates
Millsite Floodplain	Vegetation	1998, 1999
Reference Floodplain	Vegetation	1998, 1999
Millsite Wetland	Surface Water	1998
	Sediment	1998
	Vegetation	1998, 1999
Reference Wetland	Surface Water	1998
	Sediment	1998, 1999
	Vegetation	1998, 1999
Disposal Cell Terrace	Vegetation	1998, 1999
Reference Terrace	Vegetation	1998, 1999

Appropriate reference areas for wetlands and terrace habitat were difficult to find. The ditch containing outflow from well 648 was the only wetland area in the vicinity of the Shiprock site that was not influenced by the contaminant plume. Small reference areas for greasewood, a terrace phreatophyte, were found east of the site at an elevation similar to the elevation of the disposal cell terrace and on the reference floodplain in the vicinity of wells 850 through 852 (Plate 1).

All ecological sampling locations are shown in Figure 4–52. Location numbers and location abbreviations (in parentheses) were identified in field books and chain of custody (CoC) forms as follows: (Note. Sample identification numbers 1248 through 1250 were not used. The location abbreviations in field books and CoC forms for sample locations 1280 through 1284 and 1285 through 1287 were changed from HSE to ECA and from HSW to WCA, respectively.)

Location 1236 (Seep 426)–Millsite floodplain wetland (FPW)
Location 1237 (Seep 425)–Millsite floodplain wetland (FPW)
Locations 1238 through 1243–Millsite floodplain wetland (FPW)
Location 1244–Bob Lee Wash/Millsite floodplain wetland (FPW)
Locations 1245 through 1247–Reference wetland (east of well 648) (REFW)
Locations 1251 through 1253–Repository (terrestrial) terrace (TT)
Locations 1254 through 1256–Reference terrace (RT)
Locations 1257 through 1259–Millsite floodplain (terrestrial) (FPT)
Locations 1260 through 1262–Reference floodplain around wells 850 through 852 (FPR)
Locations 1263 through 1265–Reference wetland (east of well 648—1999) (REFW)
Locations 1266 through 1273–Reference floodplain near wells 850 through 852—1999 (FPR)
Locations 1274 through 1276–Repository (terrestrial) terrace—1999 (TT)
Locations 1277 through 1279–Reference floodplain used in place of the 1998 reference terrace locations for greasewood collection–1999 (RT)
Locations 1280 through 1284–East Contaminated Area on floodplain near well 854 (ECA)
Locations 1285 through 1287–West Contaminated Area – floodplain near well 856 (WCA)
Locations 1288 through 1292–1st Wash west of U.S. Highway 666)–1999 (FW)

Field sampling locations for all 1998 samples in Figure 4–52 were established by a Garmin GPS III global positioning system and were converted into state plane coordinates. Sample locations for 1999 were estimated from existing maps, previous sampling locations, or monitor wells.

4.6.2.1 Surface Water and Sediment Sampling Methods

Surface water and sediment samples were collected from September 2 through September 4, 1998, at the millsite floodplain wetland and the upgradient reference wetland. Nine co-located samples of sediment and surface water were collected at the millsite floodplain wetland, but only three samples were collected at the reference wetland in part because of the small area. In June 1999, three additional sediment samples were collected at the reference wetland. The purpose of the additional samples was to pool both the 1998 and 1999 data sets for improved statistical power based on a larger sample size.

Consistent with EPA guidance (EPA 1989a), the number of samples satisfied a coefficient of variation (CV) of 15, a minimum detectable relative difference (MDRD) between 10 and 20 percent, a confidence of 80 (Type I error, false positive), and a power of 90 (Type II error, false negative). These values are based on a 1-sided, single sample distribution. Other factors considered in the selection of sample size were the small areal extent of the affected sites and the amount of sample material available for collection. The surface water samples were grab samples; sediment samples were from a nominal depth of 0 to 6 in. below the sediment surface. Surface water sample collection preceded sediment and biota tissue collection. All surface water and sediment sampling containers were certified as precleaned from an industrial supplier.

Surface Water Methods

Both filtered and unfiltered surface water samples were collected at the same locations as the sediment samples for the 1998 sampling season. Surface water samples associated with the 1998 ecological sampling locations were not collected in 1999. The filtered sample represents the soluble component for aquatic receptors, while the unfiltered sample represents surface water ingested by terrestrial receptors. Filtered surface water samples were identified with an "F" suffix on the sample identification number while unfiltered samples received a "U" (unfiltered) suffix. Each sample bottle was first rinsed with the surface water; the rinse water was then discarded prior to sample collection. A sample was collected by immersing the bottle just below the water surface and filling to just below the mouth of the bottle. Samples were then filtered using a 0.45-µm filter and acidified accordingly. Table 4–27 provides a summary of analytes, preservatives, containers, and other information pertaining to surface water sample collection.

Sample labels showing the date, time, location, laboratory bar code, sampler, analyses requested, preservatives, and comments were applied to each container and secured with clear plastic tape. All sample containers were placed in coolers containing ice for transport to the GJO Analytical Chemistry Laboratory. A CoC form was completed for all samples, and a CoC label was placed over each cooler. All samples were maintained under strict chain of custody.

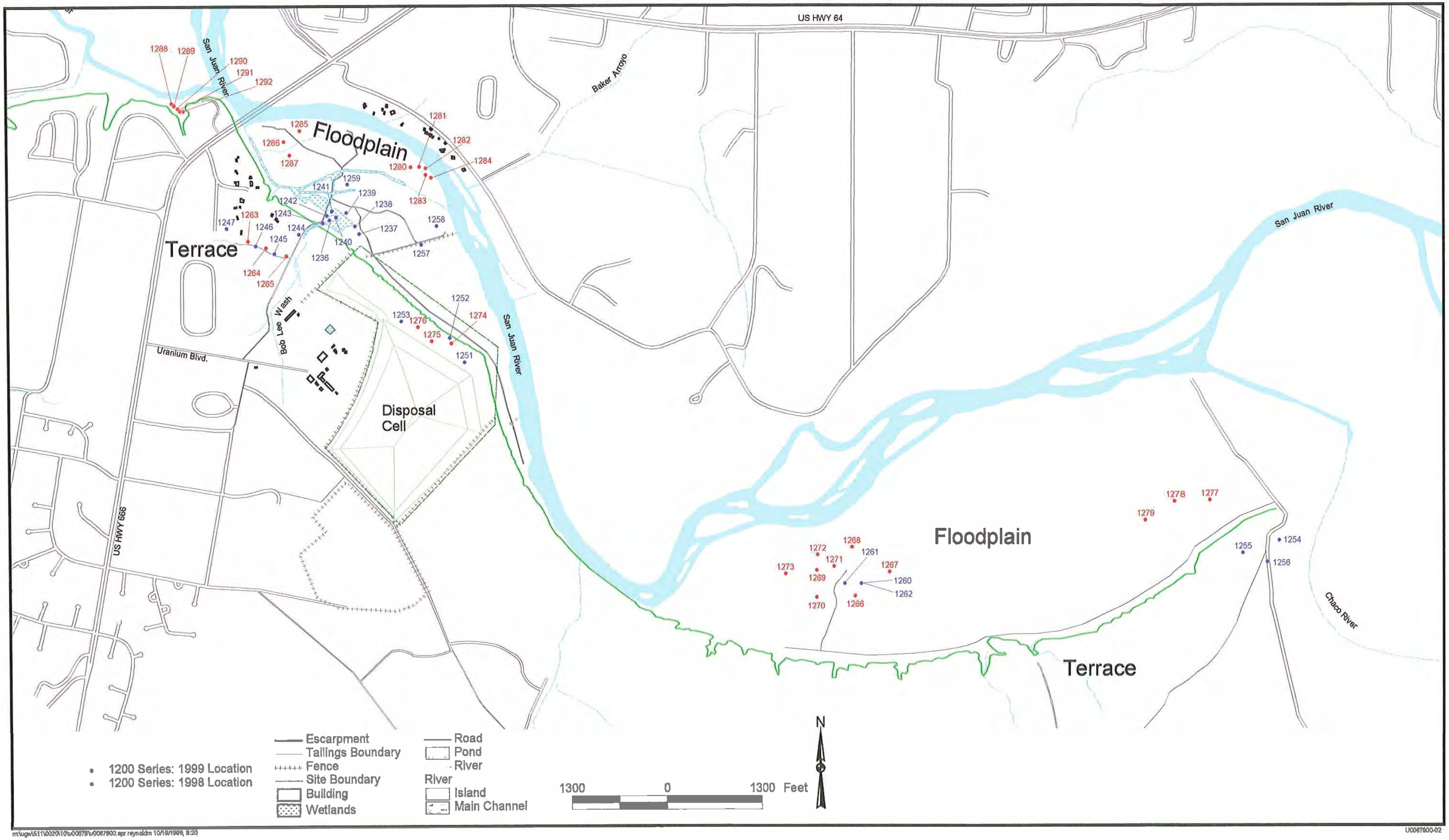


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Figure 4–52. Surface Water, Sediment, and Vegetation Sampling Locations for the Ecological Risk Assessment

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Table 4–27. Summary of Surface Water Sampling Parameters – 1998[a]

Analyte	Preservative	Container	Holding Time	Method
Antimony	HNO_3 – pH <2; cool 4 °C	500 mL amber HDPE	6 months	ICPMS
Arsenic				ICPAES
Magnesium				ICPAES
Manganese				ICPAES
Radium-226				AS
Selenium				ICPAES
Sodium				ICPAES
Strontium				ICPAES
Thorium-230				ICPMSFIA
Uranium				ICPMS
Nitrate	H_2SO_4 – pH <2; cool 4 °C	125 ml HDPE	28 days	IC
Sulfate	cool 4 °C only	125 ml HDPE	28 days	IC

[a]HDPE– high-density polyethylene.
H_2SO_4–sulfuric acid.
HNO_3–nitric acid.
mL–milliliter.
C–centigrade or Celsius.
AS – Alpha spectrometry.
ICPMS–Inductively coupled plasma-mass spectrometry.
ICPMSFIA–Inductively coupled plasma-mass spectrometry-flow injection analysis.
ICPAES–Inductively coupled plasma-atomic emission spectroscopy.
IC–Ion chromatography.

Sediment Methods

Each sediment sample represented a composite of three or four locations where vegetation material was present. The area for collection was typically a circle with a radius of less than 5 ft. Excess organic matter and larger rocks and pebbles were removed from the sample prior to compositing. The contents of one stainless-steel auger (i.e., one subsample) was collected at each composite location and placed in a large stainless steel mixing pan. All subsamples were mixed thoroughly with a stainless steel spoon prior to removing approximately 4 ounces (114 g) of material for metals analysis. In addition, a 125-mL high-density polyethylene (HDPE) bottle was collected for nitrate and another for sulfate in the 1998 sampling activities. A separate bottle for sulfate and another bottle for both nitrate and ammonia were used in the 1999 field collection. Table 4–28 provides a summary of analytes, preservatives, containers, and other information pertaining to sediment sample collection.

Sample labels were applied to each container and secured with clear plastic tape. All sample containers were placed in coolers containing ice for transport to the GJO Analytical Chemistry Laboratory. A CoC form was completed for all samples and a CoC label placed over each cooler. All samples were maintained under strict chain of custody. The analytical method for the sediment samples included a complete acid digestion rather than an acid leach as was used in some previous sediment sampling efforts.

Table 4–28. Summary of Sediment Sampling Parameters—1998 and 1999

Analyte	Preservative	Container	Holding Time	Method
Antimony	cool 4 °C	4 ounce amber glass	6 months	ICPMS
Arsenic				ICPAES
Magnesium				ICPAES
Manganese				ICPAES
Radium-226				AS
Selenium				ICPAES
Sodium (1998 only)				ICPAES
Strontium				ICPAES
Thorium-230				ICPMSFIA
Uranium				ICPMS
Nitrate	cool 4 °C	125 mL HDPE	28 days	IC
Sulfate	cool 4 °C	125 mL HDPE	28 days	IC
Ammonia as NH_4 (1999 only)	cool 4 °C	125 ml HDPE	28 days	SPEC

HDPE–high-density polyethylene.
mL–milliliter.
C–centigrade or Celsius.
ICPMS–Inductively coupled plasma-mass spectrometry.
ICPMSFIA– Inductively coupled plasma-mass spectrometry-flow injection analysis.
ICPAES–Inductively coupled plasma-atomic emission spectroscopy.
IC–Ion chromatography.
SPEC–Spectroscopy.

Quality Control Samples

Field blanks and equipment rinses were collected at only the millsite floodplain wetland (1998). These samples consisted of distilled, deionized water appropriately preserved and cooled in the field. The field blank was prepared by pouring distilled, deionized water directly from the carboy into the appropriate sampling bottle and preserving as necessary. The equipment rinse consisted of pouring distilled deionized water from the carboy over the cleaned sampling equipment (auger, sampling pan, shears, and spoons) and collecting the rinsate in the appropriate sampling containers and preserving and cooling as necessary. Because of the closeness of the millsite and reference wetlands and the small number of samples, no additional equipment rinse and field blank samples were collected.

A field-duplicate surface water sample was collected at the Shiprock wetland location 1243. The field duplicate was identified with "D" suffix appended to the sample identification number. No duplicate samples were collected in June 1999.

4.6.2.2 Plant Tissue Sampling Methods

Vegetation samples collected in 1998 consisted of cattails, bulrush, cottonwood, and greasewood. The 1999 samples consisted of cattail, greasewood, cottonwood, and Russian olive plant tissues. Each sample consisted of material composited from an area around the designated sample location. Cattail and bulrush samples were collected at the same locations as sediment and surface water samples. No sediment or surface water samples were collected at greasewood, cottonwood, or Russian olive locations because no water was present.

Co-located Vegetation Samples

Vegetation samples consisting of cattails and bulrush were collected at both the millsite and reference wetland locations in 1998. During 1999, cattails were collected again at both locations. These samples were co-located with the surface water and sediment samples (1998) and sediment-only samples (1999).

Samples were collected by digging up an entire plant or cluster of plants with a stainless steel shovel. Excess sediment was rinsed off the plants prior to separating the roots and stems. Stems and roots were processed with pruning shears with stainless steel and polyethylene cutting edges. The roots and stems were rinsed thoroughly with sample water, followed by tap and distilled deionized water rinses, until rinsates contained no visible soil or sand particles. All plant materials received a final distilled, deionized water rinse prior to bagging. Stems and roots were composited separately. Stems and roots were double-bagged in clean zip-lock type storage bags. Sample labels were applied to each outermost zip-lock type bag and secured with clear plastic tape. All samples were kept in coolers containing ice for transport to the GJO Analytical Chemistry Laboratory. A CoC form was completed for all samples, and a CoC label was placed over each cooler. All samples were maintained under strict chain of custody. Samples that could not be processed directly at the laboratory by freeze drying were placed in freezers at 4° C. Table 4–29 provides a summary of analytes, preservatives, containers, and other information pertaining to biota tissue collection.

Table 4–29. Summary of Biota Sampling Parameters (1998 and 1999)

Analyte	Matrix	Preservative	Container	Holding Time	Method
Antimony	cattail, bulrush, cottonwood, greasewood, Russian olive	cool 4 °C	double 1-gal zip-lock type bags	6 mos	ICPMS
Arsenic					ICPAES
Magnesium					ICPAES
Manganese					ICPAES
Radium-226					AS
Selenium					ICPAES
Sodium					ICPAES
Strontium					ICPAES
Thorium-230					ICPMSFIA
Uranium					ICPMS

[a]AS – Alpha spectrometry.
ICPMS–Inductively coupled plasma- mass spectrometry.
ICPMSFIA–Inductively coupled plasma-mass spectrometry-flow injection analysis.
ICPAES–Inductively coupled plasma-atomic emission spectroscopy.

Cottonwood, Greasewood, and Russian Olive Samples

Six composite greasewood samples consisting primarily of leaves and small stems were collected at the disposal cell terrace in 1998 and 1999. Three greasewood samples were also collected at the terrace reference area in 1998. In 1999, three additional greasewood samples were collected at the other floodplain reference location near wells 850 through 852. Samples were collected by randomly snipping both leaves and stems from three or four plants close together and placing them in zip-lock type bags. Samples were cleaned the same as co-located vegetation samples except that stems and leaves were not segregated but processed together.

Three cottonwood samples (*Populus fremontii*) were collected at each of three general locations on the millsite floodplain and at the floodplain reference area in 1998 and in1999. Sample collection and preparation followed the method used for greasewood samples. The areal extent of cottonwood sample collection was larger than for greasewood.

Samples of Russian olive consisting of stems and leaves were collected at the floodplain reference area near wells 850 through 852 and in an area in the north part of the floodplain near well 856 that overlies contaminated ground water. Sample collection and preparation followed the method used for greasewood samples.

Location numbers and location abbreviations (in parentheses) where plant tissue samples were collected were identified in field books and CoC forms as follows:

Locations 1236 through 1237—Millsite floodplain wetland (FPW)—bulrush
Locations 1238 through 1243—Millsite floodplain wetland (FPW)—cattail
Location 1244—Bob Lee Wash/Millsite floodplain wetland (FPW)—cattail
Locations 1245 through 1247—Reference wetland (REFW)—both bulrush and cattail
Locations 1251 through 1253 and 1253 composite—Terrace terrestrial (TT)—greasewood
Locations 1254 through 1256—Reference terrace (RT)—greasewood
Locations 1257 through 1259—Floodplain terrestrial (FPT)—cottonwood
Locations 1260 through 1262—Floodplain reference (FPR)—cottonwood
Locations 1263 through 1265—Reference wetland (REFW)—cattail only (1999)
Locations 1266 through 1268—Floodplain terrestrial (FPT)—cottonwood (1999)
Locations 1269 through 1273—Floodplain terrestrial (FPT)—Russian olive (1999)
Locations 1274 through 1276—Terrace terrestrial (TT)—greasewood (1999)
Locations 1277 through 1279—Reference terrace (RT)—greasewood on floodplain (1999)
Locations 1280 through 1284—East Contaminated Area on floodplain (ECA)—greasewood (1999)
Locations 1285 through 1287—West Contaminated Area on floodplain (WCA)—Russian olive (1999)
Locations 1288 through 1292—1st wash west of U.S. Highway 666

Cattail samples were uniquely identified by adding an "R" (root) or "S (stem) suffix to each sample identification. All roots for the same sample identification and field location number were processed as one sample. All stem material for each sample identification and field location number was also processed as one sample. Similarly, all sample bags of greasewood and cottonwood with the same laboratory identification number were processed as a single sample.

Quality Control Samples

A field duplicate cattail sample was collected at Shiprock floodplain wetland location 1243. The field duplicate was identified with a "D" (duplicate) suffix appended to the sample identification number. The equipment rinsate and field applied to the biota collection as well. No additional quality control samples were collected in 1999.

4.7 Summary of Additional Data Needs

Several key areas of data deficiency were identified during this investigation. Table 4–30 presents these data objectives and the proposed actions required to fulfill each data objective.

Table 4–30. Data Objective and Proposed Action for Acquiring that Data

Data Objective	Proposed Action
Identify ground water pathways where contaminated terrace water feeds the floodplain alluvial aquifer	• Install additional well nests: one on floodplain north of disposal cell near wells 613 and 614 and one on terrace immediately to the south • Bore into the filled-in drainages on terrace just west of well 735 and east of well 827 and complete as wells with screens near the contact with Mancos Shale
Evaluate if a source is present in the floodplain aquifer	• Backhoe will be used to collect three soil samples between the land surface and the water table (approx. 5 ft) at as many as 30 locations on a grid. The GJO mobile laboratory will be used to acid leach the samples and to perform preliminary uranium analyses. As many as 10 samples with the highest uranium concentrations will be sent to the GJO Analytical Chemistry Laboratory for further analysis of COCs and evaluation
Evaluate how the source can be isolated	• Engineering evaluation of the technologies that could be used to isolate, contain, or control the source of contamination in the floodplain alluvial aquifer
Evaluate the extent of the floodplain contaminant plume that extends northward to the San Juan River	• Drill and complete one new monitor well between wells 619 and 854
Confirm the flow rates for natural flushing in the floodplain	• Conduct tracer tests
Evaluate the infiltration potential through radon cover borrow pit	• Use Hydropunch to measure thickness of residual loess in bottom of borrow pit • Evaluate effect of diverting runoff from borrow pit
Identify the ground water flowpath from the disposal cell to Many Devils Wash	• Install as many as 5 additional wells to be completed near the top of the siltstone bed; predict target completion depth at each location on the basis of surveyed elevation and estimated structure contour of the top of the siltstone bed
Identify the eastern limit of the terrace contamination	• Use Hydropunch to bore in as many as 20 locations east and southeast of Many Devils Wash • Sample formation fluids, if present, for mill-related constituents NO_3, SO_4, and U

Data Objective	Proposed Action
Identify the western limit of the terrace contamination	• Install as many as 5 well points using a backhoe in the island area; sample ground water for mill-related constituents NO_3, SO_4, and U • Ecological sampling of leaf tissues and soils in the island area. • Collect additional surface water samples in area of surface water drainage from gravels north of high school • Add one or two additional monitor wells in area north of high school
Improve water balance for numerical modeling of terrace	• Measure the discharge off the escarpment and from irrigated areas • Results of flux measurements would be used to perform source-term modeling
Evaluate nature and extent of terrace background	• Perform regional reconnaissance of other equivalent terraces both upstream and downstream of site and on both sides of San Juan River • Check Rattlesnake Wash for surface water and salt deposits • Check Many Devils Wash upstream of west fork confluence for ground water and salt deposits
Identify top-of-bedrock elevation at selected areas on terrace	• Redrill and complete one new monitor well near well 834.
Map plant.communities and habitat types west of the U.S. Highway 666 bridge	• Collect plant relevé data in riparian and wetland areas west of the bridge that are influenced by site-related ground water • Delineate and map plant communities and habitat types
Expand the ecological risk assessment to include areas west of the U.S. Highway 666 bridge	• Refine the conceptual risk model and food web • Collect additional surface water, sediment, and vegetation samples from seeps and the floodplain west of the bridge • Evaluate chemical analyses against appropriate ecological benchmarks
Classify and map landscape units with respect to evapotranspiration rates	• Classify and delineate vegetation with respect to differences in evapotranspiration • Assign evapotranspiration ranges to mapping units based on literature values
Evaluate potential changes in ecological risk associated with ground water remediation alternatives	• Identify possible changes in the conceptual risk model associated with the remediation alternatives. • Collect any needed additional field data • Revise risk evaluation as appropriate; for example, assess potential effects of natural flushing on endangered fish habitat in the San Juan River
Evaluate potential changes in ecological risk associated with future land-use alternatives	• Determine potential future land-use alternatives based on consultation with the Navajo Nation and appropriate regulatory agencies • Identify possible changes in the conceptual risk model • Collect any needed additional field data and revise risk evaluations as appropriate.

5.0 Site Conceptual Model

This section describes the main physical and chemical characteristics and features of the Shiprock site from a multidisciplinary perspective. Two block diagrams illustrate the hydrological, geochemical, and ecological components of the site conceptual model. The purpose of the block diagrams is to simplify the field conditions and organize the data so that the system can be analyzed and described more readily. The important physical aspects that control the movement of water and dissolved contamination are identified, together with ecological systems that are affected by the water.

Figure 5–1 is a block diagram of the entire area affected by the Shiprock UMTRA site. It illustrates the important physiographic features that define the landscape. Two general areas are illustrated: the terrace and the floodplain. Upland areas south of the disposal site and an escarpment north of the disposal site bound the terrace. The floodplain area is bounded by the escarpment and the San Juan River.

Terrace ground water is anthropogenic and partly contaminated with residual radioactive material, except for areas being flushed by irrigation water. The Helium Lateral Canal, located approximately 1 mi west of the disposal cell, provides the source of the water that flushes the terrace ground water system. The canal also accounts for most of the ground water that presently flows through the terrace system. The escarpment gradually disappears west of U.S. Highway 666 and north of the Shiprock High School. Most of the irrigation-derived ground water returns to the San Juan River and its distributary channel through the gap formed between the western point of the escarpment and the western edge of the terrace system.

Figure 5–2 presents a site conceptual model that shows the interactions between the terrace system and floodplain alluvial aquifer in the Shiprock area. The Shiprock site directly impacts both ground water systems because of leaching of residual radioactive material from the milling process. Contamination from the milling activities is transported along ground water flow paths to surface exposure points in Bob Lee Wash and Many Devils Wash, and to the wetlands in the floodplain alluvium and the San Juan River.

Summaries of water-balance components of both the terrace ground water system and the floodplain alluvial aquifer were presented in Tables 4–7 and 4–4, respectively. In those tables, the alluvial flows were expressed in units of cubic feet per day and the terrace ground water system flows were expressed in units of cubic feet per year. However, it is also possible to express these components with smaller numeric values. Consequently, the various flow components are now plotted in units of acre-feet per year in Figure 5–2. Table 5–1 is a key that captures the original values from Tables 4–4 and 4–7 and transforms them to the desired units.

The terrace ground water system receives no natural recharge from the Mancos Shale; consequently, the southern boundary of the system is considered no flow, while the remaining boundaries of the flow system are discharge-flux boundaries. The terrace system receives recharge from internal sources such as infiltration from the radon-cover borrow pit, the gravel pit, the disposal cell, and irrigation water in the quantities shown on Table 5–1 and Figure 5–2. Most of the volume of contaminated ground water is contained within the buried ancestral river channel where an estimated 50 million gallons of ground water are stored.

Table 5–1. Estimated Magnitudes of Major Flow Components for Floodplain Alluvial Aquifer and Terrace Ground Water System, Shiprock, New Mexico UMTRA Site

Flow Component	Inflow	Inflow (acre-feet per year)	Outflow	Outflow (acre-feet per year)
Floodplain Alluvial Aquifer	(ft^3/day)		(ft^3/day)	
(See Table 4–4)				
Inflow from San Juan River	3,600	30.2		
Inflow of Recharge	2,600	21.8		
Inflow from Well 648	12,320	103		
Outflow to San Juan River			19,400	162.56
Subtotal: Floodplain Alluvial Flow Component	18,500	155	19,400	162
Terrace Ground Water System	(ft^3/year)		(ft^3/year)	
(See Table 4–7)				
Inflow through Radon Cover Borrow Pit	227,500	5.2		
Infiltration from Gravel Pit	<< 39,000	<< 0.90		
Infiltration through Disposal Cell	10,500	0.24		
Infiltration of Irrigation Water	53,600,000	1,230		
Discharge to Escarpment			562,000	12.9
Discharge to Many Devils Wash			21,000	0.48
Discharge to Irrigation Return-Flow System			15,768,000	362
Discharge to San Juan River			37,529,000	862
Subtotal: Terrace Ground Water System	53,880,000	1,236	53,880,000	1,237
Grand Total (rounded)	53,900,000	1,390	53,900,000	1,400

Note: The conversion from cubic feet per day to acre-feet per year is accomplished by multiplying by 0.0084. The conversion from cubic feet per year to acre-feet per year is obtained by dividing by 43,560.

The terrace ground water system contains high uranium, nitrate, and sulfate concentrations near the former ore storage area and the processing site. Discharge from this section of the terrace alluvial aquifer flows toward Bob Lee Wash, where seepage and springs deliver uranium, sulfate and nitrate concentrations to the land surface. Because the contaminated ground water discharge in Bob Lee Wash is a potential risk to humans and livestock, interim actions designed to eliminate possible exposure to the water have been proposed.

South of the disposal cell, the terrace ground water system contains mainly nitrate and sulfate contamination. The ground water in this area appears to migrate rather slowly and may even be partially trapped within a basin at the site of an ancestral San Juan River channel. This section of the terrace system possibly receives up to 5.2 acre-feet per year of recharge through the radon cover borrow pit. Discharge from this area may flow east toward Many Devils Wash, presumably along the top of a thin, eastward dipping siltstone bed in the Mancos Shale, becoming oxidized as it passes near the NECA gravel pit. When the ground water discharges into Many Devils Wash, at a rate of approximately 0.48 acre-feet per year, there is a probable livestock-exposure point. Interim actions designed to cover the exposed water in this wash also have been proposed.

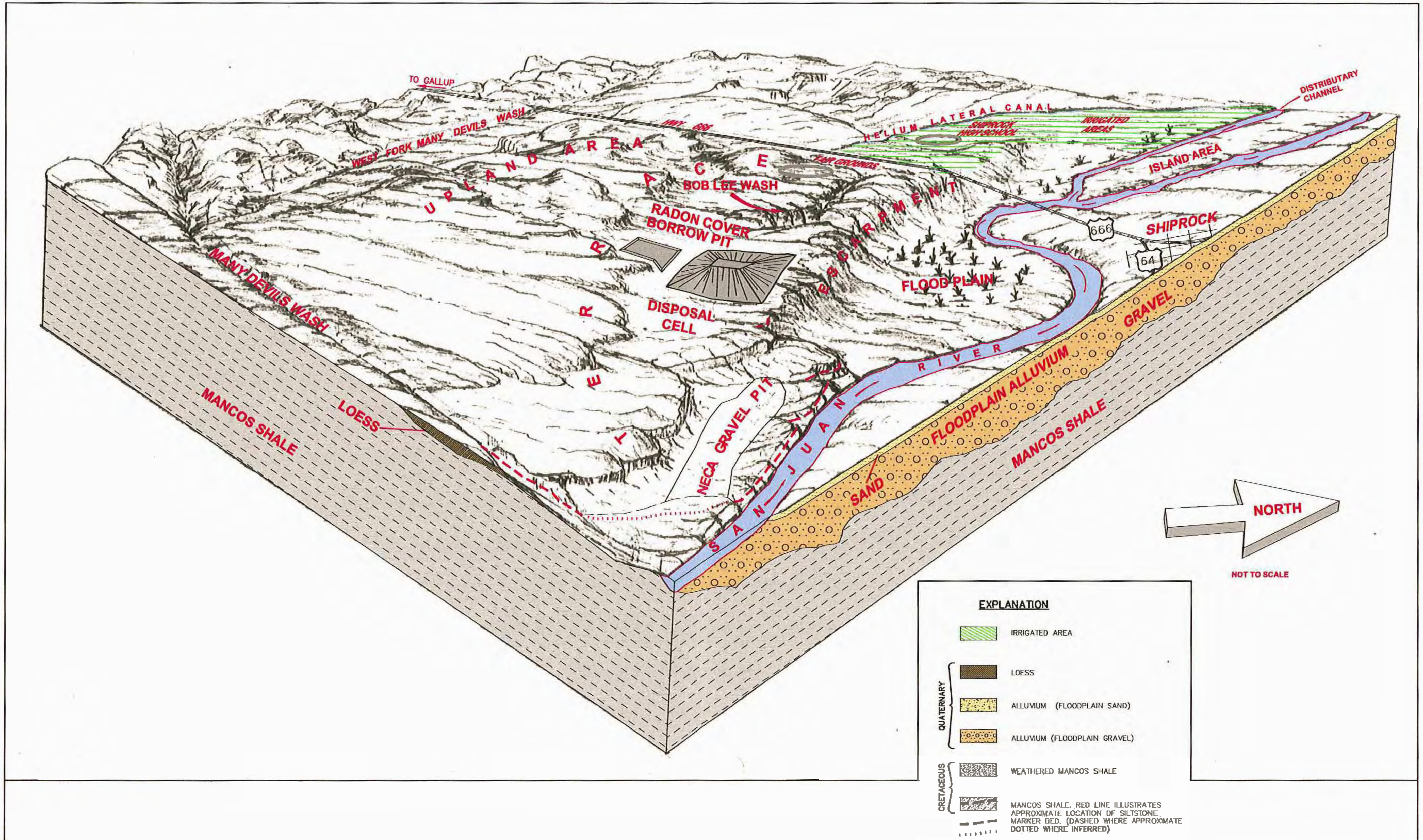

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Figure 5–1. Physiographic Block Diagram of the Shiprock, New Mexico, UMTRA Site

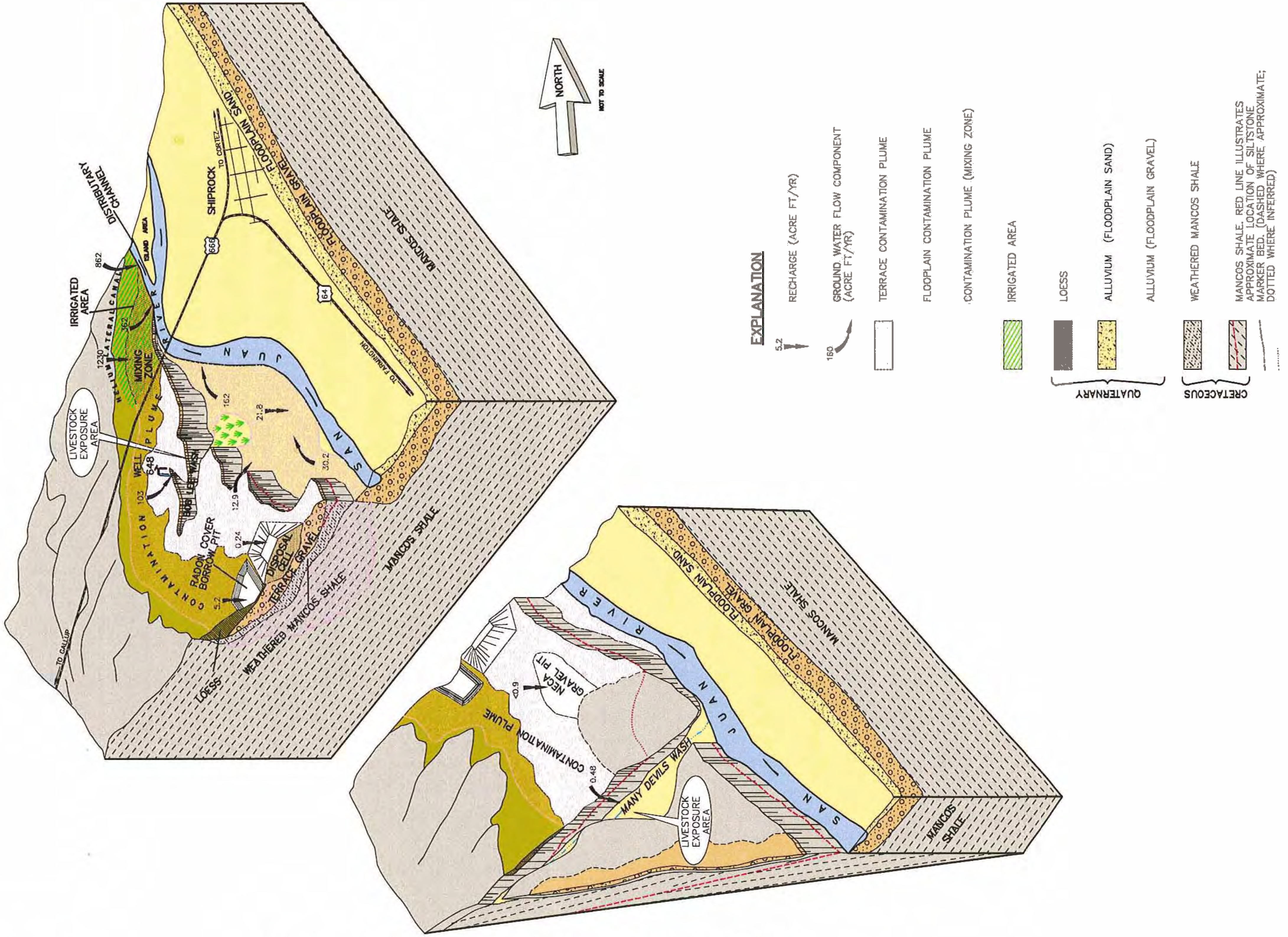


Figure 5–2. Site Conceptual Model of the Shiprock, New Mexico, UMTRA Site

Another component of discharge from the buried channel section of the system flows west to northwest in the area west of U.S. Highway 666. This area is characterized by declining contaminant concentrations further northwest where the ground water mixes with the irrigation water from the Helium Lateral Canal. Irrigation water in the mixing zone infiltrates at approximately 1,230 acre-feet per year and discharges to the San Juan River either through the irrigation return flow canal system or through ground water discharge directly to the San Juan River. Contaminants of concern exist above UMTRA MCLs west of U.S. Highway 666 and, on the basis of sampling results, appear to discharge into the distributary channel west of the U.S. Highway 666 bridge. The total discharge of ground water from the terrace over the length of the escarpment is approximately 12.9 acre-feet per year. The ecological risk associated with the ground water discharge to the distributary channel area will be evaluated during additional characterization.

The floodplain alluvial aquifer is bounded by the escarpment along its southern margin and by the San Juan River along its northern margin. The main sources of recharge to the floodplain alluvial aquifer are (1) 103 acre-feet per year from flowing-well 648, (2) 30.2 acre-feet per year from the San Juan River, and (3) 21.8 acre-feet per year from infiltration of precipitation and runoff. Seepage from the terrace system is relatively minor in terms of its quantity; however, its quality is a potential source of degradation for the alluvial aquifer. The concentrations of COCs next to the escarpment have not changed appreciably over time. Transport modeling suggests that the floodplain alluvial aquifer would flush readily if the source were removed. Therefore, the indication is that either a source exists in the floodplain alluvium or there is a source pathway from the terrace. Part of the 12.9 acre-feet per year of water that discharges from the terrace ground water system probably contains the contamination that degrades the floodplain alluvial aquifer north of the disposal cell.

The northern margin of the floodplain alluvial aquifer is where the ground water discharges into the San Juan River. The cumulative discharge from the alluvial aquifer is approximately 162 acre-feet per year. Over much of the discharge reach, the ground water is dominantly composed of the 103 acre-foot component from flowing-well 648, and therefore it does not constitute an ecological risk. Ground water with mill-related contaminants enters the San Juan River upstream of the well-648 discharge reach. As concluded in Section 6, "Baseline Risk Assessment," the consequences of this component of ground water discharge on the aquatic and terrestrial habitats is negligible.

End of current text

6.0 Baseline Risk Assessment

6.1 Human Health Risks

A BLRA was previously prepared for the Shiprock Site (DOE 1994). Most of the methodology used in that risk assessment followed standard EPA risk assessment protocol (EPA 1989a), though the BLRA did not calculate potential risks for noncarcinogenic constituents. Instead, calculated exposure intakes were compared with a range of contaminant doses associated with various adverse effects. Data used in that report were collected from 1988 to 1993. Since that time, additional data have been collected to more completely characterize the site and to represent more recent site conditions. Updated and revised toxicological data are also available for some site-related constituents. These new data were used to reevaluate COPC identification and assessment of associated risks. This BLRA update uses the earlier risk assessment results and conclusions as a starting point from which to evaluate the more recent data.

6.1.1 Summary of 1994 BLRA Methodology and Results

As described in previous sections, two different surficial hydrogeologic units are recognized in the vicinity of the Shiprock site—floodplain alluvium and the terrace alluvium. While there is likely some contribution of ground water from the terrace system to the floodplain aquifer, these two systems were considered different enough to be evaluated separately in the original BLRA. One of the major distinctions between these two systems is the source of recharge. The floodplain alluvium is a natural aquifer and is recharged primarily from the San Juan River. Ground water from alluvial deposits located on a floodplain upstream from the Shiprock site was sampled to represent the quality of floodplain ground water that existed before milling activities began.

Conversely, it is probable that the terrace ground water system did not exist before the start of milling activities at the Shiprock site and was formed primarily because of discharge of milling-related fluids. Continued recharge to the terrace alluvium is largely from man-made sources (e.g., irrigation and septic systems). Because no pre-millsite terrace ground water likely existed, no background water quality data are available to serve as a baseline in the evaluation of site-related adverse affects and the development of an appropriate compliance strategy for that system.

In addition to ground water from the two systems, the 1994 BLRA also evaluated potential risks associated with direct and indirect exposure to surface water on the floodplain that is contaminated through discharge of ground water to the surface. The following sections provide summaries of the potential risks associated with exposure to ground water in these three different situations, as determined in the 1994 BLRA.

6.1.1.1 Floodplain Alluvium

The 1994 BLRA identified 19 constituents associated with the floodplain aquifer at the Shiprock site as being present at levels statistically above background concentrations for the area. This initial list was screened to first eliminate constituents with concentrations within nutritional ranges and then to eliminate contaminants of low toxicity and high dietary ranges. These two steps eliminated five and three constituents, respectively, resulting in the following COPC list: antimony, arsenic, cadmium, magnesium, manganese, nitrate, selenium, sodium, strontium, sulfate, and uranium. These contaminants were retained for further risk analysis.

A number of potential routes of exposure were evaluated: ingestion of ground water as drinking water in a residential setting, dermal contact with ground water while bathing, and ingestion of garden produce irrigated with ground water. Ingestion of meat and milk from ground water-fed livestock was also considered; however, nitrate and sulfate concentrations in floodplain ground water were so high that livestock could not survive chronic ground water exposure. Therefore, this exposure route was considered not viable and was eliminated from further consideration from a human health perspective. Note that the nitrate and sulfate concentrations ***do*** constitute a real and current risk to livestock in the area even though it is not a significant pathway for human health. Results of the exposure assessment indicated that intakes for all constituents were negligible from exposure routes other than drinking water. Therefore, only exposure through ingestion of ground water as drinking water was retained for more detailed evaluation. Both infants and adults were considered as likely receptors.

Calculated exposure intakes were presented along with contaminant intakes associated with a range of adverse health effects. Potential risks associated with exposure to noncarcinogenic constituents were discussed in a qualitative fashion; carcinogenic risks were quantified and compared to EPA's acceptable risk range of 1×10^{-4} to 1×10^{-6}.

For the noncarcinogenic contaminants nitrate and sulfate, the most sensitive receptor population is infants. Results of the BLRA showed that the most significant health risk is associated with nitrate. If ground water was used for drinking water, the possible exposure greatly exceeds the potential lethal level for infants. Sulfate concentrations were also well above the range expected to result in severe diarrhea or death because of dehydration in infants.

Adult exposure intakes were evaluated for the other noncarcinogenic contaminants. Cadmium and strontium intakes were below oral reference doses (RfDs) established by EPA. Estimated intakes of uranium greatly exceeded its RfD; arsenic, antimony, selenium, and manganese intakes also exceeded their respective RfDs, but to a lesser degree. It was noted, however, that most of the RfDs were established at levels well below those shown to demonstrate actual adverse effects. Exposure estimates for sodium are 3 times greater than the National Research Council's recommended intake and could result in hypertension; magnesium intakes have been shown to be associated with diarrhea in adults, though toxicity data related to more severe effects are unavailable.

Carcinogenic risks calculated for adult exposure to uranium and arsenic both exceeded the upper bound of EPA's acceptable risk range of 1×10^{-4} by approximately 1 order of magnitude.

6.1.1.2 Terrace Alluvium

Because of the lack of background ground water quality data for the terrace alluvium, no statistical comparison could be performed to determine COPCs for terrace alluvial ground water. Instead, COPCs were selected based on their clear association with uranium milling activities and their elevated concentrations with respect to regional waters. Four constituents were evaluated as COPCs—nitrate, sulfate, uranium, and ammonia as ammonium. Only the ground water ingestion pathway was considered; infants and adults were evaluated as potential receptors.

Exposure intakes of both nitrate and sulfate exceed potentially lethal levels for infants. Adult intakes of uranium exceed the EPA RfD. Carcinogenic risks associated with exposure to uranium are within EPA's acceptable risk range.

6.1.1.3 Floodplain Surface Water

Several pathways were considered likely for exposure to surface water on the floodplain. Sediment ingestion, incidental water ingestion, and dermal absorption of contaminants from surface water were evaluated for children. It was assumed that they would contact the contaminated media during play on the floodplain. Exposure to adults was considered via ingestion of meat and milk obtained from livestock that were watered with contaminated surface water and grazed on contaminated pasture grasses. The contaminants evaluated for the floodplain surface water included selenium, strontium, and uranium.

Exposure intakes calculated for all pathways for noncarcinogenic contaminants are below levels at which adverse health effects would be expected. Carcinogenic risks associated with exposure to uranium are below even the lower bound of EPA's acceptable risk range.

6.1.2 BLRA Update

As mentioned previously, the original BLRA considered several potential routes of exposure to contaminants and eliminated all but one, ingestion of ground water in a residential setting, as insignificant. Therefore, the ground water ingestion pathway is the only route of exposure considered in this BLRA update. Note that all risks discussed in this document are hypothetical with respect to human health. On the basis of current ground water use, no risks are present as no exposure pathways are complete. Therefore, this assessment concerns only potential risks that could exist in the future if land and water usage changes.

Risk calculations presented here follow EPA's *Risk Assessment Guidance for Superfund Methodology* (EPA 1989a), which involves determining a point estimate for excess cancer risk from current or potential carcinogenic exposures (risk is equal to lifetime intake times cancer slope factor) and a hazard quotient (HQ) for noncarcinogenic exposures (HQ is equal to exposure intake divided by reference dose). EPA's acceptable carcinogenic risk range is 1×10^{-6} to 1×10^{-4}, which is an excess cancer risk of 1 in 1,000,000 to 1 in 10,000 compared to the general population. Risks exceeding this range are potentially unacceptable. For noncarcinogenic exposures, an HQ exceeding 1 is potentially unacceptable. HQs from multiple contaminants and/or pathways are often summed to estimate cumulative noncarcinogenic risks; these summed HQs are referred to as a hazard index (HI). HIs greater than 1 also represent potentially unacceptable exposures. Therefore, it is possible for a number of individual contaminants to each have "acceptable" HQs of less than 1, that, when summed, represent a potentially unacceptable cumulative risk. Figure 6–1 provides exposure intake equations and default assumptions used in intake calculations for this BLRA update.

In this update, which uses point-exposure doses, single values are used for each parameter required in the risk calculations. Calculations to determine contaminant intakes use standard

Residential Exposure Scenario – Ground Water Ingestion

Chemicals: Intake (chronic daily in mg/kg-d) = (Cw * IRw *EF * ED)/(BW * AT)

Radionuclides: Intake (lifetime in picocuries) = Cw * IRw * EF * ED

Where
Cw = contaminant concentration in water
IRw = ingestion rate for water (2 liters per day default for adults; 0.64 liter per day for infants)
EF = exposure frequency (350 days per year)
ED = exposure duration (7 years for adults and 1 year for infants for noncarcinogens; 50 years for carcinogens)
BW = body weight (70 kilograms for adults; 4 kilograms for infants)
AT = averaging time (365 days * ED for noncarcinogens; 365 days * 70 years for carcinogens)

Incidental Exposure Scenario – Surface Water

Ingestion of Chemicals: Intake (chronic daily in milligrams per kilogram per day) = (Cw * IRw *EF * ED)/(BW * AT)

Where
Cw = contaminant concentration in water
IRw = ingestion rate for water (0.05 liter per day for children aged 6-12 years)
EF = exposure frequency (3 months per year at 7 days per week = 90 days plus 3 months per year on weekends = 24 days; total = 114 days per year)
ED = exposure duration (7 years for children aged 6-12 years playing on floodplain)
BW = body weight (38.3 kilograms for children aged 6-12 years)
AT = averaging time (365 days * ED for noncarcinogens; 365 days * 70 years for carcinogens)

Figure 6–1. Exposure Intake Equations and Default Assumptions

exposure factors for the adult population (EPA 1989b). Risk calculations performed for floodplain ground water use the 95 percent upper confidence level (UCL95) on the mean concentrations to provide reasonable worst-case risk estimates for probable future ground water uses. Though future use of the terrace alluvial ground water is unlikely because of its generally poor quality and limited extent, risk estimates using maximum contaminant concentrations are provided for purposes of discussion and comparison. Exposure to floodplain and terrace surface water represents the only potentially complete pathway that currently exists. Maximum surface water concentrations are used in calculations to provide worst-case risk estimates for these possible exposures.

The same methodology was used to calculate carcinogenic risks for this BLRA update as was used in the original BLRA (i.e., receptors are adults with exposure average over 70 years). For all risk calculations, benchmarks for acceptable contaminant intakes (e.g., reference doses and slope factors) are best available data from standard EPA sources (e.g., Integrated Risk Information System, Region III Risk-Based Concentration Table).

Analytical results for nitrate presented in this document are concentrations of nitrate reported as NO_3. Other references may report nitrate values as N (nitrogen), also referred to as nitrate-nitrogen. The conversion factor for these different reported quantities is 1 milligram (mg) N (or nitrate-nitrogen) is equal to 4.4 mg nitrate (as NO_3). Thus the UMTRA ground water standard for nitrate is 10 mg/L as N or 44 mg/L as NO_3. For consistency in this BLRA update and for ease in use of reported analytical data, all concentrations of nitrate are expressed as NO_3.

6.1.2.1 Floodplain Alluvium

This BLRA update uses the COPC list from the original BLRA as a starting point to evaluate current data for ground water in the floodplain alluvium. This current evaluation assumes that no additional COPCs are now present that were not identified in the original BLRA. However, there may be two exceptions to this assumption. First, vanadium was eliminated as a COPC in the BLRA because it was detected at similar concentrations to background. On the basis of historical information and because vanadium concentrations appear to be higher south of the San Juan River compared with north of the river, the potential for inclusion of vanadium as a COPC was reevaluated. Ground water samples from the June 1999 sample event were analyzed for vanadium and were below or at the detection limit. Therefore, vanadium can be eliminated from further consideration as a COPC. Second, ammonium was reevaluated because of its conversion to ammonia in ground water. Risks to ammonia can occur from volatilization in a residential setting.

As noted previously, the following COPCs were identified in floodplain alluvial ground water: antimony, arsenic, cadmium, magnesium, manganese, nitrate, selenium, sodium, strontium, sulfate, and uranium. Data from 1998–1999 sampling of floodplain alluvial wells indicates that concentrations of antimony, arsenic, and cadmium were at or below their respective detection limits in all wells, with few exceptions. Therefore, these three constituents are eliminated from further evaluation as COPCs. All other COPCs are present at levels sufficiently above background to retain them for further evaluation in this BLRA update.

Table 6–1 presents the maximum, mean, and UCL95 values for each COPC in the floodplain alluvial ground water based on the last two rounds of ground water sampling available at the time of this writing. Though older data are available, only recent data were used to provide the most current estimate of contaminant concentrations in the plume. Also included for comparison are the applicable UMTRA ground water standards (if available) or other potentially relevant water quality standards or benchmarks, including risk-based concentrations (RBCs). The RBC for a given contaminant represents a concentration in drinking water that would be protective of human health provided that

- Residential exposure is appropriate.
- Ingestion of contaminated drinking water is the only exposure pathway.
- The contaminant contributes nearly all the health risk.
- EPA's risk level of 1 × 10^{-6} for carcinogens and an HI of 1 for noncarcinogens is appropriate.

If any of these assumptions is *not* true, contaminant levels at or below RBCs cannot automatically be assumed to be protective. For example, if multiple contaminants are present in drinking water, a single contaminant may be below its RBC but still be a significant contributor to the total risk posed by drinking the water. However, if an RBC is exceeded, it is an indication that further evaluation of the contaminant is warranted. RBCs are intended for use in screening-level evaluations.

Table 6–1. Shiprock—Floodplain Alluvial Ground Water Data Summary—1998-1999[a]

Contaminant	Maximum (mg/L)	Mean (mg/L)	UCL95 (mg/L)	UMTRA Std (mg/L)	Other Std (mg/L)	RBC[b] (mg/L)
Ammonia as NH_4	602	33.5	61.8			0.28 as NH_3 175 as NH_4[c]
Magnesium	3,570	797	1,065			
Manganese	12.8	3.305	4.082		0.05[d]	1.7
Nitrate	3,480	637	951	44		255
Selenium	1.1	0.114	0.171	0.01	0.05[e]	0.18
Sodium	6,400	1,671	2,078			
Strontium	17.1	8.97	9.306			22
Sulfate	23,800	6,341	7,898		250[d]	
Uranium	3.95	0.766	1.049	0.044		0.11
Vanadium[f]	0.0017	N/A	N/A			0.33

[a] Data from December 1998 and March 1999 sampling events; GJO Analytical Chemistry Laboratory analyses; wells 610, 612, 614 through 617, 619, 620, 624, 626, 628, 630, 732 through 736, and 853 through 857. Ammonia data includes Mancos well 608.

[b] Risk-based concentration; EPA Region III.

[c] This was estimated from Emerson and others (1975) with a pH of 7.0 and an average annual ground water temperature of 8 °C.

[d] National Secondary Drinking Water Regulation Standard.

[e] National Primary Drinking Water Regulation Standard.

[f] Based on June 1999 sampling.

No standards or benchmarks have been established for magnesium and sodium based on human-health concerns. The secondary standard for sulfate is based on considerations of taste and odor and not on effects to human health. Because of the lack of toxicity data, potential risks from exposure to these three contaminants cannot be quantified. Exposure intakes are calculated for these constituents, but potential adverse effects are considered in only a qualitative fashion.

The major pathway evaluated quantitatively in this BLRA update for floodplain alluvial ground water is drinking water ingestion in a residential scenario. Adults were evaluated as the primary receptor group; infants were also evaluated for exposure to sulfate and nitrate because they represent the most sensitive receptor population. The residential ingestion scenario was evaluated for all contaminants except ammonia. The major risks resulting from ammonia exposure are from inhalation of ammonia in the gaseous form through volatilization from ground water. Risks were calculated using default inhalation exposure parameters for a residential setting (EPA 1991). Analytical results for ammonia were reported as NH_4. The actual amount of ammonia gas, NH_3, available for volatilization was calculated for site-specific temperature and pH using data compiled by Emerson and others (1975). Note that risks associated with ammonia for a residential setting require that exposure occurs within a closed structure in which volatilized ammonia is trapped through use of ground water for domestic purposes (drinking, bathing, laundry, etc.). Because the higher concentrations of ammonia (via ammonium) occur at locations where it is generally impractical to construct a residence, potential exposures to ammonia should be considered as a worst-case scenario. For exposure scenarios where exposure does not occur in a closed structure (e.g., recreational use), volatilized ammonia would quickly dissipate to the atmosphere and risks would be negligible.

The meat/milk ingestion pathway was considered for livestock exposed to alluvial ground water through grazing and watering. As in the original BLRA, this pathway was eliminated because of acutely toxic levels of sulfate and nitrate; livestock could not survive the chronic ingestion of water required to bioaccumulate contaminants for transfer to humans. The original BLRA also examined potential human exposure to contaminants through ingestion of ground water-irrigated produce. These exposure intakes present no significant risks. Concentrations of alluvial ground water used in those calculations were all higher than UCL95 concentrations presented in this BLRA update. Therefore, risks associated with ingestion of ground water-irrigated produce remain at insignificant levels and were not further quantified in this document.

6.1.2.2 Terrace Alluvium

Nitrate, sulfate, and uranium were evaluated for drinking water ingestion in a residential scenario (adults for all contaminants; infants for nitrate and sulfate) based on the most recent monitoring data. Because concentrations of sulfate and nitrate in the terrace alluvium are even higher than in the floodplain alluvium, meat/milk ingestion of livestock watered and grazed on floodplain ground water was not considered a viable pathway for the reasons stated in the previous section. Nearly all contaminant concentrations in samples from terrace wells are below those used in the original BLRA to calculate exposures to ground water-irrigated produce. Therefore, use of terrace ground water for this purpose would be expected to present no significant risks, and this exposure scenario is not considered further.

Ammonia exposure from inhalation was evaluated using the following data (all concentrations are in milligrams per liter):

	Maximum	Mean	UCL95	RBC[a]
Ammonia as NH_4	2,160.0	102.0	179.0	0.28 as NH_3 175 as NH_4

[a]See Table 6–1.

The UCL95 of the mean is slightly greater than the RBC; however, the maximum concentration (from well 603) is much greater than the RBC.

6.1.2.3 Surface Water

The original BLRA evaluated only exposure to surface water present in floodplain locations. The only contaminants considered were selenium, strontium, and uranium, though other constituents are elevated at floodplain surface water locations. Since that time, surface water has been sampled from Bob Lee Wash and Many Devils Wash, located west and east of the former millsite, respectively. Surface water at these locations is fed by ground water from the terrace alluvium. In this BLRA update, surface water from both terrace and floodplain locations are evaluated.

Exposure to surface water in terrace locations was evaluated for the terrace ground water COPCs—nitrate, sulfate, and uranium. The exposure scenario evaluated was for children playing on the terrace who may experience incidental ingestion of and dermal contact with surface water. As in the original BLRA, only noncarcinogenic risks from exposure to contaminants were evaluated because of the relatively short exposure duration for this scenario. Carcinogenic risks are expected to be insignificant because these risks are calculated based on averaging these short-term intakes over a lifetime of potential exposure. Because of acutely toxic levels of sulfate and nitrate to livestock, the meat/milk ingestion pathway was eliminated from further consideration. The small quantity of surface water present in these locations is not likely to support significant irrigation; therefore, ingestion of surface water-irrigated produce is not considered a viable pathway.

For floodplain surface water, exposure to children playing on the floodplain was also evaluated. Ingestion and dermal contact were both considered. To be consistent, contaminants evaluated included all COPCs identified in floodplain ground water. Similar calculations were performed using concentrations of contaminants in both floodplain and terrace alluvial ground water, in the event that this water is routed to the surface for some permissible use (e.g., agricultural) and is available for incidental ingestion and/or dermal contact. Children were also evaluated for this scenario as representing the most sensitive receptor population.

In the original BLRA, intakes of contaminated sediments associated with surface water were also calculated and were identified as constituting an insignificant risk. Sediment intakes were not quantified in this BLRA update. However, it is unlikely that sediment concentrations are significantly different from those used in the previous intake calculations, and it can be assumed that risks associated with incidental sediment ingestion are still low and insignificant.

The meat/milk ingestion pathway was not quantitatively evaluated in this BLRA update. The original BLRA determined that this exposure pathway presented no adverse health risks from contaminants most likely to bioaccumulate in livestock. Current concentrations of these constituents are not significantly different from those used in that evaluation, and this pathway is considered to pose no unacceptable present or future risk. Because floodplain surface water contaminant concentrations are lower than those in floodplain ground water, ingestion of garden produce irrigated with surface water should pose no unacceptable risk and is not evaluated further.

6.1.3 Results

6.1.3.1 Floodplain Alluvium

Table 6–2 presents the results of risk calculations for use of floodplain alluvial ground water as drinking water in a residential exposure scenario. The greatest risks posed for this scenario are to infants from ingestion of nitrate and sulfate. Nitrate exceeds acceptable levels by more than 20 times; predicted intakes are in the range of potentially lethal levels. Likewise, though no RfDs have been developed for sulfate, calculated intakes are within the range of those reported as lethal to infants.

The greatest noncarcinogenic risks to adults are posed by ingestion of uranium and, to a lesser degree, manganese and nitrate. Intakes of magnesium and sulfate are within ranges associated with laxative effects in adults, and sodium intakes are within the range associated with hypertension effects; however, RfDs are not available for these constituents and they are evaluated only qualitatively. Calculated HQs for selenium and strontium are both below 1, though selenium approaches this value and is well above its UMTRA standard of 0.01 mg/L. Strontium and ammonium together make up less than 5 percent of the total risk (using infant risks for nitrate) and can probably be eliminated from further consideration as COPCs in floodplain alluvial ground water.

Carcinogenic risks associated with uranium exceed the upper end of EPA's acceptable range for both UCL95 and mean ground water concentrations.

Table 6–2. Shiprock–Floodplain Surficial Aquifer Residential Ground Water Ingestion Risk Calculations

Noncarcinogens—Ground Water Ingestion Only (adults, except where noted)

Contaminant	Cw95[a] (mg/L)	IRw (L/day)	EF (days/yr)	ED (yr)	BW (kg)	AT (day)	Intake (mg/kg-d)	RfD[b] (mg/kg-d)	HQ
Magnesium	1065	2	350	7	70	2,555	29.178	n/a[c]	n/a
Manganese	4.082	2	350	7	70	2,555	0.112	0.047	2.38
Nitrate	951.3	2	350	7	70	2,555	26.063	7	3.72
Infants	951.3	0.64	350	1	4	365	145.953	7	20.85
Selenium	0.1713	2	350	7	70	2,555	0.005	0.005	0.94
Sodium	2078	2	350	7	70	2,555	56.932	n/a	n/a
Strontium	9.306	2	350	7	70	2,555	0.255	0.6	0.42
Sulfate	7,898	2	350	7	70	2,555	216.384	n/a	n/a
Infants	7,898	0.64	350	1	4	365	1,211.748	n/a	n/a
Uranium	1.049	2	350	7	70	2,555	0.029	0.003	9.58

Carcinogens—Ground Water Ingestion Only (adults)

Contaminant		Cw[a]	IR	EF	ED	BW	AT	Intake	SF[b]	Risk
U234+238	UCL95	719	2	350	50	n/a[c]	n/a	2.52E+07	5.32E-11	1.34E-03
(pCi/L)	mean	525	2	350	50	n/a	n/a	1.84E+07	5.32E-11	9.78E-04

Non-Carcinogens–Inhalation Through Water Use in Residential Setting[d]

Contaminant	Cw-95	IR	EF	ED	BW	AT	Intake-95	RfD[2]	HQ
Ammonia (UCL95)	0.049408	15	350	30	70	10950	0.0102	0.0286	.355

[a] Contaminant concentration in ground water, UCL95 values. Data from December 1998 and March 1999 sampling events.

[b] Reference doses (RfDs) and slope factors (SFs) from best available EPA sources.

[c] n/a = not applicable.

[d] IR = 15 m^3/d of air default; concentration in air = water concentration × water-to-air volatilization factor × conversion factor
Default volatilization factor = .0005; conversion factor is 1000L/m3
Maximum NH_3 in Shiprock ground water is 18.08 mg/L, UCL95 is 3.184 mg/L.

6.1.3.2 Terrace Alluvium

Results of risk calculations for use of terrace alluvial ground water as drinking water in a residential setting are provided in Table 6–3. This exposure scenario is improbable because of the generally poor water quality in this system (even in areas presumably outside the influence of the site) and its questionable sustainability as a regular water source. However, these calculations are useful for comparison purposes. The only COPCs evaluated were nitrate, sulfate, and uranium.

Table 6–3. Shiprock—Terrace Alluvium Residential Ground Water Ingestion Risk Calculations

Noncarcinogens—Ground Water Ingestion Only (adults, except where noted)

Contaminant	Cw-max[a] (mg/L)	IRw (L/day)	EF (days/yr)	ED (yr)	BW (kg)	AT (day)	Intake (mg/kg-d)	RfD[b] (mg/kg-d)	HQ
Nitrate	7,820	2	350	7	70	2,555	214.247	7	30.61
Infants	7,820	0.64	350	1	4	365	1,199.781	7	171.40
Sulfate	15,000	2	350	7	70	2,555	410.959	n/a[c]	n/a
Infants	15,000	0.64	350	1	4	365	2,301.370		
Uranium	3.04	2	350	7	70	2,555	0.083	0.003	27.76
Mean	0.2503	2	350	7	70	2,555	0.007	0.003	2.29

Carcinogens—Ground Water Ingestion Only (adults)

Contaminant		Cw	IR	EF	ED	BW	AT	Intake	SF[b]	Risk
U234+238	max	2,085	2	350	50	n/a	n/a	7.30E+07	5.32E-11	3.88E-03
(pCi/L)	mean	171.7	2	350	50	n/a	n/a	6.01E+06	5.32E-11	3.20E-04

Non-Carcinogens–Inhalation Through Water Use in Residential Setting[d]

Contaminant	Cw	IR	EF	ED	BW	AT	Intake	RfD[2]	HQ
Ammonia (max)	1.728	15	350	30	70	10,950	0.3551	0.0286	12.415
Ammonia (UCL95)	0.14324	15	350	30	70	10,950	0.0294	0.0286	1.029

[a] Maximum contaminant concentration in ground water. Data based on results of 1998-1999 sampling events; GJO Analytical Chemistry Laboratory analyses.

[b] Reference doses (RfDs) and slope factors (SFs) from best available EPA sources.

[c] n/a = not applicable.

[d] IR = 15 m^3/d of air default; concentration in air = water concentration × water-to-air volatilization factor × conversion factor Default volatilization factor = .0005; conversion factor is 1,000L/m^3 Maximum NH_3 in Shiprock ground water is 345.6 mg/L, UCL95 is 28.64 mg/L.

As with the floodplain alluvial ground water, the most severe adverse health effects in this exposure scenario would be associated with intakes of nitrate and sulfate by infants. Calculated exposure intakes are higher than those determined for the floodplain aquifer and likewise are within the range of potentially lethal levels. Adult intake levels for sulfate would also be expected to produce laxative effects.

The maximum detected concentration of uranium in terrace ground water is associated with significantly elevated risks, both noncarcinogenic and carcinogenic. However, these high concentrations are rare, and risks calculated based on mean aquifer concentrations are much lower. Noncarcinogenic risks based on the mean are approximately double an "acceptable" HQ of 1. Carcinogenic risks associated with mean concentrations are approximately 3 times the high end of EPA's acceptable risk range.

Excessive risks may occur with the inhalation of ammonia from ammonium in ground water. This could be an important issue if ground water was used in a residence in the vicinity of well 603.

6.1.3.3 Surface Water

Table 6–4 presents the results of risk calculations for incidental ingestion of and dermal exposure to surface water by children playing on the floodplain. All COPCs evaluated for floodplain alluvial ground water were included in the analysis. Risks associated with this exposure pathway are well below potentially unacceptable levels, even based on exposure to maximum detected contaminant concentrations in samples of floodplain surface water. Highest risks are associated with maximum concentrations of manganese, though only a single sample had a significantly elevated concentration. Calculated sulfate intakes are below levels shown to produce any adverse effects.

Table 6–5 presents risks calculated for incidental ingestion of terrace surface water. Only COPCs evaluated for terrace alluvial ground water were included. Bob Lee Wash and Many Devils Wash samples are considered separately because of the significantly different concentrations detected in samples from those two locations. Risks calculated for nitrate and uranium at both locations are below potentially unacceptable levels. Intakes calculated for sulfate in Many Devils Wash are at the low end of the range that could result in laxative effects, though these effects would probably be temporary. Calculated risks for both these locations are considered to be worst case, not only because maximum contaminant concentrations were used but also because the poor taste produced by these constituents would discourage ingestion of even small amounts of water.

Calculations were also performed for incidental exposure to floodplain and terrace alluvial ground water, in the event that ground water was routed to the surface for purposes other than drinking water (e.g., perhaps sprinkler irrigation in parks or some similar purposes). The same exposure parameters were used, assuming that children would be the most likely and most sensitive receptors for these exposures. Tables 6–6 and 6–7 present the results of these calculations, which are similar to those for floodplain and terrace surface water. Incidental exposure to floodplain surface water would not result in any unacceptable risks. Risks would be higher for the more contaminated terrace system, but total risks would still be acceptable, using even maximum contaminant concentrations. Sulfate intakes for terrace ground water are at the low end of the range that could result in laxative effects, though these effects would likely be temporary.

6.1.3.4 Summary and Recommendations

A summary of potential human health risks associated with site-related ground water and surface water is presented in Table 6–8 for the various pathways evaluated either quantitatively or qualitatively in this BLRA update. The following observations can be made based on the analysis presented in this document:

- The only unacceptable human health risks associated with the Shiprock site are for use of floodplain and terrace ground water systems for drinking water purposes in a residential setting. In addition, inhalation of ammonia from terrace ground water could present excessive risk if it is used as the primary water source in a residence.

Table 6–4. Shiprock—Surface Water Incidental Ingestion/Dermal Exposure Pathways (floodplain alluvium source; see Figure 6-1 for Explanation of abbreviations)

Contaminant	Cw-max[a] (mg/L)	Sa (cm^2)	Pc (cm/hr)	Cf (L/cm^3)	ET (hr/day)	EF (day/yr)	ED (yr)	IRw (L/day)	BW (kg)	AT (day)	Intake Ingested (mg/kg-d)	Intake Absorbed (mg/kg-d)	Total dose (mg/kg-d)	RfD (mg/kg-d)	HQ (mg/kg-d)
Magnesium	681	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.278	0.003	0.2804	n/a[b]	n/a
Manganese	16.4	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.007	0.000	0.0068	0.047	0.144
2nd highest	5.08	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.002	0.000	0.0021	0.047	0.045
Nitrate	552	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.225	0.002	0.2273	7	0.032
Selenium	0.158	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.000	0.000	0.0001	0.005	0.013
Sodium	7320	497	0.001	0.001	1	114	7	0.05	38.3	2555	2.985	0.030	3.0143	n/a[b]	n/a
Strontium	19.8	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.008	0.000	0.0082	0.6	0.014
Sulfate	17100	497	0.001	0.001	1	114	7	0.05	38.3	2555	6.972	0.069	7.0417	n/a	n/a
2nd highest	5650	497	0.001	0.001	1	114	7	0.05	38.3	2555	2.304	0.023	2.3266	n/a	n/a
Uranium	0.682	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.000	0.000	0.0003	0.003	0.094

[a] Based on GJO Analytical Chemistry Laboratory data for 1998 - 1999 sampling events.
[b] n/a = not applicable.

Table 6–5. Shiprock—Incidental Surface Water Ingestion/Dermal Exposure Pathways (terrace alluvium source; see Figure 6-1 for explanation of abbreviations)

Contaminant[a]	Cw-max (mg/L)	Sa (cm^2)	Pc (cm/hr)	Cf (L/cm^3)	ET (hr/day)	EF (day/yr)	ED (yr)	IRw (L/day)	BW (kg)	AT (days)	Intake Ingested (mg/kg-d)	Intake Absorbed (mg/kg-d)	Total dose (mg/kg-d)	RfD (mg/kg-d)	HQ (mg/kg-d)
Nitrate (BL)	2112	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.861	0.009	0.8697	7	0.124
(MD)	4660	497	0.001	0.001	1	114	7	0.05	38.3	2555	1.900	0.019	1.9190	7	0.274
Sulfate (BL)	12925	497	0.001	0.001	1	114	7	0.05	38.3	2555	5.270	0.052	5.3224		
(MD)	27400	497	0.001	0.001	1	114	7	0.05	38.3	2555	11.172	0.111	11.2831		
Uranium (BL)	2.415	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.001	0.000	0.0010	0.003	0.331
(MD)	0.24	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.000	0.000	0.0001	0.003	0.033

[a] BL = Bob Lee Wash samples; GJO Environmental Sciences Laboratory analyses.
[b] MD = Many Devils Wash samples; GJO Analytical Chemistry Laboratory analyses.

Table 6–6. Shiprock—Floodplain Ground Water Incidental Ingestion/Dermal Exposure Pathways

Contaminant	Cw-max[a] (mg/L)	Sa (cm^2)	Pc (cm/hr)	Cf (L/cm^3)	ET (hr/day)	EF (day/yr)	ED (yr)	IRw (L/day)	BW (kg)	AT (days)	Intake Ingested (mg/kg-d)	Intake Absorbed (mg/kg-d)	Total dose (mg/kg-d)	RfD (mg/kg-d)	HQ (mg/kg-d)
Magnesium	1065	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.434	0.004	0.4386	n/a[b]	n/a
Manganese	4.082	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.002	0.000	0.0017	0.047	0.036
Nitrate	951.3	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.388	0.004	0.3917	7	0.056
Selenium	0.1713	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.000	0.000	0.0001	0.005	0.014
Sodium	2078	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.847	0.008	0.8557	n/a	n/a
Strontium	9.306	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.004	0.000	0.0038	0.6	0.006
Sulfate	7898	497	0.001	0.001	1	114	7	0.05	38.3	2555	3.220	0.032	3.2523	n/a	n/a
Uranium	1.049	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.000	0.000	0.0004	0.003	0.144

[a] Based on GJO Analytical Chemistry Laboratory data for 1998 - 1999 sampling events.
[b] n/a = not applicable.

Table 6–7 Shiprock—Incidental Terrace Ground Water Ingestion/Dermal Exposure Pathways

Contaminant	Cw-max[a] (mg/L)	Sa (cm^2)	Pc (cm/hr)	Cf (L/cm^3)	ET (hr/day)	EF (day/yr)	ED (yr)	Irw (L/day)	BW (g)	AT (days)	Intake Ingested (mg/kg-d)	Intake absorbed (mg/kg-d)	Total dose (mg/kg-d)	RfD (mg/kg-d)	HQ (mg/kg-d)
Nitrate	7820	497	0.001	0.001	1	114	7	0.05	38.3	2555	3.189	0.032	3.2202	7	0.460
Sulfate	15000	497	0.001	0.001	1	114	7	0.05	38.3	2555	6.116	0.061	6.1769		
Uranium	3.04	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.001	0.000	0.0013	0.003	0.417
mean	0.2503	497	0.001	0.001	1	114	7	0.05	38.3	2555	0.000	0.000	0.0001	0.003	0.034

[a] Based on GJO Analytical Chemistry Laboratory results.

Table 6–8. Summary of Potential Human Health Risks—Shiprock

	Drinking Water Residential	Incidental Exposure Dermal/Ingestion	Ingestion of Livestock[a]	Water-Irrigated Produce Ingestion
Floodplain Ground Water	Y[b]	N[c]	n/a[d]	N
Terrace Ground Water	Y	N	n/a	N
Floodplain Surface Water	n/a	N	N	N
Terrace Surface Water	n/a	N	n/a	N

[a] Meat and milk from livestock watered and grazed on contaminated water.
[b] Y = risks are unacceptable.
[c] N = no unacceptable risks.
[d] n/a = pathway not applicable.

- The contaminants of greatest concern in ground water are nitrate and sulfate, which are present in both floodplain and terrace ground water samples at levels that are potentially lethal to infants.

- Uranium is the contaminant that poses the greatest noncarcinogenic risks for adult consumption of floodplain ground water; nitrate, manganese, and selenium are of lesser importance. Risks posed by strontium are low enough to be considered insignificant. Noncarcinogenic risks posed by average uranium concentrations in terrace ground water are approximately 2 times the "acceptable" risk level (HI = 1).

- Concentrations of uranium in both floodplain and terrace ground water result in risk estimates that exceed the high end of EPA's acceptable carcinogenic risk range.

- Exposure to contaminated surface water by children playing in the terrace or floodplain areas is unlikely to present any unacceptable risk.

- Concentrations of nitrate and sulfate in the terrace and floodplain ground water and the terrace surface water are high enough to be acutely toxic to livestock. Therefore, bioaccumulation of contaminants by livestock and transfer to humans through meat and milk ingestion is not considered viable because the animals would die and not be slaughtered for food. Contaminant concentrations in floodplain surface water are low enough that bioaccumulation effects in livestock would not adversely affect human through meat and milk consumption.

- Produce irrigated with any site-related water would not accumulate sufficient levels of contamination to produce unacceptable risks through human consumption.

For a compliance strategy for the Shiprock site to be protective of human health, relatively few restrictions on water use or access must be imposed. Unacceptable risks to humans would only be posed by use of terrace or floodplain ground water as a primary source of drinking water. Use of any ground water or surface water for agricultural purposes would not present unacceptable risks to humans, though floodplain and terrace ground water and terrace surface water would be unsuitable for watering livestock because of risks to the animals themselves. Incidental exposure to floodplain or terrace surface water by children playing in those areas would not result in unacceptable risks. Therefore access need not be restricted to prevent this type of exposure.

6.2 Ecological Risk Assessment

Two types of activities were conducted to evaluate potential ecological risks at the Shiprock site—visual surveys and sampling for chemical analysis to support a screening-level ERA. The visual surveys were conducted in 1998 and 1999 and focused on the identification of threatened and endangered (T&E) species and their potential habitats in the vicinity of the site. Sampling for chemical analysis of surface water, sediment, and vegetation was also conducted in 1998 and 1999, as discussed in Section 4.6, "Ecological Field Investigations." Results of the T&E surveys are discussed in Section 6.2.1. Descriptions of the methodology and results of the ERA are presented in Section 6.2.2.

6.2.1 T&E Surveys

The first T&E survey (Ecosphere Environmental Services 1998) was conducted in summer 1998 to determine the potential effects that could occur because of proposed characterization well installation activities. Because most of the proposed wells were at terrace locations, those areas were the primary focus. A second survey (Ecosphere Environmental Services 1999) was conducted in winter 1999 to support proposed well installations and a water distribution system in the floodplain, which was the area of focus.

Results of the studies indicate that the Mesa Verde cactus is present in the terrace region but does not have suitable habitat in the floodplain. Western burrowing owls were also observed in the terrace areas. Though not observed, suitable habitat exists in the floodplain area for the southwestern willow flycatcher. An aquatic survey was not conducted, but the San Juan River is known to be within federally designated Critical Habitat for the Colorado squawfish and razorback sucker. Roundtailed chub are also known to be present in the river. There is no evidence that site-related contamination has had adverse effects on any T&E species. Table 6–9 presents a summary of the results of the two T&E surveys.

6.2.2 Ecological Risk Assessment

6.2.2.1 Results of 1994 Ecological Risk Assessment

The 1994 ERA used the COPCs that were known to be present in elevated levels in ground water as a starting point for evaluating potential ecological risk. These constituents are listed in Table 6–10. Surface water and sediment samples from the San Juan River and on the floodplain were collected and analyzed. Table 6–10 also indicates in which samples the constituents were detected. Sampling results were compared with applicable water and sediment quality criteria, if available.

Table 6–9. Summary of T&E Surveys

Flora/Fauna	Potential Habitat?		Species Observed?	
	Terrace	Floodplain	Terrace	Floodplain
Bald eagle	Y	N	N	N
Southwestern willow flycatcher	N	Y	N	N
Peregrine falcon[a]	N	N	N	N
Mountain plover	Y	N	N	N
Ferruginous hawk	N	N	N	N
Golden eagle	N	N	N	N
Western burrowing owl	Y	N	Y	N
Rough-legged hawk	Y	N	N	N
Pronghorn	Y	N	N	N
Black-footed ferret	N	N	N	N
Colorado squawfish	San Juan River		NA[b]	NA
Razorback sucker	San Juan River		NA	NA
Roundtailed chub	San Juan River		NA	NA
Northern leopard frog	N	Y	N	N
Mesa Verde cactus	Y	N	Y	NA

[a] delisted August 1999.
[b] NA = not available.

Table 6–10. Summary of Ecological Contaminants of Potential Concern in Ground Water, Surface Water, and Sediments in 1994 ERA

Constituents Above Background in Ground Water[a]	Constituents Detected in San Juan River Water[b]	Constituents Detected in San Juan River Sediments[b]	Constituents Detected in Floodplain Surface Water and Sediments[c]
Ammonium			
Antimony	X		
Arsenic	X	X	
Boron			
Cadmium			
Calcium			
Chloride			
Magnesium	X		
Manganese		X	X
Nickel			
Nitrate			X
Phosphate			
Polonium-210			
Potassium			
Radium-226		X	
Selenium			X
Sodium	X		
Strontium	X	X	X
Sulfate	X		
Thorium-230	X		
Uranium		X	X
Zinc			

[a] Ground water constituents that exceeded background at the 0.1 significance level.
[b] Ground water constituents were excluded that were either not detected in surface water or sediment or the median concentration adjacent to and downgradient from the site was less than concentrations upgradient of the site.
[c] Selection of constituents analyzed from floodplain pond water and sediment was not based on a comparison to reference areas.

Results of the 1994 ERA indicated that the only risks associated with site-related contamination could be to animals that used surface water from seep 425. The primary risk is associated with sulfate and nitrate. Concentrations were present that were at acutely toxic levels. Samples from the floodplain area and the San Juan River locations did not exceed any water or sediment quality criteria, though few criteria exist for the identified COPCs. Because soil-to-plant and water-to-plant concentration data were unavailable for many COPCs, the BLRA concluded that it was not possible with existing data to evaluate whether plant tissue concentrations are phytotoxic or could result in adverse effects to animals foraging on contaminated vegetation. Ground water was unsuitable for crop irrigation. Livestock and wildlife watering on the floodplain would experience no adverse effects. It was also concluded that the potential for COPCs to represent a food chain hazard (via bioaccumulation and biomagnification) was also low, though no tissue samples were analyzed.

Insufficient water quality criteria and sediment quality criteria were available to conduct a thorough evaluation of the adverse effects of surface water, sediment, ground water, and plant uptake on ecological receptors. Additional characterization and evaluation were recommended.

6.2.2.2 Ecological Risk Assessment Update

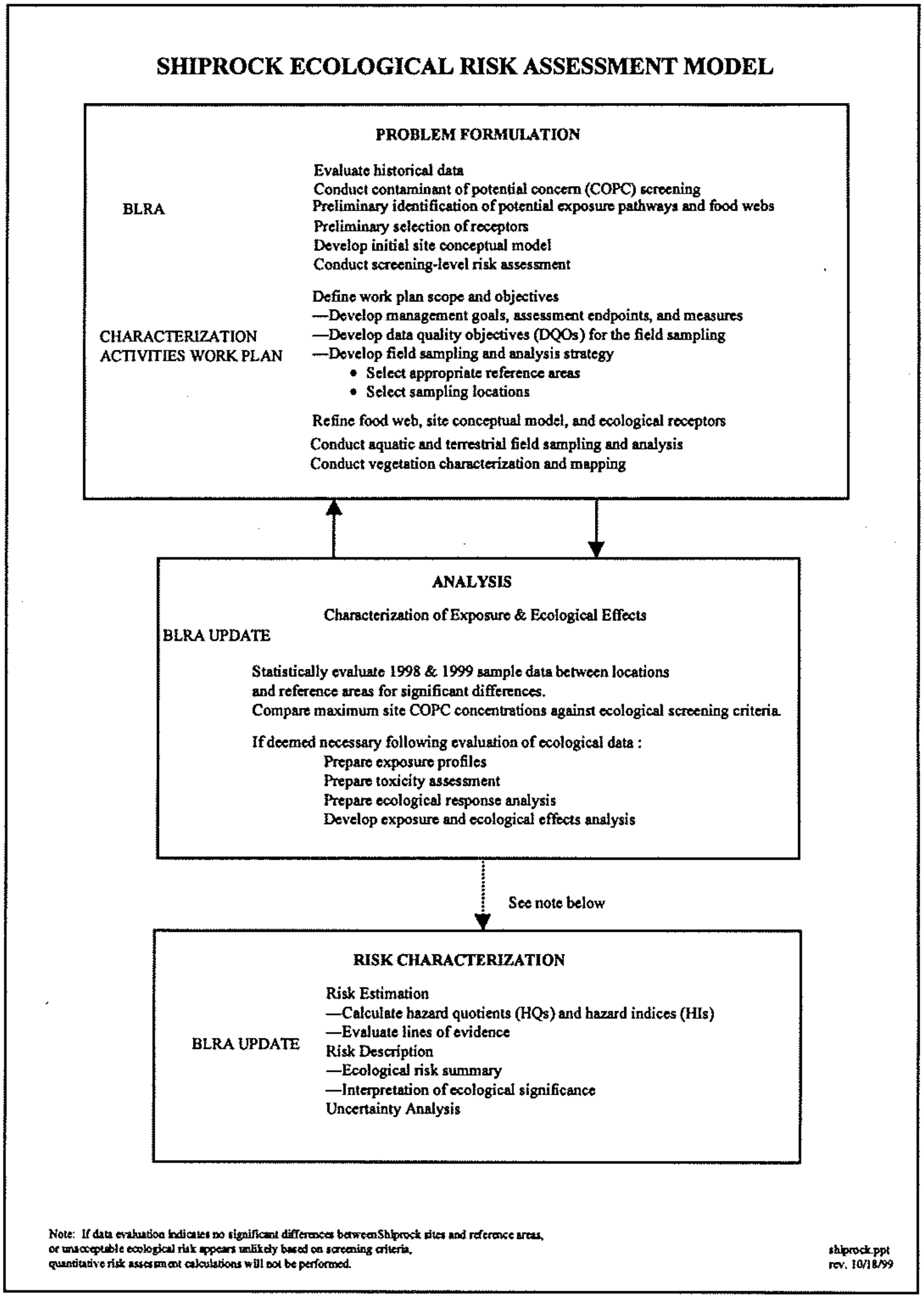
ERA is a process that evaluates the likelihood that adverse ecological effects are occurring or may occur as a result of exposure to one or more stressors (EPA 1992). A stressor is any physical, chemical, or biological entity that can induce an adverse ecological response.

The purpose of this risk assessment is to identify and characterize adverse effects, if any, on the ecosystem at the Shiprock, New Mexico, site. For ecological risks to occur at the Shiprock site, pathways must exist for exposure of biological receptors to biotic and abiotic media contaminated by ground water. Screening-level assessments of ecological risks at the site evaluated COPCs, potential pathways, receptors, and adverse effects (DOE 1994).

This ERA is based on relevant components of the EPA guidance provided in the *Guidelines for Ecological Risk Assessment* (EPA 1998) and the *Framework for Ecological Risk Assessment* (EPA 1992).

Risk Assessment Methodology

The ERA contains three main components: (1) problem formulation, (2) analysis, and (3) risk characterization. A tiered approach to the risk assessment process was followed by performing the screening-level BLRA, collecting additional samples, and evaluating more recent 1998 and 1999 data, with the possibility of proceeding to a quantitative risk assessment pending the outcome of the data review. A discussion of the problem formulation component is presented in the following sections. A risk assessment model for the Shiprock site is shown on Figure 6–2. Following the evaluation of the 1998 and 1999 ecological data, the risk assessment process may or may not be followed by the analysis phase. Depending on the outcome of the analysis phase, risk characterization may not be necessary for this screening-level assessment. For some risk assessments, risk characterization may not be necessary based on the levels and types of contaminants (see "Risk Assessment Discussion" later in this section).



SHIPROCK ECOLOGICAL RISK ASSESSMENT MODEL

PROBLEM FORMULATION

BLRA

Evaluate historical data
Conduct contaminant of potential concern (COPC) screening
Preliminary identification of potential exposure pathways and food webs
Preliminary selection of receptors
Develop initial site conceptual model
Conduct screening-level risk assessment

CHARACTERIZATION ACTIVITIES WORK PLAN

Define work plan scope and objectives
—Develop management goals, assessment endpoints, and measures
—Develop data quality objectives (DQOs) for the field sampling
—Develop field sampling and analysis strategy
- Select appropriate reference areas
- Select sampling locations

Refine food web, site conceptual model, and ecological receptors
Conduct aquatic and terrestrial field sampling and analysis
Conduct vegetation characterization and mapping

ANALYSIS

Characterization of Exposure & Ecological Effects

BLRA UPDATE

Statistically evaluate 1998 & 1999 sample data between locations and reference areas for significant differences.
Compare maximum site COPC concentrations against ecological screening criteria.

If deemed necessary following evaluation of ecological data :
Prepare exposure profiles
Prepare toxicity assessment
Prepare ecological response analysis
Develop exposure and ecological effects analysis

See note below

RISK CHARACTERIZATION

BLRA UPDATE

Risk Estimation
—Calculate hazard quotients (HQs) and hazard indices (HIs)
—Evaluate lines of evidence
Risk Description
—Ecological risk summary
—Interpretation of ecological significance
Uncertainty Analysis

Note: If data evaluation indicates no significant differences betweenShiprock sites and reference areas, or unacceptable ecological risk appears unlikely based on screening criteria, quantitative risk assessment calculations will not be performed.

shiprock.ppt
rev. 10/18/99

Figure 6–2. Ecological Risk Model for the Shiprock, New Mexico, UMTRA Site

Problem Formation

In the problem formulation phase, the need for a risk assessment is identified, and the scope of the problem is defined. Evaluation of available data helps to develop site conceptual models, food webs, risk hypotheses, endpoints, and measures. The principal product from these activities is the analysis plan, which may include activities for new data collection as well as how existing data will be used to complete the risk assessment. The problem formulation phase typically requires the greatest amount of effort, and the success of the risk assessment depends on a thorough and technically defensible planning process.

The problem formulation phase in the risk assessment process was represented in part by the BLRA (DOE 1994), which was a screening-level risk assessment. The primary input to this phase is the integration of available information. Historical analytical data for the Shiprock site were reviewed to determine if concentrations of analytes in ground water, surface water, and sediment might pose an ecological risk. Other input included information gathered on the Shiprock geologic setting, ground water hydrology, geochemistry, and ecological habitat. Principal products of this phase included COPC screening and preparation of a characterization work plan (DOE 1998c). Since the BLRA, additional abiotic and biotic samples have been collected at Shiprock and at upgradient reference areas, and these data were incorporated into the risk assessment process.

For this version of the BLRA update, data evaluation is limited to analytical data obtained from the GJO Analytical Chemistry Laboratory. All data gathered specifically for the ERA, which includes September 1998 and June 1999, have been included in this draft update. Any other surface data collected after March 1999 will be addressed in an addendum to this SOWP.

Ecological Contaminants of Potential Concern

Ecological COPCs were defined in the screening-level risk assessment as those constituents that exceeded background concentrations (Table 6–10). The water quality of samples from upgradient wells was considered to be representative of background conditions for the floodplain aquifer (DOE 1994).

For the purposes of this BLRA update, any COPC observed in either surface water or sediment samples, as noted in Table 6–10, was assumed to be a COPC in both sediment and surface water for the 1998-1999 ecological field sampling. Inclusion of the analytes as COPCs regardless of medium was meant to be conservative. Only the metals listed in Table 6–10 were analyzed in biota tissue samples. Anions (sulfate and nitrate) were not analyzed in vegetation tissue because of the likely biotransformation of these chemical species in plant tissue; the absence of regulatory-approved, definitive analytical methodology for biota; and a general lack of toxicity data. Furthermore, nitrate acts as a plant fertilizer. Anions are typically addressed in a semiquantitative manner.

Ecological Site Conceptual Model

Conceptual models for ecological risk assessments are developed from information about stressors, potential exposure, and predicted effects on an ecological entity (the assessment endpoint). Conceptual models consist of two principal components (EPA 1998):

- A set of risk hypotheses that provide descriptions of predicted relationships among stressor, exposure, and assessment endpoint response, along with the rationale for their selection.
- A diagram that illustrates the relationships presented in the risk hypotheses.

The following is the risk hypothesis proposed for the Shiprock site:

Risk hypothesis: Milling operations at the Shiprock site have resulted in varying levels of ground water contamination. Hydrogeologic information regarding plume migration suggests that contamination might be present in the San Juan River adjacent to and downgradient of the Shiprock site. This contamination could result in contaminant exposure directly or indirectly to wildlife and plant receptors that use or inhabit the site. Process water may have mounded in the weathered Mancos Shale and in overlying alluvium on the terrace, creating ground water that is thought to be moving radially in a northerly direction and discharging as seeps on the escarpment above the floodplain. This hydrological system is identified as the terrace alluvium in the BLRA (DOE 1994). The area below these seeps is associated with a small wetland created by the discharge from artesian well 648 west of Bob Lee Wash. The seeps are providing a contaminant source to the wetland. The seeps and other ground water sources discharging into the wetland may have contaminated sediment, surface water, and vegetation.

In addition, phreatophytes growing both on the disposal cell terrace and floodplain may uptake contaminants through their root systems, thereby creating potential exposure pathways by providing forage to herbivores. The BLRA (1994) suggests that some of the terrace alluvial ground water may have migrated down through the Mancos Shale and may flow toward the San Juan River, which is the local base level in the region. Other than the San Juan River, the only noteworthy aquatic habitats are the Shiprock floodplain wetland and a small wetland channel created by the outflow from well 648 (i.e., the reference wetland).

For the purposes of this SOWP, the pathways for exposure have been divided into five evaluation regions:

- Shiprock floodplain wetland.
- Floodplain terrestrial (including two surface areas that overlie contaminated ground water).
- Terrace terrestrial.
- San Juan River.
- Areas west of U.S. Highway 666 – these areas have only been recently been identified as potentially affected by milling operations; limited initial sampling was conducted in this region in spring 1999.

Three reference areas were chosen for comparison to these regions:

- Reference wetland—wetland channel just west of Bob Lee Wash that is outflow from artesian well 648 (Figure 4–52).

- Floodplain reference—floodplain area shown on Figure 4–52 associated with well cluster 850 through 852.
- Reference terrace—terrace area shown in Figure 4–52 associated with wells 800 through 803 (all dry).

Because the stressors are chemical contaminants, the Shiprock risk hypothesis is considered a stressor-initiated risk hypothesis. However, no apparent ecological effects have been observed that would provide a cause-and-effect relationship.

As part of the initial problem formulation in the BLRA, a generalized site conceptual model was developed for the Shiprock site. That model has since been revised to address current and potential exposure pathways based on all the available data (Figure 6–3).

An exposure pathway is the mechanism by which a contaminant in an environmental medium (i.e., the source) contacts an ecological receptor. A complete exposure pathway includes

- Contaminant source.
- Release mechanism that allows contaminants to become mobile or accessible.
- Transport mechanism that moves contaminants away from the release.
- Ecological receptor.
- Route of exposure (e.g., dermal or direct contact, inhalation, or ingestion).

Ecological Food Web

Ecological receptors that could potentially be exposed to COPCs were identified in the BLRA (DOE 1994) and included mammalian and avian species. A food web for the Shiprock site (Figure 6–4) illustrates the significant dietary interactions between the terrestrial and aquatic receptors.

The food web also depicts the major trophic-level interactions and shows nutrient flow and transfer of matter and energy through these levels. It was developed from the species lists and consideration of the exposure pathways. The food web diagram was used to portray potential routes of COPCs from the ground water to biotic species at various trophic levels, with receptor species being components of this food web.

The terrestrial receptor categories include

- Omnivores, carnivores–include fox, coyote, and raccoon
- Herbivores—include mule deer, cottontail, and some mice and vole species
- Vegetation—includes phreatophytes such as black greasewood, cottonwood, and other plant species
- Terrestrial invertebrates—include soil fauna

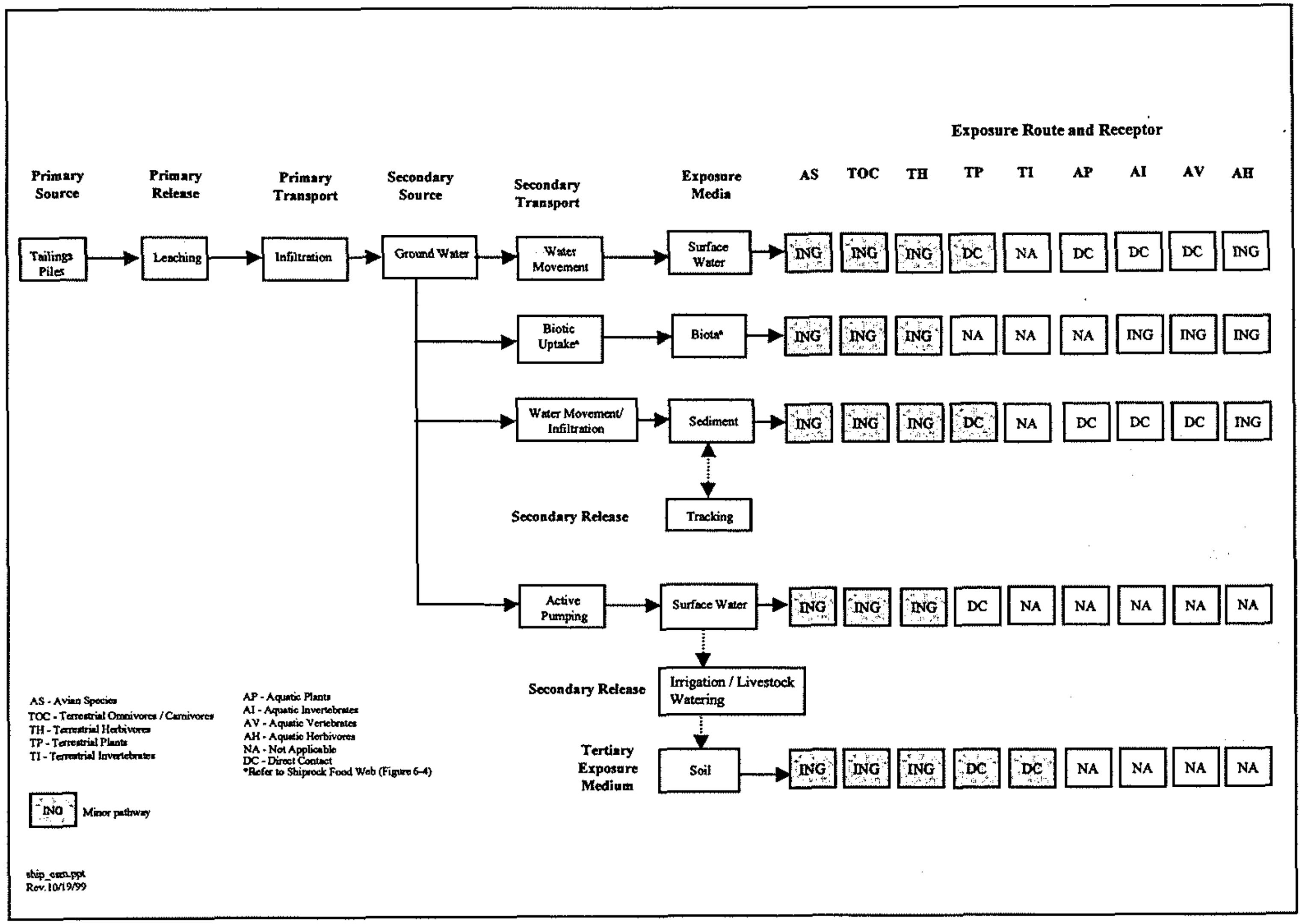


Figure 6–3. Shiprock Site Conceptual Model

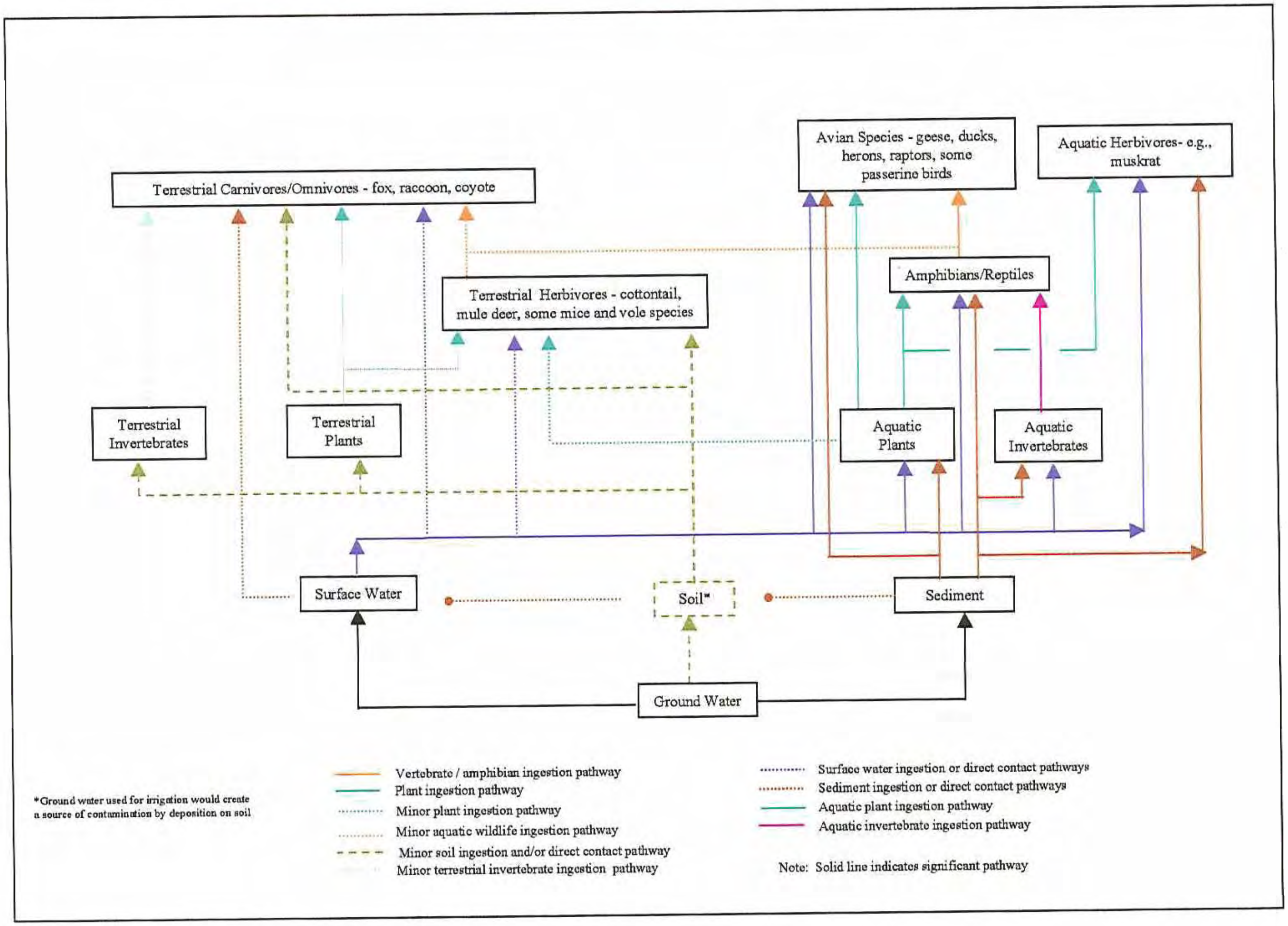


Figure 6–4. Generalized Food Web for Shiprock Ecological Receptors

The aquatic receptor categories include

- Avian species—include great blue heron, geese, ducks, and some passerine birds
- Herbivores—include muskrat
- Vertebrates—include amphibians, reptiles, and fish
- Plants—include phreatophytes such as cattail, bulrush, willow, and common reed
- Invertebrates—include benthic invertebrates

Only complete exposure pathways are quantitatively and qualitatively evaluated in an ERA. To be conservative, the following potential exposure pathways were *considered* for evaluation:

- Surface water—ingestion and direct contact
- Soil—ingestion and direct contact
- Sediment—ingestion and direct contact
- Dietary—ingestion of forage or prey, as appropriate, by receptor

Because the contaminants associated with the Shiprock site are inorganics, dermal absorption pathways have not been included in this screening assessment. Dust inhalation is also excluded from this from this preliminary assessment, as it is considered a minor exposure pathway relative to soil or sediment ingestion.

The pathways that are subsequently addressed in further detail were divided into current and future hypothetical exposure scenarios.

Current Exposure Scenario

The terrestrial ecology of the Shiprock site is greatly influenced by low annual precipitation and a history of heavy grazing. Desert shrubs and annual weeds dominate the vegetation, with little or no grassy understory. Tree cover in the area is limited and occurs primarily on the floodplain adjacent to the San Juan River as groups of cottonwood (*Populus fremontii*), tamarisk (*Tamarix ramosissima*), and Russian olive (*Elaeagnus angustifolia*). The disposal cell terrace ground cover is sparse, and only a few scattered greasewood (*Sarcobatus vermiculatus*) shrubs, which are phreatophytes with root systems capable of tapping into the terrace alluvial aquifer, are present. Plant cover consists primarily of halogeton (*Halogeton spp.*), Russian thistle (*Salsola kali*), kochia (*Kochia scoparia*), and other weedy species that are not likely to have root systems capable of reaching the aquifer.

The floodplain has been used for limited livestock grazing; however, the area around the disposal cell is currently fenced to deter entry by larger wildlife. Wildlife can enter the floodplain through the river corridor or adjacent properties and could then reach the disposal cell terrace. Because the contaminated tailings have been contained, ingestion of contaminated soils does not represent a complete exposure pathway. The surface water associated with the ecological habitats at Shiprock consists of the floodplain wetland, the San Juan River, Bob Lee Wash, Many Devils Wash, and other minor agricultural drainage ditches. The surface water in Bob Lee Wash consists of outflow from artesian well 648. Herbivores grazing on floodplain vegetation, such as cottonwood, Russian olive, greasewood, and grasses, may be exposed to contaminants through biouptake from the underlying aquifer and subsequent transfer into the plant roots and aboveground growth.

The riparian habitats associated with the San Juan River, the floodplain wetland, and the reference wetland represent the areas of significant potential exposure. Terrestrial receptors such as foxes, coyotes, skunks, raccoons, deer, and rodents likely use the riparian corridor for food items and as a drinking water source. Consequently, they are also exposed to potentially contaminated sediments. These terrestrial receptors typically do not spend most of their time in the riparian or aquatic areas.

Aquatic receptors living in the wetland habitat on the floodplain downgradient from the millsite and disposal cell have the potential to ingest contaminated sediment, surface water, and vegetation. The primary vegetation types in the floodplain wetland include cattail, bulrush, and common reed. Aquatic wildlife species have the potential for the greatest exposures. Larger herbivores prefer to browse on leafy material; smaller mammals and birds seek plant seeds and roots. The muskrat forages on the types of vegetation found along the riverbanks and on the wetlands. Beavers, which are strictly herbivorous, are not likely to be present in the Shiprock area. Higher trophic receptors such as coyotes, eagles, and hawks may in turn feed on small mammals or birds that have ingested contaminated food items. Aquatic avian species such as the great blue heron, ducks, geese, and killdeer frequent the San Juan River and represent ecological receptors with significant exposure potential. Aquatic invertebrates, amphibians, reptiles, and fish are also in direct contact with potentially contaminated sediment, surface water, and aquatic vegetation. These receptors can also serve as prey for eagles, herons, and other wildlife.

Future Hypothetical Exposure Scenario

Without institutional controls, ground water could possibly be pumped and used for irrigation and livestock watering or industrial uses. This practice would create a source for ground water and surface water ingestion, direct contact with terrestrial vegetation, and deposition of ground water and surface water on the soil. The soil would then represent an additional source medium for ingestion and direct contact. Large-scale irrigation with ground water is not considered a likely future pathway because surface water is the main source of irrigation water in the Shiprock area. As long as there is the possibility of pumping ground water for agricultural purposes, it is assumed that the potential exists for these two exposure pathways.

Data Evaluation

Summary statistics were calculated for each analyte at each site and reference location. These are provided in Tables 1 through 28 in Appendix H, "Data Evaluation of Ecological Risk Assessment." A statistical comparison of contaminant concentrations for each site location with its appropriate reference location was conducted to determine if the concentrations of a COPC at a site location was significantly different and higher than that at its respective reference location (these are presented in Tables 29 through 33 in Appendix H. In most instances, the reference area COPCs were not significantly different from, or were higher than, the site locations and could be eliminated from further consideration. Summaries of the COPCs retained after this screening process are presented in the following sections. A more detailed evaluation of each COPC by media and location is provided in Tables 34 through 39 in Appendix H.

Risk Assessment Discussion

This BLRA update represents a screening-level risk assessment, and is therefore more conservative than a detailed, quantitative risk assessment. Because there is considerable uncertainty associated with the screening benchmarks, the approach is intended to err on the side of being more protective of ecological receptors.

Current Ecological Sampling Data

The results of the ecological sampling indicate generally low levels of a few COPCs in sediment, surface water, and plant tissues. The occurrences of most elevated concentrations coincide with the seeps along the escarpment below the disposal cell. These seeps represent small areas where contaminants are concentrated. However, by the time the sediment and surface water associated with the seeps reach the wetland, contaminant levels are greatly reduced. The contaminants associated with the seeps represent small areas of ecological impact. Nitrate concentrations in surface water samples from most of the floodplain wetland sample locations exceeded the Colorado agricultural standard of 100 mg/L nitrate + nitrite, which was the only value available for comparison. The following COPCs were identified as potentially posing an unacceptable ecological risk at the Shiprock floodplain wetland when compared with the reference wetland and available screening criteria:

- Selenium, sulfate, and uranium concentrations in sediment.
- Nitrate, selenium, sulfate, and uranium concentrations in surface water.
- Selenium concentrations in cattail stems and cattail roots and selenium and uranium concentrations in bulrush stems and roots.

No COPCs were identified in the greasewood samples collected on the terrace adjacent to the disposal cell. The analytes were compared with concentrations in greasewood samples collected in 1998 at an upgradient terrace area and in greasewood samples collected in 1999 on the floodplain. The vegetation on the disposal cell terrace does not appear to be accumulating contaminants from the underlying ground water system.

Cottonwood stems and leaves on the floodplain appear to be accumulating some contaminants when compared with cottonwood tissues collected at the floodplain reference area. The following COPCs were identified as potentially posing an unacceptable ecological risk on the Shiprock floodplain when compared with the reference area and available screening criteria:

- Arsenic, manganese, radium-226, selenium, and sodium concentrations in cottonwood stems and leaves.

The number of samples collected on the floodplain below the disposal cell in 1998 was limited to only three because of the scarcity of material available for collection. As such, no rigorous statistical evaluations could be conducted. It is unlikely, however, that cottonwood represents a significant ecological risk on the floodplain because herbivores would also browse other vegetation.

Greasewood samples at five locations on the floodplain in an area (east contaminated area) overlying contaminated ground water around well 854 indicated no elevated concentrations of COPCs when compared with tissue concentrations from the reference area.

Selenium in three samples of Russian olive leaves and stems was elevated in what was identified as the west contaminated area with respect to the reference tissue concentrations. No other analytes were elevated with respect to the reference area concentrations. As a conservative measure, selenium should be retained as a COPC. This west area is on the floodplain around well 856 and overlies contaminated ground water.

Selenium levels in five samples of cattail stems and roots appeared to be elevated in the 1st wash (west of U.S. Highway 666 bridge) with respect to the reference wetland tissue concentrations. No other analytes were elevated with respect to the reference area. As a conservative measure, selenium should be retained as a COPC.

On the basis of sample size and variability, the strongest line-of-evidence factors for basing risk conclusions are the surface water and sediment results. In spite of the smaller sample sizes and greater natural variability, the biota data serve as an additional but insignificant line of evidence. The tissue results show that Shiprock site concentrations of the majority of analytes are the same as or less than the reference area concentrations.

The majority of the abiotic data indicated no significant differences between Shiprock site and reference area analyte concentrations. In most of the cases, the elevated concentrations coincided with the seeps above the floodplain wetland. To maintain a conservative approach, the following constituents were retained as COPCs, even though their occurrences appear to be primarily isolated:

- Selenium, sulfate, and uranium concentrations in sediment (Shiprock floodplain wetland).
- Nitrate, selenium, sulfate, and uranium concentrations in surface water (Shiprock floodplain wetland).
- Selenium concentrations in cattail stems and cattail roots and selenium and uranium concentrations in bulrush stems and roots (Shiprock floodplain wetland).
- Arsenic, manganese, radium-226, selenium, and sodium concentrations in cottonwood stems and leaves (Shiprock floodplain).
- Selenium concentrations in Russian olive leaves and stems (west contaminated area around floodplain well 856).
- Selenium concentrations in cattail stems and roots (1st wash area).

Because the occurrences, for the most part, are localized, elevated concentrations of some inorganics in surface water, sediment, and vegetation at these locations probably do not present an unacceptable ecological risk. Although unlikely, the possibility remains that an isolated effect or mortality could be associated with these locations; however, no negative ecological effects have been observed.

Because the data evaluation did not indicate an unacceptable ecological risk at the Shiprock site as a whole, but rather in isolated areas of small impact, the ERA concludes with the analysis phase. Exposure estimates and stress-response profiles have not been calculated, and no risk characterization was performed.

Conclusion

Some residual milling-related constituents apparently persist at the Shiprock site, as shown by the sporadic elevated concentrations of inorganics in surface water, sediment, and biota samples. On the basis of a review of the analytical data and screening criteria, these isolated occurrences are not likely to present significant ecological risks. No apparent damage to ecological resources was observed during site visits. The floodplain wetland represents a significant aquatic habitat in a desert environment and serves as shelter and both a water and nutritional source for a variety of ecological receptors.

Natural flushing is expected to help diminish ground water COPC concentrations on the floodplain to negligible levels and thereby prevent significant bioaccumulation of contaminants through phreatophytes growing in the terrestrial habitat. This situation depends on the future land use at the millsite and on surrounding Navajo Nation lands. The terrace ground water system will likely continue to act as a contaminant source unless it is eliminated. The contamination will be expressed as elevated COPC concentrations at the seeps at the bottom of the escarpment, in Bob Lee Wash, and in Many Devils Wash.

Elevated concentrations of COPCs in surface water, sediment, and biota at the wetland are expected to diminish over time as a result of natural ground water flushing. This process could be expedited by removal of the terrace alluvial ground water. The sediment concentrations do not indicate widespread site-related contamination, although elevated concentrations of a few contaminants in some of the biota suggest that some degree of bioaccumulation is occurring. Constituent concentrations in sediment and biota are likely to persist for a longer period of time.

On the basis of the limited data review, the water and sediment qualities of the San Juan River do not appear to have been degraded by site operations. River water samples collected downgradient of the site did not significantly differ in contaminant concentrations from upgradient locations based on 1998 sampling results. Relevant water quality criteria were not exceeded.

The occurrence of elevated selenium concentrations in all media suggests that perhaps milling operations have mobilized this metal or that the Shiprock region contains naturally high concentrations of selenium. Other explanations for the elevated selenium concentrations should be explored. The amount of soil data for this BLRA update was limited. Other information sources should be reviewed that could help establish the nature and extent of regional selenium concentrations and possibly remove selenium as a COC for the area.

The BLRA update did not look specifically at livestock use of water at the highly contaminated seeps. However, concentrations of nitrate and sulfate currently present are as high as those present in the original BLRA and that were considered to be acutely toxic. Therefore, a current risk exists to livestock that could intake sufficient amounts of this highly contaminated water. Though it is unlikely that many animals would be affected, this does represent a complete ecological pathway.

Because potential ecological risks at the Shiprock site are negligible (except for livestock at seeps) and the most commonly occurring COPCs (selenium, uranium, nitrate, and sulfate) are the same ones presenting the greatest potential risks to human health, a compliance strategy based on human health concerns will also be protective of potential ecological receptors.

6.3 Summary of Risk Assessments

Human health and ecological risks were evaluated in Sections 6.1 and 6.2, respectively. When the millsite area was compared with the ecological study reference area, elevated levels of some of the COPCs were found in samples from the millsite area, but most were lower than concentrations in samples from the reference area. Potential risks to the environment were determined as negligible. Major risks and the final list of COCs for the Shiprock site are therefore based on human health.

Tables 6–11 and 6–12 show the COPCs from the BLRA, rationales for retaining or deleting them, and the final list of COCs for both the floodplain and the terrace. All constituents listed as COCs either exceed UMTRA standards or acceptable risk levels, with the exception of sulfate. Risks for sulfate could not be determined due to lack of an RfD. However, levels of sulfate in the floodplain and terrace systems far exceed levels that have been determined to produce no adverse effects. The five COCs identified in Table 6–11 represent the overwhelming percentage of risk for the Shiprock site. Sodium and magnesium on the floodplain were qualitative COPCs only; they were not included as COCs because reliable toxicological data required for their risk evaluation are not available. However, these constituents probably make up only a minor part of the overall risk. Any compliance strategy that results in a decrease in concentration of the retained COCs will also cause a decrease in the other constituents that represent a small fraction of the total risk.

Table 6–11. Floodplain Human Health Risk COPC Updates

COPCs From BLRA	UMTRA MCL (mg/L)	Comments and Rationale for Retaining or Deleting a COPC for Human Health Risk	COC Yes (Y) or No (N)
Antimony		Mostly below detection limits; similar to background concentrations; not retained	N
Arsenic	0.05	Mostly below detection limits; similar to background concentrations; not retained	N
Cadmium	0.01	Mostly below detection limits, similar to background concentrations; not retained	N
Magnesium		Exceeds background concentrations, qualitative COPC, not retained	N
Manganese		HQ[a]>1; Negative health effects probable	Y
Nitrate	44	HQ>1; UCL95 for data exceeds UMTRA MCL	Y
Selenium	0.01	UCL95 for data exceeds UMTRA MCL	Y
Sodium		Exceeds background concentrations; qualitative COPC; not retained	N
Strontium		Mostly below background concentrations; below risk-based concentration; not retained	N
Sulfate		Toxicity data are currently under evaluation by EPA but concentrations are high enough to be of probable concern	Y
Uranium	0.044	UCL95 greater than UMTRA MCL. Exceeds EPA's carcinogenic risk range	Y

[a] HQ = hazard quotient.

Table 6–12. Terrace Human Health Risk COPC Updates

COPCs From BLRA or Added From This Study	UMTRA MCL (mg/L)	Comments and Rationale for Retaining or Deleting a COPC for Human Health Risk	COC Yes (Y) or No (N)
Ammonia as Ammonium (added)		Ammonium exceeds background concentrations. Screened out as ingestion of ammonium; retained because inhalation of ammonia could be of potential health risk under residential scenario.	Y
Manganese (added)		HQ[a]>1; Negative health effects probable	Y
Nitrate	44	HQ>1; UCL95 *for data exceeds* UMTRA MCL	Y
Selenium (added)	0.01	UCL95 for data exceeds UMTRA MCL	Y
Sulfate		Toxicity data are currently under evaluation by EPA but concentrations are high enough to be of probable concern	Y
Uranium	0.044	UCL95 greater than UMTRA MCL. Exceeds EPA's carcinogenic risk range	Y

[a] HQ = hazard quotient.

End of current text

7.0 Ground Water Compliance Strategy

The framework defined in the PEIS (DOE 1996b) governs selection of the strategy to achieve compliance with EPA ground water standards. Stakeholder review and acceptance of the final PEIS is documented and supported by the Record of Decision (CFR v.62, No.18, 1997). Section 7.1, "Compliance Strategy Selection Process," presents a discussion of how the selection process was used to determine the ground water compliance strategy at the Shiprock site. Section 7.3, "Future Ground Water Monitoring Activities," presents a proposed future ground water sampling and analysis plan to monitor the effectiveness of the selected remedy and compliance with EPA ground water standards.

7.1 Compliance Strategy Selection Process

Figures 7–1 and 7–2 present summaries of the framework used to determine the appropriate ground water compliance strategies for the Shiprock site. The framework takes into consideration human health and environmental risk, stakeholder input, and cost. A step-by-step approach in the PEIS resulted in the selection of three general compliance strategies:

- ***No remediation***—Compliance with the EPA ground water protection standards would be met without altering the ground water or cleaning it up in any way. This strategy could be applied for those constituents at or below MCLs or background levels or for those constituents above MCLs or background levels that qualify for supplemental standards or ACLs, as defined in Section 2.2.1, "Uranium Mill Tailings Radiation Control Act."

- ***Natural flushing***—This strategy would allow natural ground water movement and geochemical processes to decrease contaminant concentrations to regulatory limits within 100 years. The natural flushing strategy can be applied where ground water compliance could be achieved within 100 years, where effective monitoring and institutional controls can be maintained, and where the ground water is not currently and is not projected to be a source for a public water system.

- ***Active ground water remediation***—This strategy would require engineered ground water remediation methods such as gradient manipulation, ground water extraction and treatment, land application, phytoremediation, and in situ ground water treatment to achieve compliance with EPA standards.

7.2 Shiprock Compliance Strategy

DOE is required by the PEIS to follow the ground water compliance selection framework presented in Figures 7–1 and 7–2 (explained in Tables 7–1 and 7–2) in selecting the appropriate compliance strategies for the surficial aquifers at the Shiprock site. Because the Shiprock site is divided physiographically and hydrologically into two regions, the floodplain and terrace areas, the surficial aquifer for each area is considered separately. The surficial aquifer in the floodplain consists predominantly of alluvium and, less importantly, of weathered Mancos Shale below it. The surficial aquifer in the terrace consists of alluvium and weathered Mancos Shale.

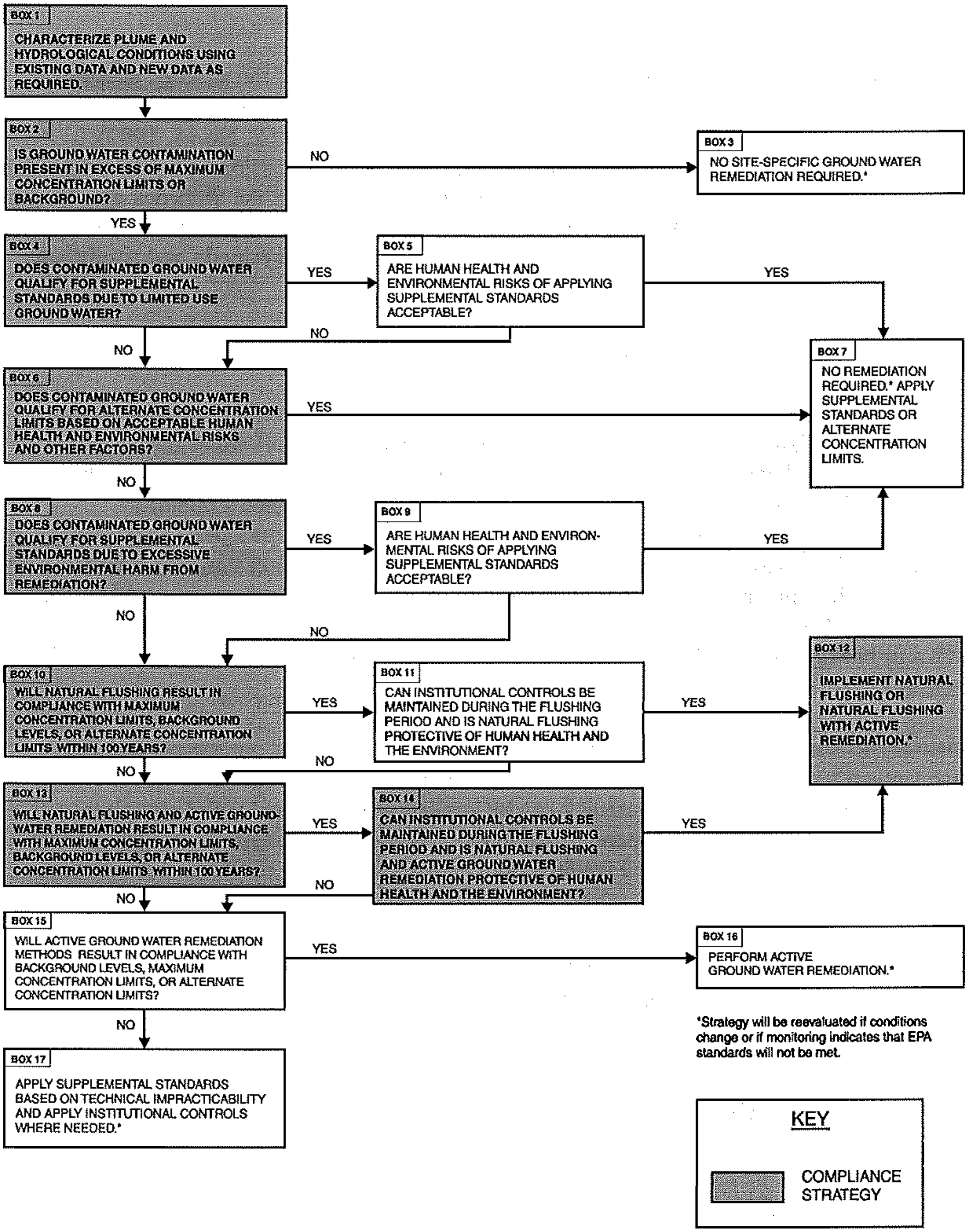


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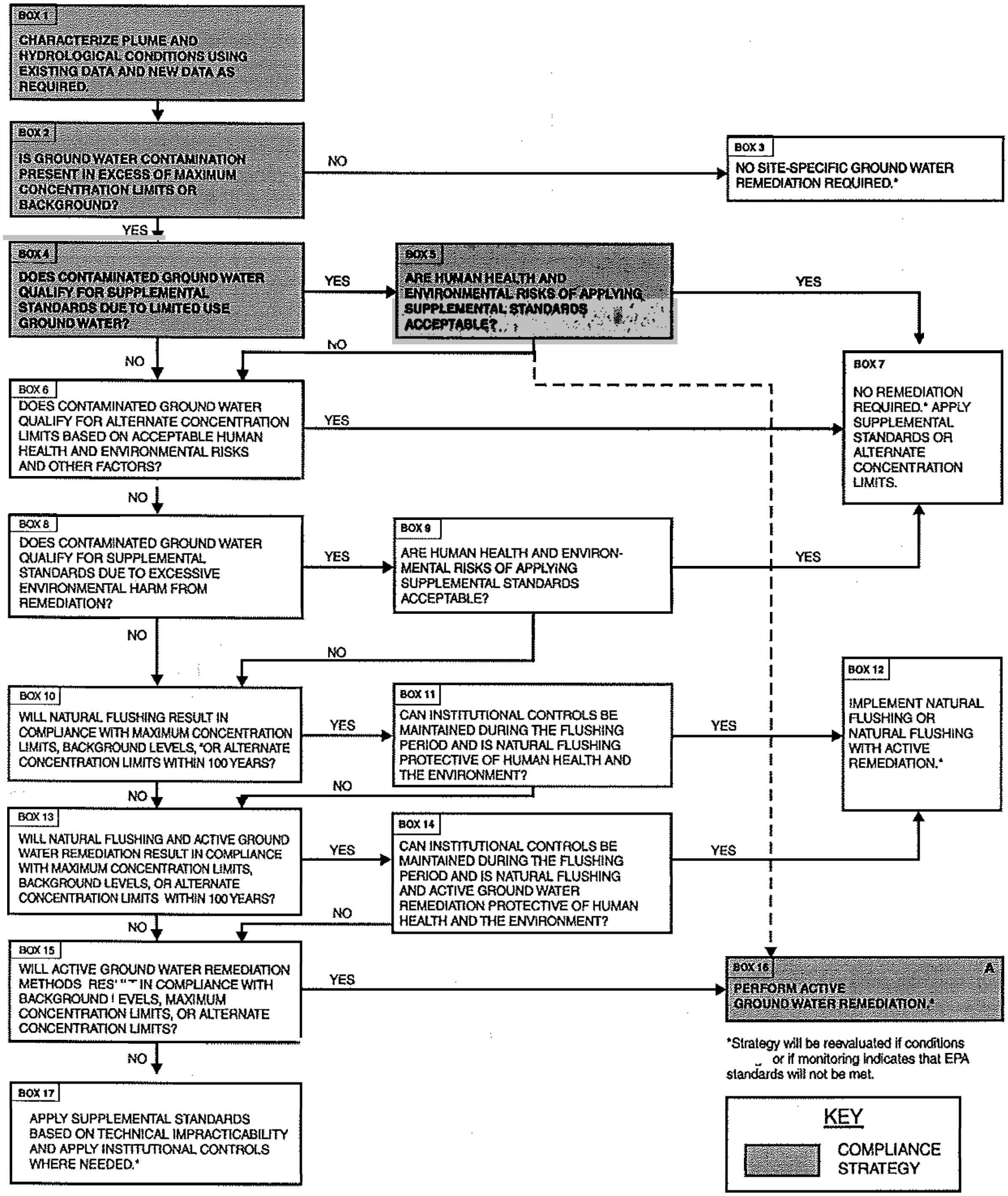
Figure 7–1. Ground Water Compliance Selection Framework for the Floodplain

Table 7–1. Floodplain: Explanation of the Compliance Strategy Selection Process for the Alluvial Aquifer

Box (Figure 7–1)	Action or Question	Result or Decision
1	Characterize plume and hydrological conditions.	See site conceptual model presented in Section 5.0 and contaminant screening presented in Section 6.0. Move to Box 2.
2	Is ground water contamination present in excess of UMTRA MCLs or background?	Nitrate, uranium, and selenium concentrations exceed the UMTRA MCLs. Sulfate and vanadium concentrations are high compared to background, and sulfate exceeds risk-based concentrations. Move to Box 4.
4	Does contaminated ground water qualify for supplemental standards due to limited use ground water?	Alluvial ground water does not currently meet any criteria for limited use. Move to Box 6.
6	Does contaminated ground water qualify for ACLs based on acceptable human health and environmental risk and other factors?	No ACLs are proposed at this time. Move to Box 8.
8	Does contaminated ground water qualify for supplemental standards due to excessive environmental harm from remediation?	Although the applicability has not been formally assessed, it is unlikely that remedial action would cause excessive harm to the environment. Move to Box 10.
10	Will natural flushing result in compliance with UMTRA MCLs, background, or ACLs within 100 years?	Ground water modeling shows that natural flushing alone will not reduce nitrate, uranium, and selenium to background or below MCLs within the 100-year time frame unless source material is removed. Move to Box 13.
13	Will natural flushing and active ground water remediation result in compliance with MCLs, background levels, or ACLs within 100 years?	Active remediation is required to remove a continuing ground water contaminant source. This will be accomplished after further analysis of floodplain soils and the terrace area between the disposal cell and floodplain. Natural flushing alone will not meet compliance requirements. Move to Box 14.
14	Can institutional controls be maintained during the flushing period and is active ground water remediation protective of human health and the environment?	Institutional controls will be maintained during the period of source removal, active ground water remediation, and natural flushing. **Move to Box 12 – implement active remediation and natural flushing.**

Prior to milling activities, the terrace area was dry as demonstrated by early aerial photographs (Figure 3-1). The terrace ground water system at Shiprock is unusual because it was created by uranium milling activities and has been draining for the past 30 years. The compliance strategy is simply to pump the remaining relic water out of the terrace sediments and allow the ground water system to revert to its original nature. Therefore, cleanup levels such as MCLs and ACLs are irrelevant. After the terrace system returns to its original state, human health and the environment will be protected. The standard PEIS flow chart does not conveniently accommodate this strategy; therefore, it has been modified.



*Strategy will be reevaluated if conditions or if monitoring indicates that EPA standards will not be met.

A Remediation will continue until risk to human health and the environment are mitigated. Terrace ground water system is a relic of uranium milling activities.

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Figure 7–2. Ground Water Compliance Selection Framework for the Terrace

Table 7–2. Terrace: Explanation of the Compliance Strategy Selection Process for the Alluvial Aquifer

Box (Figure 7–2)	Action or Question	Result or Decision
1	Characterize plume and hydrological conditions.	See site conceptual model presented in Section 5.0 and contaminant screening presented in Section 6.0. Move to Box 2.
2	Is ground water contamination present in excess of UMTRA MCLs or background?	Nitrate, uranium, and selenium concentrations exceed the UMTRA MCLs. Sulfate and vanadium concentrations are elevated compared to background and sulfate exceeds risk-based concentrations. Move to Box 4.
4	Does contaminated ground water qualify for supplemental standards due to limited use ground water?	Alluvial ground water does not currently meet any criteria for limited use. Move to Box 5.
5	Are human health and environmental risks of applying supplemental standards acceptable?	**No, move to box 16 and perform active remediation.** The ground water system was produced by uranium milling activities at this site. When it is removed from the ground and the system reverts to its original hydrologic setting, no ground water will exist.
6	Does contaminated ground water qualify for ACLs based on acceptable human health and environmental risk and other factors?	N/A
8	Does contaminated ground water qualify for supplemental standards due to excessive environmental harm from remediation?	N/A
10	Will natural flushing result in compliance with UMTRA MCLs, background levels, or ACLs within 100 years?	N/A
13	Will natural flushing and active ground water remediation result in compliance with MCLs, background levels, or ACLs within 100 years?	N/A
15	Will active ground water remediation result in compliance with MCLs, background levels, or ACLs?	N/A

The DOE-proposed compliance strategy for the floodplain surficial aquifer is active remediation to enhance contaminant reduction in combination with natural flushing, institutional controls, and the establishment of an ACL for selenium (Figure 7–1). This strategy consists of evaluating and eliminating the contaminant source, reducing contamination in the most contaminated portion of the aquifer, and then allowing the system to flush naturally; institutional controls and monitoring would ensure safety of the public and environment.

Compliance standards for uranium and nitrate are their respective UMTRA standards of 0.044 mg/L and 44 mg/L (as NO_3). For manganese, the cleanup objective is the maximum background concentration of 12.8 mg/L. An ACL is proposed for selenium and its numerical value will be based on future modeling and analytical results. The high distribution ratio and relatively high concentrations of selenium in the aquifer make it unlikely that the UMTRA standard of 0.01 mg/L can be met in a reasonable period of time. In addition, because the surficial aquifer contains weathered Mancos Shale, a known source of elevated selenium, an ACL is warranted. The cleanup goal for sulfate is uncertain at present because sulfate toxicity is still undergoing review by EPA. Recent studies indicate that sulfate concentrations to 1,500 mg/L produce no adverse effects (EPA 1999). However, concentrations higher than this have contributed to the floodplain contamination by the outflow from Bob Lee Wash and are outside the influence of the site. A cleanup goal for sulfate will be recommended in the addendum to this SOWP.

As noted above, the DOE-proposed compliance strategy for the terrace is active remedial action until human health and the environment are protected (Figure 7-2). This strategy involves pumping until the quantity of ground water is reduced to that of the original terrace system, which essentially was nothing. Other possible compliance strategies could involve supplemental standards if (1) widespread ambient contamination that cannot be cleaned up using treatment methods reasonably employed in public water supply systems or (2) concentrations of TDS that are in excess of 10,000 mg/L can be demonstrated. These latter two possible compliance strategies depend on locating ground water that represents background conditions in the terrace system. Terrace monitor wells installed to date either have insufficient ground water volume for sampling or have ground water that contains site-related contaminants. However, additional wells are planned in fiscal year 2000 at other locations in an attempt to establish background water quality for the terrace.

Figures 7–1 and 7–2 provide an explanation of how the strategies were selected; Tables 7-1 and 7-2 present an explanation of the figures. Each of the compliance strategy components is discussed in the following sections.

7.2.1 Human Health and Ecological Risks

Tables 6–11 and 6–12 present an overview of human health risks for the floodplain and terrace ground water systems, respectively. Ecologic risks at the site are considered negligible, except for livestock at seeps. An interim action is proposed to eliminate these risks. The tables provide the original list of COPCs from the 1994 BLRA (DOE 1994), appropriate MCLs, and rationales for retaining or deleting the COPCs based on 1998 and 1999 data. The constituents in the right column of each table labeled "Y" are considered COCs for the Shiprock site. For details on human health and ecological risks, see Section 6.0, "Baseline Risk Assessment."

7.2.2 Floodplain Strategy—Active Remediation and Natural Flushing

7.2.2.1 Active Remediation

An area containing high uranium, nitrate, selenium, and sulfate concentrations extends northward from the base of the escarpment from a line connecting wells 735, 610, 614, and 615 toward well 854 (Figure 7–3). This shape of the contaminant plume results from a mounding effect of water from Bob Lee Wash (and artesian well 648) entering the floodplain and flowing northward and northwestward through the subsurface to the San Juan River. This Bob Lee Wash water diverts the normal northwest flow of ground water in the floodplain northward toward the San Juan River in the area of well 854. The high concentrations along this path may be due to either residual source materials that were left at the base of the escarpment after conclusion of remediation or a source of contaminated water that continues to flow from the terrace.

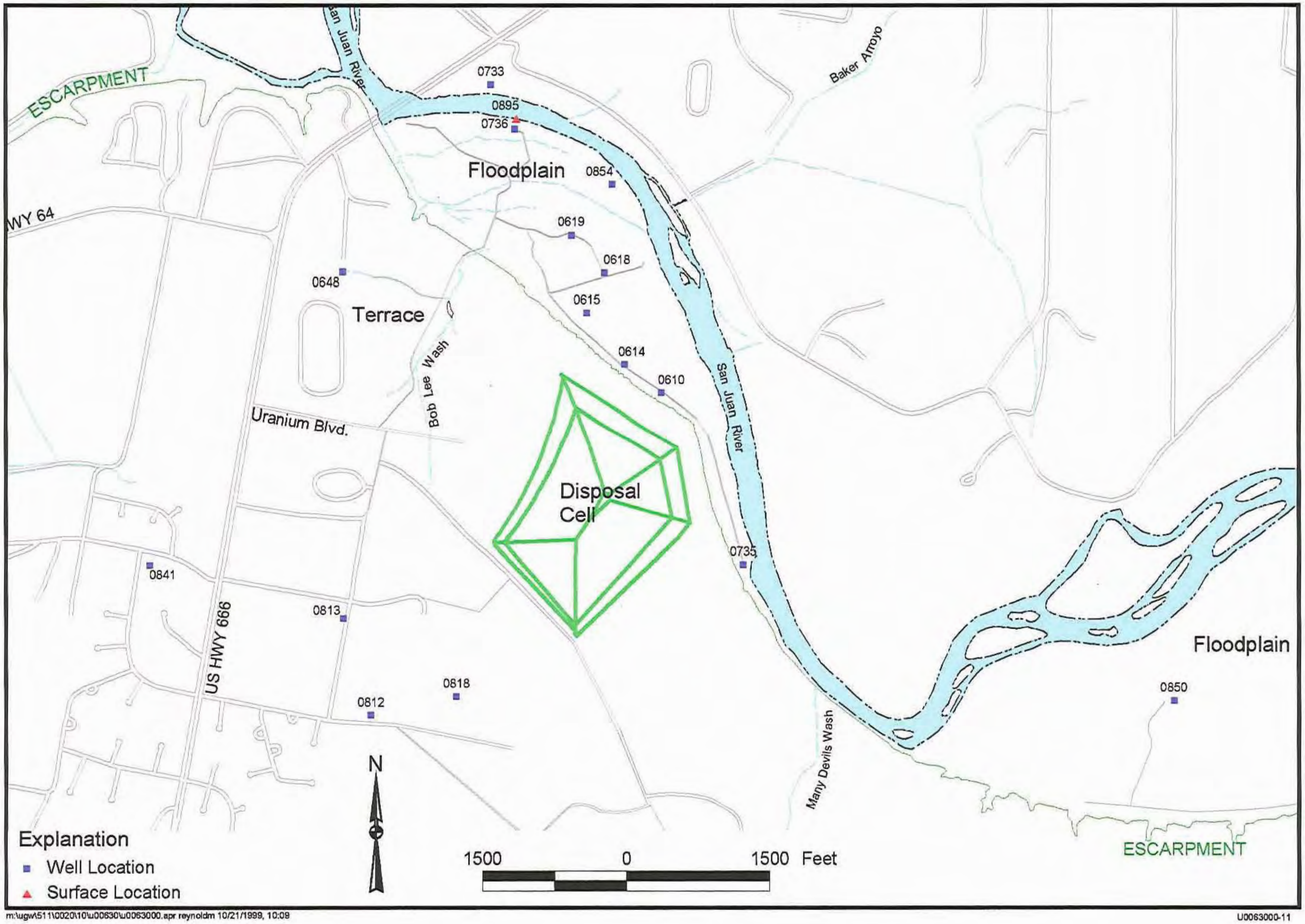

Figure 7-3. Proposed Monitoring Locations for the Shiprock Site

Additional characterization work is planned for fiscal year 2000 to determine the source of contamination. During remedial action in 1986, verification of tailings removal was mainly based on monitoring for radium-226. Other constituents may have been left on the floodplain. Additional characterization will consist of sampling surface and subsurface soil in the area around wells 735, 610, 614, and 615 to determine if elevated concentrations of constituents other than radium-226 are present. If nothing anomalous is found, the terrace between the disposal cell and the escarpment will be examined to determine if contaminated water is moving through it or if contaminated water is moving from or below the disposal cell into the floodplain.

Active remediation of soil or ground water in the floodplain may be necessary to control a continued source of contamination. If contaminated soil is found, it will be removed. If a continued source of contaminated water is found, it will be intercepted and treated upgradient of the floodplain. Details of these active remediation options are described in Section 8.0 "Development and Evaluation of Active Remediation Alternatives."

7.2.2.2 Natural Flushing

Results of ground water contaminant transport modeling are presented in Section 4.5, "Numerical Ground Water Modeling." Nitrate concentrations are predicted to diminish to acceptable levels after about 10 years of flushing. Uranium concentrations are predicted to decrease to acceptable levels within the same period of time. Selenium concentrations will not decrease as rapidly, but are also expected to diminish to acceptable levels within 100 years. Sulfate will flush at about the same rate as nitrate, but sulfate is constantly being added to the floodplain aquifer from the outflow of artesian well 648. This well water flows down Bob Lee Wash to the floodplain and percolates into the alluvium, accounting for about 60 percent of the ground water in the floodplain. Sulfate in water from well 648 averages more than 2,000 mg/L, so concentrations are not expected to decrease below this concentration in the floodplain aquifer. Well 648 is screened from 1,482 to 1,777 ft in the Morrison Formation. This zone is not contaminated from uranium-ore processing and it contains naturally elevated sulfate concentrations.

The current evaluation for adverse health effects to humans from directly ingesting floodplain ground water shows potential risks from manganese, nitrate, selenium, sulfate, and uranium. Surface water presents no unacceptable risks. After any additional source material is eliminated and the aquifer has flushed for 100 years, all constituents will be down to concentrations below MCLs, ACLs, or to background. Sulfate concentrations will still be approximately 2,000 mg/L in both surface and ground water, which presents a borderline risk for ingestion by cattle.

7.2.3 Terrace Strategy—Active Remedial Action

To reduce potential risks to humans and livestock, interim actions are planned along Bob Lee Wash and Many Devils Wash to limit access to the washes and to prevent exposure to the contaminated water issuing from terrace alluvium and weathered Mancos Shale (see Section 8.0, "Development and Evaluation of Active Remediation Alternatives."). The compliance strategy for the terrace is active remedial action until potential risks to humans and the environment have been eliminated.

7.2.3.1 Active Remedial Action

An artificial perched ground water table was produced during active milling when an estimated 150 million gallons of water used during processing percolated into the ground; an estimated 50 million gallons remain (see Section 4.3, "Hydrologic Characterization"). The water used during milling was from the San Juan River and was purchased by the Federal Government. This water has slowly been removed from the terrace for the past 30 years by seepage along the base of the escarpment and into Bob Lee Wash and Many Devils Wash and by seepage down through other pathways into the floodplain to the east and north. The predominant joint direction of N40E (Figure 4–6) may provide a preferred flow direction for any residual ground water remaining in the terrace.

A pump and evaporate system is proposed on the terrace to eliminate potential risk from water surfacing in seeps in Bob Lee Wash and Many Devils Wash. Details of all the active remedial alternatives are discussed in Section 8.0, "Development and Evaluation of Active Remediation Alternatives."

7.2.4 Institutional Controls

DOE and the Navajo Nation will cooperate with local authorities to restrict use of contaminated ground water during the remedial action period. Restrictions may take the form of a drilling moratorium, permit restrictions, or other administrative means.

7.2.4.1 Floodplain Controls

Several controls are in place to prevent access to potentially harmful contaminated ground water in the Shiprock floodplain during remedial action and the 100-year natural flushing period. The southwest boundary of the floodplain is a near-vertical escarpment 50 to 60 ft high that separates the floodplain from the terrace. The narrow southern end of the floodplain is fenced just north of well 735, and a locked gate is maintained across the road at the bottom of Bob Lee Wash where it enters the floodplain. Northwest of Bob Lee Wash, the escarpment continues to the end of the floodplain at the U.S. Highway 666 bridge. Access to the floodplain is controlled by the Navajo Nation and DOE.

7.2.4.2 Terrace Controls

The disposal cell is fenced on three sides and warning signs are posted indicating radioactive materials are stored in the area. The cell is open to the east and north for a short distance to the escarpment edge. Southeast of the disposal cell, the NECA gravel pit is fenced eastward nearly to Many Devils Wash. South of the cell, the radon cover borrow pit is fenced around its perimeter and posted with "keep out" signs. North and northwest of the cell, the NECA yard and pond area are fenced and posted. Planned interim actions along Many Devils Wash and Bob Lee Wash will limit access to these drainages. Additional controls may be required in the washes west of U.S. Highway 666 to ensure that no one drinks the contaminated ground water that comes to the surface.

7.3 Future Ground Water Monitoring Activities

The monitoring strategy for the alluvial aquifer in the floodplain is designed to assess the progress of active remediation and the natural flushing process. Results of future monitoring of terrace ground water will be used to assess the active remediation and, as a best management practice, to demonstrate that only limited ground water quantities remain in the terrace. Proposed monitoring locations are shown on Figure 7–3.

7.3.1 Floodplain Monitoring Requirements

7.3.1.1 Active Remediation

A treatment system will operate in the floodplain alluvial aquifer for at least 1 year and possibly longer until contaminant levels have been reduced enough that natural flushing can achieve cleanup goals within the permitted 100-year period. During this period, monitor wells 735, 610, 614, 615, 618, and 854, located along the arcuate trend of the ground water plume from the base of the escarpment to the San Juan River, will be sampled semiannually. Samples will be analyzed for manganese, nitrate, selenium, sulfate, and uranium concentrations; results will be compared with concentrations in samples collected annually from background well 850 and from well 733 north of the San Juan River (Table 7–3).

Concentrations of analytes will be considered acceptable when the manganese concentrations decrease to the maximum background concentration of 12.8 mg/L; selenium concentrations reach the ACL based on future ground water modeling and analytical results, and when the uranium and nitrate concentrations reach the UMTRA standards of 0.044 mg/L and 10 mg/L (as N, 44 mg/L as NO_3), respectively. Additional modeling will be conducted in fiscal year 2000 to refine the time required for removal of the selenium concentration to its ACL. The final cleanup standard for sulfate is uncertain.

7.3.1.2 Natural Flushing

Natural flushing will continue for at least 10 years after remedial action is completed, according to floodplain modeling. During this time, wells 614, 619, 735, and 736 and the surface water location 895 along the San Juan River will be sampled annually. After 10 years, the sampling frequency and the list of constituents to be analyzed will be reevaluated. Samples will be analyzed for manganese, nitrate, selenium, sulfate, and uranium (the same analytes as during active remedial action). Action levels for these analytes will also be the same as with active remedial action.

7.3.2 Terrace Monitoring Requirements

7.3.2.1 Active Remedial Action

A pump and evaporation system will operate to de-water the terrace ground water system for at least 1 year and possibly longer. During this period, monitor wells 812, 813, 818, and 841 in the area of maximum-saturated alluvial thickness will be tested to assure flow rates are diminishing.

Table 7–3. Summary of Monitoring Requirements

Location	Monitoring Purpose	Analytes	Frequency
610	Remedial action, floodplain	Mn, NO_3, Se, SO_4, U	Semiannually for 5 years
614	Remedial action, floodplain	Mn, NO_3, Se, SO_4, U	Semiannually for 5 years
615	Remedial action, floodplain	Mn, NO_3, Se, SO_4, U	Semiannually for 5 years
618	Remedial action, floodplain	Mn, NO_3, Se, SO_4, U	Semiannually for 5 years
735	Remedial action, floodplain	Mn, NO_3, Se, SO_4, U	Semiannually for 5 years
854	Remedial action, floodplain	Mn, NO_3, Se, SO_4, U	Semiannually for 5 years
Surface Water	North of Well 856, Remedial action, floodplain	Mn, NO_3, Se, SO_4, U	Semiannually for 5 years
850	Background, floodplain	Mn, NO_3, Se, SO_4, U	Annually for 10 years
733	Background, floodplain	Mn, NO_3, Se, SO_4, U	Annually for 10 years
619	Natural flushing, floodplain	Mn, NO_3, Se, SO_4, U	Annually for 10 years
735	Natural flushing, floodplain	Mn, NO_3, Se, SO_4, U	Annually for 10 years
736	Natural flushing, floodplain	Mn, NO_3, Se, SO_4, U	Annually for 10 years
Surface Water	North of Well 856, Natural flushing, floodplain	Mn, NO_3, Se, SO_4, U	Annually for 10 years
812	Remedial action, terrace	NA[a]	Semiannually for 5 years
813	Remedial action, terrace	NA	Semiannually for 5 years
818	Remedial action, terrace	NA	Semiannually for 5 years
841	Remedial action, terrace	NA	Semiannually for 5 years

[a] NA = not applicable.

7.3.2.2 Proposed Future Land Use

The Navajo Nation has several plans for the use of land over the contaminant plume in the area west of the NECA facility and Bob Lee Wash that includes

- Moving the fairgrounds facilities about 3 mi to the south.
- Constructing a hotel and several other businesses in the area of the former fairgrounds.
- Constructing a multipurpose cultural center, including sports fields, in the area south of the shopping center.
- Constructing a new Diné College facility in the tract east of the Shiprock High School.

For more information about future land use, see Section 3.0, "Present and Anticipated Land and Water Use."

8.0 Development and Evaluation of Active Remediation Alternatives

As presented in Section 7.0, "Ground Water Compliance Strategy," the selected ground water compliance strategy for the Shiprock site is a combination of active remediation and natural flushing. The terrace will be remediated by dewatering of the ground water system to prevent further contamination of the floodplain and surface waters until the output of the extraction wells declines to the point that human health and the environment are protected. The remediation mechanism for the floodplain will be natural flushing in combination with active remediation of the most contaminated area.

The purpose of this section is to develop and evaluate different remediation alternatives and recommend a treatment process for remediation of site ground water contamination. For the terrace, the alternatives evaluation process will follow the model that was used for the Tuba City and Monument Valley sites on the Navajo Nation in Arizona. However, in the case of the floodplain, the situation is more complex because the nature and extent of a possible continuing contamination source has not been defined. For the present, contaminated water will be pumped from the floodplain to the terrace and treated with terrace water.

As described in Section 4.0, "Site Characterization Results," attempts to locate ground water in a background terrace location have so far been unsuccessful. All indications are that all the ground water in the terrace system is a result of the milling activities which used water from the San Juan River that was paid for by the Federal Government. Therefore, DOE does not need to obtain permits for use or disposal of this water.

The estimated volume of ground water in the floodplain is about 150 million gallons. The volume of contaminated ground water that might have to be treated would be no more than about half this quantity. Initial indications are that the Navajo Nation has sufficient water rights to permit extraction of such a volume from the floodplain and that they are willing to assign the required rights to DOE with no additional cost to the UMTRA Ground Water Project.

The chemical compositions of the terrace ground water system and the floodplain aquifer are sufficiently similar that any treatment process that works effectively for the terrace system should also be effective for the floodplain. Therefore, even though discussions concentrate on developing treatment alternatives for the terrace, the same treatment unit can and should be used for the floodplain as well.

Section 8.1 presents an overview of the process used to evaluate and screen technologies and alternatives for remediation of the terrace, including a detailed explanation of the evaluation criteria. Section 8.2 develops a list of potential technologies that could be used for remediation, evaluates the technologies as they might be applied to the terrace, and screens out technologies that are not feasible. Section 8.3 lists technologies that passed the initial screening, combines the technologies into alternatives, and develops the parameters that will be used for the detailed evaluation, which is presented in Section 8.4. Section 8.5 presents the proposed alternative for active remediation, along with discussions of how the proposed method may be deployed and the uncertainties and limitations of the proposed alternative. Finally, Section 8.6 describes the interim actions that will be taken to limit exposures to contaminated ground water in and around the Shiprock site before and during the remediation process.

8.1 Process for Development and Evaluation of Technologies and Alternatives

This section presents an overview of the process used to select proposed alternatives for remediation of contaminated ground water in the terrace system at the Shiprock site. It also includes descriptions of the criteria used to evaluate technologies and alternatives.

8.1.1 Overview of the Process

The process used to select proposed alternatives for remediation of contaminated ground water includes

- Develop, evaluate, and screen technologies that could be used for remediation.
- Combine the technologies into alternatives and evaluate the alternatives.
- Select an alternative as a proposed remediation method.

Technologies considered could be used for extraction of ground water, disposal of ground water, or treatment of ground water. The initial screening of technologies, generally qualitative in nature, considered whether the particular technology was appropriate for use at Shiprock, given the types, quantities, and locations of the contaminated water, and the concentrations of contaminants at the site. This initial screening did not consider cost or implementability except in the most general sense. The technologies that were considered appropriate for detailed review, based on the initial screening, were then combined into alternatives for extraction, treatment, and disposal.

The next step in the process was the evaluation of the alternatives to determine the preferred alternatives for extraction, treatment, and disposal. The evaluation of alternatives used the same criteria as the evaluation of technologies (i.e., effectiveness, implementability, and cost) but was conducted in more detail and included a detailed cost estimate for each alternative. The final step in the evaluation of alternatives was a comparative analysis of the alternatives considering the evaluation criteria.

The last part of the process presents the proposed treatment process for remediation of the terrace system and describes the limitations of the proposed approach.

8.1.2 Evaluation Criteria

Each remediation alternative was evaluated for its effectiveness, implementability, and cost. The proposed alternative is the one that represents the best mix of all three criteria. The evaluation criteria were developed from standard engineering practice for assessing the feasibility of any large-scale project. A discussion of each evaluation criterion is provided in the following sections.

8.1.2.1 Effectiveness

The effectiveness evaluation criterion considers a number of factors, including

- Remediation time frame.
- Conformance with ground water system restoration standards and goals.
- Short-term effects (i.e., effects of remediation on workers, the community, and the environment).
- Disposal of treatment residuals.

Remediation Time Frame

DOE has established 20 years as a goal for remediation of the contaminated ground water under the UMTRA Ground Water Project. The estimated volume of contaminated ground water in the terrace system at the Shiprock site is 50 million gallons. Thus, a complete extraction and remediation of all water from the terrace system over a period of 20 years would require an overall extraction rate of only 5.3 gpm, which is unreasonably low.

Assuming a 90-percent on-stream factor, an influent rate of 1 gpm is equivalent to 473,040 gallons per year. Thus, remediation of the entire volume of 50 million gallons of contaminated water in 1 year would require an average feed rate of 106 gpm; in 2 years, 53 gpm; and in 3 years, 35 gpm. The additional water from the floodplain would approximately double these volumes. The treatment systems for the Tuba City and Monument Valley sites were sized for treatment capacities of approximately 100 gpm. Treatment of the terrace system at Shiprock in 1 year using a treatment system with a capacity of 100 gpm would require an on-stream factor of 95 percent, which does not seem unreasonable for a system operating for a short period of time under close scrutiny. Using this treatment capacity will also facilitate comparisons by making it possible to use the same cost database that was used for the two other Navajo Nation sites. Therefore, the evaluation of treatment technologies will assume a treatment rate of 100 gpm and a total remediation time of 2 years.

The capacity of the treatment system is not the only consideration in determining the remediation time frame. Before the water can be treated, it must first be extracted. A remediation strategy that has the goal of dewatering the ground water system implies a decline in extraction rates as the remediation progresses. It is highly unlikely that the extraction system, even though it can initially develop the desired extraction rate of 100 gpm, will be able to sustain that rate for the duration of remediation. So the remediation may take longer than the design period of 1 year. One criterion for evaluating treatment alternatives will be "turn-down," the ability to operate at less than the design throughput rate, to determine the capability of the system to handle the inevitable decline in extraction rate.

Conformance with Aquifer-Restoration Standards and Goals

The treatment standards for UMTRA Ground Water projects are the MCLs specified in 40 CFR 192.04, Table 1. These MCLs govern the quality of the water in the aquifer after remediation, not the quality of the effluent from any treatment process. Because the remediation strategy for the terrace specifies dewatering, aquifer restoration standards are irrelevant to the terrace remediation. As described in Section 7.0, "Ground water Compliance Strategy," the terrace system will be dewatered until monitor wells 812, 813, 818, and 841 demonstrate yields are reduced to levels that no longer feed seeps in Bob Lee and Many Devils Washes (see Section 7.3.2). No attempt will be made to remediate the terrace system to meet MCLs. The quality of any effluent from the treatment system will be dictated by disposal requirements, not directly by MCLs.

The principal remediation strategy for the floodplain ground water is natural flushing. Active remediation will be used in a localized area. Floodplain ground water will be required to meet MCLs. Hydrologic modeling indicates that, if any continuing influent source is removed or treated, the natural flushing process will be able to reduce concentrations to below MCLs before the statutory requirement of 100 years. Reinjection of treated water into the floodplain from the treatment process is not presently contemplated. The extent, if any, to which treated water from the floodplain would be required to meet MCLs will be determined when the ultimate configuration of the floodplain remediation system, including the disposal of the treated water, is decided.

Although treatment standards do not apply to the terrace ground water, knowledge of the composition of the ground water in the terrace is required for the design of the treatment system. Table 8–1 presents the composition of the terrace ground water, based on analytical data from the March 1999 sampling. The average concentrations of COCs in the terrace ground water system are computed by averaging the contaminant compositions of samples from the 24 wells in that system which exceeded the MCL for at least one COC. Also shown, for comparison purposes, is the composition of the floodplain ground water, averaging the compositions of samples from the 21 wells in the floodplain that exceeded the MCL for at least one COC, and the background composition of the ground water based on the average composition of samples from wells 850, 851, and 852. These wells are located on the floodplain upstream of the former millsite and are not true background water for the terrace, but no true background ground water in the terrace has yet been found. All concentrations are in milligrams per liter.

Table 8–1. Average Composition of Shiprock Contaminant Plumes

Constituent	Terrace	Floodplain	Background
Ammonia	36.7	52.54[a]	0.084
Manganese	1.535	3.90	1.512
Nitrate	1,388	834	0.241
Selenium	0.761	0.140	<0.001
Sulfate	7,178	6,845	1,527
Uranium	0.331	0.865	0.017

[a] Ammonia is not a COC for the floodplain.

Short-Term Effects

Short-term effects consider the effects of the remediation program on the community, workers, and the environment. The Shiprock site is located mainly within the developed areas of the town of Shiprock, New Mexico, the largest community in the Navajo Nation, and is directly adjacent to residences, businesses, and recreational facilities. U.S. Highways 64 and 666 pass within a few hundred yards of the site. These highways are heavily traveled by tourists and residents throughout the year. All users of the highways are also classified as part of the community.

Evaluating the effects to workers entails considering the risks to people employed to construct the treatment system and to those employed to operate and maintain the system during its operational life, as well as individuals supporting the remedial action, such as samplers and equipment operators disposing of treatment residuals.

The evaluation of short-term effects also considers environmental effects. Environmental effects include potential environmental harm caused by deployment of a technology or alternative and whether the potential harm of remediation outweighs the benefits to be derived from restoration of the alluvial ground water system.

Disposal of Treatment Residuals

Active treatment processes produce a significant amount of residual waste. This waste may include dissolved solids from the ground water, as well as the residuals from any other chemicals that may have been added during the treatment process (e.g., antiscalants or softening agents). These residuals must be contained during the remediation process and must be disposed of either during or at the end of remediation.

8.1.2.2 Implementability

Implementability is an assessment of the feasibility of building, operating, and maintaining a remediation system.

The following aspects of feasibility will be discussed in this SOWP:

- Ease of construction.
- Ease of operation and maintenance.
- Expected reliability.
- Ability to handle changes in influent composition.
- Ability to handle increases in extraction capacity.

Ease of Construction

The Shiprock site is part of the largest community in the Navajo Nation and is within 30 mi of Farmington, New Mexico, which contains a significant petroleum processing and support industry. Skilled construction labor should be readily available in the area. Therefore, little advantage exists, other than cost (which is evaluated separately), for treatment systems that are easier to construct.

Consideration of construction also requires examining the uncertainty associated with construction, such as the potential for schedule delays caused by technical problems.

Ease of Operation and Maintenance

In general, systems that are more complex require a higher level of skill to operate and maintain. Complexity can be either process complexity or mechanical complexity, and each type has its particular demands on the skills of the operations and maintenance staff. Individuals who are skilled in the operation and maintenance of extraction and treatment systems are not readily available on the Navajo Nation, and the short duration of treatment at the Shiprock site means that it may be difficult to attract skilled operating and maintenance personnel for the Shiprock remediation project. Systems that are easy to operate and maintain will be preferred over systems that are more challenging.

Expected Reliability

Reliability includes both the physical reliability of the equipment making up the system and the process reliability, which considers the potential for variability in process performance on both a day-to-day basis and a year-to-year basis. Evaluation of the potential reliability of a treatment system must consider the technical and operational complexity and required level of training for operators.

Ability To Handle Changes in Influent Composition

The concentrations of contaminants in the terrace ground water system are expected to change as dewatering progresses. The composition may also change if currently unknown hot spots (small areas of highly contaminated water) are identified as extraction progresses. Some technologies are better suited to handle such variations than others, and this ability will be considered in evaluating technologies for use at the Shiprock site.

Ability To Handle Variations in Extraction Capacity

Because considerable uncertainty regarding the extent of contamination in the terrace ground water system still exists, a likelihood persists that the actual volume of the contaminant plume will be significantly higher than the present estimate. At the other extreme, the overall feed rate to the terrace treatment system will inevitably decrease over time as the ground water system dewaters and wells go dry. Should the plume volume significantly exceed the current estimates, it is unlikely that the extraction capacity of the system would have to be increased to handle more water than is currently planned. The more likely scenario is that the treatment duration would be extended, since it is much less than the DOE goal of 20 years. As the feed rate decreases, the treatment system would have to have sufficient turndown capability to handle the decrease in influent rates. The ability of a remediation system to handle such changes must be considered in evaluating technologies for use at the Shiprock site.

8.1.2.3 Cost

Once the initial screening of technologies has eliminated those that are not suitable for technical reasons, cost estimates for treatment processes which pass the initial screening process will be developed. Capital costs (both direct and indirect) and operating and maintenance (O&M) costs are calculated for each process. The accuracy of the cost estimates for evaluation of the alternatives is defined to a level of accuracy of +50 percent to -30 percent. The total cost of the remediation over the life of the project is determined by combining the initial capital cost for the treatment system with the estimated O&M costs over the project duration, using a net present worth analysis. By discounting all costs to a common base year, the costs for expenditures in different years can be compared on the basis of a single figure (i.e., the net present worth). The Office of Management and Budget (OMB) recommends calculating net present worth using a real interest rate (i.e., a rate that does not consider inflation) to discount out-year costs that have not been adjusted for inflation.

Most remediations under the UMTRA Ground Water Project are designed to operate for approximately 20 years. When total project costs are calculated for such a lengthy time, total O&M costs become much greater, and thus a much more significant consideration, than the capital cost. For instance, both the Tuba City and Monument Valley sites are using the distillation treatment process. Distillation is capital intensive, but the relatively moderate operating costs of the process made it a competitive option for the duration of those remediation projects. The Shiprock remediation will be designed to operate for only 1 year. Thus the capital cost for remediation at Shiprock may be expected to equal or exceed the O&M cost, and it will have a correspondingly greater effect on the overall cost calculation.

Where possible, direct capital costs are developed from invoice costs of similar systems. If that information is not available, generic unit costs, vendor information, and conventional cost-estimating guides have been used. O&M costs are based on labor costs, energy costs, material and equipment costs, and maintenance costs.

8.2 Evaluation of Technologies

8.2.1 Technologies Considered for Remediation

During the process of alternatives evaluation for the Tuba City and Monument Valley sites, technologies for ground water extraction, effluent discharge, and treatment were evaluated. This process is described in the Final SOWPs for those sites. Where applicable, the lessons learned during development of treatment processes for Tuba City and Monument Valley were also applied to the Shiprock site.

Table 8–2 presents a comparison of the average plume compositions in the terrace system at Shiprock with those at Tuba City and Monument Valley, using the most recent analytical data for all sites. All results are given in milligrams per liter. It is readily apparent that the terrace ground water at Shiprock is more highly contaminated than the aquifers at Tuba City and Monument Valley.

Table 8–2. Average Composition of Shiprock, Tuba City, and Monument Valley Contaminant Plumes

Constituent	Shiprock Terrace	Tuba City	Monument Valley
Ammonia	36.7	38.9	86.8
Nitrate	1,388	974	242
Selenium	0.761	0.033	0.003
Sulfate	7,178	2,120	846
Total Dissolved Solids	14,057	5,134	1,688
Uranium	0.331	0.286	0.010

Given the higher levels of contaminants at the Shiprock site, technologies that were viable for use at the other sites may not be appropriate for Shiprock. Also, the higher contaminant levels at Shiprock will affect the economic evaluations so that technologies which were economically viable at the other sites may not be so at Shiprock or vice versa. Finally, the much shorter duration of treatment at Shiprock means that capital costs will be a more important factor in economic evaluations, and operations and maintenance costs will be much less important than was the case at the other sites.

8.2.2 Extraction Technologies

Two types of extraction-well systems were considered: Conventional vertical wells and horizontal wells.

8.2.2.1 Conventional Vertical Wells

Vertical wells are the most commonly used ground water extraction devices, so the bulk of field experience and knowledge relates to conventional vertical wells. Installation of vertical wells is relatively straightforward in most cases. Tests of newly installed vertical wells at the Monument Valley and Tuba City UMTRA sites have demonstrated that vertical wells can provide highly satisfactory yields when combined with proper well design, construction, and development. Vertical extraction wells can be readily converted to injection wells if needed, or vice versa, and can also be easily decommissioned when necessary. The theoretical performance of a vertical well can be simulated analytically or numerically during the design process using readily available and accepted mathematical formulations, but no comparable knowledge base exists for other technologies.

8.2.2.2 Horizontal Wells

Horizontal well technology was originally developed in the oil and gas industry and has been applied during recent years to environmental engineering. The technique is deployed using directional drilling methods. Typically, boreholes are initially advanced in the vertical orientation and later are turned to a horizontal orientation. Although the initial cost of installing a horizontal well is relatively high, a cost saving may result from lower O&M costs because fewer wells are required due to the greater screened length possible with a horizontal well.

The implementation of horizontal-well technology is considered expensive and risky compared with conventional vertical wells. The long lengths of well screen required increases the difficulties of well completion and development. Other difficulties could evolve later in the project as the ground water cleanup proceeds because few options are available for sealing off the restored parts of the ground water system.

8.2.2.3 Choice of Extraction Technology

The terrace ground water system at the Shiprock site is a relatively unpromising candidate for installation of vertical wells. Because of the shallow saturated thickness of the terrace system, the screened, productive length would be one-third or less of the total well depth. The shallow depth would also reduce the yield from conventional vertical wells so that many such wells would be required. A few horizontal wells, strategically located, could serve the function of many vertical wells.

Another prospective advantage of horizontal wells is that the technology can be used where vertical wells cannot be deployed, such as beneath the disposal cell, to accelerate the flushing and recovery of contaminants. In addition, the use of horizontal wells obviates the need for a complex network of distribution piping, a significant consideration at Shiprock because the site is located in a populated area and the disruption attendant in constructing a network of distribution piping, and the potential for damage to the system once it is in operation, would be considerable.

However, the shallow saturated thickness of the ground water in the terrace system means that horizontal wells must be drilled accurately for the borehole to stay in the saturated zone. The soil material in the terrace system contains gravel and cobbles, and drillers would have considerable difficulty maintaining the drill direction in such material. No such problem exists with vertical wells. A nonproductive or underproducing vertical well can be replaced at modest cost, while replacing or redrilling a horizontal well would be formidably expensive. These concerns offset the potential advantages of horizontal wells for the Shiprock site. **Therefore, vertical wells were recommended for use as part of the extraction process for the terrace system at the Shiprock site.**

Contamination on the floodplain is limited to a confined area that can easily be addressed with a small number of vertical wells.

8.2.3 Effluent Discharge Technologies

This section provides descriptions of the ways in which effluent from the treatment plant can be discharged.

8.2.3.1 Evaporation

Evaporation treats extracted ground water by allowing the water to evaporate under conditions in which the nonvolatile contaminants are contained and allowed to concentrate for later disposal. The ground water in the terrace system already belongs to DOE, and the Navajo Nation has indicated that it has, and is willing to assign to DOE, sufficient water rights to permit evaporation of ground water from the floodplain. Because evaporation produces no effluent, it is both a treatment and a disposal technology. The advantages and disadvantages of evaporation as a treatment option are discussed in Section 8.3, "Evaluation of Alternatives."

8.2.3.2 Discharge to Surface Water

Under this option, the extracted and treated ground water would be discharged to the San Juan River, either directly or by way of Bob Lee Wash or Many Devils Wash. The feasibility of this option would depend on the quality of the treated water, because discharge to the San Juan River would require a permit from the Navajo Nation.

8.2.3.3 Effluent Discharge Technologies Recommended for Detailed Evaluation

Evaporation would be used as the effluent-discharge technology for the terrace system if the economic evaluation shows it is the most attractive remediation technology. Discharge to surface water could be used if another treatment technology is selected that produces an effluent which is acceptable for introduction into the San Juan River. The final selection of treatment discharge technology(ies) must be deferred until the treatment alternatives evaluation is completed.

8.2.4 Treatment Technologies

Many treatment processes were identified as potentially applicable for cleaning up the terrace ground water system at the Shiprock site. The processes can be categorized as follows:

- Evaporation systems.
- Distillation systems.
- Through-medium processes such as ion exchange.
- Biological processes.
- Chemical treatment processes.
- Membrane separation processes.

This section provides a review of the potential applicability of these treatment processes to the terrace ground water system and eliminates those that are obviously unsuitable. The processes that are not eliminated in this first screening will be evaluated in greater detail in Section 8.3, "Evaluation of Alternatives."

8.2.4.1 Evaporation Systems

Solar evaporation, in which contaminated water is fed into large lined or unlined outdoor ponds at influent rates that match the rate of natural evaporation, is an established method for reducing the volume of contaminated surface or ground water in arid and semiarid regions of the United States. Nonvolatile contaminants such as nitrates, sulfates, uranium, and other components of TDS, which are the only constituents of concern at Shiprock, will not evaporate and instead will concentrate as a sludge that must be periodically removed for disposal. Solar evaporation systems are constrained by climatic effects, notably temperature (solar radiation), humidity, and wind.

Pan evaporation rates at the Shiprock site are estimated at about 70 in. per year, while precipitation at Shiprock averages about 7 in. per year. Thus, an evaporation system at Shiprock would be expected to be effective for most of the year. The surface area required to achieve complete evaporation would be considerable, however. Preliminary calculations suggest that a solar evaporation pond for the Shiprock site would require a surface area of about 1 acre for every 2 gpm of influent. Thus, for example, treating an influent rate of 100 gpm would require a solar evaporation pond with a surface area of about 50 acres.

The effectiveness of solar evaporation systems can be significantly enhanced by adding spray systems in which water is sprayed as a fine mist into the air above the solar pond. The fine mist droplets evaporate more readily than does the bulk water at the pond surface. Use of a spray system can substantially reduce the size of the pond required. For instance, addition of a spray system could reduce the size of the evaporation pond for the Shiprock site by a factor of about 25. However, addition of a spray system considerably increases the complexity of the system and requires more maintenance and operator attention than simple solar evaporation.

In general terms, evaporation is a low-cost remediation option for large quantities of contaminated water in arid climates. **Because there is no requirement to recover treated water from either ground water system, evaporation was selected for detailed evaluation as a treatment alternative for the terrace.**

8.2.4.2 Distillation Systems

In a simple distillation process, water is vaporized by heating it to its boiling point. The water vapors are then condensed and recovered as clean water. Nonvolatile contaminants such as nitrates, sulfates, uranium, and other components of TDS will not evaporate. Instead, they will concentrate in the evaporation chamber and must be removed at an appropriate rate. If no volatile contaminants are present, the condensed water will be of high quality and can be used for virtually any purpose. The concentrate, or brine, may be taken off site for disposal; alternately, it may be evaporated to dryness and the residue can then be disposed of as a solid.

Distillation is an expensive treatment technology to implement because of the significant capital costs of distillation equipment. However, distillation does recover almost all the water, and the product water is of high quality. Because the Shiprock ground water does not contain volatile contaminants, the condensate from a distillation system will be of such high quality that the concentrations of contaminants will be below regulatory standards for drinking water by orders of magnitude.

Distillation was chosen as the primary treatment technology at the Tuba City and Monument Valley sites. Demonstration of this technology in a pilot study conducted at the Tuba City site in September and October 1998 confirmed the applicability of distillation to UMTRA Project ground waters. The full-scale distillation treatment system is scheduled for deployment at Tuba City in the first quarter of 2000. A similar system will be deployed at Monument Valley in 2001, and a second treatment system is scheduled to be deployed at Tuba City between 2002 and 2004 to increase the treatment capacity at that site so that remediation can be completed within the project goal of 20 years. The short duration of remediation at the Shiprock site would make it possible for a distillation system to be initially deployed at Shiprock and then moved to the Tuba City site once remediation at Shiprock is complete. The modular nature of the equipment being used at Tuba City makes this option viable. Under this scenario, the Shiprock and Tuba City projects would divide the cost of the distillation unit, with Tuba City absorbing most of the cost because it will have the equipment for a much longer time. This sharing of systems would minimize the cost of implementing the distillation system at Shiprock. **Accordingly, distillation was selected for detailed evaluation as a treatment alternative at the Shiprock site.**

8.2.4.3 Through-Medium Processes

In a through-medium process, a flow stream is passed through a column or reactor containing an insoluble adsorptive or exchange medium. Synthetic ion exchange resins, which are manufactured to have high affinities for certain types of ions, are widely used in through-medium processes for removal of uranium and many other dissolved ionic contaminants.

Ion exchange processes are generally impractical for liquids with TDS concentrations higher than about 1,500 mg/L. The TDS level in the terrace system will average nearly 10 times this amount, and the TDS level in the floodplain is even higher. At such high concentrations, the on-stream time of an ion exchange unit treating the Shiprock ground water would be poor, because of the need for frequent regeneration, chemical consumption would be high, and the volume of regenerant liquid would be excessive. Thus, ion exchange processes appear to be a poor choice as a remediation technology for Shiprock.

Another type of through-medium process uses zero-valent iron (ZVI) to remove a wide variety of contaminants from ground water. A passive ZVI barrier has been installed at the Durango, Colorado, UMTRA Project site for removal of radionuclides and metallic contaminants. ZVI is an effective process for removal of heavy metals, uranium, and nitrate. However, its efficacy for removal of ammonia has not been demonstrated, and it is ineffective for sulfate removal. **Because ammonia and sulfate are both COCs for Shiprock, ZVI is not an appropriate primary treatment technology for the Shiprock site, and it was not retained for detailed evaluation.**

8.2.4.4 Biological Processes

Biological processes use bacteria to convert hazardous compounds to other forms that are less hazardous or more amenable to disposal. These processes may be conducted either in situ by injecting the bacteria and/or the carbon nutrient source into the aquifer or ex situ by pumping the water into an above-ground treatment pond or reactor. In situ biological processes were reviewed during the Innovative Treatment Remediation Demonstration (ITRD) process and were rejected for further consideration in the UMTRA Ground Water Project. Therefore, this section will deal only with ex situ processes.

Nitrate, one of the principal regulated COCs in the Shiprock ground waters, is amenable to treatment with biological processes. Biological denitrification can reduce nitrate levels in water to less than the MCL or to the background level. The primary byproduct of denitrification is nitrogen gas (N_2), along with small amounts of nitrous oxide (N_2O). Because nitrogen gas is relatively inert, denitrification generates a treatment residual that does not require handling and disposal, and it has no significant effect on the environment.

Denitrification may be conducted either in a pond or in a biological reactor or series of reactors. A pond-based denitrification process at Shiprock could operate only seasonally because the denitrification reaction loses effectiveness when the water temperature drops below about 50 °F, and it would be impractical to maintain the temperature of a large outdoor pond at 50 °F during the winter months. The treated water would require posttreatment to remove residual organics before it would be suitable for discharge to the San Juan River. Therefore, at Shiprock the biological denitrification process is best suited for indoor reactors, rather than an outdoor pond.

The average sulfate concentration in the terrace system is about 7,000 mg/L. Bacteria that have an affinity for nitrate also have an affinity for sulfate, and desulfurization will take place in parallel with denitrification. While biological denitrification generates nitrogen gas that does not require special handling or disposal and has no significant effect on the environment, biological desulfurization produces hydrogen sulfide (H_2S) as a by-product. Hydrogen sulfide is malodorous, explosive, and extremely toxic. From the bacteriological standpoint, denitrification is the preferred reaction path. However, given the high sulfate levels present in the terrace ground water system, it is virtually inconceivable that denitrification can proceed to the extent required to reduce nitrate levels to below 44 mg/L without significant desulfurization.

Laboratory studies have indicated that sulfate-reducing bacteria can be effective at reducing concentrations of uranium in uranium-bearing ground waters, by reducing the soluble hexavalent form to the tetravalent form that is amenable to precipitation. This process has not yet been implemented in a full-scale water-treatment process, so potential barriers to full-scale operation have not yet been explored. Biological processes do not address selenium, which would need to be removed using some other process.

While removal of sulfate, manganese, selenium, and uranium by biological processes is problematic, those constituents can be easily treated using a membrane process such as nanofiltration or reverse osmosis. Such a combined process was investigated for the Tuba City site but was deemed economically unfeasible because the need for constant operator attention to the membrane process resulted in impractically high O&M costs, despite the low capital cost of the system. However, the much shorter treatment duration of the Shiprock system means that low capital cost is a more important consideration for the Shiprock site than was the case for Tuba City or Monument Valley. **Therefore, biological denitrification was retained for detailed evaluation as part of an integrated treatment process for remediation of the terrace ground water at Shiprock.**

8.2.4.5 Chemical Treatment

Chemical treatment is typically defined as a system using precipitation, coagulation and flocculation, gravity settling, and filtration processes and generally includes addition of chemicals for pH adjustment and formation of precipitates. Such systems are effective for removal of COCs such as uranium, radium, and sulfate. However, conventional chemical treatment processes are not effective for removal of nitrate, which would have to be addressed by some other technology.

Nitrate could be removed using an ex situ biological denitrification process downstream of the chemical process. The removal of sulfates in the chemical process by precipitation of barium sulfate obviates the need for a biological desulfurization step, thus eliminating the need to dispose of hydrogen sulfide formed as a by-product of biological desulfurization.

The alternatives analysis performed during the preparation of the SOWP for the Tuba City remediation project included a detailed analysis of a combined process using biological denitrification along with a chemical process for removal of sulfate and uranium. That analysis assumed that a DOE-owned 100-gpm chemical treatment facility, which was then in operation at the Monticello, Utah, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) site, would be used for the Tuba City remediation. Even with that assumption, the cost analysis for this system at Tuba City concluded that it was a poor choice for that site largely because of high operating costs resulting from the cost of barium chemicals necessary to remediate the sulfate levels at Tuba City. The sulfate concentrations at Shiprock are about 3 times higher than those at Tuba City. Also, the Monticello chemical treatment facility has been claimed by another site and is not available for use at Shiprock, so a new chemical treatment unit would have to be designed and fabricated. **Therefore, chemical treatment does not appear to be viable and was not chosen for detailed evaluation as a treatment alternative.**

8.2.4.6 Membrane Separation Processes

Membrane separation includes all processes in which extremely fine or molecular-level filters are employed. The fine filter, operated under pressure, allows clean water to pass through the element as a clean stream, or permeate, on the downstream side of the element, while the contaminants collect as a concentrate stream, or brine, on the upstream side. The most commonly employed membrane separation processes, in increasing order of effectiveness in removal of dissolved ionic species, are ultra-filtration, nanofiltration, and RO. As a general rule, the more completely a membrane separation process removes contaminants from an aqueous stream, the more brine is produced.

The high levels of nitrate in the Shiprock ground water render any membrane separation process technically unfeasible as a stand-alone system. The nitrate ion has a small molecular diameter and is difficult to remove through filtration. RO, the most effective of the membrane separation processes, can remove nitrate ions at 70- to 90-percent efficiency. The average nitrate concentration in the terrace system (see Table 8–1) is 1,388 mg/L. Meeting the treatment standard of 44 mg/L would require a nitrate removal efficiency of almost 97 percent, which is beyond the capability of any membrane process. Thus, the nitrate removal efficiency of membrane separation processes appears to be inadequate for the requirements of the Shiprock project.

However, membrane separation processes are effective for removal of manganese, selenium, sulfate, and uranium, the other principal COCs at Shiprock. As noted in Section 8.2.4.4, "Biological Processes," biodenitrification is an effective and proven technology for treatment of nitrate-contaminated ground water. Biological denitrification, coupled with membrane separation for removal of selenium, sulfate, uranium, and other COCs with larger molecular diameters than nitrate, has the potential to be an effective treatment process for Shiprock. **Accordingly, the membrane separation process was retained for detailed evaluation, as part of a combined process incorporating biological denitrification, as a treatment alternative for remediation of Shiprock ground water.**

8.3 Evaluation of Alternatives

This section combines technologies evaluated in the previous section into extraction alternatives and treatment alternatives for the terrace ground water system. The floodplain will not be considered directly, but the efficacy of potential extraction and treatment alternatives for use with the floodplain system will be noted during the detailed evaluations.

8.3.1 Extraction Alternatives

Remediation of the terrace will use vertical extraction wells. Administrative issues associated with implementing the extraction alternatives would be minimal because the ground water on the terrace is anthropogenic, resulting from milling activities.

Remediation of the floodplain will use conventional vertical wells.

8.3.1.1 Terrace Extraction Technology—Vertical Extraction Wells

The terrace extraction system consists of vertical wells extending across the saturated zone in the terrace system. The extraction wells would supply feed water for the terrace treatment system. The initial flow rate is projected to be at least 2.5 gpm per well. Over time, the yield per well is expected to decline as the ground water system is dewatered. The overall extraction process is expected to take 1 year for the terrace and an additional year for the floodplain.

8.3.1.2 Effectiveness

Vertical wells are by far the most commonly used technology for ground water extraction. DOE-GJO has conducted several studies of well drilling and construction methods at different UMTRA Project sites and has refined the techniques for constructing wells with high yield per foot of screened area, which is important given the small thickness of the saturated zone at Shiprock. Figure 8–1 shows the distribution of recovery wells that might be considered to achieve dewatering of the terrace ground water system at the required rate. The estimated pumping rate of 2.5 gpm per well, with a total of 47 wells, produces a maximum total extraction rate of 117 gpm when all wells are operating. Actual pumping rates would be determined in the field after the wells were emplaced. Other wells may be installed along the east side of Bob Lee Wash if further studies indicate a need.

8.3.1.3 Implementability

Construction of the well field would be relatively straightforward and could be accomplished using readily available technology. The technical obstacles to constructing a remediation well field are relatively few. Potential obstacles include how to obtain the maximum possible ground water withdrawal rate from each well, how to control sand pumping, and how to control the pumping rates in a large well field. These obstacles can probably be overcome through careful well-design, construction, and development techniques.

8.3.1.4 Cost

The total capital cost for this extraction alternative has not been estimated at this time. Because it is common to all treatment alternatives, the cost of the extraction is not relevant to the process of treatment selection.

8.3.2 Treatment Alternatives

The treatment alternatives to be evaluated in this section are

- Treatment Alternative 1—Solar Evaporation with Spray Enhancement
- Treatment Alternative 2—Distillation
- Treatment Alternative 3—Membrane Separation and Biological Denitrification

The treatment system for the terrace ground water will be designed to treat approximately 50 million gallons, the amount that is estimated to be necessary to dewater the ground water system. The planned duration of the terrace remediation is 1 year, so the average treatment rate is 106 gpm. A similar scenario is proposed for the floodplain.

Cost estimates for all treatment processes will be compared based on a net present worth, calculated over the total project life, using the OMB standard discount rate of 7 percent.

8.3.2.1 Treatment Alternative 1—Solar Evaporation With Spray Enhancement

Effectiveness

All COCs in the terrace ground water system are nonvolatile (with the limited exception of ammonia, for which a pH-sensitive volatile component exists) and will be retained in the brine as the water evaporates for disposal at the end of the project. The evaporation rate for a spray nozzle designed for continuing operation under high solids loading levels is about 5 to 10 percent water loss per pass through the nozzle.

A disadvantage of a spray system, as opposed to a simple evaporation system, is that the water in the simple evaporation pond may be evaporated to dryness. A spray system, however, can only be operated as long as the pond contents remain liquid. Once the liquid in the pond reaches a certain concentration of solids, the efficiency of the spray system begins to drop dramatically. The concentration of solids at this point is still low enough that disposal is impractical without further concentration. The sludge mixture must be evaporated further by solar evaporation before disposal. This step can be done either by taking the spray system out of service and letting the water evaporate in the pond or by transferring the sludge to a second pond for dewatering. Given the short operating lifespan of the Shiprock treatment system, the capital cost of a separate sludge pond cannot be justified. The spray pond can be converted to a simple solar evaporation pond for the sludge at the end of the project, although the time required for the final concentration may be significant because of the small surface area of the pond.

Spray systems usually cannot be operated when wind speeds exceed 15 knots (17 mi per hour). At such times the sprays would be shut off and the pond would operate as a solar evaporation pond. Winds at the Shiprock site are such that the spray system may be expected to be out of service at times.

Evaporation meets the requirements of 40 CFR 192 and is protective of human health and the environment. The only residual produced is the concentrated sludge. The volume of sludge is minimized with this treatment option because evaporation does not require any pretreatment, so no additional chemicals are required.

Implementability

Addition of a spray system to an evaporation pond adds complexity and requires a significantly higher degree of oversight than a simple solar evaporation system. The spray system could operate continuously, although the rate of evaporation from the sprays would be reduced at night. The Shiprock system would spray water that is contaminated with radionuclides into the atmosphere. The concentration of radionuclides in the water would increase significantly as the pond contents become more concentrated. Operating such a system without continuous monitoring is not practical because of the potential for loss of radionuclide containment.

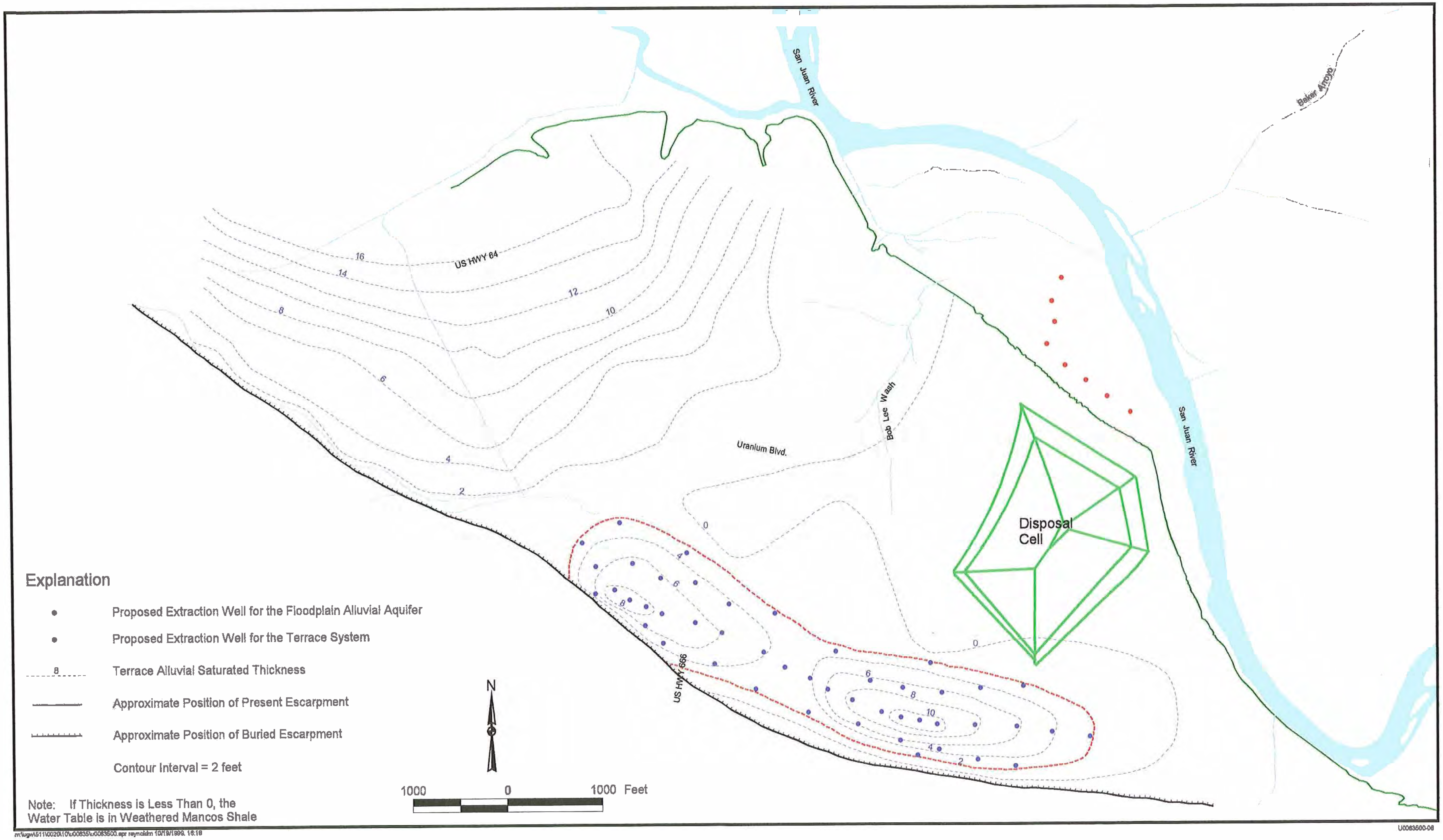

Figure 8–1. Proposed Extraction Wells for the Floodplain Alluvial Aquifer and the Terrace Ground Water System at the Shiprock, New Mexico, UMTRA Site

A pond designed for continuous operation of the spray system would be smaller and less costly to construct than one sized to operate only during daylight hours or during a day shift, but it would require additional staffing. Preliminary estimates indicate that the lower operating costs of a pond designed for operation only during the day shift will more than offset the increased capital cost associated with the larger pond size over the brief duration of the Shiprock remediation. Therefore, the system would be designed assuming operation only during the day shift.

Operating the system would require the following principal functions: embankment inspection and maintenance, liner inspection and repair, water-level monitoring, circulation pump monitoring and maintenance, spray system monitoring and maintenance, and monitoring for leaks. All these functions could be performed by a single operator during the day shift, and the first three functions could be performed with periodic inspections. The need for inspections could be minimized by installing and maintaining adequate fencing to keep livestock and wildlife away from the pond.

Monitoring for leaks consists primarily of monitoring the water levels in the sumps of the leak-detection system, which can be done remotely using a telemetry system. Leak-detection sump pump status could also be monitored remotely using telemetry. Maintenance and repair of pumps and spray nozzles is an on-site function, but round-the-clock presence of maintenance personnel is not required because the spray system will not be operated continuously.

The principal environmental compliance issue associated with maintaining a large, lined pond is uncontrolled release through overflow or leaks. Use of a double-lined pond and an interliner leak-detection system would control subsurface releases. Such engineering controls are highly reliable. Overflow of the pond is unlikely because the water level in a large pond changes relatively slowly and the pond will be monitored on a regular basis by operating personnel.

A large, open body of water in an arid region attracts birds and insects, creating a potential exposure pathway for contamination. As the pond contents become more concentrated, the concentration of uranium, metals, and metalloids (e.g., selenium) in the pond water will increase. Birds and insects may be attracted to the pond and exposed to high levels of contaminants. The risk increases with a spray system in which contaminants become airborne. Thus, the ability to control waterfowl and insect access to heavily contaminated water would be a concern.

Waste disposal will not be an ongoing function for the evaporation system because the bulk of the concentrated sludge can be disposed of at the end of the remedial action. Final disposal will entail stabilizing and removing about 12,000 tons of sludge from the pond and transporting the mass to an authorized disposal site. The pond liner system will also be removed and disposed of at an authorized disposal site at the end of its service life.

Cost

The estimated size of the spray evaporation system that would be required to treat 106 gpm, with the spray system operating only during the day shift, is 1.25 acres. The capital cost of a spray evaporation system of this size is estimated at $870,000, and annual operating costs will also be about $870,000. The net present worth of this treatment alternative, projected over the total estimated time of 2 years, is $2.44 million.

8.3.2.2 Treatment Alternative 2—Distillation

Effectiveness

Evaporation and water recovery using distillation is an established and proven technology for treatment of contaminated water. Table 8–3 presents data that were developed during pilot testing, at the Tuba City site, of a distillation system similar to the one proposed for Shiprock. All concentrations are given in milligrams per liter except for uranium, which is in milligrams per liter.

Table 8–3. Performance of Distillation System

Parameter	Influent	Effluent
Ammonium	61.9	2.09
Nitrate	819	2.48
Sulfate	2,440	0.824
TDS	4,900	37
Uranium	146	<1.1

Most of the TDS in the effluent consisted of ammonium. The ammonium levels in the water from the wells used for the tests at Tuba City were higher than those in the terrace ground water at Shiprock, and the Tuba City tests established that ammonium concentrations in the effluent can be minimized by careful control of the evaporator pH. On the basis of these data, the treated effluent from the distillation system should consistently contain less than 50 mg/L of dissolved solids. The effluent typically will meet or exceed drinking water standards with no further treatment required and will be suitable for any discharge purpose. The concentrated brine, which contains essentially all the dissolved solids, radionuclides, and other nonvolatile contaminants from the original feed, is expected to average about 12 percent of the total feed, given the concentration of contaminants in the Shiprock ground water.

Pretreatment for the feed water is expected to consist of the addition of sulfuric acid for removal of carbonate and of an antiscalant to minimize fouling of the heat-transfer surfaces. The pretreatment chemicals will concentrate in the brine, where they are expected to increase the volume of the residual solids in the evaporation pond by about 5 percent.

Distillation meets the requirements of 40 CFR 192 and is protective of human health and the environment. The treated effluent is of high quality, and the volume of the concentrated brine is only slightly higher than that produced by the evaporation process.

Implementability

Commercial distillation units are self-contained and include all instrumentation required for monitoring and controlling the operation. The units are designed for outdoor operation with no building required to house the unit. The operation of the unit can be monitored at a remote location using the instrumentation and computer software provided as part of the package. The electricity demand of the distillation unit is low.

Commercial distillation systems are reliable and generally require a low level of oversight and only scheduled maintenance during their operating life. Installation of the distillation unit will be straightforward and can be done by project construction personnel working under the supervision of the system supplier. Operation of the distillation system will require a minimum of managerial and technical supervision. The acid pretreatment system can operate unattended, although periodic replenishing of the acid will be required. The cost estimate for the operation of the distillation system allows for two full-time employees 7 days a week on day shift for operation and maintenance.

For optimal operation, the distillation system should be operated as nearly continuously as possible. However, it is expected that the flow rate produced by the extraction system will be variable. To dampen variations in the extraction rate and produce a constant flow rate of feed to the distillation unit, a feed tank of approximately 10,000-gallon capacity would be erected at the site immediately adjacent to the treatment unit. Water from the extraction system would flow into the feed tank, and the distillation unit would take its feed from the tank; the level in the feed tank would be allowed to vary as needed.

Concentrated brine is continuously generated by the distillation process. The brine as discharged from the distillation unit is expected to contain no more than about 10-percent suspended solids, a solids loading low enough that disposal is impractical without further concentration. The brine must be evaporated to dryness. Preliminary calculations indicate that use of a small spray-enhanced solar evaporation pond would be more cost-effective than a larger solar evaporation pond for this purpose. For a discussion of the implementability of solar ponds, see the "Implementability" section under "Treatment Alternative 1—Solar Evaporation with Spray Enhancement."

Cost

The capital cost of the distillation system for the terrace system, including the evaporation pond and required ancillary equipment, is estimated at $3.29 million; annual O&M costs would be about $1.01 million. The present worth cost of this treatment alternative is $5.12 million. These estimates assume that the distillation system is used only at the Shiprock site, and thus the Shiprock project must absorb the entire capital cost.

As described in Section 8.2.4.2, the short duration of remediation at Shiprock makes it feasible to deploy a distillation system at Shiprock for remediation, then disassemble that unit, ship it to Tuba City, and install it at that site. The Tuba City remediation project is expected to last until approximately 2020, so the unit would be used for 16 or 17 years at Tuba City and for only 1 or 2 years at Shiprock. In this scenario, the Shiprock project would assume the cost of initial installation, disassembly at the end of treatment, and a share of the capital cost proportionate to the total portion of its operating lifetime that it would spend at Shiprock. The Tuba City project, which would have the unit for most of its operating lifetime, would absorb the bulk of the capital cost.

Assuming a 2-year duration of treatment at Shiprock, the unit would be deployed for treatment at Shiprock during the year 2003. At the end of that year, it would be disassembled and shipped to Tuba City, where it would be reassembled and operated until 2020. Thus, it would operate at Shiprock for 2 years and at Tuba City for 16 years.

The estimated capital cost of the unit is $2.1 million. This includes $110,000 for installation, so the capital cost of the equipment alone is $1.99 million. One-ninth of this, Shiprock's share, is $220,000. The cost of disassembly at the end of remediation is estimated at $160,000. The cost of the small spray-evaporation system, infrastructure for the unit, and other auxiliary and incidental costs bring the total capital cost of the installation to $1.06 million, and the cost of operating the unit for 1 year is $1.01 million. So the net present worth of this treatment alternative is $2.89 million.

The risks in this approach are, first, that the unit would need to remain at Shiprock longer than 1 year, and, second, that Tuba City would need the unit before remediation at Shiprock was complete. The second does not necessarily presume the first. However, in a practical sense, the current and anticipated level of funding for the UMTRA Ground Water Project will not permit the purchase of more than one distillation system per year. The second phase of treatment at Tuba City is not planned to begin until after remediation has begun at Shiprock. Therefore, there is little likelihood that the unit would be needed at Tuba City sooner than 1 year after remediation at Shiprock has begun.

The possibility that the unit could be needed at Shiprock longer than 1 year must also be considered. There are two reasons why the timetable for remediation at Shiprock might be extended beyond 1 year: (1) The capacity of the extraction system might decline gradually rather than quickly, so that the criteria for supplemental standards cannot be met in 1 year, or (2) the floodplain remediation might require treatment of a significant quantity of water from that source. The decay in extraction rate as dewatering proceeds will be asymptotic, but it is not possible to predict the rate of decay or to project the likelihood that the remediation will require the presence of the treatment unit significantly beyond 1 year.

The distillation system will require construction of a small spray evaporation pond, with an influent capacity of about 13 gpm. In the event that the terrace system continues to yield water at reduced, but still significant, rates for more than 1 year, the distillation system could be disassembled and sent to Tuba City on schedule, and dewatering could continue using the spray-evaporation pond. The extraction rate would necessarily be limited to the capacity of this pond, so if the rate of decay of extraction system yield is gradual, this could artificially extend the duration of remediation at Shiprock. The spray-evaporation pond could also be used to treat contaminated water from the floodplain (assuming that production of treated water from the floodplain is not necessary), but the extraction and remediation rate would be limited to the capacity of the spray system.

8.3.2.3 Treatment Alternative 3—Biological Denitrification With Membrane Separation

Effectiveness

During spring 1998, data were collected on the effectiveness of the RO and nanofiltration processes in support of the remediation of the Monticello, Utah, CERCLA site. These data were collected from two pilot tests using the RO process and one test using the nanofiltration process. The feed water was taken from the feed pond for the Monticello wastewater treatment plant. Table 8–4 presents a summary of the results of these tests. The values given are the percent removal for each constituent, comparing the total quantity in the feed with the total quantity in the product water (permeate). The first RO test was optimized for maximum rejection of

Table 8–4. Removal Efficiency for RO and Nanofiltration Processes

Constituent	RO (first test)	RO (second test)	Nanofiltration
Calcium	99.6	99.6	97.6
Chloride	98.3	98.5	84.2
Magnesium	99.6	99.6	97.8
Nitrate	92.8	76.8	61.9
Selenium	(no data)	(no data)	97.0
Sodium	98.2	98.4	87.8
Sulfate	97.5	98.9	97.4
Uranium	99.4	99.4	98.3

contaminants and generated about 25-percent brine, while the second RO test was optimized for minimum brine generation and produced about 13-percent brine; the nanofiltration test produced about 20-percent brine.

Thus, both membrane separation processes are highly effective against most of the TDS constituents that are present in the Shiprock terrace ground water. The primary exceptions are nitrate and ammonia (ammonia was not present in detectable quantities in the contaminated water at Monticello, so no data were collected on ammonia removal in the study presented in Table 8–4). Neither RO nor nanofiltration is sufficiently effective at removing nitrate to meet the MCL of 44 mg/L given the high concentrations of nitrate in the Shiprock ground water. The proposed process does not use membrane separation to remove nitrate. The nanofiltration process removes other TDS, including sulfate, so that the feed to the biological treatment system contains primarily nitrate. Ammonia can be removed using ammonia stripping, a proven technology.

Assuming that the performance of the full-scale nanofiltration system is comparable to that of the pilot unit tested in 1998, the composition of the nanofiltration process effluent, which is the feed to the biodenitrification system, can be predicted. Table 8–5 presents the results of this prediction. The concentrations of all species, but most noticeably nitrate, in the effluent are higher than might be expected because only about 80 percent of the total feed reports to the effluent stream, with the rest going to brine.

Table 8–5. Predicted Effluent Concentration from Nanofiltration System

Constituent	Feed (mg/L)	Removal Efficiency (%)	Product (mg/L)
Calcium	462	97.6	13.9
Chloride	590	84.2	117
Magnesium	965	97.8	27.0
Manganese	1,535	96.4	0.070
Nitrate	1,388	61.9	665
Selenium	0.761	97.0	0.028
Sodium	1,937	87.8	297
Sulfate	7,178	97.4	236
Uranium	0.331	98.3	0.0072

Studies of the biological denitrification and desulfurization processes indicate that desulfurization will not proceed unless the sulfate loading is 300 mg/L or higher. The predicted sulfate concentration in the nanofiltration effluent is below this threshold, indicating that desulfurization, with its potentially serious consequences, is not likely to be a concern.

Extensive data have been gathered on the efficacy of the biological denitrification process at DOE's Weldon Spring facility near St. Louis, Missouri. The treatment cycle implemented at Weldon Spring produces an effluent containing less than 44 mg/L of nitrate, the MCL for that constituent, from a feed containing about 2,200 mg/L nitrate. The predicted nitrate concentration in the effluent from the nanofiltration unit, as shown in Table 8–5, is 665 mg/L. Thus the denitrification process is capable of meeting MCLs at influent concentrations higher than those that will be treated at Shiprock.

The effluent from the denitrification reactor would be discharged to an RO system to remove residual solids. The permeate from the RO system, which would constitute about 70 percent of the total influent to the treatment system, would be discharged as clean water. The brine, or concentrate, would be directed to a spray-evaporation pond, where it would combine with the brine from the nanofiltration process.

This treatment alternative produces an effluent that meets or exceeds the requirements of 40 CFR 192 and is protective of human health and the environment. Nanofiltration can achieve nearly complete removal of uranium, sulfate, and other dissolved solids from the raw water. Biological denitrification can achieve removal of nitrate from the treatment plant effluent sufficient to meet or exceed the regulatory treatment standard, and the RO polishing step will ensure the quality of the product water that is discharged.

Implementability

Nanofiltration and RO systems are commercially available as packaged treatment systems. One such system was operated at the Monticello CERCLA site during 1998 and 1999. This unit was purchased, deployed, and put into operation within a few weeks. The systems typically are well instrumented and require a minimum of operator attention. There is a low potential for schedule delays in the construction of the system at the Shiprock site. However, specialists will be needed to oversee construction of the system.

Specially trained personnel will be needed to operate the system. An extensive training program will be needed if Navajo Nation residents are to operate this alternative without extensive oversight by DOE technical contractors. A moderate degree of management oversight will be required to ensure that the plant operates safely and efficiently.

The combined process is expected to generate about 10 percent more sludge than the evaporation process. However, the two membrane processes will generate a much higher quantity of brine (reject water) than distillation, on the order of 30 percent of the total feed. This volume of brine will require a significantly larger spray-evaporation pond than the pond required for the distillation system. For a discussion of the implementability issues associated with the construction and operation of spray evaporation ponds, see the "Implementability" section under "Treatment Alternative 1—Solar Evaporation with Spray Enhancement."

The denitrification system consists of a pair of sequencing batched reactors (SBRs) in which the denitrification reaction will take place. The reactors will be operated in a "fill and draw" system in which one reactor is filling while the other is undergoing the denitrification process and preparing for discharge at the end of the treatment cycle. The system will require significant design work but will not be particularly difficult to construct.

Operation of the denitrification facility will take close operator attention. Denitrification is a batch process with a number of process steps that must be carefully controlled. For instance, the pH will drop rapidly once the denitrification process is under way and acidic ions are liberated. The pH of the ground water is around 6.5. If the pH in the reactors drops below about 6, denitrification will stop, and once it has stopped, it cannot be restarted easily. Also, at the end of the nitrate treatment cycle, it may be necessary to aerate the treated water to get the pH into a neutral (7 to 8) range and to strip residual organics that contribute to chemical oxygen demand.

The design presented in this SOWP is based on information from a system vendor who estimated that the denitrification process would require about 16 hours to reach completion. On the basis of this residence time, the SBRs must have a capacity of around 200,000 gallons each. The cost estimate assumes that the SBRs will have approximately this volume. However, sources at the Weldon Spring facility indicate that the ponds there require 3 to 5 days to complete denitrification. This would increase the size of the denitrification reactors at Shiprock to more than 1 million gallons.

The design upon which the cost estimate is based assumes that SBRs can be used. However, the treatment system should not be designed and installed without first testing this assumption on a laboratory or pilot scale. If biological denitrification were chosen as part of the remediation technology at Shiprock, a testing program should be completed before the final design is begun.

The cost estimate assumes that two operators per shift, with round-the-clock operator presence, will be required for continuous operation. One operator will work primarily on the membrane separation units, and the other operator will concentrate on the SBRs. A high degree of management oversight will be required to ensure that the plant operates safely and efficiently. The chemicals necessary for operation of the chemical treatment plant are not available near the site. The nearest source of commercial quantities of chemicals is Albuquerque, New Mexico.

Increasing the capacity of the treatment system will require installing additional membrane separation units and building additional SBRs.

Cost

The capital cost of the membrane-biological treatment system as described, with a capacity of 106 gpm, is estimated at $1.63 million, and annual operating costs will be about $1.47 million. The net present worth of this treatment alternative, for the total estimated remediation time of 2 years, is $4.32 million.

8.4 Comparative Evaluation of Alternatives

The following section compares the three alternative treatment technologies and recommends a proposed treatment alternative for implementation at the Shiprock site. The treatment alternatives are compared with one another on the basis of the evaluation criteria presented in the introduction to this section. To differentiate, where necessary, between the spray evaporation system proposed as Treatment Alternative 1 and the spray evaporation system used for final concentration of the brine generated by the distillation and membrane/biological treatment systems, Treatment Alternative 1 will be referred to as the ground water evaporation system, and the brine spray-evaporation system for Treatment Alternatives 2 and 3 will be referred to as the brine evaporation system.

8.4.1 Comparative Effectiveness

8.4.1.1 Remediation Time Frame

The three treatment alternatives cannot be differentiated based on this criterion. It is possible to design a system, using any one of the three treatment processes, that will meet the required project time schedule. The project time frame is affected by the extraction system, but this is common to all three treatment alternatives. Therefore, this criterion will be dropped from the list of criteria used for evaluating the treatment alternatives for the Shiprock site.

8.4.1.2 Conformance with Project Treatment Standards (40 CFR 192) and Goals

As described in Section 8.1.2, "Evaluation Criteria," the goal of remediation is to dewater the terrace system. All the technologies will achieve this goal. All the treatment processes can be designed to provide optimal protection of health for the plant operators and people living or working in the vicinity, as well as those who depend on the alluvial aquifer for part or all of their water supply.

Should it become desirable to use treated water from the Shiprock remediation for any purpose (the most likely scenario is that remediation of a substantial portion of the floodplain proves necessary and obtaining the necessary water rights proves more difficult than is currently thought), the quality of the treated water from the distillation process is expected to be higher than that from the biological/membrane process, although both are quite high. Evaporation does not produce treated water.

8.4.1.3 Short-Term Effects

All the treatment alternatives are relatively benign in terms of their effect on workers, the community, and the environment. The greatest potential for releases of radionuclides or other hazardous substances is from the spray-evaporation ponds, which are used in all three alternatives. A larger pond is more vulnerable to such accidental releases than a small pond, because releases are most likely to come from the sprays around the perimeter of the pond. Assuming that the distillation system is similar to that being used at Tuba City, leaks from the system itself will not result in releases because the system operates under vacuum. The greatest threat from the biological denitrification system is the accidental production of hydrogen sulfide from desulfurization. There is a slight chance for releases or other damage from the chemical addition used in the distillation and biological denitrification with membrane separation processes, but careful attention to design for chemical containment should minimize this likelihood.

8.4.1.4 Disposal of Treatment Residuals

All treatment processes produce a concentrated sludge that contains the dissolved and suspended solids that were removed from the ground water during treatment. The ground water in the terrace system contains the equivalent of an average of 4,068 tons of sludge per year, based on the average TDS concentration. Sludge production may be expected to vary over the lifetime of the project. The initial rate of sludge production will be relatively high because the extraction rate will be highest at the beginning of the remediation project, and it will decline towards the end of the remediation cycle as the yield of the extraction wells declines.

Distillation (Treatment Alternative 2) will produce about 5 percent more sludge than spray evaporation (Treatment Alternative 1) because of the small amount of sulfuric acid and antiscalant that will be added to the distillation process. Biological denitrification with membrane separation (Treatment Alternative 3) will produce more sludge than distillation, and about 10 percent more than spray evaporation, because of the greater amount of chemicals required and the biological sludge that will be generated.

The other major treatment residual will be the pond liners, pumps, piping, and other paraphernalia that will be disposed of at the end of the remediation program. This is a comparatively small quantity. Because the brine evaporation ponds are smaller than the ground water evaporation pond, they will generate proportionately less of this material. The distillation pond will generate about half as much as the pond required for biological denitrification with membrane separation. Used piping, process equipment, filter elements, etc., that are discarded during treatment or are left over from the treatment systems at the end of the remediation should qualify for free release and disposal at any commercial landfill operation or reuse elsewhere if the need exists. For this reason, estimates of the volume of such materials have not been made.

8.4.2 Comparative Implementability

8.4.2.1 Ease of Construction

The distillation treatment system is a self-contained unit and will be relatively simple to construct. The brine evaporation pond will be more difficult to construct, requiring skilled contract labor to install the liners and the leak-detection systems. The constructability of the ground water evaporation pond is comparable to that of the brine pond, although its larger size will add somewhat to the complexity. The nanofiltration and RO units will be self-contained, but the SBRs will be custom designed and built, and the relatively large number of interconnections between process units will significantly increase the complexity of construction for this process.

8.4.2.2 Ease of Operation and Maintenance

The distillation system is a packaged system designed to require minimal operator interface beyond routine monitoring and is expected to be relatively easy to operate. The system will shut off automatically in the event of problems and will relay the required information to the system monitor. The cost estimate for the distillation system assumes only a single day-shift operator for operations and maintenance, though the operator for the evaporation pond and the extraction system will be available to supplement this operator on the rare occasions that additional labor is expected to be needed. These positions are specialty jobs, and individuals filling them will require extensive training. Maintenance of the distillation system is expected to be infrequent but will not be inexpensive because special parts and services that may only be available from the vendor or manufacturer will be required to repair and maintain these units.

Operation of the spray-evaporation ponds will require monitoring the function of the spray nozzles and pumping systems to eliminate pluggages and leaks, as well as the pond monitoring operations described in "Implementability" for "Terrace Treatment Alternative 1—Solar Evaporation With Spray Enhancement." The larger size of the ground water evaporation pond means that it will require more monitoring and maintenance than the smaller brine evaporation system.

The nanofiltration and RO units are packaged systems. Based on experience with a similar unit at Monticello, the operation of these units is expected to require one full-time operator. The SBRs are expected to require the attention of another operator. The process is not expected to operate overnight unattended, so the cost estimate for biological denitrification with membrane separation includes round-the-clock operator coverage.

8.4.2.3 Expected Reliability

The distillation system is expected to require less than 10-percent down time for routine maintenance. The spray evaporation systems will be somewhat less reliable because of the large number of moving and static parts. The ground water evaporation pond will be less reliable than the brine evaporation pond because its larger size means that it contains more trouble-prone parts. The biological denitrification with membrane separation system includes more unit operations than either of the other two processes, including interfaces between the continuous membrane processes and the batch denitrification process, and may be expected to be less reliable because of the increased complexity.

8.4.2.4 Ability To Handle Changes in Influent Composition

Evaporation, as a process, is not affected by changes in influent composition. Changes in influent concentration will affect the rate of brine generation in the distillation system. However, the contaminants in the ground water are not volatile, so the distillation system is expected to be reasonably tolerant of changes in influent. The membrane processes are also highly nonselective, and the SBRs will be instrumented to permit them to handle significant changes in nitrate loading. One potential problem would be a significant increase in sulfate loading in the feed, or in the nanofiltration effluent, that could cause an increase in the sulfate in the SBR feed, allowing desulfurization to take place. Sulfate loading will have to be closely watched during remediation.

8.4.2.5 Ability To Handle Variations in Extraction Capacity

The turndown capability of the spray evaporation systems is almost infinite because the spray system can be operated for as many hours per day as required to maintain liquid inventory.

The Tuba City distillation unit, with a design flow capacity of 100 gpm, can be operated at feed rates as low as 25 gpm. The turndown capability of each of the two cells in that unit is about 50 percent, and if necessary, one of the cells can be turned off completely. The turndown capability of the Shiprock unit would be comparable. Feed rates less than 25 gpm could be accommodated by putting the unit into hot standby while the feed tank is filled, although this mode would compromise the energy efficiency of the process.

Membrane systems typically lose efficiency when operated at feed rates significantly below their design rate. The SBRs are batch systems and can be operated at essentially any turndown by allowing more time between batch operations.

8.4.3 Comparative Cost

The estimated capital cost, annual O&M cost, and total project cost, expressed as the net present worth (NPW) for each of the individual treatment processes were presented in Section 8.3, "Evaluation of Alternatives," and are presented in Table 8–6. Table 8–6 also includes the cost of a distillation system that is shared with Tuba City, assuming that Shiprock operates the unit for 2 years and Tuba City operates it for 16 years. These cost estimates are for the treatment systems only. Costs for the extraction system have not been estimated because extraction is common to all treatment alternatives and does not affect the comparative evaluation. All costs are in millions of dollars.

Table 8–6. Costs of Treatment Processes

Treatment Alternative	Capital	O&M	NPW
Spray Evaporation	$0.87	$0.87	$2.44
Distillation	$3.29	$1.01	$5.12
Distillation (cost shared with Tuba City)	$1.06	$1.01	$2.89
Biological Denitrification With Membrane Separation	$1.63	$1.47	$4.32

8.4.4 Comparative Summary

The preceding discussion presents 10 evaluation criteria and compares the treatment alternatives for each of these criteria. Table 8–7 lists each of these evaluation criteria and gives the relative rating for each criterion for the three treatment alternatives, with 1 being the highest and 3 the lowest. For example, for criterion 1, Conformance with Project Treatment Standards (40 CFR 192) and Goals, the project goal is dewatering of the terrace system, and all the treatment alternatives will meet this goal, none better than any other. However, the possibility exists that the remediation technology may be required to produce treated water. If this turns out to be the case, distillation, which produces more treated water, of higher quality, than the other two processes, would become the preferred alternative; biological denitrification with membrane separation would be second choice; and spray evaporation, which does not produce treated water, would be third choice.

Determination of Proposed Treatment Process

Treatment Alternative 1—Spray Evaporation is first choice for three of the subjective evaluation criteria (Residual Disposal, Ability to Handle Changes in Influent Composition, and Ability to Handle Variations in Extraction Capacity) and also offers the lowest initial capital outlet and the lowest total project cost. It is second choice for four of the other five subjective criteria. The only area where spray evaporation is not the first or second choice is Conformance with Project Treatment Standards and Goals, and then only because it does not produce treated water. If production of treated water is not a requirement of the project, and at this time it does not appear that it will be, this criterion would be eliminated from the ratings, and spray evaporation would

Table 8–7. Comparative Ranking of Treatment Alternatives

Criterion	Rating on Each Criterion		
	1	2	3
Conformance with Aquifer Restoration Standards (40 CFR 192) and Goals	Distillation	Bio/Membrane[a]	Evaporation
Short-Term Effects	Distillation	Evaporation[b]	Bio/Membrane
Disposal of Treatment Residuals	Evaporation	Distillation	Bio/Membrane
Ease of Construction	Distillation	Evaporation	Bio/Membrane
Ease of Operation and Maintenance	Distillation	Evaporation	Bio/Membrane
Expected Reliability	Distillation	Evaporation	Bio/Membrane
Ability to Handle Changes in Influent Composition	Evaporation	Distillation	Bio/Membrane
Ability to Handle Variations in Extraction Capacity	Evaporation	Distillation	Bio/Membrane
Comparative Cost—Initial Capital Outlay[c]	Evaporation	Bio/Membrane	Distillation
Comparative Cost—Present Worth	Evaporation	Bio/Membrane	Distillation

[a] Bio/Membrane = Biological Denitrification with Membrane Separation
[b] Evaporation = Spray Evaporation
[c] Assumes cost of distillation unit is not shared with Tuba City

have the distinction of rating either first or second on all criteria. However, if production of treated water does become a requirement, spray evaporation would have to be judged unacceptable. Obviously, it is essential that this determination be finalized before design of the treatment system begins.

Treatment Alternative 2—Distillation is first choice for five of the eight subjective evaluation criteria (Conformance with Project Treatment Standards and Goals, Short-Term Effects, Ease of Construction, Ease of Operation and Maintenance, and Expected Reliability) and is second choice for the other three. From a purely process standpoint, then, distillation appears to be the preferred choice.

It should be pointed out that the "subjective" rankings here are more subjective than might normally be the case, because all three treatment alternatives require construction and operation of a spray-evaporation pond. In DOE's judgment, the much larger size of the pond required for the spray evaporation treatment alternative adds so much complexity and risk that distillation, even though it also employs a spray-evaporation pond, is expected to be easier to construct, operate, and maintain than the spray evaporation treatment system.

Distillation has by far the highest capital cost, however. And because of the short treatment duration at Shiprock, the high capital cost results in distillation having the highest overall total project cost even though its O&M costs are lower than those of the biological denitrification with membrane separation process. The cost rankings in Table 8–7 assume that the capital cost of the distillation unit would not be shared with Tuba City. If the cost were to be shared with Tuba City on the basis described earlier, the cost difference between distillation and spray evaporation would be less than the uncertainty in the cost estimates, and they would be considered equivalent both on capital cost and total project cost.

Distillation is currently being implemented at the Tuba City UMTRA Ground Water Project site, and will be implemented at the Monument Valley UMTRA Ground Water Project site in fiscal year 2001. Thus, DOE will have actual experience operating this process at two UMTRA

Ground Water Project sites by the time remediation begins at Shiprock. This is not true of either of the other two processes, and is a significant advantage for distillation.

Treatment Alternative 3—Biological Denitrification with Membrane Separation is the last choice for seven of the eight subjective criteria; only on Conformance with Project Standards and Goals does it manage to move into second place. This ranking does not imply that this alternative is a poor choice. Biological denitrification and membrane separation are proven treatment technologies that are probably in wider use around the world than either of the two competing processes. Given what DOE now believes to be the requirements of the Shiprock project, biological denitrification with membrane separation does not appear to be the preferred alternative. However, there is still uncertainty regarding some of the basic assumptions underlying the Shiprock project, and, depending on the final resolution of those issues, it is possible to construct a scenario under which this alternative might become the process of choice.

The ultimate choice of remediation technology for Shiprock depends on the resolution of two issues: First, will it be necessary for the treatment process to produce treated water? And, second, will it be possible to share the costs of fabrication of the Shiprock treatment system with the Tuba City remediation project?

So the "decision tree" for selection of the treatment process is as follows:

(1) Will it be necessary for the treatment process to produce treated water?

No - Select spray evaporation as the treatment process. Skip the next question.
Yes - Move on to the next question.

(2) Will it be possible to share the costs of fabrication of the Shiprock treatment system with the Tuba City remediation project?

Yes - Select distillation as the treatment process.
No - Select biological denitrification with membrane separation as the treatment process.

DOE currently believes that if remediation of the floodplain is required, the Navajo Nation has sufficient water rights to permit extraction of the required volume from the floodplain, and the Navajo Nation is willing to assign the required rights to DOE with no additional cost to the project. Cost sharing with the Tuba City project, if implemented on the basis described previously, has the potential to make the cost of distillation and spray evaporation equivalent. However, this concept introduces its own complications. The uncertainty in the rate of decline of extraction rates in the terrace, and/or the potential need to treat significant amounts of water from the floodplain, might force an extension of the remediation at Shiprock, which could adversely affect the remediation schedule at Tuba City.

Given these assumptions, Treatment Alternative 1—Spray Evaporation, which offers the lowest cost of any of the treatment processes and is technically competitive, is the preferred treatment technology for the Shiprock ground water remediation project.

8.5 Proposed Remediation Process

8.5.1 Description of Proposed Remediation Process

The proposed remediation process consists of the extraction and treatment systems. This section presents a discussion of each of those systems.

8.5.1.1 Proposed Extraction System

The objective of the proposed pumping alternative is to extract contaminated ground water from the terrace system and deliver it to the treatment system at a rate that will dewater the terrace ground water system within 1 year and the floodplain system the next year.

The extraction system for the terrace system consists of 47 vertical extraction wells, varying in depth to a maximum of about 60 ft with screened lengths varying from 5 to 15 ft. The expected flow rate per well is 2.5 gpm, giving the extraction system a peak capacity of 117 gpm once all wells are in service. Figure 8–1 presents a conceptual arrangement of the wells. Eight extraction wells are currently planned for the floodplain. This number and their location could change based on field studies planned for fiscal year 2000.

A typical extraction-well design for the Shiprock site consists of a 10-in.-diameter borehole completed with 6-in.-diameter stainless steel wire-wrapped well screen and a blank PVC riser. The section of the well containing the well screen will be completed with an appropriately sized sand pack. The final design of the well and the size of the pump will be optimized based on field conditions.

8.5.1.2 Proposed Spray-Evaporation Treatment System

The output of the extraction wells will be piped directly to the spray evaporation pond. The preliminary design of this pond suggests an area of about 1.25 acres, with a minimum depth of 6 ft. The pond will contain approximately 100 fog-type spray nozzles, fed from 13 circulating pumps. The spray system will be operated during the day shift only and will be shut down at times of high wind.

The pond will be double-lined utilizing appropriate geosynthetics and geocomposite materials, and will incorporate an interliner leak-collection sump with level controls and a sump pump and a leak-detection system for the lower liner. Although wildlife in this populated area is not common and there are other sources of clean water for waterfowl and migratory birds in the immediate vicinity, appropriate wildlife and bird controls and mitigation measures will be incorporated in the design.

8.5.2 Summary

The proposed system will meet the project goal of dewatering the terrace ground water system. The water from this system, which is anthropogenic and results primarily from milling activity at the site, will be extracted and evaporated. All hazardous constituents will be retained in the pond and removed for disposal at a remote location at the conclusion of the remediation project. When additional information about any sources of continuing contamination to the floodplain is evaluated, the contaminated water from that source will also be directed to the evaporation pond.

8.5.3 Limitations of Proposed Alternative

The Shiprock remediation is problematic for a number of reasons that have been detailed elsewhere in this SOWP. Unresolved technical and political issues include the following:

- The exact extent of contamination in the terrace ground water system has not yet been determined.
- There is a strong possibility of a hydrologic connection between the terrace system and the irrigated areas on the terrace to the northwest.
- Ground water in a background terrace location has not been found.
- The exact connection between the contamination in the terrace ground water system and the seeps along Bob Lee Wash, Many Devils Wash, and the escarpment has not been established.
- The existence of a continuing source of contamination into the floodplain is based on hydrologic modeling. Additional sampling and analyses are required to establish the nature and extent of any continuing source.
- DOE does not have final confirmation of the water rights that would permit the use of evaporation at the site.

A successful remediation will require resolution of all of these issues. For instance, the remediation of the terrace ground water assumes that percolation into the ground from other sources is negligible and that it can be dewatered fairly quickly. Once dewatering begins, if there is a hydrologic connection between the contamination in the ground water system and the irrigated areas to the northwest, the extraction will begin to draw relatively uncontaminated water from the irrigated areas. This action could potentially introduce a considerable volume of water that is not a result of milling operations and does not require remediation.

Dewatering of the terrace ground water is predicated on the assumption that contaminated water from the milling operations is slowly migrating toward the edges of the terrace, creating contaminated seeps along the escarpment at the edges of the terrace and in washes that incise the terrace. Dewatering the large saturated zone in the center of the terrace system is expected to cut off the source of water to these seeps, which will eventually dry up, eliminating the risk. The hydrologic connection between the saturated zone and the seeps has not been established. If dewatering of the terrace ground water does not dry up the seeps, the remediation program as currently outlined will not be successful. Additional wells may be required near Bob Lee Wash and Many Devils Wash, directly upgradient of the washes toward the disposal cell.

Technical criteria will need to be established to evaluate the success of the remediation. These criteria will be developed in the GCAP after discussion with stakeholders. The GCAP will define the logic that will be used to evaluate the success or failure of the remedial actions. It will also propose the steps that might be taken if the remediation fails to have any effect on the seeps at the terrace periphery or reducing contamination on the floodplain at the base of the seeps.

Even more so than most remediation projects, the Shiprock project is driven by the success of the extraction process. The main factors that influence the effectiveness of ground water extraction systems are hydraulic inefficiencies, heterogeneity of the ground water system, and sorption of contaminants to the ground water system material. Hydraulic inefficiencies account for the diffusion of contaminants into low-permeability sediments and hydrodynamic isolation (stagnation points) within a well field. Heterogeneities of the ground water system (e.g., changes in the hydraulic conductivity and effective porosity) will affect the ability to extract ground water from all areas of the ground water system. The sorption of contaminants to the ground water system material retards the movement of the contaminants in the ground water. The more a contaminant sorbs to the ground water system matrix, the more ground water must be extracted to remove the contaminant.

If dewatering of the terrace and floodplain fails to achieve the desired risk elimination, other methods of protecting human health would have to be pursued. A provision in 40 CFR 192 allows the use of ACLs that would be set at higher concentrations than the current cleanup goals but that would still be protective of human health.

Interim actions (see following section) are currently planned for the Shiprock site before remediation begins. These actions include capturing the highly contaminated seeps along Bob Lee Wash and Many Devils Wash and providing containment of the drainage until it can reach the San Juan River where it will be infinitely diluted. If the remediation program described in this document is unsuccessful, the only alternative may be to upgrade these installations to make them permanent.

8.6 Proposed Interim Actions

Several areas in which the potential for risk exists have been identified. These potential risks are outside the area that would be immediately affected by the proposed remediation process and will require independent actions. These risk areas are Bob Lee Wash, Many Devils Wash, and to a lesser degree, the radon cover borrow pit.

Table 8–8 presents the concentrations of each of the terrace COCs in surface water samples from the two washes, based on the December 1998 sampling at sample point 885 and the March 1999 sampling at the other two points. It also gives the concentrations of each of these contaminants from a June 1998 sampling of artesian well 648, which outflows onto the floodplain through Bob Lee Wash. All concentrations are given in milligrams per liter.

Table 8–8. Surface Water Contamination on the Terrace

Constituent	Sample Location			
	885	886	889	Well 648
	Bob Lee Wash	Many Devils Wash	Many Devils Wash	Outflow to Bob Lee Wash
Ammonia	0.378	0.137	0.0788	0.585
Manganese	0.0387	0.0052	0.0091	0.0886
Nitrate	284	3,800	3,570	0.0265
Selenium	0.119	2.78	2.44	<0.001
Sulfate	4,930	23,400	21,400	2,000
Uranium	1.23	0.193	0.178	<0.001

8.6.1 Bob Lee Wash

Bob Lee Wash is west and northwest of the disposal cell and the NECA facility. Outflow from artesian well 648 discharges into Bob Lee Wash before the wash drains onto the floodplain. The flow in Bob Lee Wash is ephemeral upstream of the well 648 outflow and perennial downstream of the outflow. The surface water in Bob Lee Wash, as measured at sample point 885 (which is upstream of the well 648 outflow), exceeds the UMTRA MCLs for nitrate, selenium, and uranium and the risk-based concentration for sulfate.

The long-term remediation strategy for Bob Lee Wash is to dewater the terrace system to eliminate the source of contaminated ground water. The interim action for Bob Lee Wash will incorporate the following actions:

- Construct a French drain along the bottom of the main wash. This drain will collect subsurface water and drain it into the main drainage downgradient of the point where well 648 outflow drains into the wash.

- Construct a French drain in the tributary drainage from the southeast to intercept any subsurface flows from the former ore processing area just to the east. This French drain would drain into the main French drain described above.

- Place riprap in low areas of the main drainage where subsurface and surface runoff has accumulated.

- Install a fence around the perimeter of the drainage area of the wash to keep livestock from entering and to minimize human access.

Dilution of surface water by water from well 648 should result in a final mixture that will only marginally exceed the risk-based standard for sulfate. Table 8–9 presents the composition of water from well 648 and surface water at sample point 662, which is downstream of where outflow from well 648 enters Bob Lee Wash.

Table 8–9. Surface Water Contamination in Bob Lee Wash

Constituent	Sample Location	
	Well 648	662
	Artesian (Bob Lee Wash)	Bob Lee Wash (below 648 outflow)
Ammonia	0.585	0.0143
Manganese	0.0886	0.0028
Nitrate	0.0265	1.38
Selenium	<0.001	<0.001
Sulfate	2,000	2,060
Uranium	<0.001	<0.001

The composition of outflow water from well 648 and surface water from location 662 are similar. This shows that the contaminated seep water in upper Bob Lee Wash is sufficiently diluted by well 648 outflow water by the time it reaches location 662.

8.6.2 Many Devils Wash

Many Devils Wash is southeast of the disposal cell and the NECA gravel pit. The wash is ephemeral south of sample point 889 at the siltstone bed nickpoint. North of that sample point, the wash seems to contain water year-round or nearly so, but the flow is low except during and immediately after storms. Many Devils Wash drains into the San Juan River at a location where no floodplain exists.

The surface water in Many Devils Wash, as measured at sample points 886 and 889, is extremely contaminated, exceeding the UMTRA MCLs for nitrate and selenium by 2 or more orders of magnitude and the MCL for uranium by 5 to 12 times. Sulfate levels in samples from Many Devils Wash are also extremely high; sulfate concentrations at both sample points exceeded 21,000 mg/L.

The long-term remediation strategy for Many Devils Wash is to dewater the terrace system to eliminate the source of contaminated ground water. The interim action for Many Devils Wash will incorporate the following actions:

- Install a French drain along the bottom of the wash south of the siltstone bed nickpoint. This drain will collect surface and subsurface water and will "daylight" on the siltstone bed at the nickpoint.
- Install riprap in the bottom of the wash from the nickpoint downstream to the mouth of the wash at the San Juan River.
- Install a fence in the main wash north of the confluence of the tributary drainage from the southeast. A fence would also be installed along the entire west boundary of the wash on the upper terrace and along the east side of the wash at strategic points tying into the loess cliffs. The fences would keep livestock from entering the wash area. A livestock pass or corridor would be fenced just above the nickpoint to allow livestock to cross the wash.

8.6.3 Notes on Interim Actions

The candidate areas will be investigated for the presence of threatened and endangered species and cultural sites. If any are identified, measures will be developed to avoid or to mitigate the effects of this action on species and/or sites.

The interim actions at Bob Lee Wash and Many Devils Wash will increase the flow of contaminated water into the San Juan River, particularly from Many Devils Wash. But its effect is expected to be insignificant considering the small flows in the washes (less than 5 gpm combined) compared with the diluting effect of the average flow rate of about 1,000 cfs, or 450,000 gpm, of the San Juan River.

At the present time, no treatment of the water collected from either of the interim actions is contemplated. The remediation program for the UMTRA Ground Water Project site at New Rifle, Colorado, includes a laboratory and pilot study of the effectiveness of ZVI on the COCs at that site, which include nitrate, ammonia, vanadium, and uranium. ZVI is known to be ineffective for remediation of sulfate. However, if the New Rifle studies indicate that use of ZVI can substantially reduce levels of nitrate or other Shiprock COCs, it would be relatively simple to add a ZVI treatment stage, either in the form of a passive barrier (such as has been incorporated at the Durango, Colorado, UMTRA Project site) or a small reactor, to reduce levels of those COCs in the ground water prior to discharge into the San Juan River.

If further hydrologic evaluation indicates that the current extraction well nests are not adequate to remove water from the seeps in the two washes, additional wells may be proposed. The location of the wells would be between the former millsite and the washes.

8.6.4 Radon Cover Borrow Pit

The radon cover borrow pit is just south of the disposal cell (Plate 1). The pit has been identified as a potential collection point for storm water runoff, which would cause subsequent infiltration of water into the terrace ground water system and perhaps under the disposal cell. There have been reports of 2 to 3 inches of ponded water in the pit after heavy rainstorms such as those that occurred during October 1998, but these reports have not been verified by DOE observation.

During the interim action period, DOE will attempt to document ponding in the pit immediately after major rainstorms to determine if it does act as a significant collection point for water drainage in the area. Should this prove to be the case, interim action for the radon borrow pit would consist of installing a drain pipe that would allow the pit to drain northwest into Bob Lee Wash.

End of current text

9.0 References

40 CFR Part 192. "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings," *U.S. Code of Federal Regulations*, July 1, 1996.

40 CFR Part 1507.3 "Agency Procedures," *U.S. Code of Federal Regulations*, July 1, 1997.

42 U.S.C. 4321 *et. seq.* "National Environmental Policy Act," Public Law 91-90, *United States Code*, January 1, 1970.

42 U.S.C. §7901 *et seq.*, "Uranium Mill Tailings Radiation Control Act," *United States Code*, November 8, 1978.

42 U.S.C. §7922 *et seq., Uranium Mill Tailings Remedial Action Amendments Act,* November 5, 1988.

60 FR 2854, "Ground Water Standards for Remedial Actions at Inactive Uranium Processing Sites; Final Rule," *Federal Register,* January 11, 1995.

Albrethsen, H., Jr., and F.E. McGinley, 1982. *Summary History of Domestic Uranium Procurement under U.S. Atomic Energy Commission Contracts*, Final Report, GJBX-220(82), prepared for the U.S. Department of Energy, Assistant Secretary for Nuclear Energy, Grand Junction Area Office, Grand Junction, Colorado.

Allen, J.W., W.D. Steele, S.J. Marutzky, and R.A. Showalter, 1983. *Radiologic Characterization of the Shiprock, New Mexico, Uranium Mill Tailings Remedial Action Site*, GJ-11(83), prepared by Bendix Field Engineering Corp. for U.S. Department of Energy, UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

American Society for Testing and Materials (ASTM), 1993. "Standard Practice for Diamond Core Drilling for Site Investigation, Designation D 2113-81 (reapproved 1993).

———, 1993. "Standard Test Method for 24-h Batch-Type Measurement of Contaminant Sorption by Soils and Sediments," Designation D 4646-87 (reapproved 1993).

———, 1995. "Standard Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers," Designation D 5092-90 (reapproved 1995).

Bench, 1996. *Screening Benchmarks for Ecological Risk Assessment,* Oak Ridge National Laboratory, Version 1.6, October.

Bonham, C.D., 1989. *Measurements for Terrestrial Vegetation,* John Wiley and Sons, New York.

Ecosphere Environmental Services, 1998. *A Survey for Sensitive, Threatened, and Endangered Species for the Proposed UMTRA Ground Water Project, Shiprock Site on Navajo Nation Tribal Land in San Juan County, New Mexico*, August.

Ecosphere Environmental Services, 1999. *A Survey for Sensitive, Threatened, and Endangered Species for the Proposed Floodplain/Wetlands Assessment for the Shiprock, New Mexico, Uranium Mill Tailings Remedial Action Project*, Februrary.

EG&G, 1981. *An Aerial Radiological Survey of the Shiprock, New Mexico, Uranium Mill Tailings Site and Surrounding Area*, prepared for the Remote Sensing Laboratory of the U.S. Department of Energy, June.

Emerson, K., R.C. Russo, R.E. Lund, and R.V. Thurston, 1975. *Aqueous Ammonia Equilibrium Calculations: Effect on pH and Temperature*, J. Fish Res. Board.

Environmental Simulations Inc. (ESI), 1999. *Guide to Using Aquifer* ^{win32}, Environmental Simulations Inc., 2997 Emerald Chase Drive, Suite 100, Herndon, Virginia 22071.

Evangelou, V.P., L.D. Whittig, and K.K. Tanji, 1984. "Dissolved Mineral Salts Derived from Mancos Shale," J*ournal of Environmental Quality*, 13(1):146–150.

Federal Register, Wednesday January 11, 1995, p. 2863 Volume 60, No. 7.

Ford, Bacon & Davis Utah, Inc. (FBDU), 1977. *Phase II—Title I Engineering Assessment of Inactive Uranium Mill Tailings, Shiprock Site, Shiprock, New Mexico*, GJT-2, prepared for U.S. Energy Research and Development Administration, Grand Junction, Colorado, March.

———, 1981. *Engineering Assessment of Inactive Mill Tailings, Shiprock Site, Shiprock, New Mexico*, DOE/UMT-0104, prepared for U.S. Department of Energy, Albuquerque Operations Office, UMTRA Project Office, Albuquerque, New Mexico, July.

Geological Society of America (GSA), 1975. *Rock-Color Chart*, prepared by the Rock-Color Chart Committee, Boulder, Colorado.

GretagMacbeth, 1994. *Munsell Soil Color Charts*, Munsell Color Company, New Windsor, New York.

Hem, J.D., 1985. "Study and Interpretation of the Chemical Characteristics of Natural Water," 3rd Edition, U.S. Geological Survey Water-Supply Paper 2254.

James, J., 1999. Personal communication, Navajo Engineering and Construction Authority, 505.368.3006, August.

Kabata-Pendias, A., and H. Pendias, 1992. *Trace Elements in Soils and Plants*, 2nd Edition, CRC Press, Boca Raton, Florida.

Leopold, L.B., M.G. Wolman, and J.P. Miller, 1964. *Fluvial Processes in Geomorphology, A Series of Books in Geology*, San Francisco, W.H. Freeman and Company.

Love, D.W., and M.L. Gillam, 1991. Navajo and Acoma-Zuni Sections, in Chapter 13, "Quaternary Geology of the Colorado Plateau," in R.B. Morrison, ed., Quaternary Nonglacial Geology; Conterminous U.S.: Boulder, Colorado, Geological Society of America, the Geology of North America, v. K-2, pp. 391-397.

Mackin, J.H., 1937. "Erosional History of the Big Horn Basin, Wyoming," *Geological Society of America Bulletin*, v. 48, pp. 813-894.

McDonald, M.G., and A.W. Harbaugh, 1988. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model: Techniques of Water-Resources Investigations of the United States Geological Survey*, Book 6, Chapter 6-A1.

McKinley and Long, 1999. Natural and Accelerated Bioremediation Research Program, Pacific Northwest National Laboratory, Richland, Washington, unpublished data.

Merritt, R.C., 1971. *The Extractive Metallurgy of Uranium*, Colorado School of Mines Research Institute, prepared under contract with the U.S. Atomic Energy Commission, 576 p.

MK Ferguson, 1987. *Shiprock, New Mexico, Uranium Mill Tailings Site Remedial Action Completion Report*, Final, three volumes, UMTRA Project Office, Albuquerque, New Mexico, August.

Molenaar, C.M., D. Nummedal, and W.A. Cobban, 1996. "Regional Stratigraphic Cross Sections of the Gallup Sandstone and Associated Strata Around the San Juan Basin, New Mexico, and Parts of Adjoining Arizona and Colorado," U.S. Geological Survey Oil and Gas Investigations Chart OC-143.

Molzen-Corbin & Associates, 1993. *Navajo Tribal Utility Authority Shiprock Water Supply Study*, Draft Final, prepared by Molzen-Corbin & Associates, Albuquerque, New Mexico.

Navajo Nation, 1998. Water Quality Standards of the Navajo Nation.

Neuman, S.P., 1972. "Theory of Flow in Unconfined Aquifers Considering Delayed Response of the Water Table," *Water Resources Research*, v. 8, No. 4, no. Aug., pp. 1031-1045.

O'Sullivan, R.B., and H.M. Beikman, compilers, 1963. "Geology, Structure, and Uranium Deposits of the Shiprock Quadrangle, New Mexico and Arizona," U.S. Geological Survey Miscellaneous Geologic Investigations Map I-345.

Parker, G.G., Sr., and C.G. Higgins, 1990. "Piping and Pseudokarst in Drylands," with case studies by G.G. Parker, Sr., and W.W. Wood, in C.G. Higgins, and D.R. Coates, eds., *Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms*, Boulder, Colorado, Geological Society of America Special Paper 252, pp. 77-110.

Pollock, D.W., 1989. *Documentation of Computer Programs to Complete and Display Pathlines Using Results from the U.S. Geological Survey Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*, U.S. Geological Survey Open-File Report 89-381.

Saggboy, M., 1999. Personal communication, Shiprock Irrigation District, 505.368.1062, August.

Stone, W.J., F.P Lyford, P.F. Frenzel, N.H. Mizell, and E.T. Padgett, 1983. *Hydrogeology and Water Resources of San Juan Basin, New Mexico,* New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 6.

Theis, C.V., 1935. "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage," *Transactions American Geophysical Union*, v. 16, pp. 519-524.

Tsosie, B.B., 1997. "Hydrogeologic Characterization of the Floodplain that Lies Below the Uranium Mill Tailings Remedial Action Site at Shiprock, New Mexico," master's thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

U.S. Atomic Energy Commission, 1974. "Report on Conditions of Uranium Millsite and Tailings at Shiprock, New Mexico," in *Summary Report, Phase I Study of Inactive Uranium Mill Sites and Tailings Piles*, Volume 1, October.

U.S. Bureau of Reclamation, 1974. *Field Permeability Tests in Boreholes: Earth Manual*, U.S. Department of Interior.

U.S. Department of Energy (DOE), 1983. *Geochemical Investigation of UMTRAP Designated Site at Shiprock, New Mexico*, UMTRA-DOE/AL-0233, prepared by G. Markos and K. J. Bush of Geochemistry and Environmental Chemistry Research, Inc., Rapid City, South Dakota, September.

———, 1984a. *Environmental Assessment of Remedial Action at the Shiprock Uranium Mill Tailings Site, Shiprock, New Mexico*, two volumes, DOE/EA-0232, UMTRA Project Office, Albuquerque, New Mexico, May.

———, 1984b. *Processing Site Characterization Report for Uranium Mill Tailings Site at Shiprock, New Mexico*, UMTRA-DOE/AL-0042, prepared for DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico, April.

———, 1985. *Remedial Action Plan and Site Conceptual Design for Stabilization of the Inactive Uranium Mill Tailings Site at Shiprock, New Mexico,* UMTRA–DOE/AL 0505040039.

———, 1993. *Recommendations for the Preparation of Environmental Assessments and Environmental Impact Statements*, Office of NEPA Oversight, Washington, DC, May.

———, 1994. *Baseline Risk Assessment of Ground Water Contamination at the Uranium Mill Tailings Site at Shiprock, New Mexico,* DOE/AL/62350-48F, Rev. 1. April 1994.

———, 1995. *Site Observational Work Plan for the UMTRA Project Site at Shiprock, New Mexico*, DOE/AL/62350–158, Rev. 0, prepared by Jacobs Engineering Group Inc. for the U.S. Department of Energy UMTRA Project Office, Albuquerque, New Mexico.

———, 1996a. *Addendum to the Sampling and Analysis Plan for the UMTRA Ground Water Project*, P–GJPO–2353, Rev. 1, prepared by MACTEC–ERS for the U.S. Department of Energy, Grand Junction Office, Grand Junction, Colorado, November.

U.S. Department of Energy (DOE), 1996b. *Final Programmatic Environmental Impact Statement for the Uranium Mill Tailings Remedial Action Ground Water Project,* DOE/EIS–0198, prepared by the UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico, October

———, 1996c. *Geophysical Surveys at the UMTRA Project Shiprock, New Mexico, Site*, DOE/AL/62350-231, Rev. 0, March 1996, prepared by prepared by Geraghty and Miller, Inc. for U.S. Department of Energy, Albuquerque Operations Office, Albuquerque, New Mexico.

———, 1996d. *Supplement to the Baseline Risk Assessment of Ground Water Contamination at the Uranium Mill Tailings Site Near Shiprock, New Mexico*, DOE/AL/62350-485, Rev. 1, prepared by Jacobs Engineering Group Inc. for U.S. Department of Energy, Environmental Restoration Division, UMTRA Project Team, Albuquerque, New Mexico, March.

———, 1997. *Organic Constituents in Ground Water at UMTRA Sites*, U.S. Department of Energy, Grand Junction Office, MAC–2013, Grand Junction, Colorado.

———, 1998a. *Environmental Procedures Catalog,* Manual, GJO–6, continuously updated, prepared jointly by MACTEC–ERS and *WASTREN, Inc.* for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

———,1998b. *Standard Test Method for the Measurement of Water Levels in Ground Water Monitor Wells.*

———, 1998c. *Work Plan for Characterization Activities at the Shiprock UMTRA Project Site*, MAC–GWSHP 1.8, prepared by MACTEC Environmental Restoration Services for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

———, 1999a. *Column Leaching of Floodplain Sediments with Synthetic San Juan River Water, UMTRA Ground Water Project, Shiprock, New Mexico, Site*, ESL–RPT–99–05, prepared by Environmental Sciences Laboratory for U.S. Department of Energy, Albuquerque Operations Office, Grand Junction Office, Grand Junction, Colorado, August.

———, 1999b. *Composition of Salt Deposits, UMTRA Ground Water Project, Shiprock, New Mexico, Site*, ESL–RPT–99–03, prepared by Environmental Sciences Laboratory for U.S. Department of Energy, Albuquerque Operations Office, Grand Junction Office, Grand Junction, Colorado, July.

———, 1999c. *Contaminants in Soils and Sediments, UMTRA Ground Water Project, Shiprock, New Mexico, Site*, ESL–RPT–99–04, prepared by Environmental Sciences Laboratory for U.S. Department of Energy, Albuquerque Operations Office, Grand Junction Office, Grand Junction, Colorado, August.

———, 1999d. *Determination of Distribution Ratios for UMTRA Ground Water Project, Shiprock, New Mexico, Site*, ESL–RPT–99–01, prepared by Environmental Sciences Laboratory for U.S. Department of Energy, Albuquerque Operations Office, Grand Junction Office, Grand Junction, Colorado, June.

U.S. Department of Energy (DOE), 1999e. *Environmental Sciences Laboratory Procedures Manual*, Revision 0, MAC–3017, prepared by MACTEC Environmental Restoration Services, LLC, for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.

———, 1999f. *Final Site Observational Work Plan for the UMTRA Project Site at Grand Junction, Colorado*, GJO-99-86-TAR, Rev. 1, prepared by U.S. Department of Energy for Grand Junction Office, Grand Junction, Colorado, May.

———, 1999g. *UMTRA Ground Water Project Management Action Process (MAP) Document*, MAC–GWADM 1.1, Rev. 1, Grand Junction Office, Grand Junction, Colorado, May.

U.S. Department of Health, Education, and Welfare, 1962. *Stream Surveys in Vicinity of Uranium Mills, IV, Area of Shiprock, New Mexico*, Public Health Service, Region VIII, Denver, Colorado, December.

U.S. Environmental Protection Agency (EPA), 1989a. *Risk Assessment Guidance for Superfund, Volume 1: Health Evaluation Manual, Part A*, EPA/540/1-89/0023, Office of Emergency and Remedial Response.

———, 1989b. *Exposure Factors Handbook*, EPA/600/8-89/04, Office of Health and Environmental Assessment.

———, 1991. *Human Health Evaluation Manual, Supplemental Guidance: Standard Default Exposure Factors*, Office of Solid Waste and Emergency Response, Directive 9285.6-03, March.

———, 1992. *Framework for Ecological Risk Assessment*, EPA/630/R-92/001, U.S. Environmental Protection Agency Risk Assessment Forum.

———, 1998. *Guidelines for Ecological Risk Assessment (Final)*, Risk Assessment Forum, EPA/630/R-95/002F, April.

——, 1999. Health Effects from Exposure to High Levels of Sulfate in Drinking Water Study. EPA 815-R-99-001, January. Office of Water.

University of Missouri-Rolla, 1981. "Pump-In Permeability Testing," Conference Proceedings, Orlando, Florida.

Ward, A.W., 1990. "Geologic Map Emphasizing the Surficial Deposits of the Farmington 30' x 60' Quadrangle, New Mexico and Colorado," U.S. Geological Survey Miscellaneous Investigations Series Map I-1978, scale 1:100,000.

Zheng, C., 1990. *MT3D, A Modular Three-Dimensional Transport Model, Version 1.5, Documentation and User's Guide*, Papadopulos & Associates, Inc., Bethesda, Maryland, March.